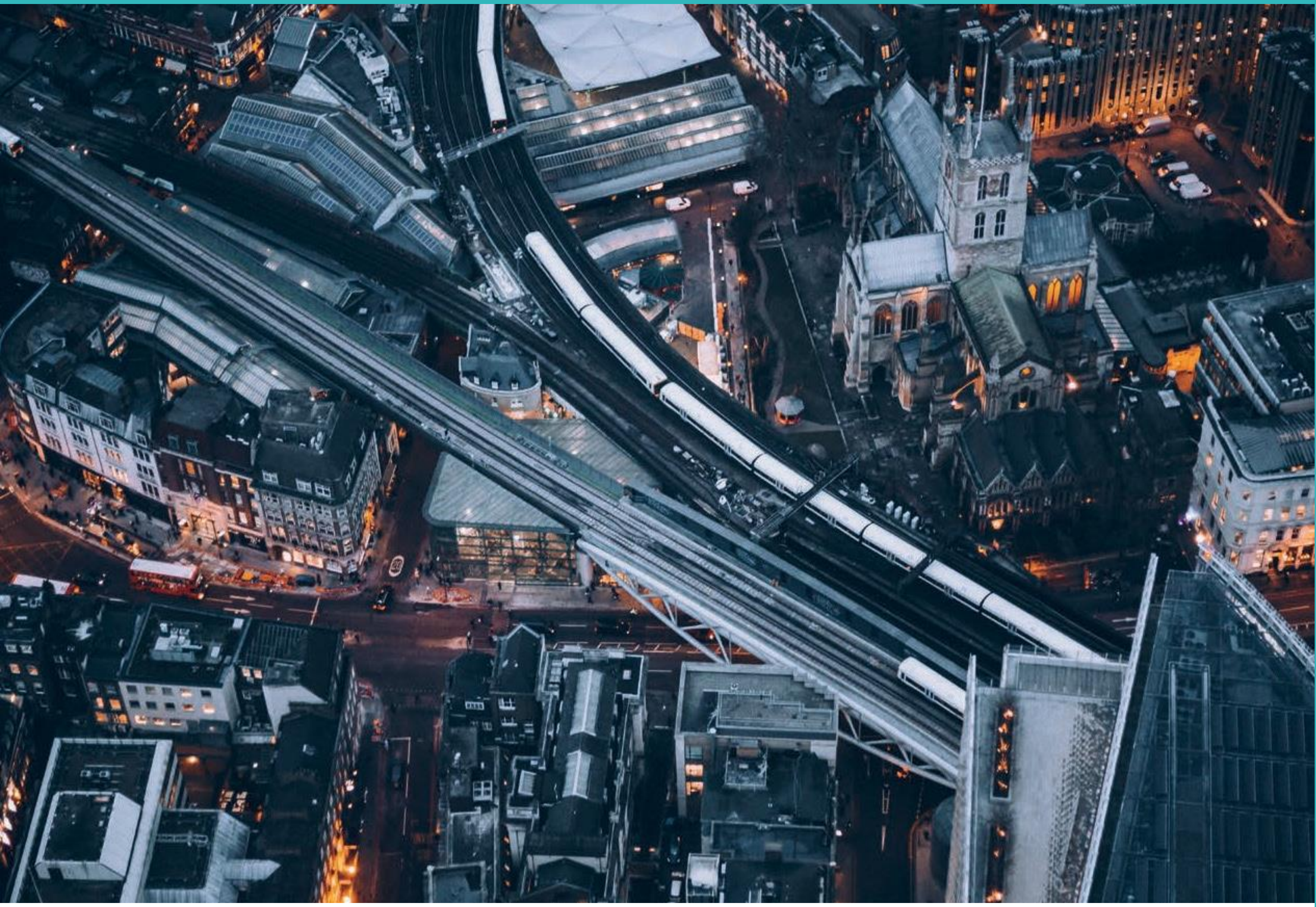


REPORT

# Foresight Project

CONFIDENTIAL

Prepared for: Northern Powergrid

Project No: 94150
Document Version: 1.0
Date: 16 July 2021

ea technology

# Contents


Background & Introduction ........ 1
Status of learning at the start of the project ........ 1
2.1 The problem that the Foresight project sought to address ........ 1
2.2 The solution which was to be demonstrated as feasible by the project ........ 2
2.3 Methods which were planned to be used in the project ........ 4
A New LV Cable Fault Management Methodology ........ 5
3.1 Stages of Fault Development ........ 5
3.2 Proactive Fault Management Methodology ........ 6
3.3 Pre-Fault Detection ........ 8
3.4 Prioritisation of Circuits for Proactive Intervention Based on Condition Assessment ........ 10
3.5 Incremental Equipment Deployment ........ 13
3.6 Method for the Location of Developing Faults ........ 15
3.7 Proactive Mitigation ........ 20
3.8 Post-Repair Monitoring and Redeployment of Equipment ........ 23
Cost Benefit Analysis ........ 25
Project Management ........ 25
5.1 Original Scope ........ 25
5.2 Change Control ........ 25
5.3 Project Execution ........ 26
Project Summary ........ 29


## Appendices


Appenidx A Monitoring System Captures to End July 2020

# Version History

| Date | Version | Author(s) | Notes |
|---|---|---|---|
| 21/05/2021 | 0.1 | David Roberts,<br>Mike Lees | Issued for Internal Comment/Approval |
| 26/05/2021 | 0.2 | David Roberts,<br>Mike Lees | Issued to Northern Powergrid |
| 16/07/2021 | 1.0 | David Roberts,<br>Mike Lees | Issue for Publication |

# Final Approval

| Approval Type | Date | Version | EA Technology Issue Authority |
|---|---|---|---|
| EA Technology | 16/07/2021 | 1.0 | Chris Lowsley |



EA Technology Limited, Capenhurst Technology Park, Capenhurst, Chester, CH1 6ES; Tel: 0151 339 4181 Fax: 0151 347 2404

http://www.eatechnology.com

Registered in England number 2566313

# Background & Introduction

The Foresight project has deployed a range of network monitoring equipment to study the development of faults on a variety of cable networks on Northern Powergrid's Low Voltage (LV) Network. Low-cost monitoring devices have been trialled to identify and locate developing faults on the cable circuits before supply outages occur. Once the location of the developing fault has been determined, its impact on the connected customers can be proactively managed. The ultimate intervention is the repair of the faulty asset as planned work in advance of the impact becoming unacceptable and, in some cases, before an off-supply event has been caused.

Experience with the ALVIN Reclose devices (multi-shot automatic reclosers) had pointed to the prevalence of fault currents of short duration that 'self-healed' before circuit protection equipment operated on circuits to which the Reclosers were deployed. These were registered by ALVIN Reclose devices as Fault Current when Closed (FCC) events and the associated waveforms captured for later analysis. It was speculated that these so-called pre-fault events could be used as harbingers of imminent customer interruptions and, if they could be located early in the development cycle, interventions could be planned to mitigate the future impact. The resulting process would be a new way to manage the performance of LV cable networks, particularly relevant should the fault rate continue to increase as the networks age and become even more critical for the reduction and potential elimination of fossil fuels from the energy landscape.

This project closedown report summarises the status of learning at the start of the project and the proposed solution, which the Foresight project aimed to demonstrate. The report then describes the solution that was identified from project learning: A new LV Cable Fault Management Methodology. This methodology uses prioritised incremental deployment of investigative and/or fault management equipment through the various stages of fault development with the express intent to mitigate the impact of the fault before it becomes unacceptable. A cost benefit assessment of the new methodology and equipment compared to current practice and description of the Project Management processes which were successfully used to manage the project are followed by a short project summary.

# Status of learning at the start of the project

## 2.1 The problem that the Foresight project sought to address

LV fault restoration and location on distribution networks can be time consuming, difficult and costly particularly in the case of underground cable transient faults. As a result of mature cable designs installed over the last 50 years, LV faults in both Northern Powergrid licence areas are becoming significant, in common with all GB DNOs.

A significant proportion of long duration interruptions to customers' supplies result from faults on the LV network, in particular cable faults. Restoration times can be lengthy, as the majority of the LV network is not monitored or controlled automatically. One of the key challenges is the inability to accurately assess the condition of LV cable systems and to predict when and where LV cable faults will occur. The table below, copied from the project initiation documentation, illustrates some of the problems encountered by traditional DNO LV networks.

| Traditional LV Network | |
|---|---|
| LV Network Faults | • Response and Isolation can take a number of hours<br>• Penalties incurred & high operational costs to resolve |
| LV Network Visibility | • Feeder overloading due to EVs, heatpumps etc<br>• Voltage or harmonic issues due to renewable generation |
| Safety | • Hazardous manual operations<br>• Contacts arcing<br>• High fault currents<br>• Damage to transformers & cables |

As demands change with the growth of low carbon technologies such as solar and wind micro-generation, electric vehicles or heat pumps becoming more mainstream, the impact of these technologies on LV grid networks, together with increasing customer awareness from the information expected from the deployment of smarter metering, will make it increasingly important to improve visibility and management of the LV network.

Avoiding LV faults requires detection of developing LV faults then localisation of each defect that will develop into a fault before it produces a supply interruption. If a cost-effective technique to monitor the condition and health of the infrastructure, identify and locate pre-fault LV cable defects could be developed and deployed then it would become practical to repair LV cable defects as planned work, carried out in a manner which reduces interruptions to customers' supplies.

The benefits accruing from the project were therefore expected to include significantly improved network performance, benefiting customer experience of the network, an increase in DNO regulated income via the IIS incentive, a significant reduction in operational costs due to unplanned work on the LV network, together with concomitant improvements in customer satisfaction and the reputation of Northern Powergrid.

## 2.2 The solution which was to be demonstrated as feasible by the project

The Foresight project aimed to demonstrate that it is possible to recognise transient electrical disturbances created by LV cable defects that will cause supply interruptions, from measurements at distribution substations. Also, to demonstrate that it is possible to use the characteristics of the measured electrical disturbances to locate the LV cable defects, enabling proactive repair to avoid supply interruptions.

In order to identify developing LV faults, it is necessary to identify transient changes in voltage or current measurements which are made remote from the location of a developing fault. There are a variety of possible causes of such network transients.

In 1974 an investigation into the behaviour of cable faults in low voltage electricity distribution networks[1,2] explained how a low voltage cable fault develops and described the disturbances caused by a "transitory fault on the power system", which has insufficient duration to cause a protective fuse to operate. The work identified the current and voltage characteristics of these pre-fault events. It also described the principles of how information on transitory faults might be used not only to predict the development of a

[1] ECRC/R715 (1974), "Prospective Current Indicators for Low Voltage Cable Fault Detection and Location", P. F. Gale
[2] Proc. IEE International Conference on Sources and Effects of Power System Disturbances (1974), "Voltage Dips Due to Transitory Low Voltage Cable Faults", (1974), P. F. Gale, Electricity Council Research Centre

low voltage cable fault but also to locate it. Using the current and voltage characteristics of pre-fault events that are described in this work, EA Technology developed algorithms to identify developing faults.

It was hoped that the Foresight project would collect a large amount of data from LV feeders and prove the veracity of the existing algorithms using this data. It was further hoped that analysis of this large data set would categorise LV network transients to reliably separate transients created by developing LV cable faults from transients created due to other causes. Hence, the Foresight project would refine the algorithms and prove that they reliably identify developing LV cable faults with sufficient confidence for pro-active repair to avoid supply interruptions to become a practical operational reality.

