WPD INNOVATION
Transforming the electricity network

OHL Power Pointer - Report on Method 1

Method 1: Directional Power Flow Monitoring

Version Control

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Western Power Distribution 2021

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1. Executive Summary

In our RIIO-ED1 business plan and DSO Transition Strategy, we have made the commitment to improve visibility of distribution network power flows.

Ofgem's RIIO-ED2 methodology draws on the principle of a smart and flexibly energy system. Ofgem is clear that the use of data lies at the heart of the energy system transition, and that a shared understanding of what is happening to power flows and the status of network infrastructure will be key enablers for creative solutions to future challenges.

WPD's Distribution System Operability Framework identified the main drivers for increased monitoring and control:

- Making informed decisions about switching and network operation;
- Ratings of transformers, as they are dependent on power-flow direction;
- Running real-time analysis like Active Network Management (ANM) will necessitate this level of detail to ensure the control systems can represent the network accurately; and
- Enabling the network to be correctly represented in power system software as this is used to determine

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.

This report has been prepared following the completion of the field trials and presents the findings of Method 1: Directional Power Flow Detection.

Power flow direction was detected at each trial location continuously through the main trial period. In many of the trial locations the direction of power flow was observed to change, frequently throughout a typical day. Directional power flows through OHL circuits have been found to be widely influenced by intermittent power injections from renewable generation connected to the network.

Case studies for the following trial areas have been presented in the report which support the key findings of the directional power flow monitoring, captured during the main trial period:

1. Commercial Road primary substation, Gloscat / Over Hosp., 11kV feeder, Gloucester, West Midlands
2. Meaford BSP and primary network, looped 33kV feeders and substations, Stoke, West Midlands
3. Hereford BSP and primary network, looped 66kV feeders and substations, Hereford, West Midlands
4. Alverdiscott SGP and Indian Queens SGP, 132kV double circuit K-Line, South West.

The results of directional power flow detection have been validated against SCADA records from local substation transducer equipment and the accuracy of the method has been found to be satisfactory for the purposes of reporting to the Control room.

The functionality has been adopted by the Control room, and directional power flow features have been integrated into the symbol for the solution on the live operations diagram.

A stakeholder engagement workshop was delivered in June 2020 to present the results of the Method, this was attended by participants from across our business, and raised important discussion points around the deployment of the solution for use in automated schemes, such as dynamic open point control, and improved operational visibility on the 33kV network to assist with informed switching decision making. The additional benefits of wider network visibility will lead to fewer conservative assumptions of the state of the network, which will ultimately improve decisions made by automated schemes. Improved decisions could include the relaxation of enforced constraints on generation, and more efficient dispatch of flexibility services. The overall benefit would likely be a reduction in the carbon intensity of the grid, where clean energy sources can be prioritised, release of headroom capacity to accommodate more connection of generation, and a more operationally efficient power system resulting in fewer technical losses.

Consideration should be given to the role of mid-feeder monitoring in the planning of future networks. Visibility of power flow direction through circuits will enable planning engineers to accurately assess the available headroom in the system to inform planning applications for new generation connections. Without due consideration a saturation point could be reached prematurely when the limits of reverse power flow capacity of primary and grid transformers are approached. This would result in curtailment of distributed generation connections without major network reinforcement.

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 transition from a passive network to an active network requires greater visibility of the direction of power flowing through network assets. Connection of renewable distributed generation and unpredictable demand profiles of consumers has resulted in the proliferation of reverse power flows through the network. It is becoming increasingly important to monitor the direction of power flows in order to make informed decisions about switching and network operation, determine reinforcement requirements and network constraints at the planning stage, run real-time analysis to ensure curtailment requirements are accurately determined and ensure ratings of transformers are sufficient, as they are dependent on power-flow direction.

This project has delivered a solution for the real-time monitoring of power flow direction through overhead line conductors without the requirement for a grounded voltage reference. The DSO can obtain significant operational benefit through the provision of an easy-to-install clip-on sensor which can provide power flow, fault flow and conductor temperature visibility which can be installed on OHLs without disruption to electricity services.

