OHL Power Pointer - Report on Method 3

Method 3: Detection of Auto-Recloser Operations

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1. Executive Summary

Rural overhead feeders are often susceptible to intermittent faults, which can be caused by tree branches or cracked insulators. To reduce the number of interruptions to customers, feeders are equipped with circuit breakers with auto-reclose sequences, installed in the primary substation, at the midpoint, or sometimes at several points along radial feeders. The principle of operation is that faults on rural networks are often caused by transient events, such as a tree branch striking an overhead conductor before falling to the ground. Auto-reclosers operate like a standard circuit breaker to clear the fault but will attempt to reclose the circuit breaker automatically within a few seconds to check if the cause of the fault has cleared.

OHL (Overhead Line) Power Pointer is a project which is funded through Ofgem's Network Innovation Allowance (NIA) mechanism, it has trialled a device capable of self-powering operation and provides real-time voltage, current, directional power flow, conductor temperature and fault activity information. This information has been used to more accurately assess network operation, such as latent generation output and directional fault detection to more quickly identify the location of faults. The project was registered in January 2019 and completed in May 2022.

This report has been prepared following the completion of the field trials and presents the findings of Method 3: Detection of Auto-Recloser Operations.

Smart Navigator 2.0 directional fault passage indicators were installed on 11kV, 33kV, 66kV and 132kV circuits during test trials and field trials across the West Midlands and South West licence areas. Several trial locations were selected downstream of auto-recloser equipment on 11kV circuits which were historically prone to fault activity, in order to maximise the likelihood of detecting auto-recloser sequences in response to faults.

Case studies of activity captured during the field trials at the following trial locations have been presented to support key findings of the Method:

1. Stafford South primary substation, Tilcon Industrial Estate 11kV feeder, Stoke, West Midlands
2. Rugeley Town primary substation, Horse Fair 11kV feeder, Stoke, West Midlands
3. Market Drayton primary substation, Hodnet 11kV feeder, Stoke, West Midlands
4. Harlescott primary substation, Food Ent Pk 11kV feeder, Telford, West Midlands

The analysis of the case studies demonstrates that the solution has successfully recorded the detection of multiple trip operations in a typical circuit breaker auto-reclose sequence. Auto-reclose trip events have been captured at primary substation feeder circuit breakers and mid-feeder switching equipment. The solution records and uploads the number of circuit breaker operations to the central iHost monitoring platform, until a manual reset is triggered remotely.

The results of auto-recloser operation detection have been validated against SCADA (Supervisory Control and Data Acquisition) records from local network switching equipment obtained by Network Services teams, and the accuracy of the method has been found to be satisfactory for the purposes of reporting to the Control room.

New features developed in the delivery of the Method have been presented on a dashboard in the iHost monitoring platform, which is accessible directly in the Control room environment from Smart Navigator 2.0 symbols located on the Network Management System (NMS) diagram.

Ofgem's RIIO-ED2 methodology decision publication, presents reasoning that a lack of robust and comparable data across all DNOs prevented the introduction of an incentive to reduce short interruptions in RIIO-ED2 and is instead looking towards a potential incentive in RIIO-ED3. The recording of short interruptions has been demonstrated under the OHL Power Pointer project and the technology developed for the Smart Navigator 2.0 could be used to support the delivery of a regulatory mechanism for incentivising reductions of short interruptions during RIIO-ED2 and RIIO-ED3 price control periods.

2. Project Background

OHL (Overhead Line) Power Pointer is funded through Ofgem's Network Innovation Allowance (NIA). The project was registered in January 2019 and completed in May 2022.

OHL Power Pointer has trialled a device that is capable of self-powering operation and provides real-time voltage, current, directional power flow and conductor temperature information. This information has been used to more accurately assess network operation, such as latent generation output and directional fault detection to more quickly identify the location of faults.

OHL Power Pointer has deployed Smart Navigator 2.0 sensors onto our network to monitor directional power flows and address the "Network Monitoring and Visibility" challenge within the "Assets" section of our "Distribution System Operability Framework".

Smart Navigator 2.0 sensors clip onto overhead lines (operating at voltages from 11kV to 132kV) and sample the voltage and current waveforms (multiple times per cycle) to determine the real-time power flow direction at that point in the network. The devices weigh less than 1kg, harvest power from the overhead line for self-sustaining operation and can be readily ported between sites for redeployment. Using encrypted DNP3 communications over mobile networks, the devices transmit power flow data from remote sites to a central system (for example, iHost or PowerOn). The sensors support over-the-air upgrades, which means their functionality can be reconfigured remotely without the need for multiple site visits.

A rendered illustration of a set of Smart Navigator 2.0 sensors installed on a three-phase overhead line is presented in Figure 2-1.

Figure 2-1: Rendered Illustration of a set of Smart Navigator 2.0 sensors

We are the first UK DNO to use Nortech's technology in these DSO applications.

Over 100 sets of Smart Navigators have been trialled in this project, covering the various Methods and nominal voltage levels of overhead lines in the South West (132kV circuits) and West Midlands (66KV, 33kV and 11kV circuits) licence areas.

3. Scope and Objectives

3.1. Scope

The project has been delivered over the course of three years, in three overlapping phases, as summarised below.

- Phase 1: Design and Build (January 2019 – April 2020)
  In this phase, the functionality of the OHL Power Pointer solution was defined for each of the five Methods (directional power flow monitoring, directional power flow estimation, auto-recloser operation detection, directional fault passage indication (FPI) and post-fault rating of overhead lines). The software was designed and implemented. Network locations were identified, and equipment installation locations were selected. In addition, the trials of the various methods were designed.
- Phase 2: Install and trial (September 2019 – February 2022)
  In this phase, the Smart Navigator 2.0 equipment (for directional power flow monitoring, auto-recloser detection, directional fault passage indication and post-fault rating determination) was installed and trialled. Initially, 50 sets of devices were installed to cover the trials of the various Methods. These devices communicated to Nortech's iHost system for rapid prototyping of the software and support with the solution design. As part of the main trials, an additional 50 sets of devices were installed, communicating to WPD's iHost system and the 50 sets installed as part of the initial trials were transitioned across to WPD's iHost system.
- Phase 3: Analysis and Reporting (January 2019 – May 2022)
  In this phase, the results from the trials were analysed and a report on the learning resulting from each of the Methods was prepared. Results and key learning outputs were disseminated and policies were written to facilitate the wider adoption of the OHL Power Pointer solution WPD's business should WPD proceed with Business as Usual (BaU) roll-out

3.2. Objectives

This section outlines the project objectives, more detail is provided later in the report.

Table 3-1: Project objectives

Objective
Create policies for equipment installation and location
Carry out assessments of the accuracy and consistency of determining power flow directions within our distribution network
Provide recommendations on the number and location of devices needed for full visibility of power flow direction
Quantify the savings gained by using the Smart Navigator to detect and communicate auto-recloser operations (rather than using visual inspections of AR equipment)

Quantify the savings made to Customers Minutes Lost (CMLs) through the use of OHL directional FPIs
Provide the control room with visibility of overhead line real-time post-fault ratings

4. Success Criteria

This section indicates the success criteria of the project, more detail is provided later in the report.