Therefore, the Foresight project aimed to demonstrate that:

1. It is feasible to measure ***"pre-fault events"*** and to use such measurements to detect and locate the position of defects in LV cables before fault;
2. New technology and new processes would enable new operational processes for managing LV faults, using greater condition awareness to detect and locate developing LV faults before they result in interruptions to supply;
3. It is feasible to avoid interruptions to supply due to faults on LV cables by a ***"detect, localise, locate & repair"*** strategy which includes:
    a. Wide-scale deployment of very low-cost monitoring technology to ***detect*** *"pre-fault events";*
    b. Time-limited, incremental deployment of more functional, higher cost technology as required, targeted using information that is derived from data provided by the very low-cost monitoring device, to first:
        i. ***localise*** the defect, i.e. identify the circuit with a defect that is developing into a fault; then subsequently
        ii. ***locate*** the defect, i.e. identify the location of the defect within the circuit; enabling
    c. Pro-active ***repair*** of the defective circuit before an LV fault occurs and customers' electricity supply is interrupted; and
4. Network performance benefits and financial benefits would accrue from managing LV cables using this approach to avoid interruptions to supply.

The proposed approach is based on the premise that:

- alert of a developing fault;
- detection of the responsible feeder and phase;
- location of the defect which is developing into a fault; and
- remediation of the defect;

are different types of activities, which require differing levels of complexity. Preferably the approach would use large numbers of simple, low-cost instruments to detect and alert, plus small numbers of complex, high-cost instruments to locate.

The concept envisioned before the start of the project, was for wide-scale deployment of an extremely low-cost voltage measuring device, connected to the LV busbar of a distribution substation. This device would detect the presence of a developing fault on a feeder that is connected to the substation and provide an alert.

It was judged, before the start of the project, that to include functionality in an alert device to determine which feeder and phase is responsible would make the device too costly for high-volume deployment. It was further considered that the cost of deploying a smaller number of higher cost portable devices only when and where a developing fault is identified was likely to be lower than the cost of including this functionality in the wide-scale deployment device.

Primary project objectives therefore included:

- Development and testing of novel techniques which can deliver a significant decrease in loss of supply, Customer Minutes Lost and Customer Interruptions originating from LV cable faults.
- Create learning and develop knowledge relating to the evolution of LV cable defects into supply interrupting faults using a method which minimises the impact on customers.
- Detection and location of developing faults, enabling remedial works to be carried out as part of a planned programme of work before faults develop into loss of supply events.
- Demonstration of the use of a network of low-cost sensing devices and associated communications.
- Demonstration that low-cost sensing devices combined with LV Reclosing devices deliver significant reduction of Customer Minutes Lost and Customer Interruptions.
- Development of a strategy and protocol for detection and location of incipient faults on the LV cable network.

## 2.3 Methods which were planned to be used in the project

The following methods were selected to be used in the project to demonstrate what was feasible and practical:

1. Measurement of electrical disturbances on LV cable networks. We considered that it was important that:
    a) Circuits were selected which had a high probability of faulting within a period that is short compared to the overall duration of the project, because the learning from the measurements was to be used to specify the required functionality of the very low-cost monitoring technology to detect *"pre-fault events"*; and
    b) Circuits that produced *"pre-fault events"* must be allowed to progress to experience non-damage faults, and ultimately to experience permanent, damage faults, so that the evolution of signals that are produced by defective LV cables can be related to the evolution of the defect and ultimately be useful for predicting time to fault of defective LV cables; but that
    c) The impact of these investigations on the supply quality of the customers that are connected to the selected circuits is minimised.

    Therefore, ALVIN® Reclose devices[3] were selected to be used to monitor the selected circuits. By using these devices customers only experienced short interruptions from non-damage faults, which otherwise would have caused the circuit protective fuse to operate and cause supply to be lost until the fuse was replaced. An appropriate data collection system would be produced to collect and aggregate the data from the ALVIN devices.

2. Analyse measured data collected by the ALVIN devices, in order to:
    a) Verify algorithms that are based on the findings of the investigation, in 1974, into the behaviour of cable faults in low voltage electricity distribution networks;
    b) Track the evolution of "pre-fault events" into the occurrence of non-damage faults, and ultimately into permanent, damage faults; and
    c) Provide information which could be used to specify the required functionality of portable, more functional, higher cost technology to ***localise*** defects and technology to ***locate*** defects in an LV cable circuit.

3. Develop and test a very low-cost sensor to ***detect*** a developing LV fault and interact with an information system to produce an alert. This method was programmed to follow the first and second method. Two versions of the very low-cost sensor were planned, the first to have 100 devices deployed, the second to have 1000 devices deployed. The second device would be an

[3] ALVIN is a registered Trademark of EA Technology Ltd

improvement, based on learning from the build, deployment, commissioning and operation of the first version. It was expected that the second version would be lower cost than the first version.

4. Develop and test a portable, more functional, higher cost technology to *localise* defects, i.e. to identify the LV cable circuit with a defect that is developing into a fault. This method was programmed to run in parallel with the first and second methods.

5. Develop and test a portable, more functional, higher cost technology and methodology to *locate* the defect, i.e. identify the position of the defect in the specific phase conductor of the previously identified LV cable feeder that has a developing fault. This method was programmed to follow the third method.

6. Deploy the technology and method in a trial area of Northern Powergrid network, in order to demonstrate effective operation of the technique; also to specify and demonstrate appropriate prototype processes and information systems, which could deliver the information needed for a successful *"detect, localise, locate & repair"* strategy to avoid interruptions to supply due to faults on LV cables.

# A New LV Cable Fault Management Methodology

The Foresight Project explored a new, proactive means to manage LV cable faults based around the prioritised incremental deployment of investigative equipment through the various stages of fault development. The aim being to ameliorate the consequences of prolonged off-supply events by early intervention, preferably before the fault causes any supply interruption.

## 3.1 Stages of Fault Development

In terms of regulatory reporting of fault incidents, including cable faults, there are two fundamental classes, damage and non-damage. In a damage incident a repair to the compromised asset is required. In a non-damage incident no repair is required; the compromised asset 'heals' sufficiently to allow the circuit to be reenergised and customer supplies returned for a period. Non-damage incidents represent the largest proportion of customer interruptions due to LV Cable incidents[4]. Eventually the conditions of compromised circuit insulation recur at the site of the developing fault and further protection operations ensue until finally repair is required, i.e., the compromised asset deteriorates to the point whereby restoration by re-energisation is no longer viable and a damage fault develops.

For the purposes of following the fault through the Project, and to allow the researchers a common parlance whilst exploring this area, non-damage incidents were segmented based upon the time-period that elapsed between incidences. The naming of the segments (or categories) was based broadly on previous work by Dr Philip Gale[5] that recognised the temporal frequency of non-damage incidences but also hinted at the nuisance factor that the developing fault causing them was inflicting both on connected customers and Northern Powergrid's operational staff. The stages of fault development were categorised as follows:

- Pre-fault – detectable events related to compromised insulation in an LV network asset that self-heals before protection operates. These are the transitory events referred to in the 1974 research. Connected customers remain unaware of the majority of these events.

[4] 73% of the protection operations on approximately 190 circuits monitored in Stage 1 of the Project were re-energised successfully within 3 minutes of a protection operation by auto-reclose sequence.

[5] The author of the previously cited work on behalf of the former Electricity Council Research Centre (from which EA Technology was formed) and more recently at Kehui, the manufacturers of the Time Domain Reflectometry instrument used in the Foresight project

- Transient fault – this is a generic term for non-damage faults. In the Foresight project the term was limited to events that cause a single operation of unknown origin that did not reoccur for a period of 90 days or more
- Intermittent fault – A further stage of fault development where the non-damage fault reoccurs more frequently than once every 90 days
- Persistent fault – A non-damage fault where there are repeated operations of protection devices at short intervals (within 6 hours of each-other)
- Permanent fault - A damage fault that requires replacement of the faulty asset to return the circuit to a satisfactory state of health.

In the present fault management procedures, auto reclose devices are considered for deployment to manage the effect of intermittent faults on connected customers until the fault becomes permanent. Developing faults can achieve this state at any time of the day or night. At this point, standard (and often lengthy) reactive location and restoration methods are enacted to first, determine the location of the fault, then resupply the affected customers and finally, repair the failed cable asset to return the circuit to satisfactory condition.

The Foresight Project has successfully trialled a proposal for a new fault management approach that takes advantage of the visibility of pre-fault events from low-cost substation monitoring. In developing this method, it has also become apparent that the data from these low-cost devices presents other opportunities to distribution network asset owners in understanding the overall health and potential acceleration of deterioration of their aging underground networks.

## 3.2 Proactive Fault Management Methodology

Proposed methods to Detect, Localise and Locate pre-fault activity have been trialled and improved over the various stages of the Foresight Project. The learning has been amalgamated into a proposed new way of managing LV cable faults. The resulting prototype Proactive Fault Management methodology is based around the prioritised incremental deployment of investigative and/or fault management equipment through the various stages of fault development with the express intent to mitigate the impact of the fault before it becomes unacceptable. Fundamental to the proposed new approach is the widescale deployment of low-cost pre-fault detectors, the data from which drives the other elements of the proactive process at the appropriate beneficial intervention points. The steps in the proposed methodology are:

- The widespread deployment of low-cost pre-fault detector equipment to provide condition assessment data for LV Cable assets
- Prioritisation of circuits with developing faults for proactive action
- Incremental deployment of fault management and/or fault location equipment to the prioritised circuits
- Location of the source of the developing fault activity before it causes unacceptable impact
- Proactive mitigation of the impact of fault progression (including planned cable repair in advance of the impacts fault becoming unacceptable or other interventions as opportunities arise)
- Post-intervention assessment of new circuit cable condition determining success or otherwise of the repair or other intervention thus allowing confident recovery of incrementally deployed equipment.

Each of these steps is visited in more detail throughout the remainder of this section of the final project report.

The first-pass methodology for proactive fault management is shown in Flow Diagram form in Figure 1.

