OHL Power Pointer - Report on Method 4

Method 4: Directional Fault Detection

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Contents

1. Executive Summary

Traditional mid-feeder fault passage indication (FPI) detects high magnitude current flowing through a sensor to alert the Control room to a disrupted section of the network. FPI assists with the efficient dispatch of field teams to the localised area of the fault, which results in restoration of supplies to customers more quickly. With increasing quantities of embedded generators connecting across the distribution network, traditional fault passage indication could lead to false alarms because generators, can also contribute towards high fault currents. This is known as back-feeding into a fault.

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

The solution has been prototyped, developed and tested 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 a solution to detect directional fault currents through overhead high-voltage distribution networks.

This report has been prepared following the completion of the field trials and presents the findings of Method 4: Directional Fault Detection.

Fault activity was detected regularly through the main trials at the majority of the trial locations. The solution was able to detect the direction of the flow of fault current in each monitored phase, and report the fault direction to the iHost platform, unsolicited. The devices were deployed primarily to provide visibility of embedded conventional (synchronous) generators back feeding into faults. Despite deploying sensors to trial locations near several synchronous generator connections on 11kV networks, it was not possible to observe such back feeding events. This could be due to the connection interface between the generators and the network, which perhaps limited the magnitude and duration of fault current to below the pre-determined trip thresholds of earth fault (>40A, >50ms) and overcurrent (>250A, >50ms).

Non-synchronous embedded generation connections, including solar parks and wind turbines, are connected through an inverter, which would likely minimise the magnitude of fault current contribution to a range approximately equivalent to the maximum rated output current of the generator (often lower than fault trip thresholds in the Smart Navigator 2.0).

Standard non-directional FPI functionality has been integrated into PowerOn from the sensors, which enables the Control room to receive alarms for permanent and momentary fault events on our network management system (NMS) network diagrams. The directional features have been made available to the Control room via the Smart Navigator 2.0 dashboard, which is accessible directly from the NMS.

The solution has demonstrated the potential to save time and costs for field staff during OHL patrols to identify the cause of faults. The directional FPI features should enable the control room to direct the team towards the location of the fault along the feeder and therefore reduce the number of operational hours spent patrolling OHL circuits.

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 detection and indication of directional fault currents through OHL circuits. The method has investigated the capture of overcurrent and earth faults, transient and permanent faults on 11kV, 33kV and 66kV OHL circuits across the West Midlands licence area.

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. Fault Detection in Distribution Networks

Faults regularly occur on electrical power systems, these can be transient faults, such as a branch striking an overhead line before dropping to the ground, or permanent, such excavation machinery cutting through an underground cable. Fault events cause large fault currents to flow from sources of energy across the network, through electrical circuits, into the location of the fault. Fault currents are interrupted quickly using circuit breakers to prevent damage or harm to humans or livestock within the vicinity of the fault. This often results in temporary or permanent loss of supply to customers, until the cause of the fault can be located and cleared, and supply safely restored (circuit breaker closes).

Traditionally in radial systems the fault currents are generated by generators connected to higher voltage networks, so the primary substation acts as the main source of fault current into the radial system. Distribution system operators often install FPIs at intervals along feeders to provide a local (and sometimes a remote alarm) signal that fault current (current above a pre-determined value) has passed through the sensor, localising the search zone to beyond the last alarmed FPI. This typically assists with the dispatch of field teams to the localised area of the fault, which results in restoration of supply to customers quickly.

With increasing quantities of embedded generators connecting across the distribution network, traditional fault passage indication could lead to false alarms because embedded generation connected within the network can also contribute towards high fault currents by ‘backfeeding’ onto the network. This could lead to fault passage indicators tripping, which could inadvertently extend the search zone to locate the cause of the fault.

Embedded generation can be categorised into two types when determining whether fault currents are likely to contribute to tripping of FPIs:

a) conventional synchronous generation such as synchronous generators, such as open cycle gas turbines (e.g. biodigester plants) which normally contribute 500-700% rated output current under fault conditions
b) inverter connected generation, such as solar arrays or wind turbines which can contribute 100-125% of rated output current during fault conditions.

Directional fault passage indication (DFPI) offers distribution network operators visibility of the direction of the flow of fault current through FPI sensors.

5.2. The Directional Fault Detection Solution for Overhead Networks

Directional fault passage indication is available for underground cables systems, ground mounted switching equipment and is normally implemented as a function within protection relays at substations. The OHL Power Pointer has developed a solution to bring this capability to OHL systems using a novel voltage detection method, without the requirement for a bonded reference to earth.

5.2.1. Smart Navigator 2.0 Sensor

Each Smart Navigator 2.0 measures the phase angle φ between the line-earth voltage and the phase current. From this the unit can derive the fault direction for the phase conductor.

Table 5-1: Determining Fault Direction from Phase Angle

-90° < φ < 90°	Fault direction Red
-180° < φ < -90° or 90° < φ < 180°	Fault direction Green

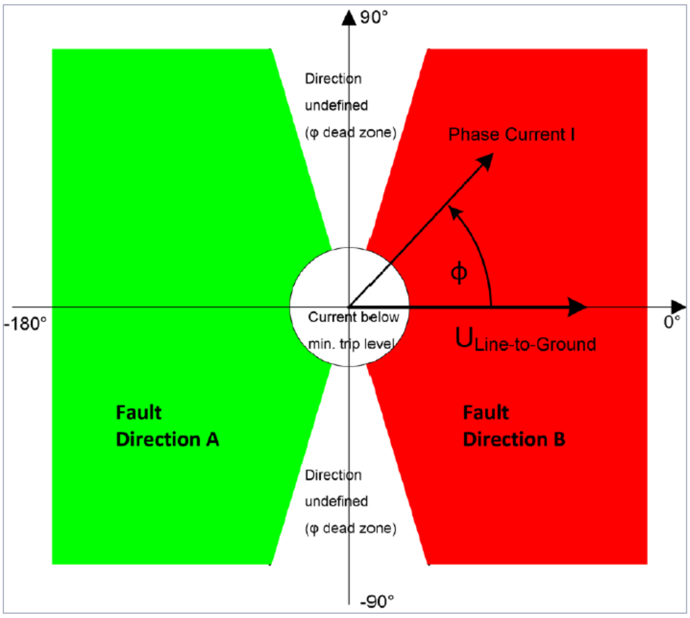

Figure 5-1 – Vector Diagram for Determination of Fault Direction

In addition to the fault direction the Smart Navigator 2.0 records the fault current magnitude and the duration in milliseconds of the fault event.