Table 4-1: Project success criteria

Success Criteria
Power flow direction determined correctly at a minimum of 10 sites across 11kV and 33kV networks
Power flow direction estimated correctly at a minimum of 10 sites across 11kV and 33kV networks
Correct detection of a minimum of 5 auto-recloser operations during the project lifetime (recognising this is dependent on faults occurring)
Direction of passage of fault current determined at a minimum of 5 sites during the project lifetime (recognising this is dependent on faults occurring)
Post-fault ratings determined for at least one circuit at or above 33kV during the project lifetime
Completion of trials of the five different Methods, with a report on each Method detailing the learning and updated business case for wider business adoption
Development of policies to facilitate the wider business adoption of the technology at the end of the project should we decide for BaU adoption

5. Details of the Work Carried Out

The project has delivered a solution for the real-time capture of fault activity and recording of circuit breaker trip operations. The method has investigated the operation of several different types of auto-reclosing circuit breaker equipment in use across the West Midlands distribution network for the protection of HV feeders at primary substations and at key intervals along HV feeders.

The Smart Navigator 2.0 solution has been deployed and tested in a live operational environment and the data captured during the field trials has been evaluated against the event history of various switching equipment installed across the network.

5.1. Short Interruptions (SIs)

Customers have, in the past, expressed preference for DNOs to focus on restoring supplies as quickly as possible, and to make sure long duration interruptions (in particular) are minimised as these often cause the greatest disruption. Ofgem's Interruption Incentive Scheme (IIS) incentivises DNOs to reduce the number and duration of customer interruptions (CIs) lasting longer than three minutes; loss of supply events lasting less than three minutes are referred to as a short interruptions (SIs).

Investments in the network and the introduction of new technologies have led to an overall improvement in the reliability of networks, which is quantified through CI and CML regulatory incentives. As we transition towards a smarter, more flexible distribution network, long duration interruptions continue to cause a significant amount of disruption to customers.

Any loss of supply is inconvenient to customers, and interruptions, regardless of their duration, impact network reliability. A short interruption can have a notable impact on customers, for example, medical equipment may depend on a continuous supply of electricity to perform its function. Loss of supply to a household Wi-Fi router causes the router to restart, disrupting user's internet access.

The data collected on the number of SIs by DNOs is less comprehensive than the equivalent data for CIs, however it is estimated that up to 80% of interruptions on distribution networks are short interruptions lasting less than three minutes. During 2021, there were c. 400,000 unplanned CIs (lasting longer than three minutes) recorded across the West Midlands licence area, which were attributable to overhead incidents.

Ofgem is consulting on establishing a minimum standard of performance for short interruptions. One possibility is to implement a financial penalty mechanism similar to Regulation 10 "Supply restoration – multiple interruptions" of the Quality of Service Guaranteed Standards, where our customers are eligible for a payment of £150 if their electricity supply fails for three hours or more, on at least four occasions in a 12 month period[1]. Ofgem's current position is that there is not enough data available across DNO licence areas to be able to set appropriate incentivisation targets for

[1] Western Power Distribution: Guaranteed Standards of Service, Regulation 10 – Multiple Interruptions, May 2021

reduction of short term interruptions, however, Ofgem's consultation[2] for RIIO-ED2 methodology points towards incentivisation of SIs in the RIIO-ED3 price control period.

5.2. Auto-Recloser Equipment in Distribution Networks

Figure 5-1 illustrates a typical 11kV radial feeder on our distribution network. There are three auto-reclosing circuit breakers identified with a blue circle. The OHL Power Pointer trial locations are identified with yellow symbols and respective site numbers. The ABI at Smiths Farm is an open point. Theoretically a fault downstream of trial site #216 would likely cause an overcurrent fault to be detected at site #256 and #216 and should be cleared by the operation of auto-recloser at Dog Inn Over. This would cause the de-energisation of the downstream circuit, resulting in voltage loss at site #216. In addition, the number of circuit breaker trip operations should be counted by the sensor at site #216, to be able to quantify the activity of the auto-recloser at Dog Inn Over.

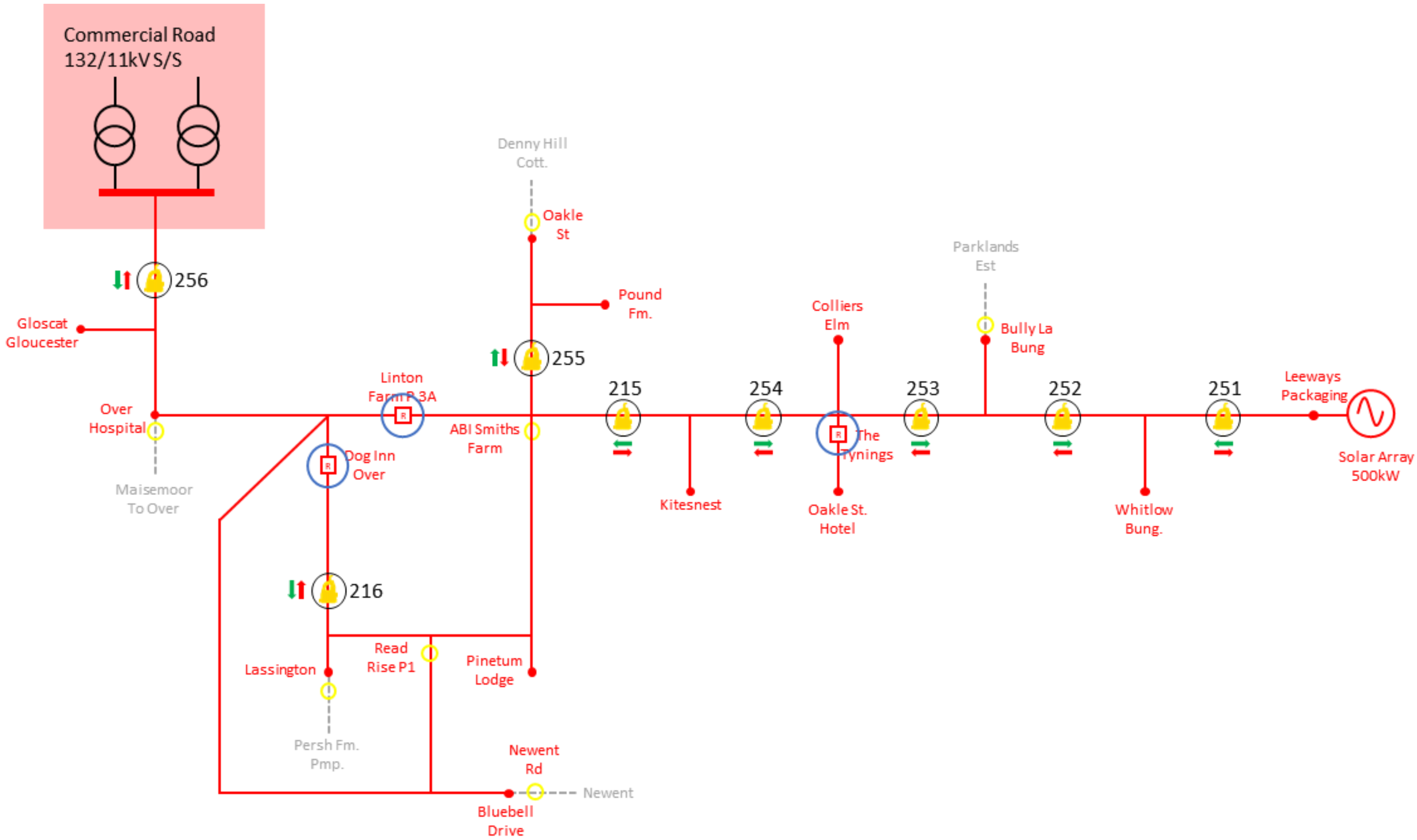

Figure 5-1: The 11kV Distribution Network

Typically, auto-recloser equipment on the West Midlands 11kV network is configured to attempt to reclose up to three times, before defaulting to 'locked-out' open state. This sequence is characterised in Table 5-1, using fictitious timestamps for illustration.