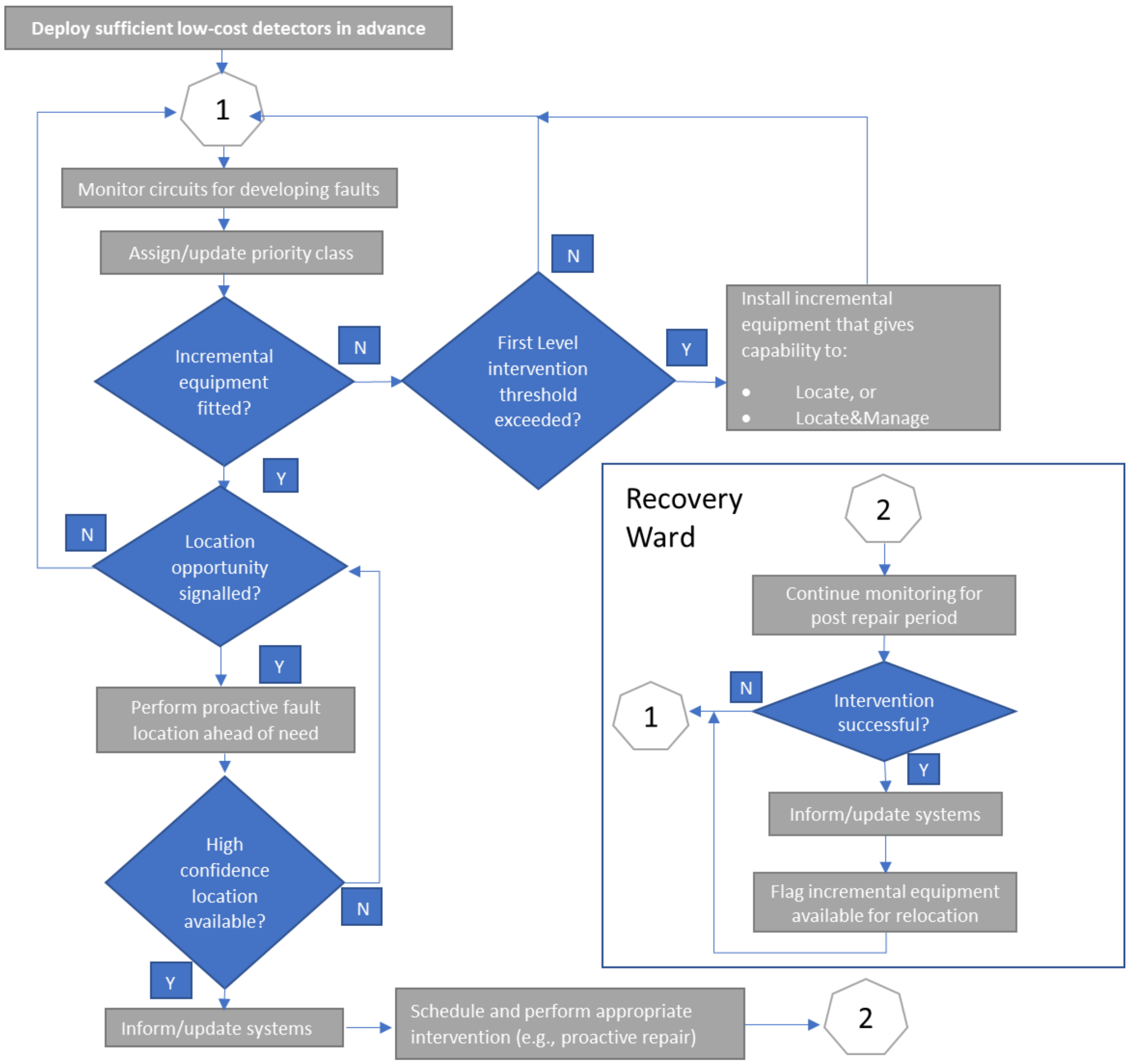



*Figure 1 Proactive Fault Management Flow Diagram*

Beneficial interventions are signalled at several points. The first intervention point is driven by the analytics on the data provided by the low-cost pre-fault detectors. The analytics indicate the circuits showing signs of development towards an off-supply event and therefore those for which a location exercise should be prioritised. Two different sets of location equipment are cited; Locate and Manage or Locate Only. Each of these location interventions involve the use of portable equipment to locate the in-circuit source of the detected and localised pre-fault activity. The Locate and Manage intervention includes the use of the ALVIN Reclosers to manage customer supplies should the fault develop to the point of supply interruption during the location exercise. The Locate Only strategy does not include Reclosers. The equipment is designed for incremental deployment meaning that the low-cost pre-fault detector equipment remains undisturbed and provides consistent data throughout the whole process. The second intervention point is driven from analysis of data from the incrementally deployed location equipment which determines when a sufficiently high credibility location is available. At that point, confirmatory field- based investigations are undertaken followed by action to mitigate the impact of the fault before it develops further.

An additional, post-intervention period of continued focussed monitoring (the 'Recovery Ward') is shown in the inset. This is used to determine the success or otherwise of the proactive intervention and indicate when any remaining incrementally deployed equipment is no longer required and therefore available for moving on to the next high priority circuit. The low-cost pre-fault detectors remain to provide a consistent data source for post-intervention reassessment of the circuit health score and to pick up future faults that may develop on that circuit or others fed from the same substation.

The overall intention is to mitigate the impact of developing faults as soon as a location is confirmed.

## 3.3 Pre-Fault Detection

In the first stage of the Project, 190 separate circuits in 136 substations were fitted with monitoring systems. The monitoring system consisted of a set of ALVIN Reclose devices and an ALVIN TDR (modified version of a Kehui TP23)[6]. The ALVIN Reclose devices were set up to capture network events on the monitored feeders while mitigating the impact of customer interruptions for those faults that went that far. They returned both timestamped event data plus captured waveforms of the event to the Project database for the analysis stage. The expectation of capturing a reasonable amount of fault related activity was exceeded. By September 2018, three months after the completion of monitoring systems installations[7] and following filtering to eliminate load related events, 8,258 fault-related waveforms had been captured for analysis. Over this same period, there were 292 protection operations recorded related to 198 separate feeder-level off-supply events on 28 circuits. Eight of the faults (on seven separate circuits) had gone on to become damage faults requiring reactive location and repair after automatic reclose and or fuse replacement had failed to restore customer supplies. The monitoring systems remained in place for the remainder of the project[8].

A typical pre-fault event, as captured by an ALVIN Reclose device, is shown in Figure 2. The events are characterised by a sharp increase in current around the time of peak voltage causing a voltage notch. The pre-fault event current reverts to normal load current sometime later and before a protection operation. Over ninety percent of the pre-fault events on the 3-phase cables monitored during the Foresight Project were single phase though many later develop into multiphase faults before they cause their first supply interruption.

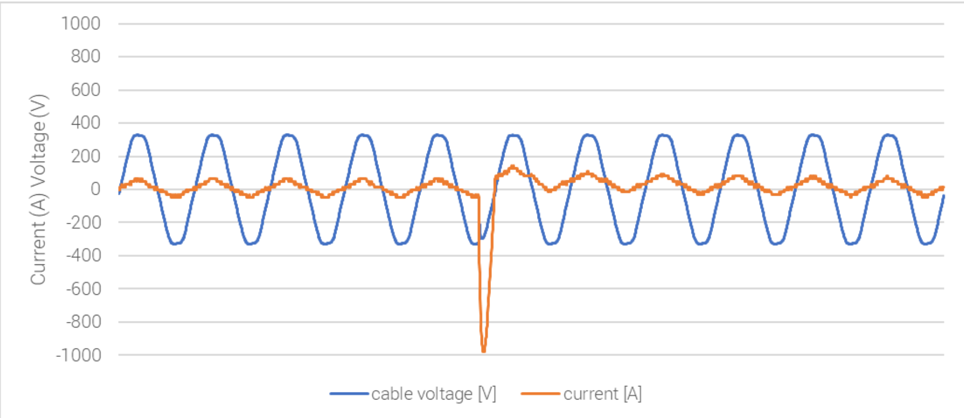



*Figure 2 A typical Pre-Fault Event Waveform as captured by ALVIN Reclose device*

As pre-fault detection devices were envisaged to be deployed at volume on a Network Operator's LV underground network, low cost and ease of installation were critical design criteria. The original intention for the project pre-fault detector was to **detect** activity at substation level followed by a separate visit to **localise** the detected activity to a particular circuit thus enabling the deployment of specialist equipment to **locate** the

[6] The modification was primarily to allow the TDR unit captures to be transmitted back to the EA Technology central servers and analysis databases along with the captures from the ALVIN Reclose devices

[7] Monitoring system installation took place between October 2017 and June 2018 in two operational regions within Northern Powergrid

[8] Over the course of the Project, 97 of the 190- monitored circuits went on to experience at least one customer interruption. There were a total of 43 permanent faults distributed over 37 different monitored circuits

developing fault. An early project innovation however combined the first two (detect and localise) stages in a single instrument, fitted in a single visit. As well as reducing the resource and organisational requirements for repeat visits to the substation to fit additional devices, the higher-functionality pre-fault detector also presented the opportunity of providing a consistent pre-fault activity data set (at circuit rather than substation level), across the monitored assets, from a single instrument. It was realised that the resulting data set, indicating relative health on a circuit-level basis, would provide a valuable resource for long term (planning timescales) LV cable asset management as well as a means to meet the primary aim of prioritising circuits for proactive fault management intervention in operational timescales.

The innovative step taken was to add a minimum current sensor set (using Rogowski Coils) to the device to supplement voltage disturbance detection on the instrument. By measuring just the neutral current on each of the outgoing cable circuits in a substation, the circuit with the developing fault that was the cause of the detected voltage dip was also identified. The enhanced function detector (referred to as the *Guard*) thus gave the desired feeder level information whilst keeping the size of the instrument practical, the cost down and the speed and ease of installation in line with cost-effective wide scale deployment.

Figure 3 shows an example of a waveform from a single-phase pre-fault event captured by a Guard device[9]. In this example, it can be observed from the disturbance to the busbar voltage measurements that the detected event was single-phase event involving just the L2 phase. The minimum set of current measurements (five 5 Rogowski Coils have been deployed in this example, one on the neutral conductor on each of the five outgoing LV cable circuits from this substation) localises the developing fault that is evident on L2, to the circuit fed from Way 2 of the LV distribution board at this substation.

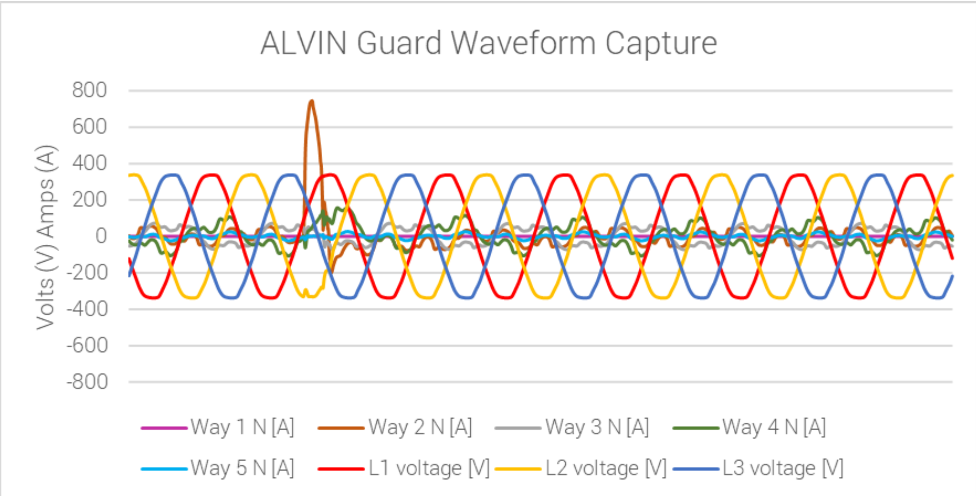



*Figure 3 ALVIN Guard Pre-fault detector waveform capture. Single phase L2-N activity on Way 2*

The Foresight Project Low-Cost Pre-Fault Detector was developed over three iterations. The final design, the ALVIN® Guard, accommodates up to eight current sensors making it suitable to cover all but the very largest of Northern Powergrid's distribution substations. A typical distribution substation installation is shown in Figure 4. On the left, a connection schematic shows an installation to a substation with 4 outgoing cable circuits. On the right is an actual installation using the ALVIN Guard.

[9] Approximately 95% of the events that were captured on the project and categorised as being associated with a developing faults were single-phase.