The data from the sensor is uploaded to the iHost monitoring platform following each fault event and displayed on the user interface.

5.2.2. Direction Convention

The Smart Navigator 2.0 sensor records power flow and fault activity using a split core current transformer that is clipped around the OHL. The orientation of the device, and thus the current transformer, on the OHL is critical to interpreting the direction of the power flowing through the circuit. The 'green' and the 'red' sides are indicated on each device with labels to assist with the installation. During the OHL Power Pointer project, the installation convention was to install the 'green' side of the device facing the nearest pole, with the 'red' side pointing along the span towards the far pole, **Figure 5-2** illustrates this concept.

Figure 5-2 –Direction of fault passage through Smart Navigator 2.0 sensors

5.2.3. Trip Configuration

Overcurrent

The Smart Navigator 2.0 sensors were configured with an upper limit of the trip threshold set to 1200A and a lower limit set to 250A, following a Definite Minimum Time (DT) characteristic, raising an alarm after 50ms. The load tracking function was enabled to adjust the exact position of the trip threshold (between the upper and lower) automatically according to the load current. This is particularly useful where exact fault currents are unknown or network topology changes regularly due to switching operations.

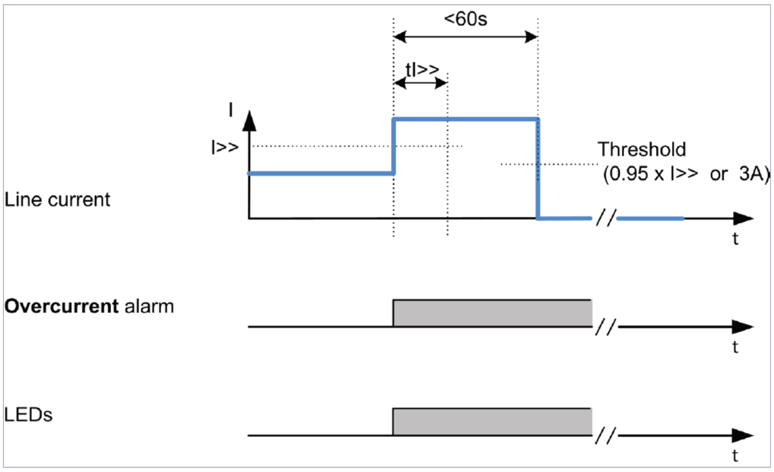

Figure 5-3 – Overcurrent Fault Detection

Rate of change of current (ΔI / ΔT detection)

High-ohmic faults (typical of earth faults) where the fault current does not exceed the maximum load current were detected with the ΔI/ΔT detection algorithm. This algorithm monitors the line current magnitude and the line voltage and assumes that an upstream protection device switches off the line in the case of a fault.

If the line current increases by more than the ΔI pick up setting for a duration longer than ΔT and the overhead line voltage drops below Vlt< within 10 seconds, then the Navigator generates a ΔI/ΔT alarm. The LEDs will start flashing and an unsolicited alarm will be issued to the Control room.

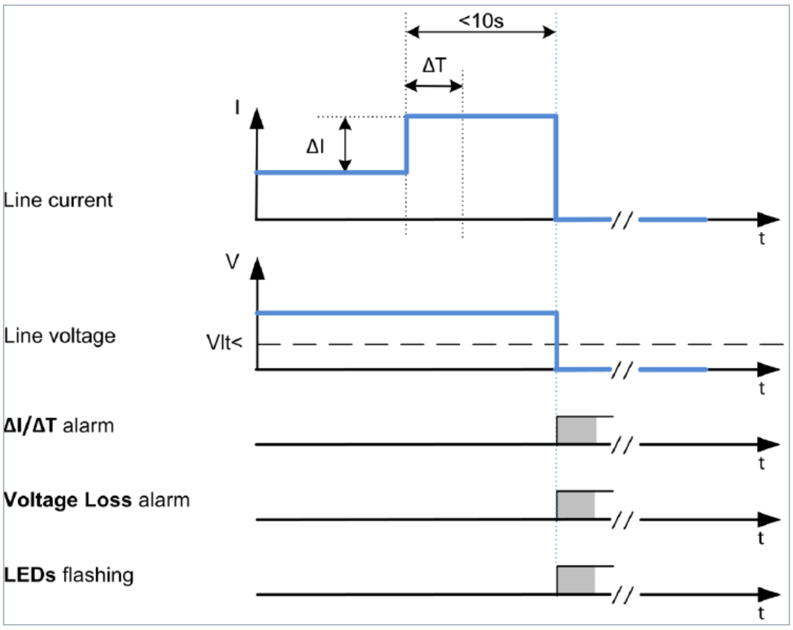

Figure 5-4 – ΔI / ΔT Fault Detection

The Smart Navigator 2.0 sensors were configured with a ΔI/ΔT trip threshold of 40A for a minimum of 50ms.

5.3. Integration with Network Management Platforms

5.3.1. Distribution Network Management System (DNMS) Integration

The fault passage indication (FPI) functionality of the Smart Navigator 2.0 was implemented in the network management system (NMS) to alert the control room to fault activity occurring on the network. The Smart Navigator 2.0 returns the initial indication of a fault, followed by a classification event to confirm whether the fault has caused a transient interruption to supply, or a permanent interruption. The fault indication is cleared on the restoration of voltage or line current, and a reset is reported to the control room. The symbol comprises a visual indicator and alarm of the health of the sensors, any disruption to communication between the Smart Navigator 2.0 and the iHost platform is reported through to the control room, where an investigation can be raised.