[2] Ofgem: RIIO-ED2 Methodology Decision: Annex 1 – Delivering value for money services for customers, December 2020

Table 5-1: Auto-Recloser Sequence of Events

Time	Operation
25/03/2021 06:34:23	Recloser opens (Fault detected)
25/03/2021 06:34:28 (+ 5s)	Recloser closes (Attempt 1)
25/03/2021 06:34:28	Recloser opens (Attempt 1 - unsuccessful)
25/03/2021 06:34:39 (+10s)	Recloser closes (Attempt 2)
25/03/2021 06:34:39	Recloser opens (Attempt 2 – unsuccessful)
25/03/2021 06:34:59 (+20s)	Recloser closes (Attempt 3)
25/03/2021 06:34:59	Recloser opens (Attempt 3 – unsuccessful)
25/03/2021 06:34:59	Recloser Locked-Out (Open)

The West Midlands distribution network comprises different types of auto-recloser switching equipment. Modern equipment is often connected to the SCADA system and can be polled from NMS for trip events and circuit breaker operations. Older equipment is not connected to the SCADA system but contains a limited event history which must be obtained locally by field teams periodically to maintain records of operation.

5.3. Trial Site Locations

The test trials were carried out with sensors installed on circuits across the West Midlands licence area, the field trials were designed to investigate both newer SCADA connected equipment, and older switching equipment on 11kV networks, where it was anticipated the automatic recording of auto-recloser operations would be most useful.

Auto-recloser operations were detected at many trial locations throughout the test trials. There were ten trial sites that were initially identified to support the development of the auto-recloser detection features. These sites were located downstream of 11kV auto-recloser equipment which recorded the highest number of operations throughout 2018. Each feeder is operated in a radial configuration and the sensors were typically installed one span downstream of the equipment. The trial sites are given in Table 5-2.

Table 5-2: Test Trial Site Locations

Trial Site #	Primary Substation	Feeder Name	Recloser ID
123	Peterchurch	Rough Leath ABI 11553 Feeder	AR RC 43022
124	Hereford North	Credenhill No.1 Feeder	AR RC 43024 BRINSOP
125	Broadway	Collin Lane Corner Feeder	AR RC 30143

126	Donnington	Donnington Local/Muller Dairy/Donnington Solar Tee Feeder	AR RC 105373 HUMBERS LA.
127	Harlescott	Food Ent Pk / Loosemores ABI 841038 / Stadco / Wa Feeder	AR RC 118670 ALBION HAYES
128	Congleton	Congleton Local Feeder	AR RC 94187 BUNGLAWTON
129	Bodenham	Ash Grove Farm P7 Feeder	AR RC 43005 NULEC 4
130	Stourport	Redstone Lane / Barnfield Rd Feeder	AR RC 47035 ASTLEY
131	Bearstone	Norton-in-Hales/Pipegate Feeder	AR RC 00059 PIPEGATE
132	Gnosall	Glendower Est/Gnosall GVR Feeder	AR RC 93878 COTON END

A summary of the events captured during the main trial period is provided in Table 5-3.

Table 5-3: Main Trial Auto-Recloser Locations – Fault Activity

Trial Site #	Primary Substation	Earth Faults & Overcurrent Faults	Earth Faults Only	Overcurrent Faults Only	Transient Faults	Permanent Faults
123	Peterchurch	-	2	-	2	-
124	Hereford North	1	-	-	1	-
125	Broadway	1	-	-	1	-
126	Donnington*	-	-	-	-	-
127	Harlescott	5	5	1	10	1
128	Congleton	2	-	-	1	1
129	Bodenham	2	-	-	-	2
130	Stourport	-	3	1	1	3
131	Bearstone	-	-	2	2	-
132	Gnosall	3	-	-	3	-

* excluded from study following storm damage to OHL equipment

5.4. The Auto-Recloser Operation Detection Solution

5.4.1. Smart Navigator 2.0 Sensor

The Smart Navigator 2.0 sensor was developed with a series of counter registers to record permanent and transient faults and circuit breaker trip operations on a per phase and per set basis. The data from the counters is uploaded to the iHost monitoring platform following each fault event and displayed on the user interface.

The sensor detects the auto-reclose operations using an algorithm to detect overcurrent followed by a period of low current. This enables the sensor to capture the individual operations of the auto-reclose sequence and quantify the number of circuit breaker 'break' events.

The sensor implements a fault classification delay of 60 seconds, to allow for auto-reclose sequence to be executed before determining whether the event was a transient or permanent interruption. The classification delay is user configurable.

The counters registers can be reset periodically by the user, by issuing a command over-the-air from iHost.

5.4.2. User Interface / Dashboard

The transient and permanent fault counters, and circuit breaker operations have been incorporated into a dashboard for the Smart Navigator 2.0 to assist with maintenance efficiency and short-term interruption quantification. The Power Flow Interruptions section of the dashboard is displayed in Figure 5-2.

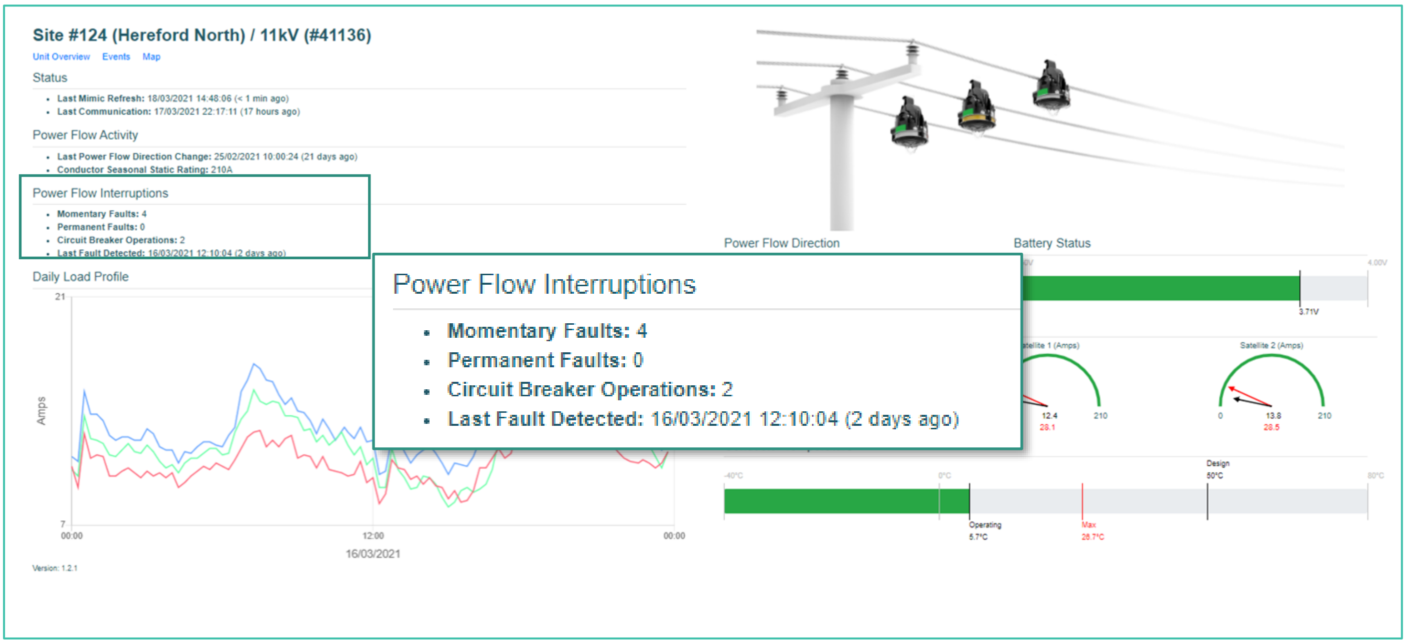

Figure 5-2: Smart Navigator 2.0 Dashboard – Power Flow Interruptions

The dashboard is directly available to users in the Control room, it is accessible in iHost via the right click menu from each Smart Navigator 2.0 symbol on the NMS diagram.