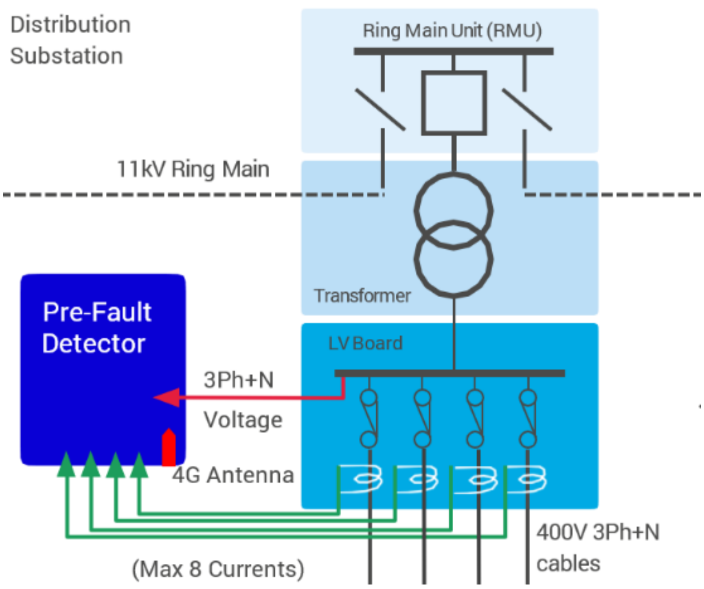



*Figure 4 Left: Pre-fault detector installation schematic Right: ALVIN® Guard Pre-fault detector in-situ*

The pre-fault detector was designed to be quick and easy to install, without tools and without needing to disconnect supplies, by a single operative where safety rules and approved practices allow. The device is self-contained: It is powered via the three-phase voltage measurement leads and has its own inbuilt cellular data modem for data communications with the central databases. Given that the number of outgoing Ways from distribution substations vary, and to keep costs down, Rogowski Coils can be added individually, as required, up to a total of eight. Once powered, the device self-boots and communication and data backhaul to the central servers commences without the requirement for any additional set-up or configuration. Indicator LEDs confirm which current channels are occupied and a further LED signals the communication signal strength, without the requirement for other commissioning equipment. The only commissioning required is to allocate the current channels to the unique feeder names in the substation. This can be done locally, or remotely once communications have been established, using a specially developed commissioning User Interface (UI) accessed on internet enabled devices. The commissioning UI has drop-down options of substation names and circuit IDs from Northern Powergrid's asset data base to eliminate commissioning paperwork, considerably speed up the data base set up process and ensure consistent naming for accurate execution of later automated analysis.

During installation of the 1,000 ALVIN Guard devices, up to 25 devices were successfully installed per day by suitably authorised staff.

## 3.4 Prioritisation of Circuits for Proactive Intervention Based on Condition Assessment

Research performed using pre-fault waveform data, from monitored circuits followed through various stages of fault development, resulted in the derivation of a set of predictive parameters. Certain predictive parameters were found to be correlated with later non-damage and damage incidents and thus provided a potential measure of compromised reliability and a predictor of future unplanned off-supply events. The initial research carried out on the data from the 190 circuits with ALVIN Reclose devices fitted was later expanded and applied to approximately 2000 circuits monitored by the ALVIN Guards.

To exploit this potential predictive power, data from the Guards is returned, in near real-time, to the central servers where automated analysis of the waveforms determines whether the captures are the result of pre-fault breakdowns or other causes. Waveforms categorised as being related to pre-fault events faults are presented for further analysis from which the predictive parameters are derived. As the pre-fault data from the Guard devices is also localised to a particular feeder, circuit level predictive assessments are derived for the entire monitored population.

The output of the predictive analysis was used in the Project to explore its use in providing actionable insights in two areas:

- Operations (pre-emptive action to limit the impact of imminent faults), and
- Asset Management (looking at future reliability and investment).

A number of ways of providing this information to people who could make use of it were implemented. Early in the project, watchlists were generated to draw attention to circuits showing unusual activity. Later, following the introduction of the predictive analysis, a dashboard was developed to present the data in a way that focussed on the perceived beneficial intervention timescale. Based on the output of the predictive analysis, each circuit in the substations equipped with pre-fault detectors was allocated a priority-rating in one of the following four classifications:

- Background: Circuits with no evidence of elevated risk
- Early Warning: Elevated activity, some possibility of a failure event in longer term timescales
- Operational Timescale: Increasing probability of a failure event
- Imminent Fail: High probability of a failure event in an imminent timescale

The classifications give an indication of the increasing probability of an off-supply event occurring and also an indicative future time to that operation in order to help prioritise proactive intervention. While the 'Background' group shows the population of monitored circuits showing no current cause for concern, the 'Imminent Fail' group offers a focus for operational action.

An extract from the prototype dashboard is shown in Figure 5. It shows the distribution of a population of approximately 2,000 monitored circuits. As the population includes the substations used in the early part of the trial, which were selected on previous fault history in order to give the best chance of generating data, it is perhaps not a surprise that there is a considerable population showing signs of movement toward failure.

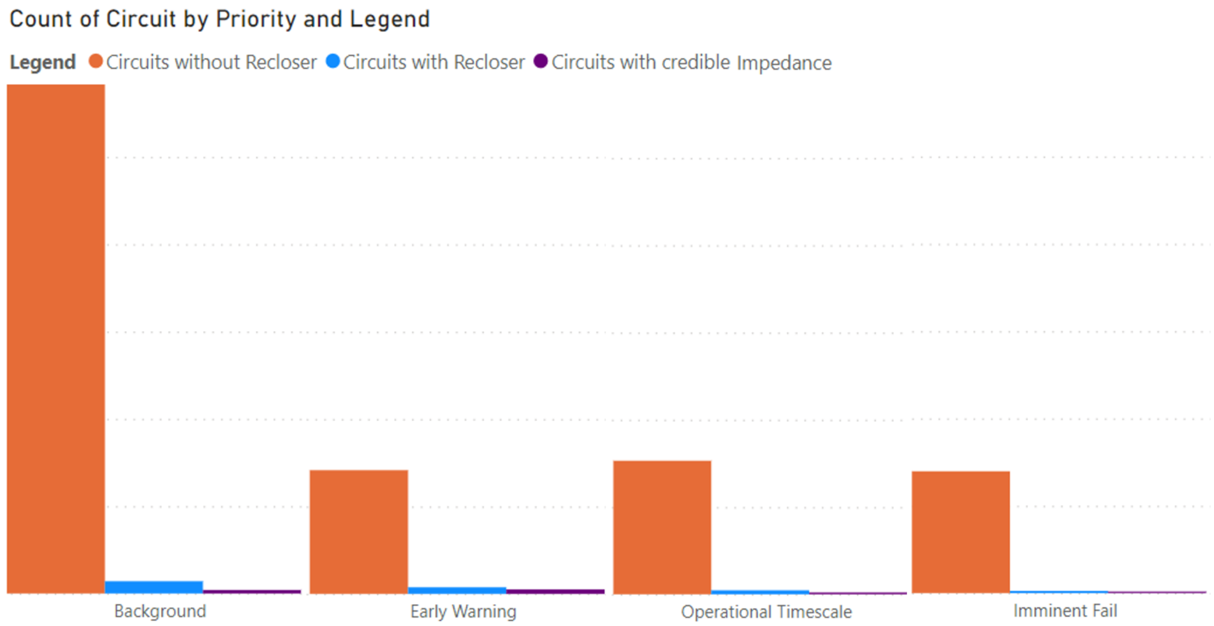



*Figure 5 Extract from first-pass dashboard showing priority distribution of a population of monitored circuits*

Not all faults are preceded by pre-fault events[10] and not all detected pre-fault events will cause a categorisation above the background level. For most circuits that went on to cause supply interruptions though, some level of signalling was available on which to instigate a pre-emptive action.

For the circuits classified into the highest priority group (Imminent Fail), approximately 40% went on to fail[11] within the duration of the project monitoring. 90% of these failed within a year of first being flagged to the category (mean time to fail of 135 days). The immediacy of required action can be appreciated by the statistical analysis that showed that 28% of the circuits that go on to fail do so within 2 weeks of first entering this group. By contrast, only 8% of those in the Early Warning priority group went on to fail within the duration of project, 60% of these within the year (mean time to fail of 280 days) and only 6.6% of those that go on to fail whilst in this group do so within the first 2 weeks of the 'Early Warning' priority being flagged.

It was further observed that the probability of failure for those circuits that had a prior fault history was approximately 20% higher than the general population and more than twice that of a circuit with the same priority ranking from waveform analysis, but without a prior fault history. LV Underground Cable Circuits with a history of causing protection operations are, seemingly, more likely to cause them in the future.

While the dashboard could be used to give a general overview of the health of the monitored circuits by comparing the relative populations in the prioritised groups, a further piece of work was undertaken to investigate the use of the data in a formal LV Cable Asset Management Model. The model was based on the Common Network Asset Indices Methodology (CNAIM) [12]. A CNAIM Model, when applied to an asset group, is typically used by Network Operator Asset Managers to maintain sufficient reliability of the installed population by optimal targeting of replacement and/or maintenance activities based on factors including age, asset type (and historical failure rates/ mechanisms), duty and measured and/or observed condition. For buried cables, while a rich history of fault occurrence is available, observation or measurement of present relative condition looking for signs of deterioration across the aging population remains somewhat troublesome. The predictive data set, generated from the outputs of the fleet of low-cost pre-fault detectors deployed across a wide asset base of LV cable circuits of varying age, type and make-up, offered an opportunity to provide continuous and consistent condition assessments based on measurement data not previously available. A prototype model was constructed using the predictive data set to create a new Pre-Fault Condition Modifier. This was used alongside Northern Powergrid's fault history data to produce a proposed new LV Cable Measured Condition Modifier and eventually a Health Score (or Index) that, in models of this type for other network assets (e.g., Transformers), is used to derive, and justify, future investment strategies for replacement of an aging population and provide a view on the success of those investments. Figure 6 shows how the Pre-Fault Condition Modifier would be used in the formal model.

[10] Approximately 15% of the persistent or permanent faults gave no prior pre-fault indication.
[11] In the long-term predictive research, 'fail' meant that off-supplies could not be restored by reclose or fuse replacement
[12] DNO Common Network Asset Indices Methodology Version 1.1, 30 January 2017: https://www.ofgem.gov.uk/system/files/docs/2017/05/dno_common_network_asset_indices_methodology_v1.1.pdf

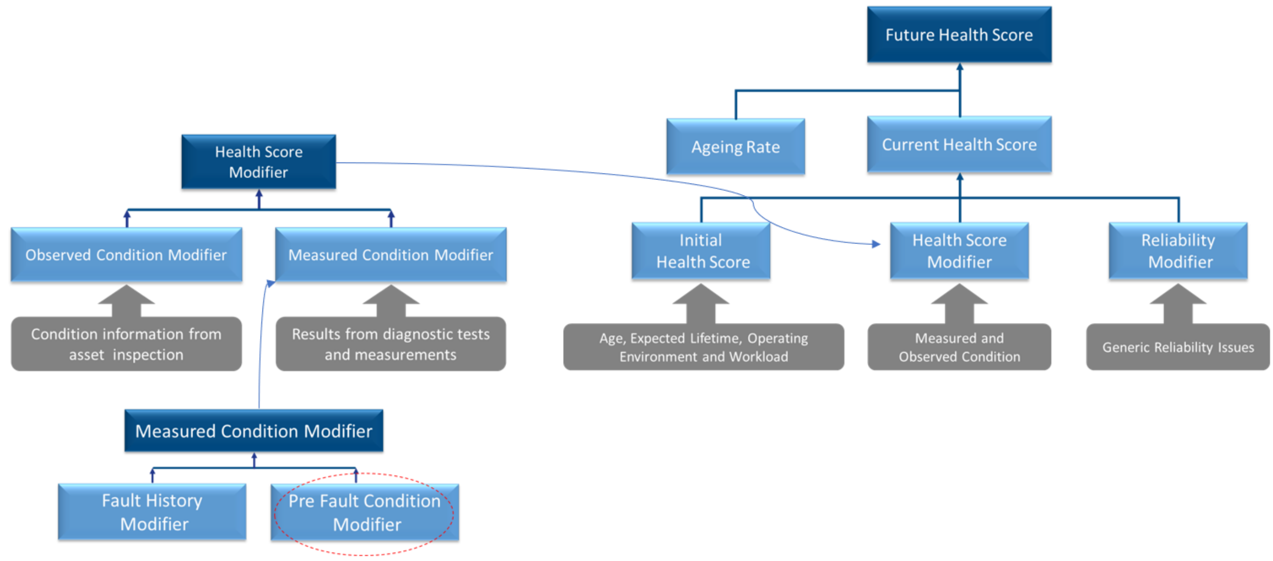



*Figure 6 Pre-fault data use in prototype CNAIM Asset Management Model*

## 3.5 Incremental Equipment Deployment

The prototype proactive fault management process developed in the foresight project builds upon information provided by pre-fault detectors. The pre-fault detectors are used to provide a consistent data set indicating the existence and prevalence of a developing fault throughout the process. The pre-fault detectors developed on the project are therefore self-contained in that they have their own inbuilt communications device, power-supply, communications and sensors. The intention is that they remain in-situ before, during and after any proactive intervention, preferably without any disturbance.