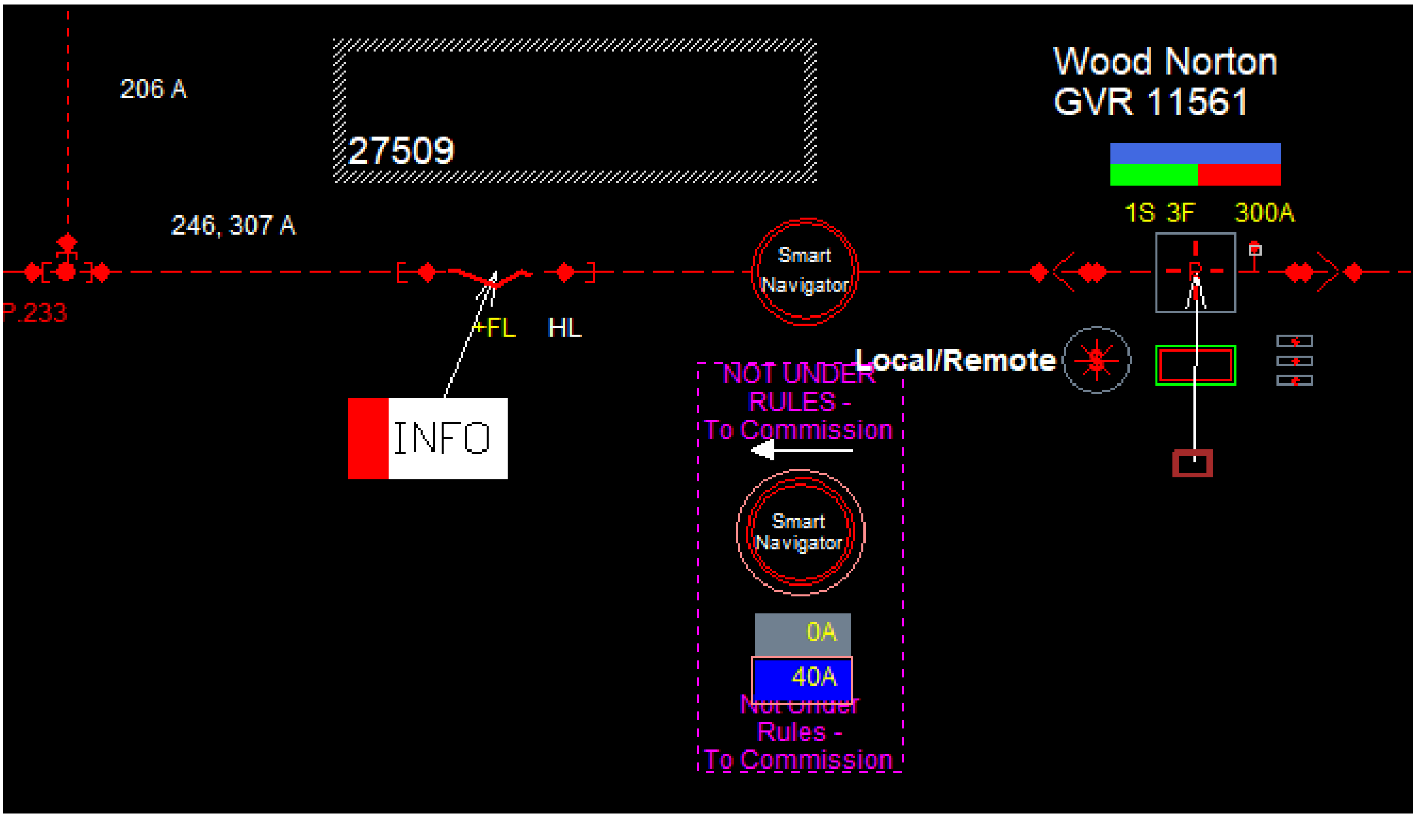

Figure 5-5: Smart Navigator 2.0 symbol in DMS diagram

Directional fault detection features of the Smart Navigator 2.0 have been made available to the control room via the SCADA interface from the iHost platform. Discussions have been held with control systems to investigate the potential for use of fault passage direction in the Automated Power Restoration System (APRS), however fault direction data is not currently supported as an input to the APRS module.

5.3.2. Visual User Interface (Dashboard & Single Line Diagram)

The data from the remote sensors is uploaded periodically over a mobile connection to the iHost monitoring platform, where time-series data can be analysed using features such as interactive trends, dashboards and single line diagrams (SLDs).

The Smart Navigator 2.0 symbol was developed to display directional fault information, and other key metrics, on SLDs in iHost. SLDs have been established for each of the trial areas with multiple sensors installed along feeders or across primary systems. This enables the Control room to visualise the direction of fault currents passing along feeders. An example of the symbol displaying a fault alarm and the direction of the fault current (both depicted as yellow icons) is presented in **Figure 5-6**. In this case, the green arrow indicates the last recorded direction of power flow through the circuit (following the power flow direction convention).