5.5. Case Studies

Several case studies have been prepared with detailed assessments from events that have been recorded on the distribution network during the main field trials. There were many fault events captured during the main field trials, the following case studies present instances of transient and permanent fault events where the auto-reclose sequence was confirmed locally at the switching equipment.

5.5.1. Stafford South – Transient Fault

A fault occurred at 06:34:24 on the morning of 20th March 2021 on the 11kV Tilcon Industrial Estate feeder supplied from Stafford South primary substation.

There are six Smart Navigator 2.0 sensors installed on various sections of the feeder. Trial sites #223 and #221 are located on a radial spur from the main circuit. Sensors at both sites detected a transient two-phase to earth fault. The assumed location of the fault and the geographical topology of the network is presented in Figure 5-3. The expected path of the fault current is projected onto the figure, and the trial sites are visible.

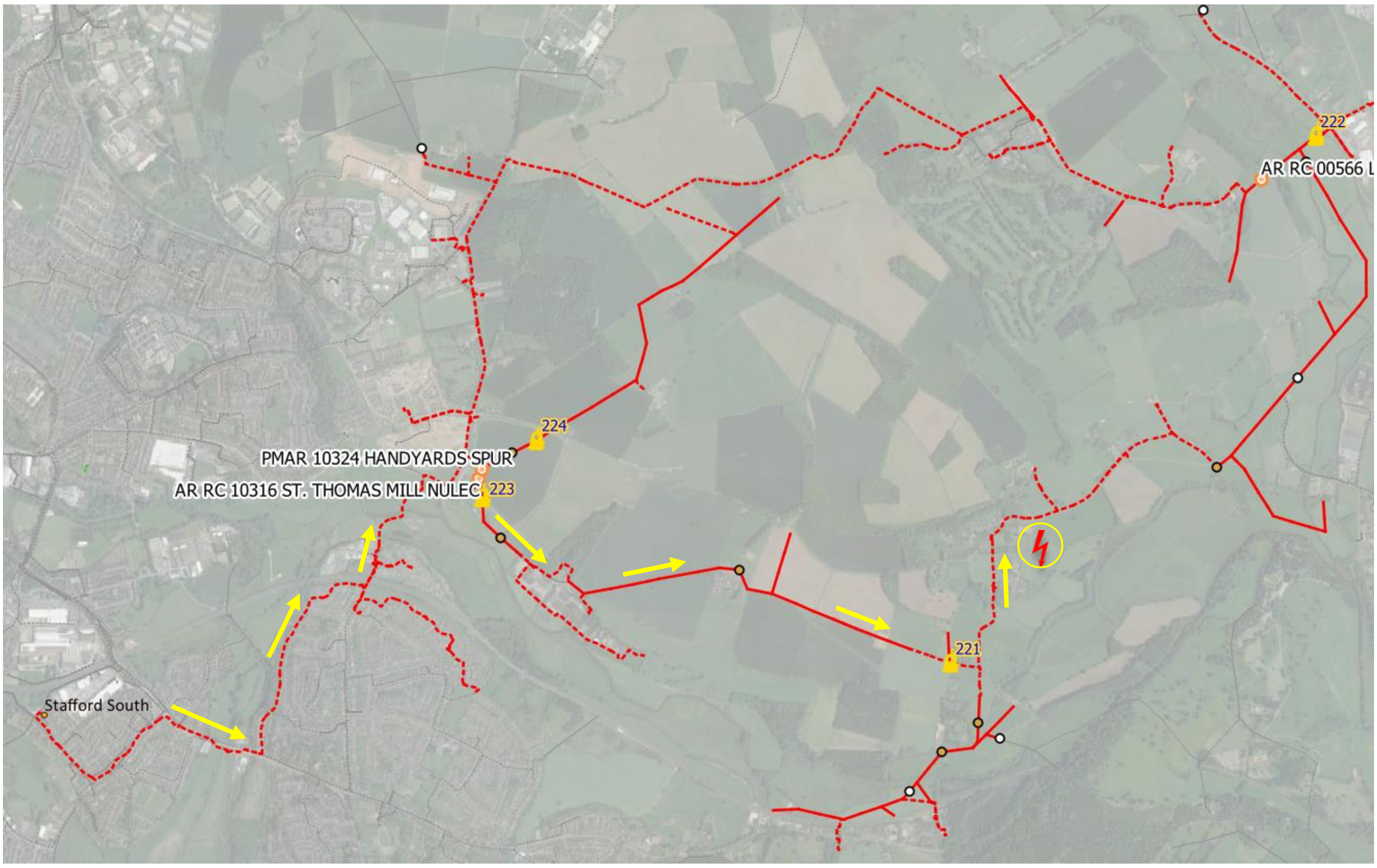

Figure 5-3: Geographical view of part of the Tilcon Industrial Estate feeder from Stafford South

The Network Services team was able to interrogate the auto-recloser at St. Thomas Mill, which provides protection for this particular spur. The event history from the equipment is presented in Table 5-4.

Table 5-4: St Thomas Mill Nulec – Event History

Time	Event History
20/03/2021 06:34:23	Recloser opens (Fault detected)
20/03/2021 06:34:28	Recloser closes (Attempt 1)

20/03/2021 06:34:28	Recloser opens (Attempt 1 - unsuccessful)
20/03/2021 06:34:39	Recloser closes (Attempt 2 – successful)

It can be deduced from the event history of the auto-recloser that the recloser opened when the fault current was detected, five seconds later the circuit breaker attempted a close sequence but immediately opened as the fault was still obstructing the circuit, then ten seconds later the obstruction had cleared and the circuit breaker reclosed successfully.

This is an example of one transient fault, where two circuit breaker trip operations were reported.

The sensors at both trial sites detected faults on the central and an outer phase. The fault information captured at each site is given in Table 5-5 and Table 5-6. At both sites, faults recorded in direction 'red' indicates the location of the fault is downstream, or beyond the trial sites.

Table 5-5: Trial Site #223 – Fault Information

Site #223	Fault Current	Fault Duration	Fault Direction
Master	-	-	-
Satellite 1	1570A	880ms	Red
Satellite 2	1463A	900ms	Red

Table 5-6: Trial Site #221 – Fault Information

Site #221	Fault Current	Fault Duration	Fault Direction
Master	-	-	-
Satellite 1	1520A	892ms	Red
Satellite 2	1401A	890ms	Red

The counter events captured by both Smart Navigator 2.0 sensors are given in Table 5-7 and Table 5-8. The data shows that the fault was correctly categorised as a transient fault, and the counters correctly recorded two trip operations. Two transient faults were reported, since both an earth fault event and an overcurrent event were captured by the sensor.

Table 5-7: Trail Site #223 – Auto-Recloser Events Detected

Site #223	Count before event	Count after event	Count increment
Master Transient Fault Counter	2	2	0
Master Permanent Fault Counter	0	0	0
Master Trip Counts	1	1	0
Trip Counts Set	1	3	+2
Permanent Faults Set	0	0	0
Transient Faults Set	4	6	+2
Satellite 1 Transient Fault Counter	2	4	+2

Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	1	3	+2
Satellite 2 Transient Fault Counter	0	2	+2
Satellite 2 Permanent Fault Counter	0	0	0
Satellite 2 Trip Counts	0	2	+2

Table 5-8: Trail Site #221 – Auto-Recloser Events Detected

Site # 221	Count before event	Count after event	Count increment
Master Transient Fault Counter	0	0	0
Master Permanent Fault Counter	0	0	0
Master Trip Counts	0	0	0
Trip Counts Set	0	2	+2
Permanent Faults Set	0	0	0
Transient Faults Set	2	4	+2
Satellite 1 Transient Fault Counter	0	2	+2
Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	0	2	+2
Satellite 2 Transient Fault Counter	0	2	+2
Satellite 2 Permanent Fault Counter	0	0	0
Satellite 2 Trip Counts	0	2	+2

This case study has confirmed the correct operation of auto-recloser detection using the Smart Navigator 2.0 sensor, for a transient fault.