At various points in the process for proactively managing developing faults, other more specialised equipment is deployed to learn more about the developing fault before more intrusive intervention, specifically its within-circuit location. The method for locating developing faults trialled in the Project (and, after successful demonstrations, proposed for use in the prototype fault management process) uses a combination of impedance to fault information (from Voltage/Current waveform captures), and distance to fault (from Time Domain Reflectometry (TDR) instrument outputs) in conjunction with a marked-up cable plan showing impedance and distance contours[13]. The method is explained in more detail in Section 3.6. Two means of obtaining the necessary information for the location algorithms were identified and trialled: Locate and Manage (incorporating Reclosers) and Locate Only (without Reclosers).

In a Locate and Manage intervention, a set of ALVIN Reclose Devices is deployed with a standalone ALVIN TDR. The ALVIN Reclose devices provide the dual function of providing the pre-fault event Voltage/Current waveform information required to derive an impedance to fault as well as managing the fault by reducing the impact of events of sufficient energy if the Locate and Manage exercise continues through to the transient and intermittent stages of fault development (see Figure 7 Left).

[13] The use of a 'contoured' cable plan on a map background used in conjunction with impedance to fault and distance to fault estimations is the subject of a patent application


*Figure 7 Left: Locate and Manage Equipment* *Right: Locate Only using Prototype Pre-Fault Locator*

Where it is not possible (or not preferred) to fit reclosers (due to lack of availability, difficulty in fitting to particular designs of LV distribution boards or reticence in interrupting customer supplies in order to fit reclosers in place of the existing fuses), a Locate Only intervention can be substituted (see Figure 7 Right). The Locate Only system incorporating a VisNet® Hub running the Low Voltage Common Applications Platform (LV-CAP®)[14] and a modified ALVIN TDR co-located in a ruggedised case was developed as part of the Foresight Project. The combined system (called the Pre-Fault Locator (PFL)) provides the same location information as the Locate and Manage equipment enabling the use of the same location methods as used in a Locate and Manage intervention.

Location equipment (particularly that which includes Reclosers) is expensive in comparison with pre-fault detectors. It makes sense therefore to have a smaller fleet of these devices that are deployed, using an intelligence-based system, to where they can be predicted to have the most benefit and for only as long as they are beneficially required. This information is provided by prioritisation algorithms working on the output of the predictive analysis which, in turn, work on the pre-fault activity data set.

Both these stackable systems can be installed (and later removed) quickly by a single authorised operative without disturbing or interrupting the connections or data flow from the pre-fault detector. Data backhaul from each of the systems is also additional and independent in line with the incremental deployment strategy.

By providing stackable location equipment and keeping the pre-fault locator equipment in-situ throughout the proactive fault management process, a consistent data set is available from which it can be determined whether the condition of the circuit has returned to sufficient health to recover the additionally deployed equipment for beneficial use elsewhere.

In the proposed methodology, once a high confidence location has been obtained, Locate Only equipment can be recovered and moved to the next most worthy site. Locate and Manage equipment however remains to help ameliorate the impact should the fault develop further before it is successfully repaired. Following a proactive repair exercise, the circuit is monitored for a post-repair period to determine the success or otherwise of the repair before Reclosers or other equipment are recovered for redeployment elsewhere.

[14] VisNet and LV-CAP are registered trademarks of EA Technology

## 3.6 Method for the Location of Developing Faults

The abundance of early data available from the monitoring systems (which included ALVIN Reclose devices (with waveform capture capability) and voltage triggered ALVIN TDR[15] devices) resulted in the early derivation of a proposed technique to locate a developing fault prior to it becoming permanent. The method used a combination of impedance to fault calculations derived from voltage/current waveform captures and a distance to fault from analysis of the outputs from Time Domain Reflectometry equipment. The method proposed for investigation at the outset of the project was to use a time domain method as the primary means of detection supplemented/ enhanced by the passive impedance to fault method. The method successfully demonstrated, however, was the reverse.

Impedance calculations are made using the information contained in Voltage/Current pre-fault and fault waveforms. For faults in the early (pre-interruption) stages of development, the prevalence of significant impedance at the point of fault makes determination of impedance of the cable to the fault non-trivial. Predictive algorithms were therefore developed to give a prediction of the cable impedance to the fault position. Other elements of the method trialled mirror those used by EA Technology for standard fault location. The most recent impedance prediction is compared with most credible of any previous captures since the last successful repair. If it is of lower value than the previously retained best impedance and of the same or better credibility, it replaces the existing retained value to give a new best impedance. The evaluated best impedance is made available on the LV Cloud Web Viewer for authorised users with internet enabled devices.

Where there are multiple developing faults on the same circuit, the method is tuned to locating the closest (lowest impedance). If that fault is subsequently found and fixed and a further fault remains, this will be picked up by the pre-fault detector devices at the substation in the post-repair cycle and, if required, a further location exercise undertaken with the previous impedance to fault removed.

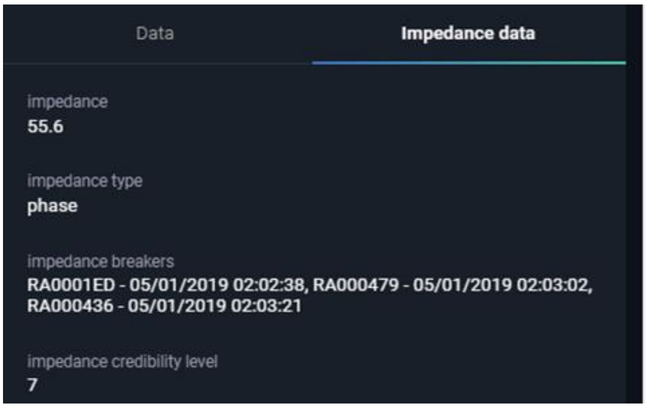



*Figure 8 Example output of the impedance to fault prediction scripts on the LV Cloud Web Viewer*

Figure 8 shows the automatically calculated estimated impedance to fault as seen on the LV Cloud Web Viewer for a particular feeder. The impedance is given in milliOhms (mΩ). The type is either Phase or Loop indicating a multi-phase fault or single-phase fault respectively. These are the values that can be used with pre-prepared contoured (marked-up) cable plans to determine candidate locations. In output in this example is from a Locate and Manage equipment set. A similar output appears for feeders populated with Locate Only equipment.

Time Domain Reflectometry equipment injects regular short pulses between selected conductors. Changes of impedance along those conductors cause reflections (echoes). The reflections are recorded for a short period after the pulse is injected creating a single pulse/echo cycle (or trace). As long as the regularity of injection is high in comparison to the duration of a typical pre-fault event, the change of impedance at the point of fault is likely to be caught in some or all of the reflected signals during the time the fault current flows.

[15] The ALVIN TDR is a Kehui T-P23 modified to be able to return captures to EA Technology's central servers

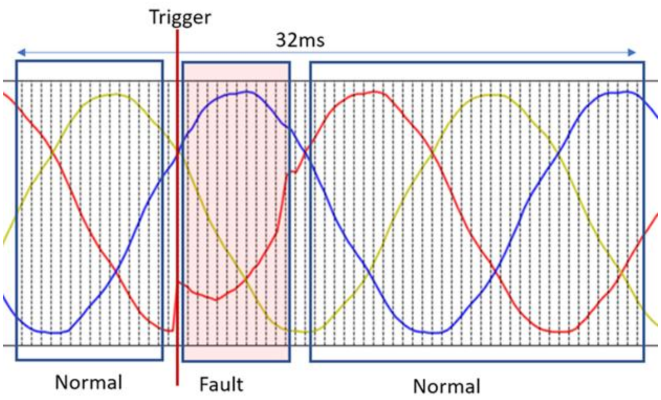



*Figure 9 TDR Capture showing 64 pulse echo cycles spanning a typical pre-fault event*

Figure 9 shows the 64 pulse-echo cycles that are recorded over 32ms in typical TDR capture. The pulses span the period of pre-fault current flow. Differences in comparisons of reflections when the fault isn't present with those when the fault is present are treated as candidate locations. As the impedance at the point of fault during a pre-fault event is relatively high (not a full short circuit), and the resulting reflections relatively weak, the capture file containing all 64 pulse echo cycles is disassembled by an analysis script and the comparison carried out digitally[16]. Differences statistically more likely to be present during the fault period than during the normal period are offered as potential distance to fault locations for use alongside the impedance locations derived from voltage/current waveforms captures of the same events.

The impedance to fault and distance to fault are used with contoured cable plans. On the cable plan, distance and impedance to fault are marked up so that the automated impedance to fault prediction can be translated to candidate locations.

Figure 10 shows the marked-up cable plan for the same network for which the impedance to fault data in Figure 8 above was provided[17]. As is typical for LV networks in Great Britain, this feeder is branched. Locations with a predicted phase impedance beyond the first branch from the substation thus have multiple possibilities whilst locations with a loop impedance returned (indicating a single-phase faults) will include single phase services too. In this example, the highest confidence location of 50 mΩ phase eventually derived has 4 potential search areas. Using the proposed method, on many networks (but not all) the possible locations on numerous branches can be further prioritised by combining impedance and distance to fault information as will be described later in this section.

[16] The file returned to the EA Technology Central Servers is the same format as that returned from a standard T-P23 and can thus be downloaded and input into the Kehui Master Viewer utility for manual evaluation if desired

[17] Subsequent analysis indicated high confidence phase impedances in the region around 50 mOhms.


*Figure 10 Example of a marked-up cable plan showing phase impedance P (mΩ) and distance D (m)*

The information from the impedance location is used as part of the noise rejection strategy for the TDR analysis. The automated analysis typically returns multiple locations along the cable route. Where a strong candidate location is returned in an area of interest as indicated by the impedance analysis, that location becomes the priority search area. An example of the output of a TDR analysis from a pre-fault event is shown in Figure 11.