5.1. Power Flow Direction

5.1.1. Measurement Theory

The phase angle between current and voltage must be measured to determine the direction of power flow through a conductor. The Smart Navigator 2.0 uses a capacitive divider to monitor the voltage, with a cage around the sensor acting as a neutral, which negates the need for a bonded reference to earth. The voltage measurement has proven to be adequate for deriving a relative phase angle and providing indication of voltage loss along the circuit. The relative phase angle is used to provide a binary indication of power flow direction through the circuit. Red and green reflective labels are included on the housing of the Smart Navigator 2.0 which provides a reference for the orientation of the sensor and binary reporting of power flow direction, an illustration of the phase angle and directional power flow detection range is presented in **Figure 5-1.**

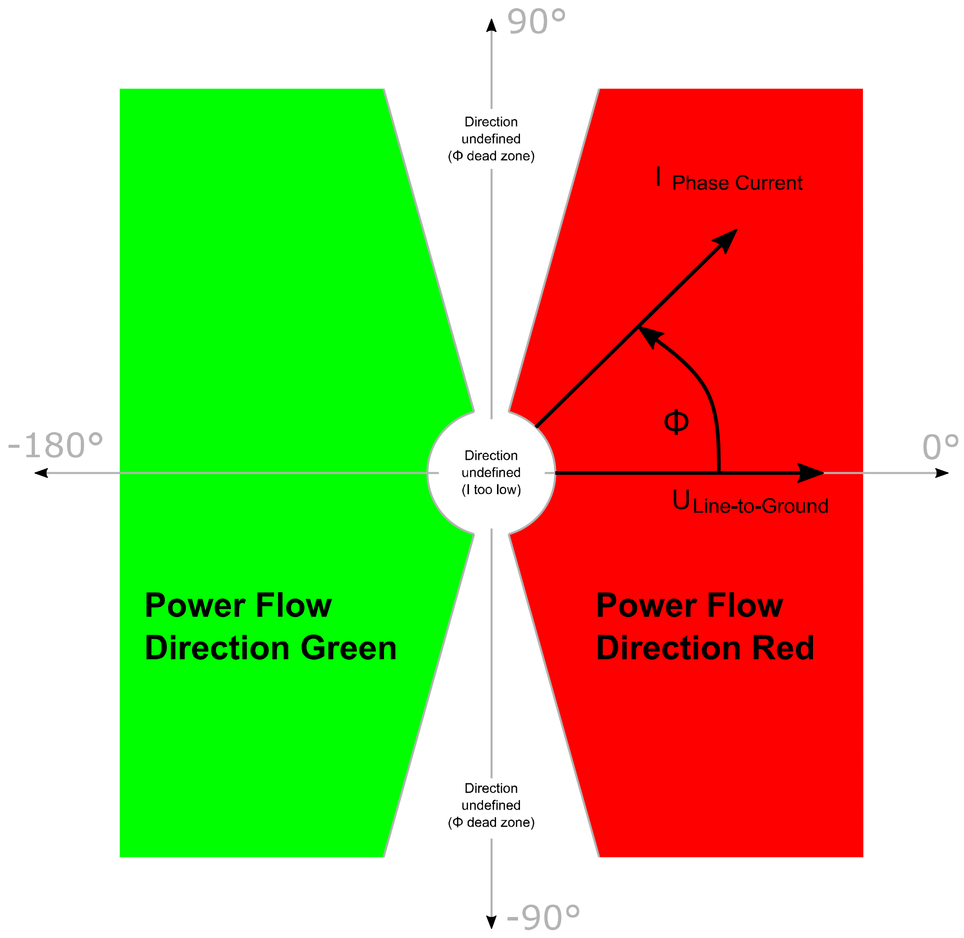

Figure 5-1: Phase angle and power flow direction

Modern substation feeder monitoring equipment typically includes solidly earthed active power transducers which accurately monitor the phase angle between voltage and current and periodically report signed megawatt values over the SCADA system to the control room. The 'sign' of the value indicates the direction of power flow through the transducer. It is important to ensure that substation transducers are installed with correct orientation to ensure the polarity of the reported values adheres to the guidance given in Standard Technique: TP6F/1[1].

5.1.2. Availability of Directional Power Flow Measurements in the Distribution Network

The 132kV system is heavily instrumented and directional power flow information is widely available to the control room. The network is less heavily instrumented on 33kV and 66kV systems, typically at customer connections and on a feeder basis at primary substations. A report[2] on available SCADA data was prepared which provides a detailed assessment of the available directional power flow measurements and suitability of measurements on a typical 33kV system. The report found that approximately half of the primary substations, in the limited sample, comprised transducers and with capability to record directional power flow measurements, these measurements are typically

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[1] WPD Standard Technique: TP6F/1, Power Measurement Conventions

[2] D_003386: Report on SCADA Time Series Data Store (TSDS), v1.1

recorded at the feeder head-end and at the transformer incomers. There is generally negligible directional power flow data captured on 11kV networks.