5.5.2. Rugeley Town – Transient Fault

A fault occurred at 16:22:47 on the afternoon of 11th May 2021 on the 11kV Horse Fair feeder supplied from Rugeley Town primary substation.

There are two Smart Navigator 2.0 sensors installed at trial sites #147 and #148 on the two main branches of the feeder, respectively. The sensor at site #148 detected a transient three-phase overcurrent fault. The assumed location of the fault and the geographical topology of the network is presented in Figure 5-4. The expected path of the fault current is projected onto the figure, and the trial sites are visible.

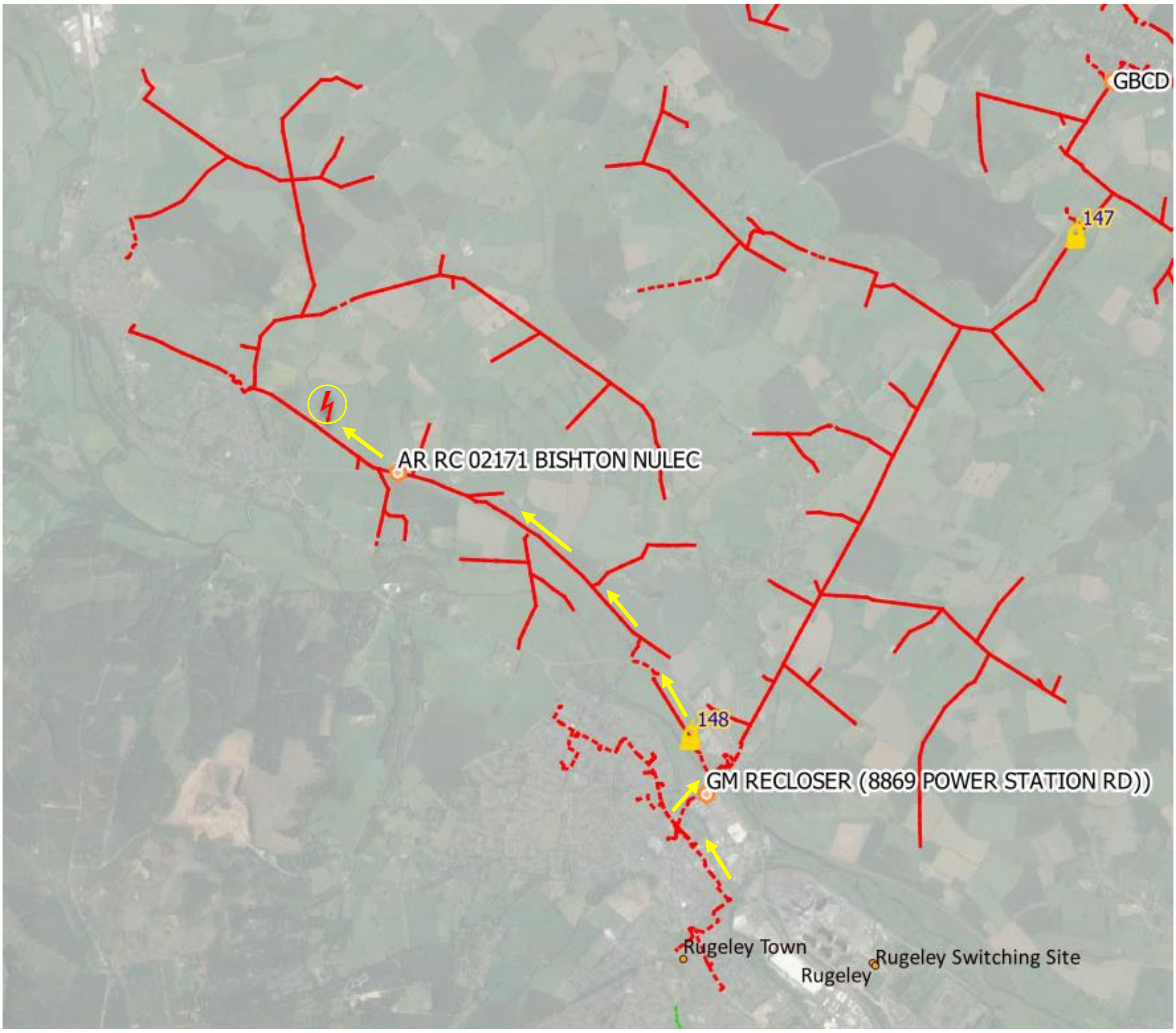

Figure 5-4: Geographical view of part of the Horse Fair feeder from Rugeley Town

The Network Services team was able to interrogate the auto-recloser at Bishton, which provides protection for this particular branch. The event history from the equipment is presented in Table 5-9.

Table 5-9: Bishton Nulec – Event History

Time	Event History
11/05/2021 16:22:45	Recloser opens (Fault detected)
11/05/2021 16:22:50	Recloser closes (Attempt 1 – successful)

The history from the auto-recloser indicates that the fault had cleared prior to the first reclose operation, five seconds after the initial trip in response to the fault.

This is an example of a transient trip where one circuit breaker trip operation was reported.

The sensors at site #148 detected an overcurrent fault on all three phases. The fault information captured by the Smart Navigator 2.0 is given in Table 5-5. Faults recorded in the 'Green' direction at this trial site indicate that the location of the fault is downstream, or beyond the trial site.

Table 5-10: Trial Site #148 – Fault Information

Site #148	Fault Current	Fault Duration	Fault Direction
Master	1240A	499ms	Green
Satellite 1	1221A	480ms	Green
Satellite 2	1073A	490ms	Green

The counter events captured by the Smart Navigator 2.0 sensor are given in Table 5-11. The data shows that the fault was correctly categorised as a transient fault, and the counters correctly recorded one trip operation and one fault. Two transient faults were reported for the set, since both an earth fault event and an overcurrent event were captured by the sensor.

Table 5-11: Trail Site #148 – Auto-Recloser Events Detected

Site #148	Count before event	Count after event	Count increment
Master Transient Fault Counter	0	1	+1
Master Permanent Fault Counter	0	0	0
Master Trip Counts	0	1	+1
Trip Counts Set	0	1	+1
Permanent Faults Set	0	0	0
Transient Faults Set	0	2	+2
Satellite 1 Transient Fault Counter	0	1	+1
Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	0	1	+1
Satellite 2 Transient Fault Counter	0	1	+1
Satellite 2 Permanent Fault Counter	0	0	0
Satellite 2 Trip Counts	0	1	+1

This case study has presented a possible error in one of the counters, however this was identified and corrected upon further examination.

5.5.3. Market Drayton – Transient Fault

A fault occurred at 07:19:58 on the morning of 14th May 2021 on the 11kV Hodnet feeder supplied from Market Drayton primary substation.

There are Smart Navigator 2.0 sensors installed at trial sites #264 and #263 on the main circuit. The circuit topology is looped, but the configuration of normally open points means that the circuit operates radially. Sensors at both sites detected a transient three-phase overcurrent fault. The assumed location of the fault and the geographical topology of the network is presented in Figure 5-5. The expected path of the fault current is projected onto the figure, and the trial sites are visible.