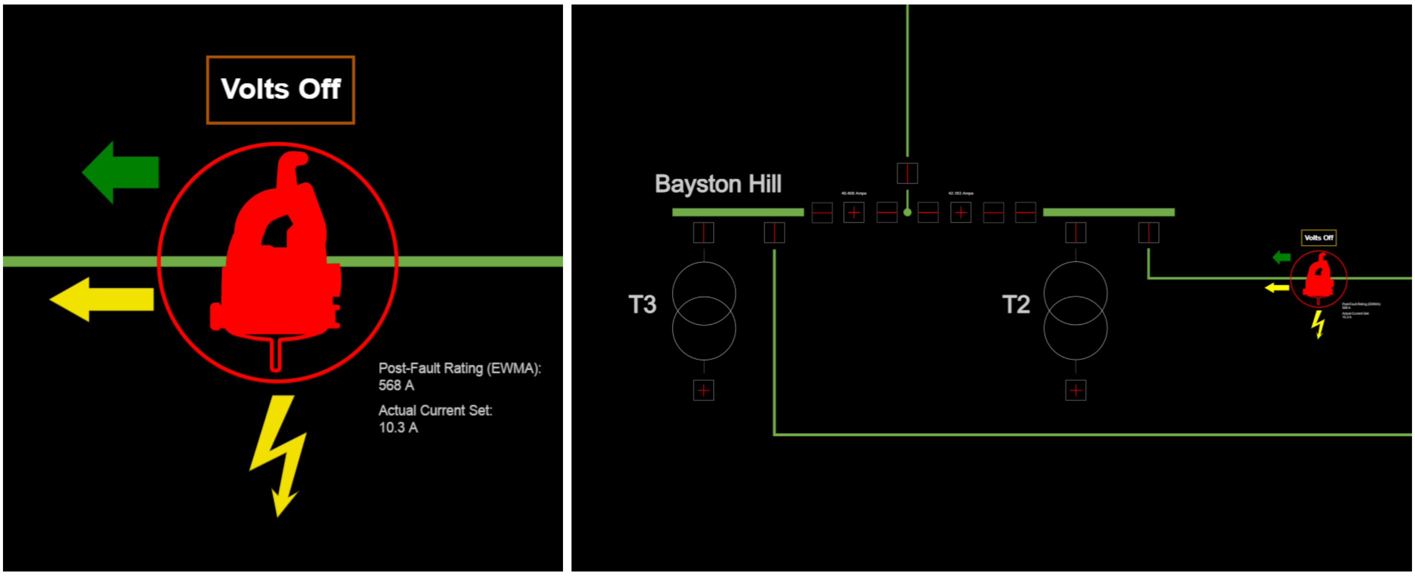

Figure 5-6 – iHost Single Line Diagram with Smart Navigator 2.0 Symbol

5.4. Case Studies

Trials were established along circuits which registered frequent fault activity during 2018, the year before the project commenced. The selection of the sites was broadly based on the topology of the feeder (mostly overhead network), volume of embedded generation connected to circuits, and the frequency of fault activity per unit length of feeder. The detailed site selection methodology is captured in the Site Selection report.

The following case studies present faults where the fault location was confirmed locally by field teams or through incident reports.

5.4.1. Station Road 11kV Circuit at Gnosall

Lower Reule farm comprises an anaerobic digestion facility located near to Gnosall, which produces biogas which can be burned in an open cycle gas turbine (OCGT). OCGTs are connected to synchronous generators which generates and exports electricity onto the distribution network. Synchronous generators have the potential to back feed into faults on the electricity distribution network.

Lower Reule farm is connected to the Station Road feeder supplied from Gnosall primary substation. A trial site for DFPI was selected which was electrically near to the output of the OCGT, along an overhead section of the feeder, in an attempt to observe fault currents being back-fed into the distribution network. The trial site location is indicated #260 in **Figure 5-7**.

Thirteen fault events were observed along the feeder at trial site #258 during the main field trials. Of these, nine were detected at trial site #259 along the feeder towards Church Eaton. Three were detected at trial site #260.

Table 5-2 presents an overview of the characteristics of the fault events recorded at trial site #260.

Table 5-2: Trial Site #260 – Fault Information

Site #260	Fault Type	Fault Current	Fault Duration	Fault Direction
29/09/2021 08:53:09	Single phase – Earth	485A	560ms	Green
26/11/2021 23:47:54	Three phase – Earth	1917A	303ms	Green (1 phase Red)
28/11/2021 03:38:46	Single phase – Earth	172A	552ms	Green

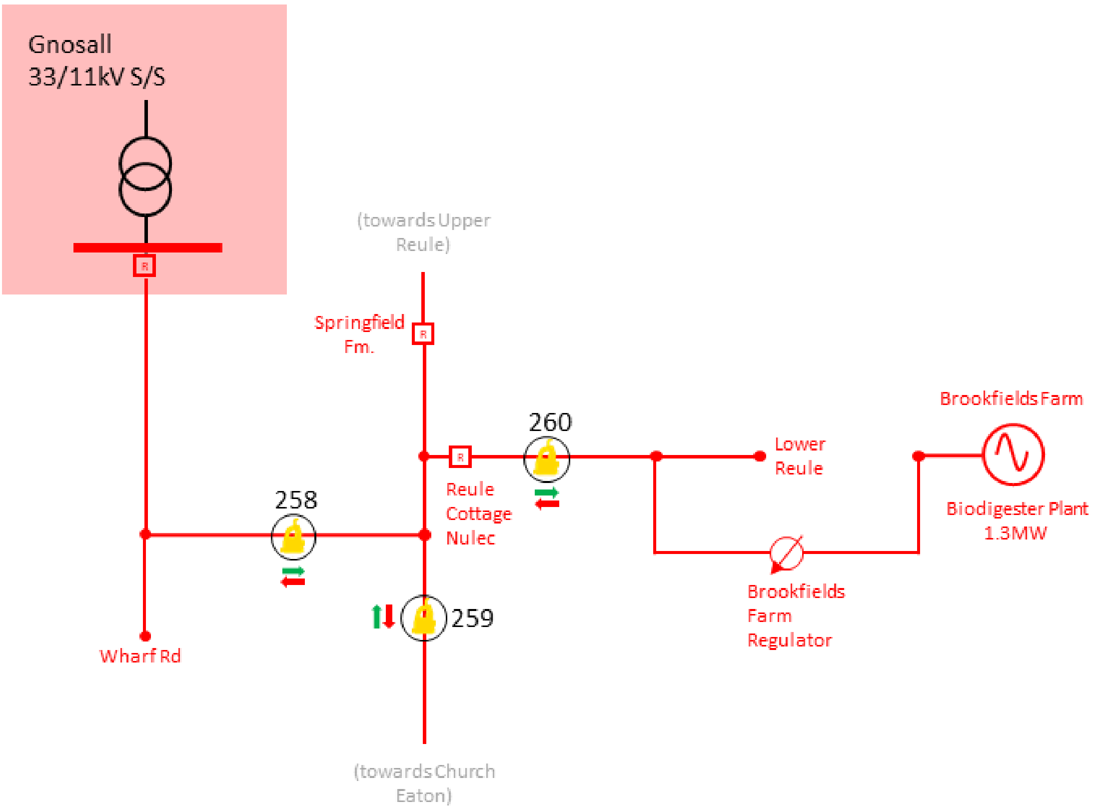

Figure 5-7 – Gnosall Primary Substation and Station Road 11kV Circuit

The events characterised in **Table 5-2** indicate that fault current flowed from the primary substation towards the embedded generator (green direction) during each trip event recorded by the sensor at trial site #260. This suggests that each fault was located between trial site #260 and the generator, or in the generator itself.