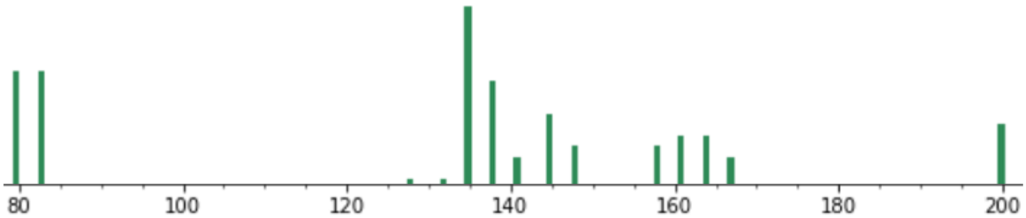



*Figure 11 Example output of TDR Analysis on Pre-fault event showing several candidate locations in meters from the substation*

On the investigated circuit shown in Figure 10, as the network is made up of combinations of different cable sizes, each of the locations has a different impedance/distance combination (see Table 1). TDR distance to fault information can thus be used to prioritise the branch for site investigation. A TDR signature near 125m, for instance, would favour location 2, whilst one near 95m would favour location 1.

*Table 1 Approximate Distance/ Impedance combinations for potential locations shown in Figure 10*

| Possible Location | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Approx Distance (m) | 95 | 125 | 170 | 190 |
| Phase Impedance (mΩ) | 50 | 50 | 50 | 50 |

Before a commitment to proactively repair is made, a positive site-based confirmation of the presence of the developing fault at the selected site is highly advantageous. Traditional site based underground cable fault location techniques have been used in the Project (e.g., fault gas sniffers, signs of local heating, temporary network rearrangement, customer information and local engineering judgement based on asset types and circuit history). The former techniques have been more successful with higher energy events that are generally associated with non-damage off-supply events (transient faults), subsequently restored by the automatic reclosers used as part of the Locate and Manage system trialled on the Project, than they are with lower energy events from faults in their earlier stages of development.

In response to the need for improving site-based confirmation of location of developing faults in the early stages of their progression to persistent or permanent faults (and additional to the original project scope) work was undertaken on a device to fulfill this need. The prototype devices (StreetSense Mats) were developed and trialled in a later part of the project.

*Figure 12 Prototype StreetSense Mats used to detect passage of pre-fault current along the candidate cable route*

Based upon the principle of residual magnetic field sensors and working in conjunction with the substation pre-fault detectors to confirm that detected anomalies were related to a pre-fault event on the circuit under investigation, StreetSense recognises the passage of pre-fault current from measurements made at pavement level at various points along the candidate cable route. The sensors, monitoring and communications equipment are located in a low-profile housing (see Figure 12) designed to be deployable by a single operative and left in situ at various points on a cable route. The devices can be left unsupervised for a period, in a similar way to a cable trench cover, without impeding pedestrian traffic. Unlike electromagnetic radiation, the residual magnetic field created by the passage of pre-fault current is largely undiminished by wet ground and is detectable at pavement level above the candidate cables. The system works in conjunction with substation monitoring systems to provide a means to discriminate between fault events and other magnetic disturbances (noise). Noise sources are relatively more common on urban pavements than in a rural environment where similar sensing technology is applied to fault location on high voltage overhead lines. The noise rejection system that allows a device such as this to function for this use case is the subject of a patent application.

Following successful early prototype tests, three deployable prototype StreetSense Mats were built utilising shallow commercial-off-the-shelf structures for use in the trial. A rechargeable and replaceable battery keeps the devices live for just over two days[18]. Detected magnetic field anomalies are captured and returned in near real time to the central servers for comparison with data from the ALVIN Guard device that simultaneously detect and localise the pre-fault event at the substation to the candidate circuit. The passage and direction of fault current is inferred from the magnitude and polarity of the captured residual magnetic field anomaly.

A waveform capture from the field trial site is shown in Figure 13. The captures from StreetSense Mats 3 and 4 indicate passage away from the substation whilst that from Mat 5 implies passage back toward the substation.

[18] It is envisaged that production versions would be designed for extended period of operation


*Figure 13 Example of coincident pre-fault event captures from the substation Guard and three StreetSense Mats at the StreetSense field trial site*

In contrast to most existing fault location techniques, the StreetSense system works best with single-phase[19] events. Degrees of imbalance that have allowed multiphase pre-fault and fault events to be detected by the minimal sensor (neutral) current monitoring on the Guards, have been found to also allow these multiphase events to be consistently detected at the early prototype trial site.

A field trial site for the prototype deployable mats was selected from the pre-fault detector data set, not due to its priority class but because it was recording multiple single phase pre-fault events per day. A pre-fault locator (deployed on the candidate circuit in a Locate Only exercise as there was a low-perceived probability of an imminent protection operation) returned a medium credibility 'best Z' in the region of 180-190 mΩ Loop Impedance. Two TDR distance to fault signatures were apparent in the search areas identified from the impedance to fault predictions – 180m and 210m. Combining these values prioritised the two candidate locations on the small 3-phase mains cables of the second branch on this network shown in red in the schematic diagram for this circuit in Figure 14.

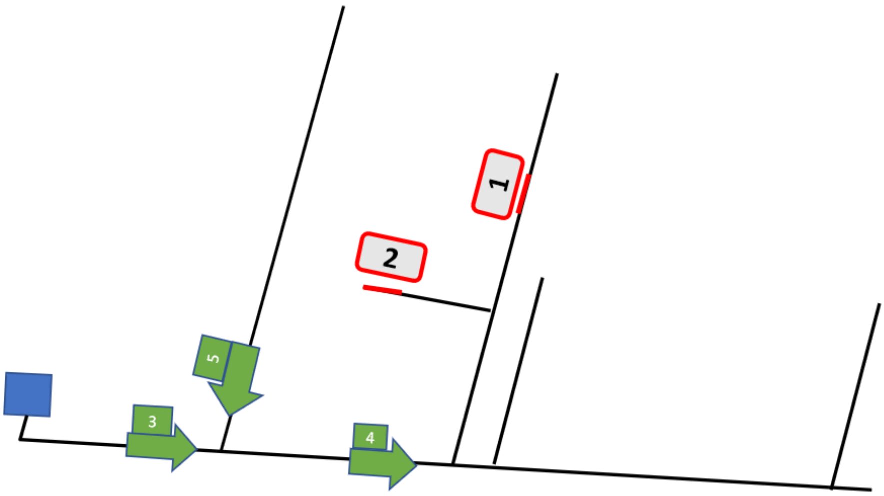



*Figure 14 Schematic of field trial site for Prototype StreetSense mats*

Initial deployment of the StreetSense Mats was carried out in January 2021, just before the end of the project. Figure 13 shows a set of simultaneous residual magnetic field captures from three separate StreetSense Mats placed around the first branch at the trial site. The placements are shown in schematic form in Figure 14. In the schematic, the arrows depict the relative magnitude of the detected residual magnetic field from the single-

[19] Single phase events make up 90% of pre-fault activity

phase pre-fault event and the direction indicates the polarity. In this instance, fault current seems to be directed past the first branch. Unexpectedly however, as this network is not interconnected, some of the return current was detected to be coming back down this branch. Encouragingly, further Mat placements implied fault passage up the second branch and not beyond correlating with the impedance and TDR signalled locations. The within branch location exercise has not yet been completed.

Follow on work is being planned to trial the application of the StreetSense devices alongside the other Foresight Pre-Fault location equipment and methods on other developing faults.

## 3.7 Proactive Mitigation

The benefits of proactive management of developing faults appear early in the deployment of the methodology. At the planning timescales (years and months), the relative population of the monitored networks that are accelerating toward unacceptable reliability is made visible. At the operational timeframes (months, weeks, and days), early action can be taken on localised circuits displaying deteriorating health to minimise the impact of an impending protection operation. Furthermore, network insights raise above the horizon actionable issues which hitherto had gone unnoticed. An example of such an issue is phase to phase faults that are cleared by the first fuse action, leaving the other partaking fuse intact, but weakened. The actionable insight is to replace both fuses to proactively mitigate the consequences of the weakened fuse.

In the Phase-Phase-Neutral Fault captured below, protection operates on the L3 feeder only. In the past this would be logged as a phase-neutral fault as knowledge of the other phase partaking in the event would not have been known. The involvement of L1 and L3 in the fault is, however, clear to see from voltage or current waveform monitoring.

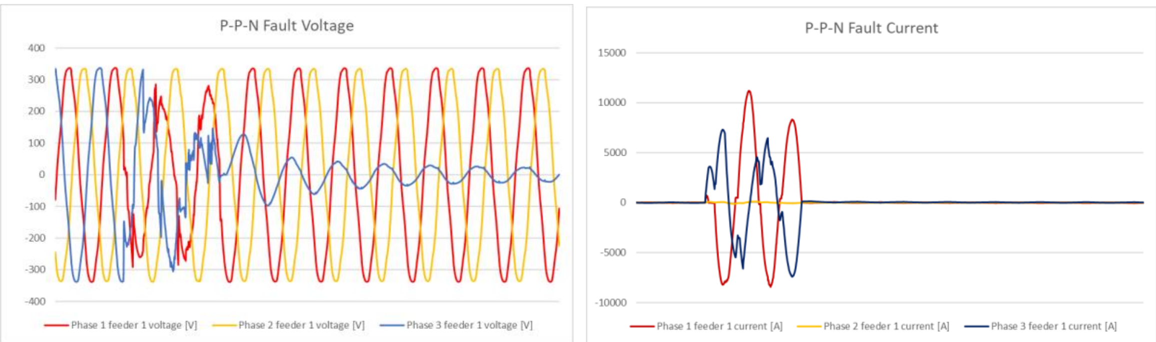



*Figure 15 Pre-fault locator capture of a phase to phase to neutral fault with protection operation on one phase only*

The ultimate objective in operational timescales is to repair developing faults before they have an unacceptable impact; if possible before they cause the first off-supply but certainly before they become persistent and/or permanent faults. Widely deploying a population of pre-fault detectors and using the predictive analysis allows advance warning of the acceleration of a proportion of developing faults to be determined. Deploying location equipment on circuits recognised to be likely to fail allows a head start in any future restoration work should the fault accelerate to becoming a damage fault. Deploying Reclosers as part of the location equipment allows management of the developing fault through the intermittent stage, reducing the impact on connected customers and associated financial impacts from the regulatory performance incentive schemes.

The substation-based monitoring used in the Foresight Project has been found generally to provide higher confidence locations for the more energetic events, which are also the events more likely to cause protection operations. Over the course of the Project, over 70% of protection operations were restored within 3 minutes (most within 40 seconds[20]) by the pre-deployment of Locate and Manage equipment (that includes ALVIN

[20] Time for restoration following the first reclose attempt using ALVIN Reclose devices on the system

Reclose devices). Some circuits that have a first transient operation can accelerate quickly to become persistent faults (that cause an unacceptable nuisance and poor quality of supply to connected customers) or permanent faults requiring urgent reactive response and restoration work to avoid a protracted period of supply loss. However, most faults observed to have been restored by successful reclose went on to experience other intermittent operations between the first registered transient operation and the persistent or permanent state. It is these circuits that form the immediate opportunity for early, proactive intervention to mitigate the impact of degenerating reliability on the connected customers. One such circuit that ended up providing an example Use Case for the execution of proactive intervention was a circuit in the Darlington (Teesside) area. The circuit is that shown previously in the example of a contoured cable plan used as part of the pre-fault location method in Figure 10.