5.1.3. Validation of Directional Power Flow Detection

The project team witnessed the factory acceptance testing of the Smart Navigator 2.0, where tests were carried out to demonstrate the correct detection of the direction of power flow through a conductor in a laboratory environment. Tests were carried out on a three-phase system using an Omicron test set generating conductor line currents of 12A magnitude, with phase angles set to L1: 0°, L2: -120°, L3: +120°. The Smart Navigator 2.0 reported power flowing in the red direction. The phase angles were subsequently set to L1: 180°, L2: 60°, L3: -60° and the Smart Navigator 2.0 reported power flowing in the green direction, indicating a successful test with results as expected. Detailed information on the factory acceptance testing is presented in Directional Smart Navigator 2.0 Factory Acceptance Test Report (D_003043)[3].

During the live field trials, Smart Navigator 2.0 sensors were installed at the mid-points of 33kV circuits and equivalent datasets from the active power transducers at the substation feeder head end were obtained from the SCADA system. The chart presented in **Figure 5-2** indicates that the direction of power flow changed several times over successive days, each time the Smart Navigator 2.0 detected the change in power flow direction accordingly, (see **Figure 5-3**); either red to green or green to red, when the sign of the MW value changed. The changes in power flow direction on this particular circuit are due to cyclical power injections from a nearby solar park. The minimum current required to determine the phase angle is approximately 3A, this was found to result in a lag of approximately 1 minute in reporting a change of power flow direction when comparing the MW signal with the Smart Navigator 2.0 data on a granular level. This helps to quantify the impact of the dead zones illustrated in **Figure 5-1**.

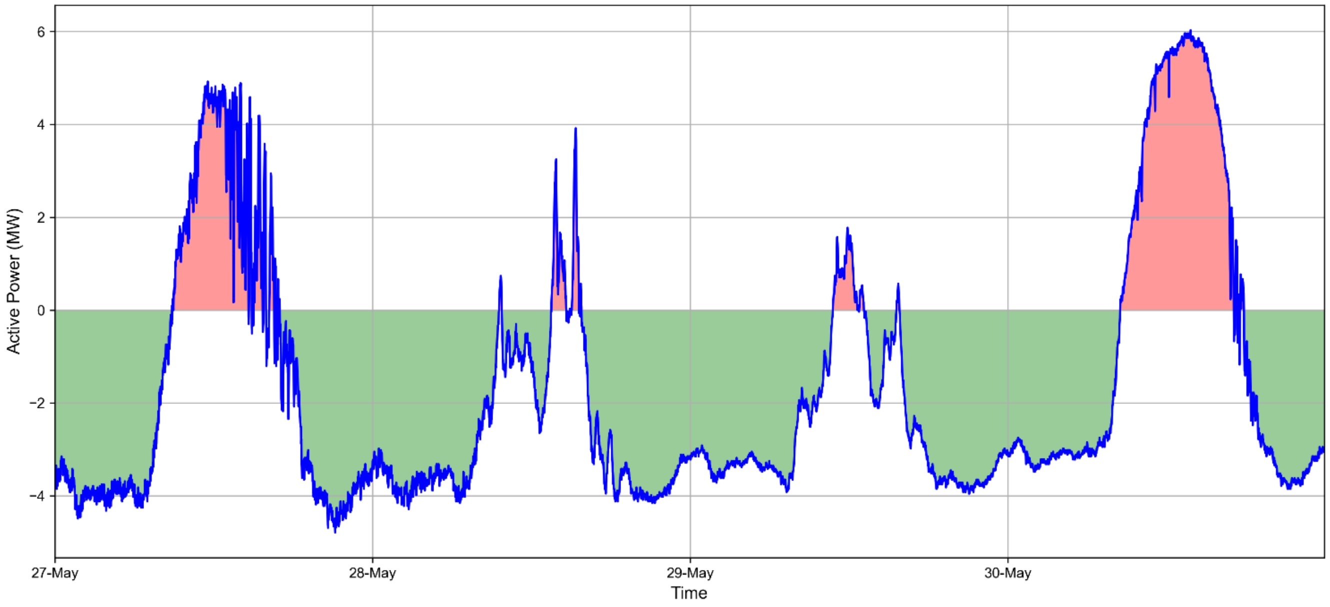

Figure 5-2: Malehurst to Bayston Hill 33kV circuit - SCADA active power measurements

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[3] D_003043: Directional Smart Navigator 2.0 Factory Acceptance Test Report, v1.0