If, hypothetically, the generator was to be observed back-feeding into the network, fault current would have been recorded flowing in the red direction at trial site #260. During the incident on the 26th November 2021, fault current was observed to be flowing in the red direction in one phase, and the green direction in the adjacent phases. This is a typical characteristic of a phase to phase fault, where a closed loop is formed between phases, with the current in one affected phase equal to the negative current in the other affected phase.

Nine instances of fault activity were observed at trial site #259. Where these events were earth faults the protection was observed to trip at Gnosall primary substation and, consequently volts were lost to the entire circuit for the period of interruption. Events captured at trial site #260 were reviewed against each interruption and it was confirmed loss of volts was recorded, but there were no trip events, which suggests that there was minimal (<40A, if any) fault current being back fed into the fault by the generator at Brookfields Farm.

5.4.2. Market Drayton 11kV Circuit and Meaford 33kV Primary Ring

An earth-fault event was detected at trial site #264 on an 11kV circuit supplied from Market Drayton primary substation. The fault occurred at 09:09:09 on 22nd April 2021. The fault was also captured as an overcurrent event by Smart Navigator 2.0 sensors installed at upstream trial sites 201, #210 and #211 on the 33kV primary system. The topology of the 33kV system and the 11kV feeder, with the Smart Navigator 2.0 trial locations is given in **Figure 5-8**. The graphic is annotated with fault current magnitude and the direction of fault passage at each trial location. The colour of the arrows corresponds with the direction convention for the Smart Navigator 2.0 sensors and indicated direction of fault passage at each site.

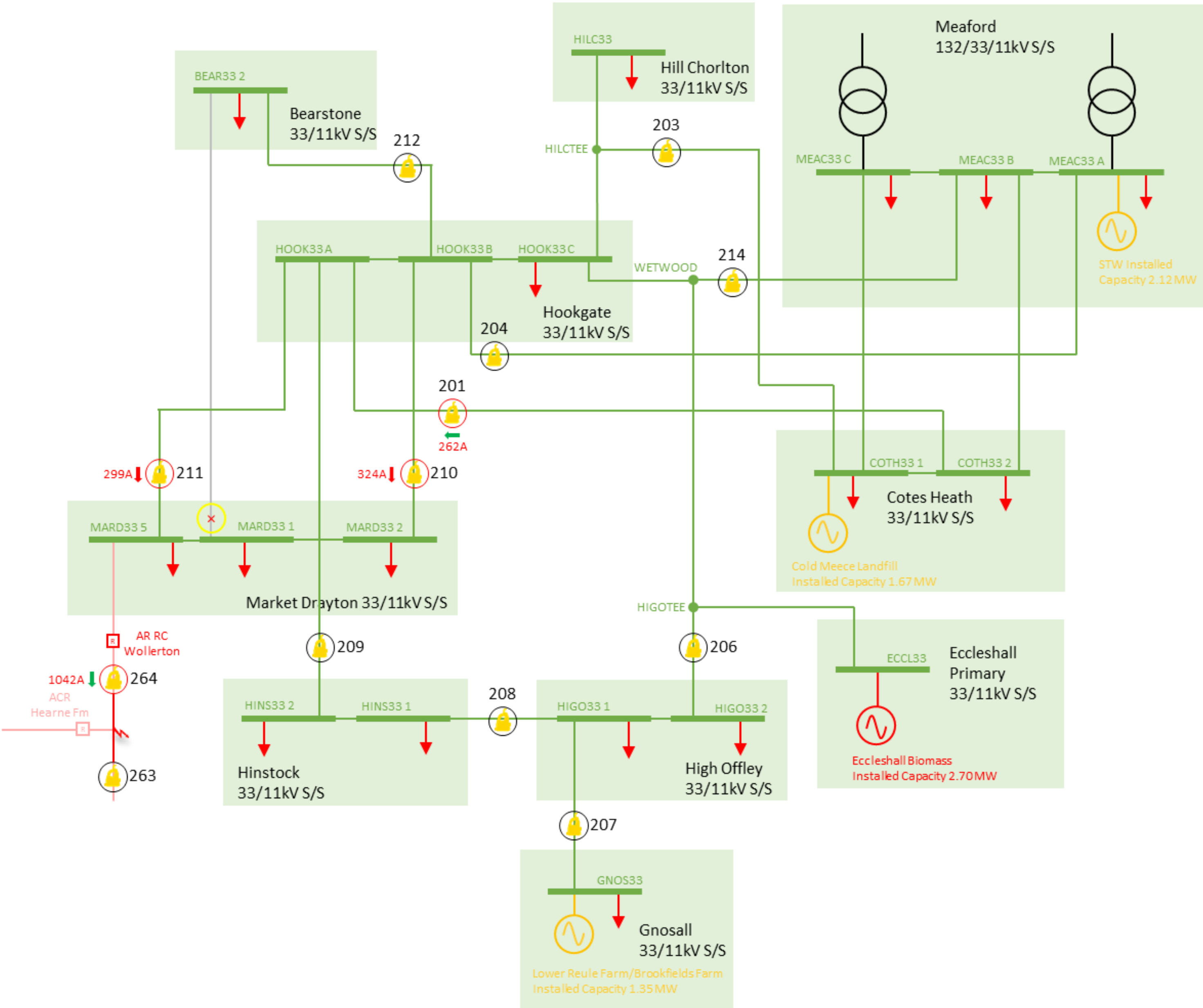

Figure 5-8 – Earth-fault Event on Market Drayton 11kV Feeder

The fault was located downstream of an auto-recloser at Wollerton, Market Drayton. The recloser history was interrogated through the DNMS and indicated that the circuit-breaker opened (09:09:11) and closed (09:09:16) suggesting one successful circuit breaker reclose action 5 seconds after tripping. The ACR at Hearne Farm was also interrogated, this equipment did not detect the fault. Trial site #263 did not detect a fault but recorded a temporary voltage loss on the circuit and the timing of this event coincided with the upstream auto-reclose operation.