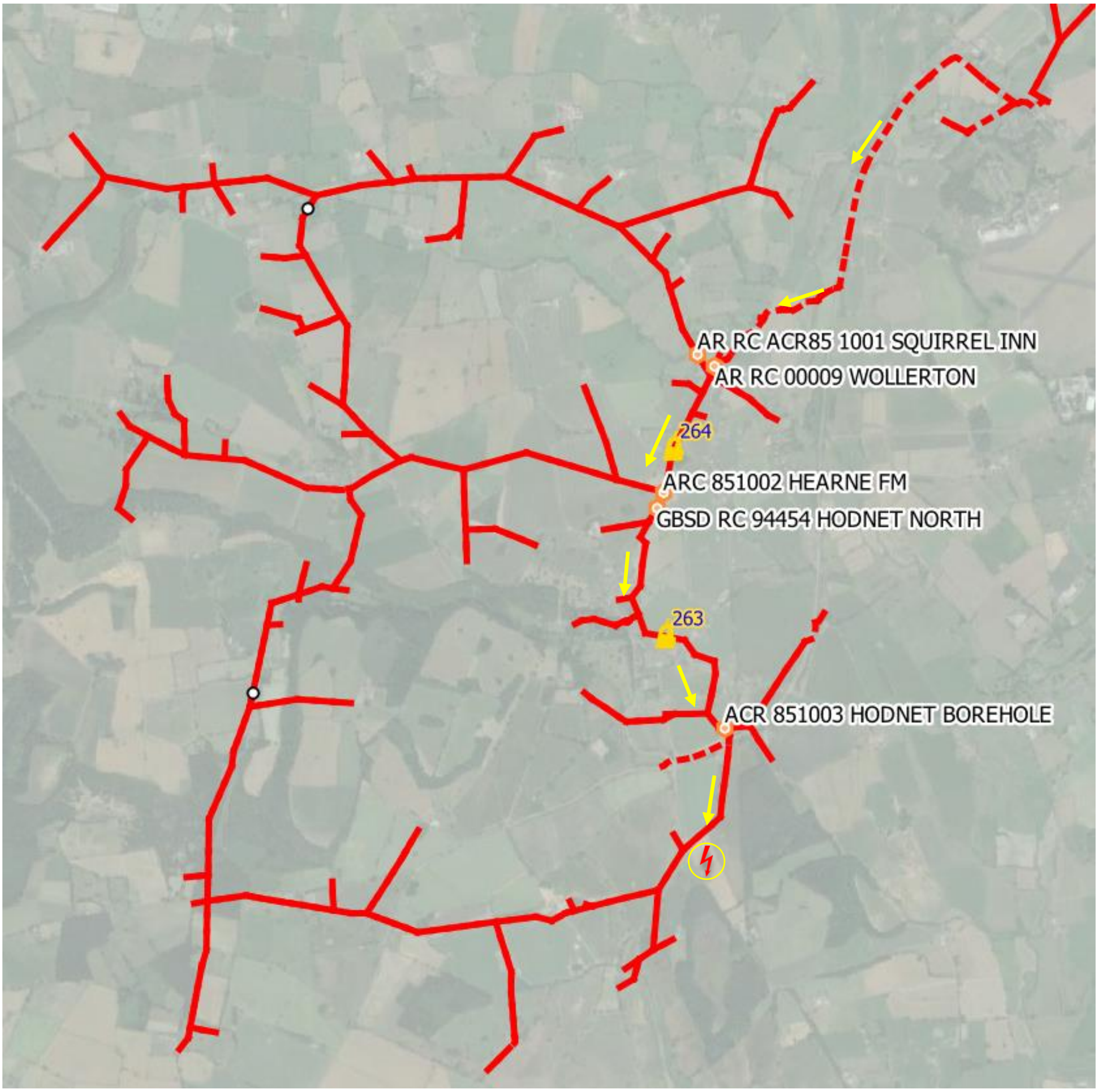

Figure 5-5: Geographical view of part of the Hodnet feeder from Market Drayton

The Network Services team was able to interrogate the auto-recloser at Hodnet Borehole, which provides protection for this particular spur. The event history from the equipment is presented in Table 5-12.

Table 5-12: Hodnet Borehole ACR – Event History

Time	Event History
14/05/2021 07:19:58	Recloser opens (Fault detected)
14/05/2021 07:20:03	Recloser closes (Attempt 1 – successful)

The history from the auto-recloser indicates that the fault had cleared in the five seconds between the initial trip in response to the fault, and the first reclose operation.

This is an example of a transient trip where one circuit breaker trip operation was reported.

The sensors at sites #264 and #263 detected an overcurrent fault on all three phases. The fault information captured by the Smart Navigator 2.0 is given in Table 5-13 and Table 5-14 . The differences in the fault direction colour reference are due to the orientation of the devices locally at the trial site. In this case both sets of sensors correctly recorded the fault direction downstream of the trial sites, towards Hodnet Borehole auto-recloser.

Table 5-13: Trial Site #264 – Fault Information

Site #264	Fault Current	Fault Duration	Fault Direction
Master	887A	419ms	Green
Satellite 1	905A	631ms	-
Satellite 2	826A	630ms	Green

Table 5-14: Trial Site #263 – Fault Information

Site #263	Fault Current	Fault Duration	Fault Direction
Master	860A	410ms	Red
Satellite 1	911A	609ms	-
Satellite 2	829A	621ms	Red

The counter events captured by both Smart Navigator 2.0 sensors are given in Table 5-15 and Table 5-16. The data shows that the fault was correctly categorised as a transient fault, and the counters correctly recorded one trip operation and one fault. Note that site #264 also detected a fault previously which was cleared by the auto-recloser at Hearne Farm which protects an adjacent spur, hence #263 was unaffected.

Table 5-15: Trail Site #264 – Auto-Recloser Events Detected

Site #264	Count before event	Count after event	Count increment
Master Transient Fault Counter	2	3	+1
Master Permanent Fault Counter	0	0	0

Master Trip Counts	1	1	0
Trip Counts Set	1	1	0
Permanent Faults Set	0	0	0
Transient Faults Set	2	3	+1
Satellite 1 Transient Fault Counter	2	3	+1
Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	1	1	0
Satellite 2 Transient Fault Counter	2	3	+1
Satellite 2 Permanent Fault Counter	0	0	0
Satellite 2 Trip Counts	1	1	0

Table 5-16: Trail Site #263 – Auto-Recloser Events Detected

Site #263	Count before event	Count after event	Count increment
Master Transient Fault Counter	0	1	+1
Master Permanent Fault Counter	0	0	0
Master Trip Counts	0	0	0
Trip Counts Set	0	0	0
Permanent Faults Set	0	0	0
Transient Faults Set	0	1	+1
Satellite 1 Transient Fault Counter	0	1	+1
Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	0	0	0
Satellite 2 Transient Fault Counter	0	1	+1
Satellite 2 Permanent Fault Counter	0	0	0
Satellite 2 Trip Counts	0	0	0

This case study has confirmed the correct operation of auto-recloser detection using the Smart Navigator 2.0 sensor, for a transient fault.

5.5.4. Harlescott – Permanent Fault

A fault occurred at 18:45:18 on the evening of 11th July 2021 on the 11kV Food Ent Pk feeder supplied from Harlescott primary substation.

There are Smart Navigator 2.0 sensors installed at trial site #127 on the main circuit which is operated in a radial configuration. The sensors detected a two-phase earth fault and overcurrent fault. The fault was located on the single phase spur to Wood Cottage secondary substation, where a tree branch compromised both overhead conductors. The geographical topology of the network is presented in Figure 5-5. The path of the fault current is projected onto the figure, the trial site #127 is indicated.