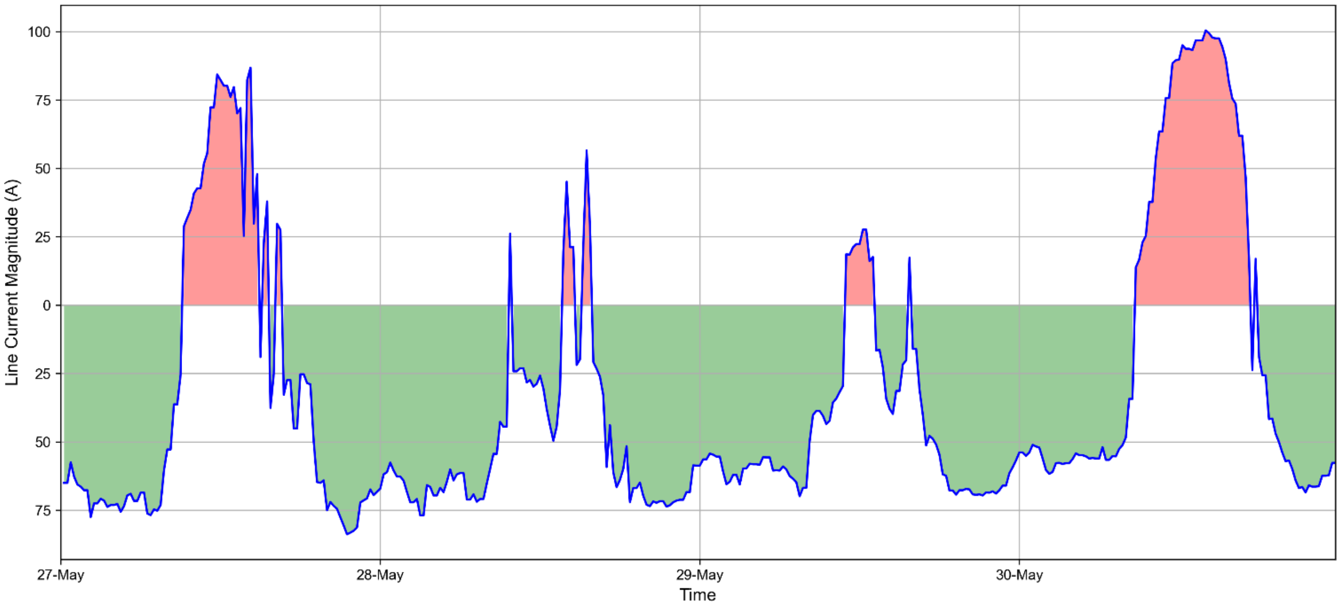

Figure 5-3: Malehurst to Bayston Hill 33kV circuit - Smart Navigator 2.0 directional power flow data

Note, the innovative voltage detection mechanism is sufficient to derive the approximate phase angle between the voltage and current flowing through the conductor. During field trials the analogue voltage measurements recorded by the Smart Navigator 2.0 were observed to vary in accordance with climatic conditions (humidity, precipitation). A bonded reference to earth would be required to derive a true voltage measurement (and consequently phase angle), this is not within the scope of the OHL Power Pointer solution. The voltage detection mechanism has proven adequate for detecting the presence of voltage on OHL circuits, and determination of the direction of power flow through circuits. The benefits of a bonded reference to earth should be evaluated against necessary additional safety considerations, such as the bridging of insulation gaps in OHL circuits, and resourcing requirements for more complex installation procedures.

5.2. The iHost User Interface and Integration into Network Management System (NMS)

The data from the remote sensors is uploaded periodically over a mobile connection to the West Midlands iHost monitoring platform, where time-series data can be analysed using features such as interactive trends, dashboards and single line diagrams (SLDs). iHost serves as a data concentrator and device maintenance platform. iHost can consolidate multiple binary and analogue events into single alarm points. Alarms and routine load information are reported from the iHost server over a DNP3 connection to the NMS, for visual representation in the Control room.

Figure 5-4 presents the Smart Navigator 2.0 dashboard which provides the user with an overview of the device health and important monitoring metrics. The direction of power flow through the feeder is presented with reference to the adjacent poles (or towers) where the Smart Navigator 2.0 is installed. There are line current magnitude gauges which present the live load through the conductor and indicate the maximum demand at the monitoring location recorded since the beginning of the calendar month. The data and time of the last recorded change in power flow direction through the feeder is also provided.