The location of the earth-fault was successfully indicated in the ‘green’ direction by the sensors at trial site #264, the fault characteristics are presented in **Table 5-3**.

Table 5-3: Trial Site #264 – Fault Information

Site #264	Fault Current	Fault Duration	Fault Direction
Master	1018A	860ms	Green
Satellite 1	117A	1279ms	Green
Satellite 2	1042A	850ms	Green

Upstream from the fault, on the 33kV network, trial sites #201, #210 and #211 recorded overcurrent events, with fault passage indicated in the direction of Market Drayton primary substation from Meaford BSP. This would suggest a large fault infeed from the 132kV system, which is typical of a conventional distribution topology.

5.4.3. Hereford 66kV Primary Ring

A three-phase-earth fault was detected at trial site #232 along the 66kV circuit between Bodenham to Leominster substations. The fault occurred at 02:49:06 on 11th March 2021 and tripped the circuit. The sensors reported a permanent fault to the iHost monitoring platform. The topology of the network and the trial locations of the Smart Navigator 2.0 sensors is given in **Figure 5-9**.

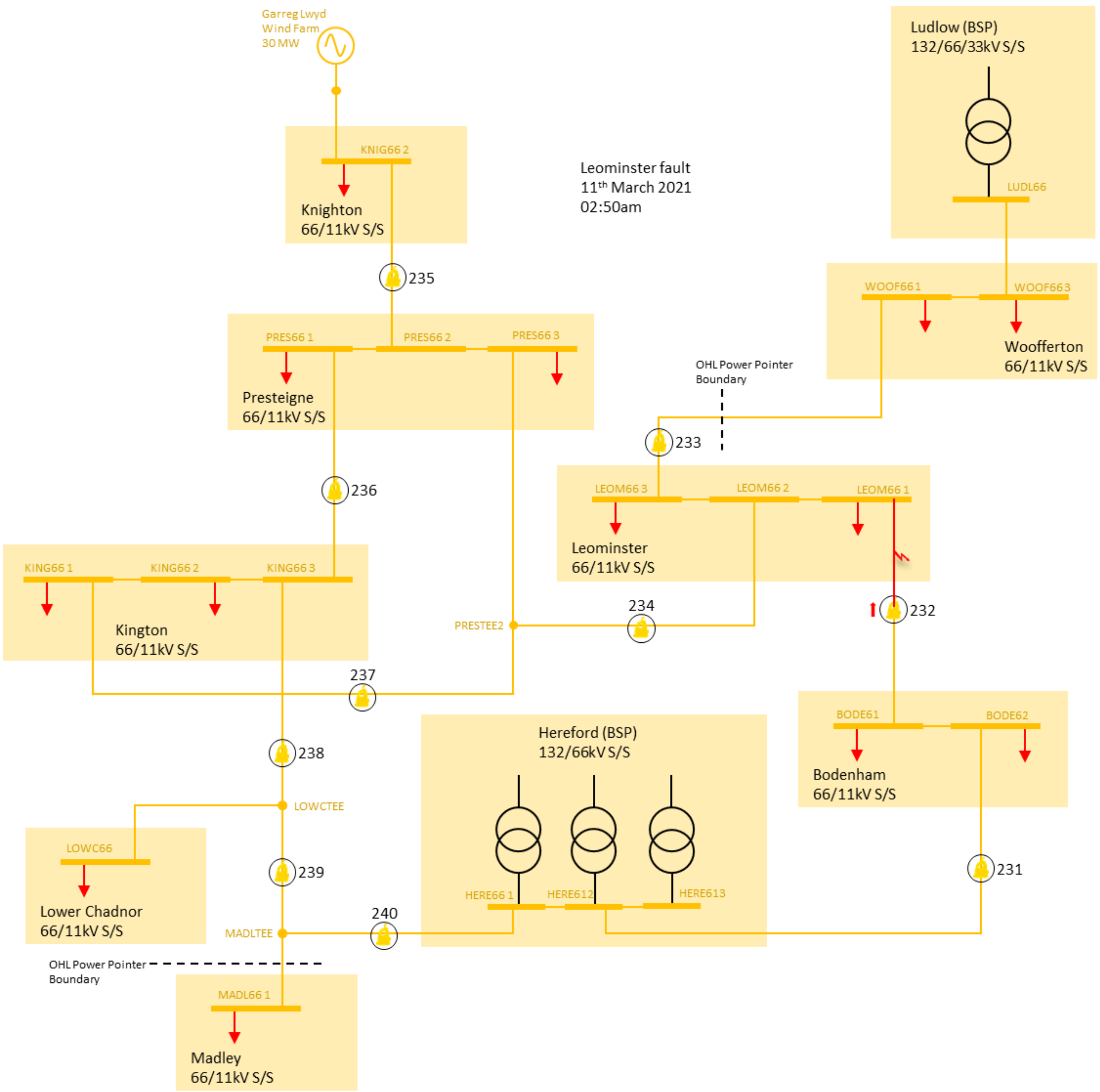

Figure 5-9 – Earth-Fault Event on Hereford 66kV Network

The graphic is annotated with a 'red' arrow at trial site #232 which is indicative of fault current flowing through the circuit towards Leominster substation.

The characteristics of the fault event were captured by the Smart Navigator 2.0 and are presented in **Table 5-4**.

Table 5-4: Trial Site #232 – Fault Information

Site #232	Fault Current	Fault Duration	Fault Direction

Master	153A	560ms	Red
Satellite 1	184A	511ms	Red
Satellite 2	434A	362ms	Red

The lines team were mobilised to patrol the line and identify the location of the fault. High winds had caused a tree to collapse on a section of the OHL midway between trial site #232 and Leominster substation. Repairs to the OHL were undertaken through the day and the circuit was re-energised at 19:07:23.

The lines team was approached for comment and an attempt was made to quantify the time incurred patrolling the circuit to locate the fault, however no further information was made available.

In this case, the directional capability of the Smart Navigator 2.0 narrowed the location of the fault to half of the circuit, where a lines team would potentially have patrolled the whole circuit. Standard non-direction FPI functionality would likely have had limited effect on determining the faulted section of the circuit, as a fault either side of the trial location would potentially have tripped the sensor due to fault infeed on both sides of the circuit, at Hereford and Ludlow BSPs.