The first signs of a developing fault on this circuit were registered by the Foresight Project monitoring system in November 2017, shortly after installation. Low-level single-phase activity was visible on phase L3. After a quiet period, the low-level activity reappeared in early August 2018 escalating to a protection operation of the Recloser on the L3 phase during a phase to phase (L1-L3) event later that same month. As the monitoring system used in the project included ALVIN Reclose devices, supplies on L3 were restored automatically 40 seconds after the protection operated. A photograph of the monitoring system on this feeder is shown in Figure 16.

*Figure 16 Substation equipment on the site used for proactive fault repair trial*

Several further protection operations involving L1-L3 occurred during the winter months, all automatically restored by the ALVIN Reclosers, drew attention to this circuit as a candidate for a proactive intervention trial. Early in May 2019, when the fault was observed to develop further as all three Reclosers picked up fault current (though only the L1 and L3 Reclose devices operated), this circuit was selected for early intervention using the proposed proactive fault management methodology.

Four potential locations were apparent from the Impedance to Fault predictions on this branched network. The TDR device on this site failed to return a standout distance to fault from the captures that were coincident with the voltage/current waveform captures from the Reclosers and therefore was unable to be used to prioritise between the candidate locations. In this case, the absence of positive reading from the cable sniffer[21] at any of the sites and the presence of a previously troublesome asset type at location 2, known not to give fault gases, favoured that one for the intervention site.

[21] The cable sniffer is a fault gas detector – it detects the concentration of fault gases produced by LV cable faults

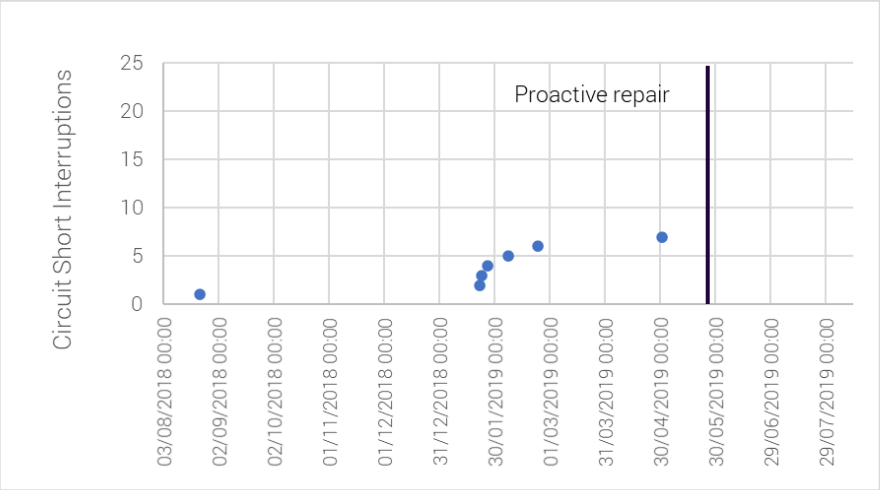



*Figure 17   Timeline of off-supply events with successful recloses leading up to proactive repair in May 2019*

The repair was planned and executed at the end of May 2019 while the fault was still in the intermittent stage of development (see Figure 17). Eight customers in the vicinity of the proactive repair were informed in advance of the works. On the day of the works, a 15m section of three phase mains cable containing two service joints and one cable end joint was recovered and replaced. The work was completed in one day (including all excavation and reinstatement) with the customers affected having been given advanced notice in accordance with normal procedures for planned work.

*Figure 18  Showing area of proactive underground asset replacement at Location 2 of the circuit shown in Figure 10*

The cable end joint and the first service joint were found in-tact. However, the second cable service joint (furthest from the cable end) was found to have significant damage. See Figure 19.

*Figure 19 Recovered service joint showing signs of damage from the area of proactive fault repair*

Unsurprisingly, it was later determined that the pattern of pre-fault activity on this circuit was related to periods of local heavy rainfall. More surprising was that a joint with such a degree of damage could continue to be managed by Automatic Reclose Devices which, up until the time of the repair, had limited the impact to the worst affected customers (on L3) to a total off-supply period of just 5 minutes over 7 separate short interruptions. Significantly for the process of proactive fault management, location information that adequately pinpointed this activity was available to the project from the first registered operation as early as August 2018.

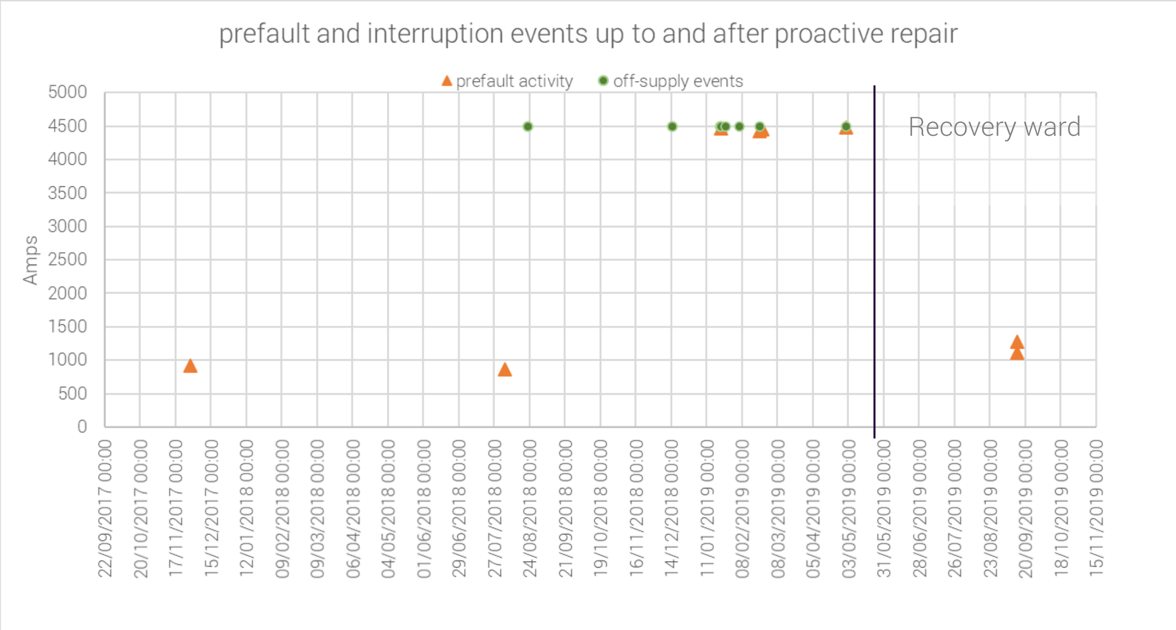
The three recovered joints were submitted by Northern Powergrid cable experts for forensic examination. The two service joints were of the same age and construction and, given their proximity to each other, presumably subject to the same environmental conditions over their lifetime. Of potential interest for the management of future performance of LV cable networks using the equipment and methods trialled in the Foresight Project, the forensic examination of the 'visually intact' joint, recovered with the damaged joint, revealed that it too was compromised. It showed indications of accelerated ageing consistent with an expectation of failure within 5 years.

Following the completion of the proactive repair works, letters were sent to the affected customers informing them of the new equipment deployed and the proactive intervention process followed to locate and repair the fault that was causing the intermittent loss in supplies, and to give them the good news of what had been found.

## 3.8 Post-Repair Monitoring and Redeployment of Equipment

The incremental deployment of equipment strategy leaves the initial pre-fault detection monitoring undisturbed prior to, during and after any mitigation. After mitigation, the circuit is tagged as being in the 'recovery ward' where it is closely monitored for other pre-fault activity, particularly under conditions recognised to have been associated with activity prior to the intervention. Improvement (or not) in the circuit health therefore becomes noticeable on a constant and consistent data set. If the intervention has failed to improve the risk status of the monitored circuits, additional equipment, where it is felt to continue to add benefit, can be left in place. Otherwise, it can be confidently recovered and redeployed to the next high-priority intervention candidate.

On the site of the proactive fault repair, it was clearly observed that following the next few periods of heavy rain, no further pre-fault activity was detected indicating the fault repair was successful. At this point in the proactive fault management procedure, the circuit priority (trending) analysis and the best-impedance values are reset allowing a new circuit health index and, if appropriate, a new location for any further developing faults to be determined. The Locate and/or Locate and Manage equipment can be recovered and redeployed.




At the end of September 2019, more activity was detected on this same circuit. It has not, however, yet signalled the need for further proactive intervention.

# Cost Benefit Analysis

A Cost Benefit Analysis (CBA) has been performed based upon a consideration of Northern Powergrid's (NPg's) present fault management methods (the Counterfactual) versus adoption of the Foresight methods and equipment proposed in this report (the Foresight Solution). The output from the Cost Benefit Analysis can be found in Annexe 1 to this Final Report.

# Project Management

## 5.1 Original Scope

The Foresight Project was scheduled for 36 months starting at the end of February 2017. The project was split into 11 stages (Stage 1 to Stage 11) with a 12th Stage added (Stage 0) for early project planning to determine the best initial approach to meet the project aims and, at various points through the project, to review and if necessary, adjust the approach as project learning and practical considerations dictated.

Stage 0 Detailed Project Planning and Network Assessment and Selection
Stage 1 Deployment of data collection devices and project data collection system
Stage 2 Data capture and development of pre-fault detection algorithms
Stage 3 Development of prototype portable pre-fault test equipment
Stage 4 Deployment and testing of prototype portable pre-fault test equipment
Stage 5 Development of prototype technology and method for location of developing fault
Stage 6 Deployment and testing of fault location technology and method
Stage 7 Deployment of first-generation low-cost fault detection devices
Stage 8 Trial of the technology and method by fault teams in a selected network region
Stage 9 Meshed Network Trials
Stage 10 Integration with existing OMS, EAM Spatial tool and PI data historian
Stage 11 Review the learning from the project and produce project closedown report

## 5.2 Change Control

A Working Level Team comprising members from both Northern Powergrid and EA Technology with various and complementary perspectives on the use of equipment and data for improving LV Performance Management, collaborated regularly on the generation of data, the assimilation and understanding of the data and the translation of the learning accrued to practical systems for the future deployment of the prototype equipment and methodologies. Regular multiday workshops for the working level team were formed around 'Show and Tell' sessions where findings and data analytics were shared, and the consequent action based upon whatever learning had been generated agreed.

Where the beneficial direction of the project differed from that envisaged during the putting-together of the original Research and Collaboration Agreement[22], Project Change Requests were created by working level team for submission to the Project Board for approval. The Project Change Requests and Project Board Structure were based on those used successfully on a previous collaborative project between Northern Powergrid and EA Technology - the Customer-Led Network Revolution Project. As such, the processes were familiar to both collaborating parties.

In all, 25 Change Requests were submitted; 24 of these were approved. Four of the Change Requests described a cost-neutral scope clarification or redirection and a further six described additional work paid for by efficiencies and savings in the delivery of other work packages. Only one item, Stage 9 trials, was deferred out

[22] which set out the original scope and timeframes

of the original scope without an alternative being substituted. The remaining Change Requests registered alterations to the project scope (either substitution or additional scope) based on opportunities arising from the early knowledge and insights generated in the analysis stages. The net result of the project changes was an increase in the overall project budget of £600,000 and an extension of the projected end date from February 2020 to May 2021.

## 5.3 Project Execution

The need for data to enable analysis to determine a practical means of determining the location of pre-fault activity dominated the early plan. In Stage 1, 200 circuit monitoring systems were rolled out to 150 substations – in some substations, more than one circuit was monitored. Two operational zones were selected for data collection, Teesside, and West Yorkshire. The two zones, one in each of Northern Powergrid's License areas, allowed a range of LV network and substation types to be covered in relatively compact areas under the control of a small number of operation staff who were able to become familiar with the aims of the project. In order to generate the desired data, substations with a history of fault events were the primary targets. This targeting proved successful in generating a large amount of early data for the analysis stage.