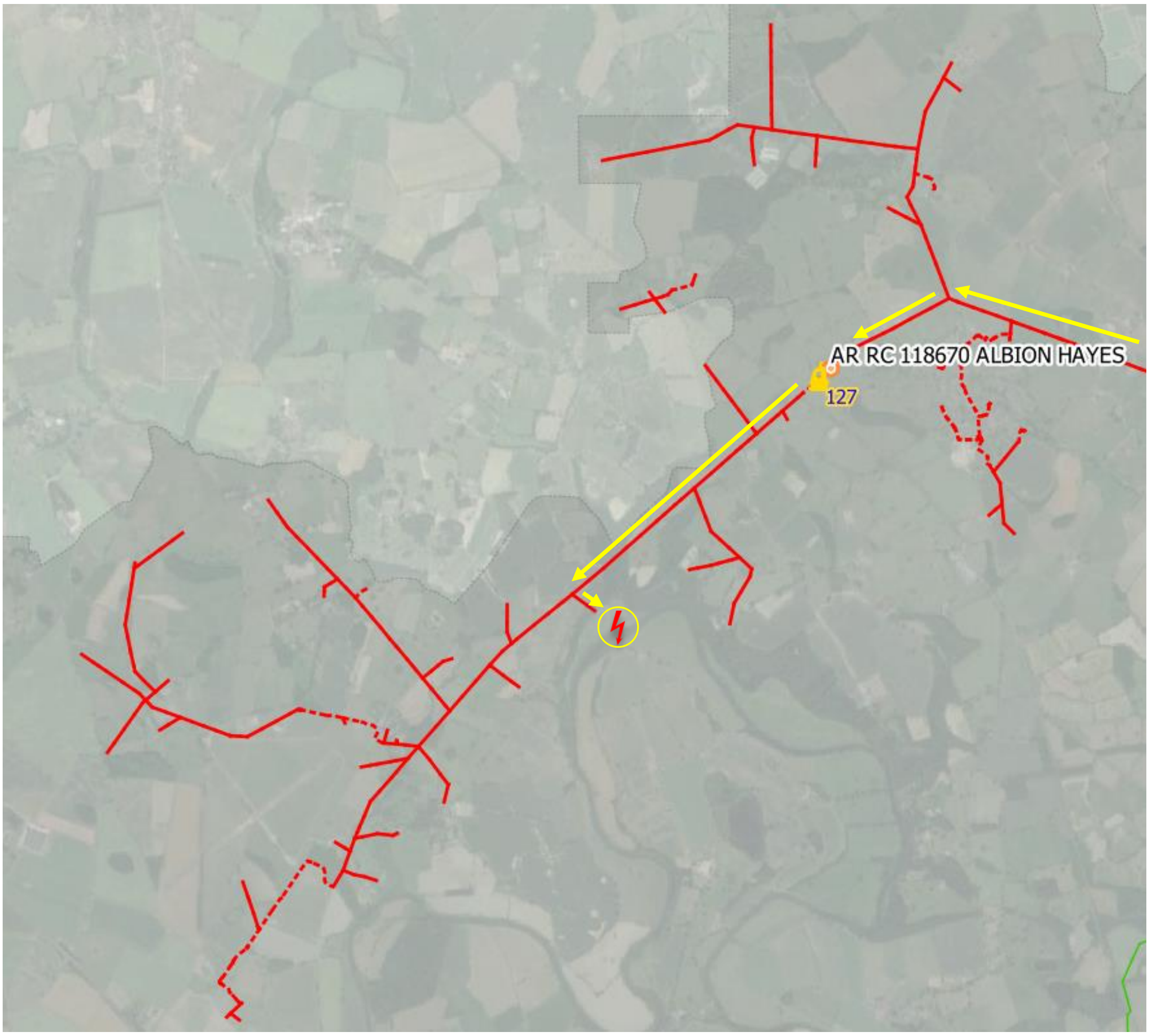

Figure 5-6: Geographical view of part of the Food Ent Pk feeder from Harlescott primary substation

The Network Services team was able to access the event history locally at the Albion Hayes (Brush GVR) auto-recloser, which provides mid-feeder protection. The event history from the equipment is presented in Table 5-12. The timestamps were inaccurate, therefore the recent history was recorded by (relevant) chronological event indices.

Table 5-17: Albion Hayes GVR – Event History

Time	Event History
11/07/2021 (Event 1)	Recloser opens (Fault detected)
11/07/2021 (Event 2)	Recloser closes (Attempt 1)
11/07/2021 (Event 3)	Recloser opens (Attempt 1 - unsuccessful)
11/07/2021 (Event 4)	Recloser closes (Attempt 2)
11/07/2021 (Event 5)	Recloser opens (Attempt 2 - unsuccessful)
11/07/2021 (Event 6)	Recloser closes (Attempt 3)
11/07/2021 (Event 7)	Recloser opens (Attempt 3 – unsuccessful)
11/07/2021 (Event 8)	Recloser lock-out (Permanent fault)

This is an example of a permanent trip where three circuit breaker trip operations were reported.

The sensors at site #127 detected an earth fault and overcurrent fault on two phases. The fault information captured by the Smart Navigator 2.0 is given in **Table 5-18**. The sensors correctly recorded the fault direction downstream of the trial site, towards the open point.

Table 5-18: Trial Site #127 – Fault Information

Site #127	Fault Current	Fault Duration	Fault Direction
Master	685A	322ms	Green
Satellite 1	-	-	-
Satellite 2	700A	343ms	Green

The event history shows that the fault was correctly categorised as a permanent fault. The counter events captured by the Smart Navigator 2.0 sensors are given in **Table 5-19**.

Table 5-19: Trail Site #127 – Auto-Recloser Events Detected

Site #127	Count before event	Count after event	Count increment
Master Transient Fault Counter	0	0	0
Master Permanent Fault Counter	0	2	+2

Master Trip Counts	0	3	+3
Trip Counts Set	1	4	+3
Permanent Faults Set	0	0	0
Transient Faults Set	2	2	0
Satellite 1 Transient Fault Counter	2	2	0
Satellite 1 Permanent Fault Counter	0	0	0
Satellite 1 Trip Counts	1	1	0
Satellite 2 Transient Fault Counter	0	0	0
Satellite 2 Permanent Fault Counter	0	2	+2
Satellite 2 Trip Counts	0	3	+3

Detection of auto-recloser operations (Trip Counts Set) were recorded correctly, each phase and the total for the circuit increased by three, indicating the circuit breaker attempted to reclose unsuccessfully three times, before locking out.

The permanent fault counter for each phase increased by two, this indicates that two fault events were recorded, an earth fault and an overcurrent fault. This method of recording is not desirable, and a request was made to the manufacturer to resolve the ambiguity by aggregating the overcurrent and earth fault events into a single counter increment to reflect a single fault incident.

The counter for recording permanent fault events on a per set basis (i.e. increment by one, per fault observed on distribution network) did not respond to the observed activity. This error was captured and reported to the manufacturer and new firmware has been deployed to correct this behaviour.

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

The Smart Navigator 2.0 has been developed to deliver the aims of the project for UK distribution networks. The main trials have proven that the technology is fit-for-purpose and provides an effective solution to count the number of circuit breaker auto-reclose operations for equipment installed on HV feeders. Furthermore the solution has demonstrated promise in the capture and quantification of short interruptions to customers.

Circuit breaker auto-reclose operations were observed regularly during the field trials. The analysis in this report has confirmed that the solution is able to successfully record the detection of multiple trip operations in a typical circuit breaker auto-reclose sequence. Auto-reclose trip events have been captured at primary substation feeder circuit breakers and mid-feeder switching equipment. The solution logs and uploads the number of circuit breaker operations to the central iHost monitoring platform, until a manual reset is triggered remotely. The implementation of this feature as business-as-usual would facilitate periodic reviews of the operation of switching equipment by Network Services teams, which could be used to inform preventative maintenance procedures.