It is evident from the analysis above that the addition of directional functionality in conventional FPIs can improve fault location in meshed networks, or networks where there are multiple sources of fault infeed.

5.4.4. South-West 132kV K-Line Circuit

An overcurrent fault event was detected at trial sites #247, #248, #249 and #250, along the 132kV K-Line double circuit between Alverdiscott and Indian Queens substations. The fault occurred at 02:02:09 on 20th April 2021. The topology of the circuit and the trial locations of the Smart Navigator 2.0 sensors is given in **Figure 5-10**. The graphic is annotated with the fault current magnitude and the direction of fault passage at each trial location, where overcurrent was detected. The green arrows are indicative of fault current flowing in the 'green' direction, in this case from Alverdiscott SGP towards Pyworthy substation.

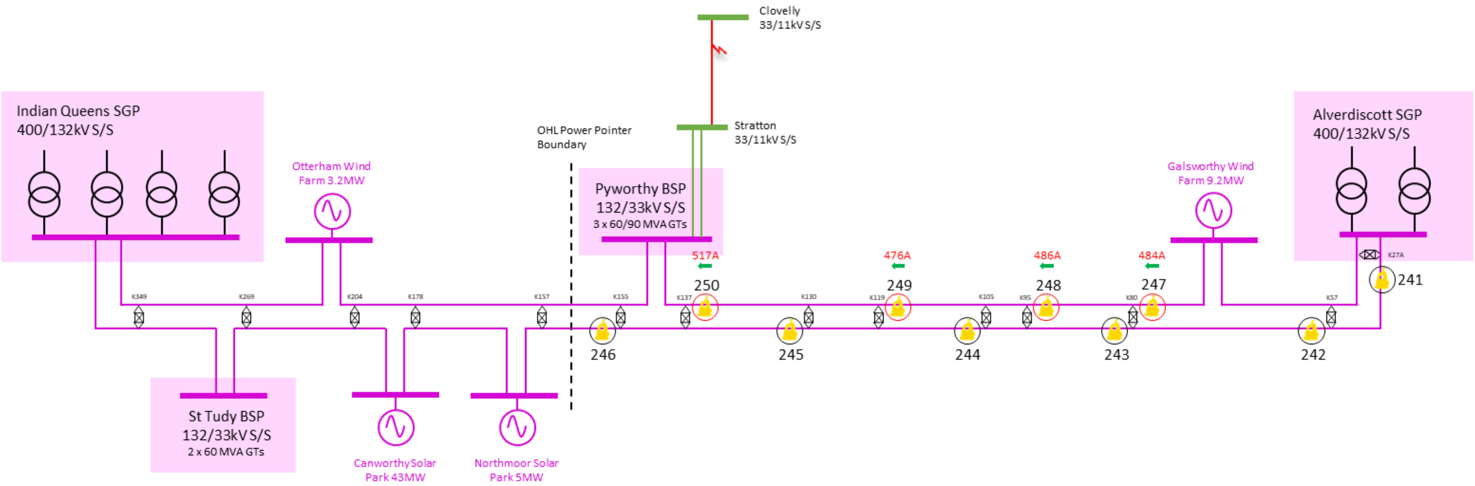

Figure 5-10 – Overcurrent Event on South-West K-Line 132kV Circuit

A preliminary incident report was obtained shortly after the fault occurred which confirmed that an earth-fault event caused the tripping of a 33kV circuit downstream of Pyworthy BSP, near to Clovelly primary substation.

The location of the fault and the topology of the network suggests that the direction of the fault current recorded by the four sets of Smart Navigator 2.0 sensors was correct, since the transmission system would likely contribute significantly towards the fault infeed on the network.

Table 5-5: Trial Site #247 – Fault Information

Site #247	Fault Current	Fault Duration	Fault Direction
Master	410A	69ms	Green
Satellite 1	484A	51ms	Green
Satellite 2	435A	60ms	Green

The fault characteristics recorded by the Smart Navigator 2.0 sensors at trial site #247 are given in **Table 5-5**. The sensors determined that the fault lasted for approximately 60ms before it was cleared, which is indicative of a typical primary circuit breaker trip time.

5.5. Validation of Fault Activity and Fault Characteristics

Incident reports have been obtained for permanent faults occurring during the field trials on the 33kV, 66kV and 132kV systems. In most cases the incident reports are comprehensive records of the switching sequences and capture 'on-the-ground' observations from field teams to support switching decisions.

Records have been obtained from auto-recloser equipment on 11kV systems to corroborate 'on-the-ground' reports from patrols by field teams.

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

The OHL Power Pointer project has successfully delivered and trialled a solution which meeting the objective of providing the control room with visibility of the direction of fault currents passing through individual phases of overhead line circuits during disturbances on the distribution network.

The solution has been prototyped, developed and tested 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 a solution to detect directional fault currents through overhead high-voltage distribution networks.

Fault activity was detected regularly through the main trials at the majority of the trial locations. The solution was able to detect the direction of the flow of fault current in each monitored phase, and the report the fault direction to the iHost platform, unsolicited.

There were issues with the firmware of the solution discovered during the field trials which caused a minority of fault events to 'latch' in the device rather than initiating a reset once the fault has cleared. This was addressed in a new firmware release which resolved the problem.

The devices were deployed to provide visibility of embedded conventional (synchronous) generators back feeding into faults. Despite deploying sensors to trial locations near several synchronous generator connections on 11kV networks, it was not possible to observe such back feeding events. This could be due to the connection interface between the generators and the network, which perhaps limited the magnitude and duration of fault current to below the pre-determined trip thresholds of earth fault (>40A, >50ms) and overcurrent (>250A, >50ms).

However, fault direction was observed to be determined successfully for each overcurrent and earth fault event captured by the solution through the field trials. Furthermore, the event history of the Smart Navigator 2.0 sensors, captured in the iHost monitoring platform, was interrogated on several occasions by the control room to corroborate SCADA information in order to promptly respond to live fault events.