The original project plan split into three workstreams, developing three different sets of instruments to enable proactive fault management: Pre-fault detection instruments, pre-fault localisation instruments and pre-fault location instruments. Each instrument (and the system surrounding it) would generate its own data set upon which algorithms could be trialled to provide the information that would be brought together later in a proactive fault management methodology. The original plan was, however, rationalised into two workstreams when a means of combining detection and localisation was realised to generate circuit-level (as opposed to substation level) pre-fault data. The resulting data set provided a valuable opportunity (in the combined detection and localisation) workstream, to explore the provision of hitherto unavailable cost-effective condition monitoring data over a large population of Northern Powergrid's cable circuits. Building on this opportunity formed the majority of the approved increased project expenditure and effort.

The large amount of generated data led to an early start on the analysis stage (Stage 2). This stage focussed mainly on location but also provided the initial data for determining trending characteristics (trending of the fault towards causing an off-supply event). During the Stage 2 analysis, which included following several faults through their development to eventual location and repair using standard permanent fault management methods, a predictive means of determining impedance to fault was postulated and subsequently applied to other developing faults. Stage 2 therefore segued directly into Stage 5 (Development of prototype technology and method for location of developing fault), culminating in a prototype pre-fault location method based on data provided by the Stage 1 monitoring equipment. The rest of Stage 5 was given over to the creation and trial of a bespoke instrument to provide pre-fault location (thus supplementing the Stage 1 equipment that was already being used for this purpose). The bespoke Pre-Fault Locator eventually supplied was designed to generate the same data as the Stage 1 monitoring system thus allowing the re-use of the already-developed pre-fault location method.

While Stage 2 and 5 provided the bulk of the location workstream, Stage 3, 4, 7 and 8 provided the development path for detection and localisation. An early version of a proposed low-cost load monitor under development by EA Technology (not part of the Foresight Project) was experimented with by adapting it to be able to capture voltage waveforms triggered by the voltage dip observed when pre-fault events occurred. This minimal voltage triggered device appeared to provide a development path to the envisaged low cost (voltage only) pre-fault detector. At the outset of the project, it was considered that a larger, more expensive, portable version of the same device, with both voltage and current capture, could be used as the portable pre-fault test device (Stage 4), capable of monitoring 5 circuits (15 phase current sensors) in a substation to localise the pre-fault activity to a particular circuit after the low-cost device had indicated substation activity. In determining the most practical option for provision of localisation in Stage 3, it was realised that a hybrid instrument could provide both detection and localisation using a minimal sensor set of just a single Rogowski coil per circuit (deployed onto the neutral conductor only). A small number of prototype instruments in different configurations formed the basis of the design for the 100 Stage 7 'first-pass' detectors which in turn formed the basis of the design for the 1000 Stage 8 detectors (ALVIN Guards). The eventual Stage 8 detectors had the capacity for 8 current measurements as well as 3 voltages. Whilst still low-cost, particularly when considering the lack of need for repeat substation visits for localisation, the Stage 8 detectors required additional funding cover. Additional work was funded to create automated systems to categorise and filter the data from the detectors for use in an asset management model, in the predictive analysis work and in visualisations intended to provide the actionable insights required for operational intervention signalling in the proactive fault management methodology. A small, later piece of work was successfully undertaken in collaboration with Northern Powergrid asset management specialists to integrate the pre-fault data set into a formal LV Cable Asset Management system as a measured condition modifier alongside static cable circuit asset data and historic performance data.

Savings in the provision of Stage 4 portable pre-fault test equipment were redirected at the development of a pre-fault locator using a novel active sensor that it was thought would out-perform the Stage 1 equipment in providing location information from substation devices. After technical difficulties, however, this development did not progress beyond the laboratory tests. The bespoke pre-fault locator development reverted to the original idea of an easy-fit device providing the same data set as the location equipment derived from the Stage 1 monitoring system and resulted in the provision and successful trial of 12 Pre-Fault Locator devices in Stage 5.

The location and detection workstreams, supplemented by the predictive analysis, were brought back together in Stage 6 (Deployment and Testing of Fault Location Technology and Method) which sought to trial the use of the data and equipment in the context of real-world proactive intervention. In considering the Proactive Fault Management Methodology, two further advantageous requirements were identified:

- The need for methods to provide information to signal intervention points
- The need for field-based location equipment for pre-fault activity to improve location confidence before invasive intervention.

The former was explored by creating a sharable dashboard based on the pre-fault data set and using the outputs from a statistical trending analysis carried out first on the data from Stage 1 Monitoring equipment and then later extended to include the conditioned circuit level pre-fault data set from the Stage 7 and Stage 8 detectors. The latter was proposed as an additional Stage to the project (Stage 12) requiring an extension to the project end date and an increase in the overall budget. The Stage 12 Change Request, to develop and trial a mobile, pavement-mounted residual magnetic-field sense-and-capture unit for detection of the passage of pre-fault currents and subsequent site-base location of faults in their early phases of development, was approved by the Foresight Project Board.

The final year of the project was affected by global COVID19 pandemic, particularly laboratory-based development work and the collaborative execution of field trials classed as non-essential work. The Stage 9 Meshed Network trials that were delayed when the equipment anticipated to be installed in Link Boxes was withdrawn from the market, were eventually deferred from the present scope. Stage 6 trials of the Proactive Fault Management Methodology were curtailed and development of the Stage 12 StreetSense devices had to be undertaken using test equipment and prototype construction methods that had to be specifically developed for safe use outside of the EA Technology laboratories. Nevertheless, with the exception of the Stage 9 Meshed Network trials, sufficient learning was generated to form an informed output in line with, and in many cases in excess of, the originally envisaged scope.

It was anticipated that successful trials of the technologies and processes that were developed in the Foresight project would include demonstration of the ability to make data available for transfer into information systems that are used by Northern Powergrid and other DNOs to manage faults on the network. In consultation with Northern Powergrid Information Technology (IT) and Operational Technology (OT) specialists, it was agreed to implement a demonstration data interface using Microsoft Service Bus from which the data could later be distributed within the Business-as-Usual systems as required. The data interface system was developed to populate an SQL database that was hosted in Microsoft Azure with data from the Foresight Devices. The database is refreshed daily with events that have occurred since the last data refresh. The interface demonstrated that that a data resource outside of the Foresight system, which can be accessed by Northern Powergrid using their preferred COTS (Commercial Off-The-Shelf) database tools, could be used to obtain data from the Foresight system in a way that should be relatively easy to re-implement in a Business as Usual (BAU) system.

In keeping with previous innovation projects undertaken in collaboration between Northern Powergrid and EA Technology, the Stage 11 works (Review the learning from the project and produce project closedown report), which includes this report, used a collaboratively created project communication plan to plan and monitor the targeting of the project outputs.

# Project Summary

The Foresight Project, a collaborative project between GB Distribution Network Operator Northern Powergrid and Solutions Provider EA Technology, has developed equipment and methods aimed at finding and fixing LV cable faults before they fail. The project has produced a data set from a fleet of low-cost pre-fault detectors that is being used to provide health index and performance improvement information for LV underground cable circuits of use in both the areas of Asset Management and Operational Network Management.

Over a four-year period, the Project has moved-on the industry status-quo of locating and repairing LV cable faults only when they become permanent (Damage) faults. The methods developed and trialled open-up the opportunity for new ways of tackling faults by intervening earlier in their life cycle and before the impact of the developing fault becomes unacceptable and, in some cases, before they cause any customer interruptions.

Not every fault gives sufficient warning that an acceleration toward a fault requiring repair to restore customer supplies is imminent, but we believe that enough do, with enough lead in time, to make proactive location and repair a viable way of operating in the future. A cost benefit analysis, incorporating the learning from the project, including the proportion of faults that could have been detected and proactively managed, and using reasonable assumptions and real data where it was available, showed a healthy net financial benefit from the adoption of the new proposed methods. The concomitant improvement in the quality of customer service when a large proportion of faults are repaired significantly earlier in their life cycle than is the standard now is additional.

The foundation of the project is the introduction of low-cost devices, methods and systems of monitoring for pre-fault activity. To realise the benefits created by use of their data, these devices have to be both widespread (to cover sufficient assets with deteriorating health but not necessarily (yet) on the radar of Network Operator Fault Management specialists) and easy to install. For economic deployment, these two requirements are mutually inclusive and formed the strategy for Guard devices developed on the project.

The developing-fault location methods trialled (using data from substation-based feeder monitoring equipment) have been proven to be able to produce sufficiently accurate location information from pre-fault activity. The highest confidence locations, however, result from the highest energy events and these are often associated with protection operation (off-supply) rather than pre-fault events. Where the locating equipment includes reclosers though, as most protection operations are associated with faults in the transient stage of operation, supplies are restored within minutes and without the need to attend site. Repairing faults before they develop to the persistent transient or permanent (damage fault) stage still delivers considerable benefits over traditional location and repair practices. The early location imperative here then turns to the introduction of fault locating equipment before the first transient operation. This therefore became the first beneficial intervention point facilitated by the predictive analysis of the Guard data in the proposed Proactive Fault Management Methodology.

Recognition of the future need to confidently locate faults in their earlier stages of development, and to provide site-based confirmation of location before repair activity is committed, led to the development of the prototype StreetSense Mats (used in conjunction with the Guards). Though more trials and development are required on this device, it is anticipated that this site-based pre-fault activity location device will be a key piece in a future Find and Fix proposition in conjunction with the other equipment and methods that the Foresight Project has produced.

It is entirely conceivable that future work on the predictive algorithms, particularly as the data set and population of faults monitored increases, will improve the predictive capabilities over where we were able to get to during the present project. Follow on work is planned to continue the data collection and explore the practical issues associated with the implementation of proactive fault management, against the backdrop of Opex and Capex budgets, organisational structure, supporting tools, operational procedures and customer messaging and interactions.

# Appendix A Monitoring System Captures to End July 2020

Approximately 190 circuits in 136 substations were consistently monitored over the course of the Project.

Analysis of the data set from the monitoring equipment up to July 2020 determined that 906 separate phase off-supply events had been captured during 577 separate feeder-level incidents. The confirmed interruption events were distributed between 85 of the 190 circuits monitored. Of a total of 23,062 pre-fault events (waveforms not associated with off-supply incidents) during the same period, 12,601 were on the 85 circuits that had experienced at least one protection operation. 37 of feeder-level incidents over this period were related to damage faults (requiring reactive repair to restore supplies)

*Table 2 Analysis of the number of pre-fault and off-supply events from 190 monitored circuits between Oct 2017 and July 2020*

| | |
|---|---|
| Number of Circuits consistently monitored | 190 |
| Number of Pre-fault Waveforms (total) | 23,062 |
| Number of Phase Interruptions (individual protection operations) | 906 |
| Number of Feeder Interruptions (either single phase or multiphase operations) | 577 |
| Number of circuits with at least one interruption | 85 |
| Number of Pre-fault Waveforms on interrupted circuits | 12,601 |
| Number of faults that became permanent over this period | 37 |

technology

Safer, Stronger, Smarter Networks

EA Technology Limited
Capenhurst Technology Park
Capenhurst, Chester CH1 6ES

t +44 (0) 151 339 4181
e sales@eatechnology.com
www.eatechnology.com