The algorithm for the quantification of transient and permanent interruptions was found to require further work:

1. There were instances where the transient (or permanent) fault counters (per set basis) were found not increment in response to a fault incident. The manufacturer acknowledged a technical issue in the firmware which prevented correct recording in the counters, and responded with a technical fix to be released in the next revision of Smart Navigator 2.0 firmware.
2. Instances of earth faults where the magnitude of fault currents was large enough to trip the overcurrent algorithm and the earth fault algorithm resulted in a double increment to the transient (or permanent) fault counters. This is not desirable since the overcurrent and earth fault trip were derived from a single fault event. The manufacturer is investigating a method to adapt this behaviour to ensure that a fault incident results in a single increment to the transient (or permanent) fault counters, regardless of whether the fault results in a simultaneous trip of the earth fault and overcurrent algorithms.

This solution has the potential to save time and costs for field staff where manual recording of circuit breaker trips would normally be required.

The success criteria for this method has been met, with correct detection of five auto-reclose operation sequences. Case studies have been presented which illustrate the results of the auto-reclose detection solution for the various stages of the auto-reclose cycle at different trial locations across the 11kV network.

7. Potential for New Learning

The solution has been integrated into the NMS and provides visual indication of the number of transient and permanent interruptions, and circuit breaker operations at each sensor location via the dashboard. Significant learning has been obtained through the project:

1. Circuit breaker operations have been captured remotely, which would ordinarily have been recorded manually.
2. Short interruptions have been recorded remotely, and the event history from the solution has been evaluated, successfully, against the local operational history of switching equipment which interrupted faults.
3. Discussions with key stakeholders confirmed that the remote capture of short interruptions and circuit breaker operations by the solution, would be desirable from older auto-recloser equipment, such as Brush GVR and Reyrolle OYT ACR which are typically not connected to the SCADA system and therefore not visible in NMS.

The following opportunities for new learning could be considered:

1. Periodic reviews of the circuit breaker operation data captured by the solution would enable maintenance teams to target preventative maintenance schemes towards frequently operating assets, in order to maximise the safety and lifespan of network switching equipment.
2. Periodic reviews of short interruption data would provide a mechanism to identify worst performing feeders and deliver balance in investment towards feeders suffering infrequent permanent interruptions, and those suffering frequent transient interruptions. This could directly improve customer satisfaction.
3. A review of the in-circuit auto-recloser protection and circuit breaker operation at primary substations should be completed for each licence areas, it is anticipated that the protection settings will be different in different areas. The outcomes of the review should provide the basis for the determination of a suitable fault classification delay. For the purposes of the project, 60 seconds fault classification delay was sufficient.
4. Ofgem's consultations ahead of RIIO-ED2 identified the need for more comprehensive data for short interruptions across the different licence areas, to provide greater understanding of how a regulatory scheme could be implemented in UK distribution networks to incentivise reductions in short interruptions. The technology has been proven under the OHL Power Pointer project, further learning could be generated to inform Ofgem consultations on a regulatory incentive to reduce SI's across multiple licence areas.

8. Conclusions of the Method

Rural overhead feeders are often susceptible to intermittent faults, which can be caused by tree branches or cracked insulators. To reduce the number of interruptions to customers, feeders are equipped with auto-reclosing circuit breakers, installed at the primary substation, often at the midpoint, and sometimes at several points along radial feeders. The principle of operation is that faults on rural networks are often caused by transient events, such as a tree branch striking an overhead conductor before falling to the ground. Auto-reclosers operate like a standard circuit breaker to clear the fault but will attempt to reclose the circuit breaker automatically within a few seconds to check if the cause of the fault has cleared.

The electricity network is evolving to accommodate more generation connections. Much of this new generation will be connected to distribution feeders. This increasing volume of distributed generation dramatically increases the impact a transient fault would have on the energy system. Even a transient fault lasting five seconds will cause distributed generation to be disconnected. By enabling greater visibility of short interruptions, field teams can be dispatched to patrol circuits to locate causes of faults and prevent transient faults developing into a permanent interruptions. The benefit to maintaining a reliable network can be realised in reduced CIs and CMLs as financial incentives and improved customer satisfaction. Ofgem's RIIO-ED2 methodology decision publication, presents reasoning that a lack of robust and comparable data across all DNOs prevented the introduction of an incentive to reduce short interruptions in RIIO-ED2 and is instead looking towards a potential incentive in RIIO-ED3.

OHL Power Pointer has delivered a solution for the quantification of short interruptions, permanent interruptions and auto-recloser circuit breaker operations. The solution is encompassed in the Smart Navigator 2.0 clip-on OHL sensor. Sets of sensors were deployed to 11kV, 33kV, 66kV and 132kV OHL networks to provide localised monitoring of directional power flows, directional fault currents, conductor temperature and auto-recloser operations.

Analysis from the main trials has been completed and the following conclusions have been drawn on the findings of Method 3: Detection of Auto-Recloser Operations.

The solution implements a counter system to record circuit breaker trip operations on a per phase basis. Transient (and permanent) faults are captured in a series of additional counters, where a fault event (overcurrent, or earth fault) results in an incremental change to the counter for each compromised phase. In addition to the individual counters which record activity on a per phase, there is a logic sequence which reviews the events and increments counters on a per set (all three phases, i.e. per circuit) basis, thereby reporting short interruptions and permanent interruptions 'per incident'.

The findings of the field trials demonstrate that the detection of auto-recloser operation has been successful across multiple trial locations. There were some technical irregularities discovered in algorithms for the recording of faults in the transient and permanent fault counters. These have been acknowledged by the manufacturer and proposals have been made to update the algorithm and changes will be published in a firmware update, which can be deployed to the devices over-the-air.

The solution has the capability to offer the business centralised recording of circuit breaker trip operations and short interruptions, this is particularly useful for older switching equipment which is not connected to the SCADA network.

For example, Brush GVR auto-reclose equipment has a local event history which is limited to ten pick-up and trip sequences, and trip operations must be recorded by taking a manual reading, locally. The installation the Smart Navigator 2.0 solution offers the Control room visibility of the operation of upstream circuit breaker trip operations along with fault passage indication, which could be a key enabler for boosting network visibility and modernising techniques for monitoring older switching equipment.

The technology for recording short interruptions has been demonstrated under the OHL Power Pointer project, further learning could be generated from a follow-on project during RIIO-ED2 to deliver a regulatory mechanism for incentivising reductions in short interruptions through the RIIO-ED3 price control period.

It is concluded that the Technology Readiness Level (TRL) of the auto-recloser detection solution has increased from TRL 5 to TRL 7 over the course of the project. The solution has been demonstrated in an operational environment, on live distribution circuits.

Glossary

Abbreviation	Term
APN	Access Point Name
ANM	Active network Management
CI	Customer Interruptions
CML	Customer Minutes Lost
NMS	Network Management System
DNO	Distribution Network Operator
DSO	Distribution System Operator
FPI	Fault Passage Indicator
HV	High Voltage
MW	Megawatt
MVAr	Mega volt-ampere
NIA	Network Innovation Allowance
OHL	Overhead Line
SCADA	Supervisory Control and Data Acquisition
SN2.0	Smart Navigator 2.0
TRL	Technology Readiness Level
RIIO-ED	'Revenue = Innovation + Incentives + Outputs' - 'Electricity Distribution'
RTU	Remote Telemetry Unit
WPD	Western Power Distribution

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