After each inception of a fault on the network, an alarm was raised and fault classification (into a transient or permanent event) was recorded by the solution and reported to the live distribution management system in the control room. The type of fault, for example, phase-to-phase, phase-to-earth was also captured, which was found to assist field teams by narrowing the potential causes of a fault.

The accuracy and consistency of the solution has been assess and quantified in a controlled laboratory environment and during the live field trials, the performance of the solution has been successfully confirmed against SCADA records, this is supported by the case studies and confirmed by field reports.

In accordance with the success criteria, directional fault detection has been determined correctly at more than five sites during the project lifetime.

7. Potential for New Learning

The solution has been integrated into the network management system (NMS) and provides visual indication of a fault event, and classification of transient or permanent fault. The direction of the fault current through each phase is indicated within the event history the Smart Navigator 2.0 dashboard, accessible via iHost from the DMS.

Significant learning has been obtained through the project:

1. The solution has been proven to be accurate and consistent for the detection of directional faults in overhead lines, without the requirement for a bonded reference to earth. This offers an option for cost effective monitoring of the overhead network, to maximise the visibility of directional fault currents in the control room.
2. Automated schemes, such as automatic power restoration systems (APRS) are not currently equipped to make enhanced switching decisions using directional fault information. This was explored during a meeting with the Control Systems team, whilst discussing the integration of standard non-directional overhead FPI functionality into APRS.
3. A dissemination workshop attended by our internal stakeholders demonstrated the need for reliable FPI in overhead systems in order to improve customer satisfaction and achieve greater rewards in terms of regulatory financial incentives for our business. It was learned that trust in traditional overhead FPI solutions by the control room had been degraded due to unreliable and outdated technology, however the field trials had instilled confidence in the latest technologies delivered in the Smart Navigator 2.0 which have been used to assist Network Services teams throughout the project.

The following opportunities for new learning could be considered:

1. The Smart Navigator 2.0 sensors capture important information about fault current magnitude and the faulted phases. These features could be exploited further using a central system of impedance models to determine the distance to the fault location and classify the fault into single phase-to-earth, or phase-phase faults, for example, to further to assist with line patrols.

8. Conclusions of the Method

Traditional mid-feeder fault passage indication (FPI) detects high magnitude current flowing through a sensor to alert the Control room to a disrupted section of the network. FPI assists with the efficient dispatch of field teams to the localised area of the fault, which results in restoration of supplies to customers more quickly. With increasing quantities of embedded generators connecting across the distribution network, traditional fault passage indication could lead to false alarms because generators, also can contribute towards high fault currents. This is known as back-feeding into a fault.

The Smart Navigator 2.0 sensor is a clip-on sensor for OHLs and provides directional fault passage indication (DFPI) to alert the control room to the faults and the direction of the fault current. This sought to reduce the possibility of false alarms if DFPIs were installed near to embedded generation.

Ahead of the main project trials, several Smart Navigator 2.0 sensors were installed on the 11kV and 33kV distribution to monitor the passage of directional fault currents near to known embedded generation connections, including utility-scale solar parks, wind turbines and several bio-digester plants (conventional synchronous generation).

Fault activity was recorded at the majority of the trial locations during the main project trails. During each event, the direction of the fault current flowing through individual phases was determined, and reported to the iHost monitoring platform using the ‘red’ and ‘green’ convention, indicating forward or reverse flow of fault current through the sensor.

Analysis of the data from the main trials has been completed, and the following conclusions have been drawn on the findings of Method 4: Directional Fault Detection.

Along radial 11kV feeders, during each fault event the direction of fault passage was recorded away from the primary substation (source), towards the remote end of the feeder (load), as would be expected in a conventional network. There was no evidence which suggested any connected embedded generation contributed significant fault current to cause a trip alarm in the Smart Navigator 2.0, which might indicate a back-feed of fault current from the embedded generator towards the source. It is not clear why there was no fault current contribution from embedded synchronous generation.

Synchronous generators are required to disconnect on detection of a loss of mains event by a G59 relay, as would normally occur after a permanent fault occurs on the network local to the generator. However, G59 relays operate after a time delay of c. 500ms, so this would ordinarily facilitate the flow of fault current for a short period, and fall within the trip curve of FPIs. It is therefore not clear why there were no events observed of synchronous generation back-feeding into faults on the distribution network.

Non-synchronous embedded generation connections, including solar parks and wind turbines, are connected through an inverter, which would likely minimise the magnitude of fault current contribution to a range approximately equivalent to the maximum rated output current of the generator (often lower than fault trip thresholds in the Smart Navigator 2.0).

Directional fault detection has, however been determined routinely for each fault which caused a trip event on both radial and meshed networks.

During one particular event along a circuit from Harlescott primary substation, the Smart Navigator 2.0 installed mid-way along the feeder was interrogated to understand the direction of fault passage. Our local helicopter unit had been mobilised to locate possible causes of an interruption on the circuit, however the field teams were guided to a location away from the fault location. Using directional fault passage indication field teams were able to confirm that the incipient fault was downstream of the sensor. The sensor provided detailed information that the incident was a single phase-to-earth fault which narrowed the possible cause of the fault, for field teams to respond and restore supply to customers quickly.

Standard non-directional FPI functionality has been integrated into PowerOn from the sensors, which enables the Control room to receive alarms for permanent and momentary fault events on network management system (NMS) network diagrams. The directional features have been made available to the Control room via the Smart Navigator 2.0 dashboard, which is accessible directly from the NMS.

The solution has demonstrated the potential to save time and costs for field staff during OHL patrols to identify the cause of faults. The directional FPI features should enable the control room to direct the team towards the location of the fault along the feeder and therefore reduce the number of operational hours spent patrolling OHL circuits.

Furthermore, with improved visibility and response to permanent faults using directional FPI functionality, supplies to customers could be restored more quickly, which could result in increased revenue through a reduction of incurred CMLs under Ofgem's regulatory Interruptions Incentives Scheme (IIS).

It is concluded that the Technology Readiness Level (TRL) of the directional fault detection solution for overhead line circuits has increased from TRL 3 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
ICCP	Inter-Control Centre Protocol
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
RTU	Remote Telemetry Unit
TRL	Technology Readiness Level
TSDS	Time Series Data Store
WPD	Western Power Distribution

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