Site #106 (Shrewsbury) / 33kV (#41138)

Unit Overview Events Map Diagram

Status

- **Last Mimic Refresh:** 01/11/2021 13:42:56 (< 1 min ago)
- **Last Communication:** Connected

Power Flow Activity

- **Last Power Flow Direction Change:** 31/10/2021 17:53:33 (20 hours ago)
- **Conductor Seasonal Static Rating:** 456A
- **Conductor Temperature Post-fault Rating:** 501A

Power Flow Interruptions

- **Momentary Faults:** 6
- **Permanent Faults:** 0
- **Circuit Breaker Operations:** 0
- **Last Fault Detected:** More than 30 days ago

Daily Load Profile

Version: 1.2.1

Power Flow Direction (Live)

Pole: 84ZYPB47

Pole: 84ZYPB46

Battery Status (Live)

Currents (Live)

Conductor Temperature (Live)

Figure 5-4: iHost Smart Navigator 2.0 dashboard

Figure 5-5 presents illustrations of the Smart Navigator 2.0 symbol within the iHost environment. The iHost Single Line Diagrams feature was used for rapid prototyping of the symbol, and to develop a specification for the integration of the Smart Navigator 2.0 features into the NMS. The green arrow indicates the direction of power flow through the feeder, power flowing in the reverse direction would be represented with a red arrow, this convention maps the polarity, recorded during the installation of Smart Navigator 2.0 sensors on OHLs, to the diagram. The yellow arrow is for directional fault indication purposes.

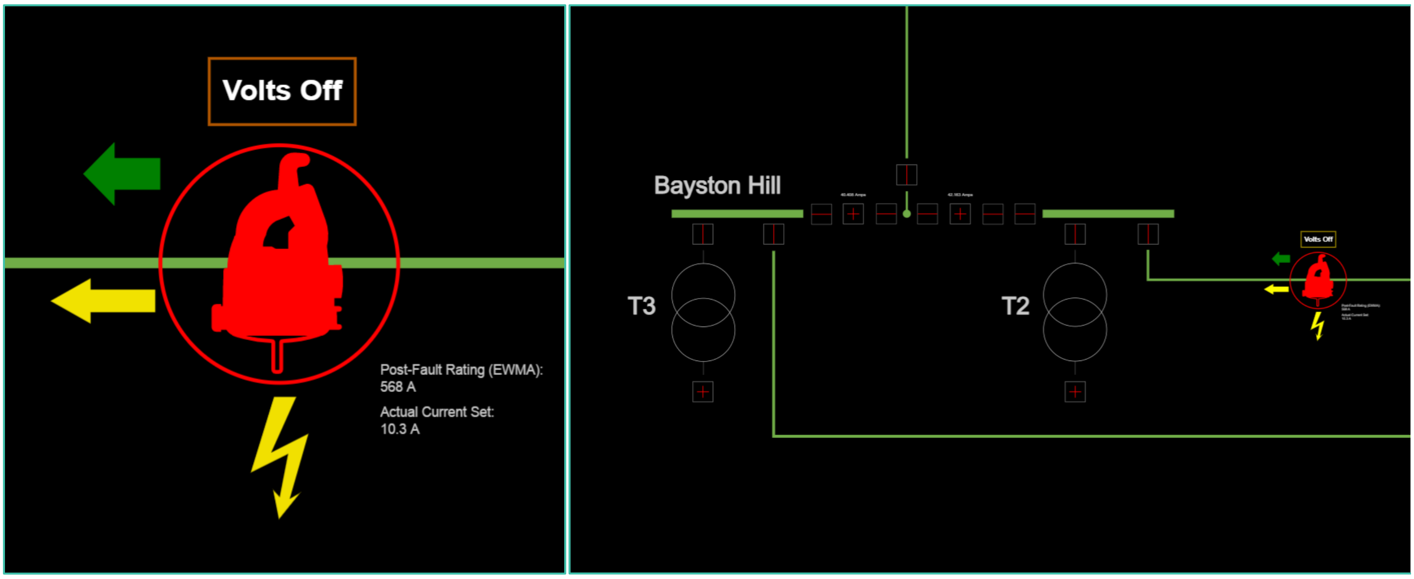

Figure 5-5: iHost Single Line Diagram with Smart Navigator 2.0 symbol

Figure 5-6 presents the Smart Navigator 2.0 symbol operating in test mode in the live NMS, A white arrow indicates the direction of power flowing through the circuit. The health of the device is confirmed by the outer circle surrounding the symbol and a current analogue is available (blue) which provides the Control room with the average line current magnitude across the phases.

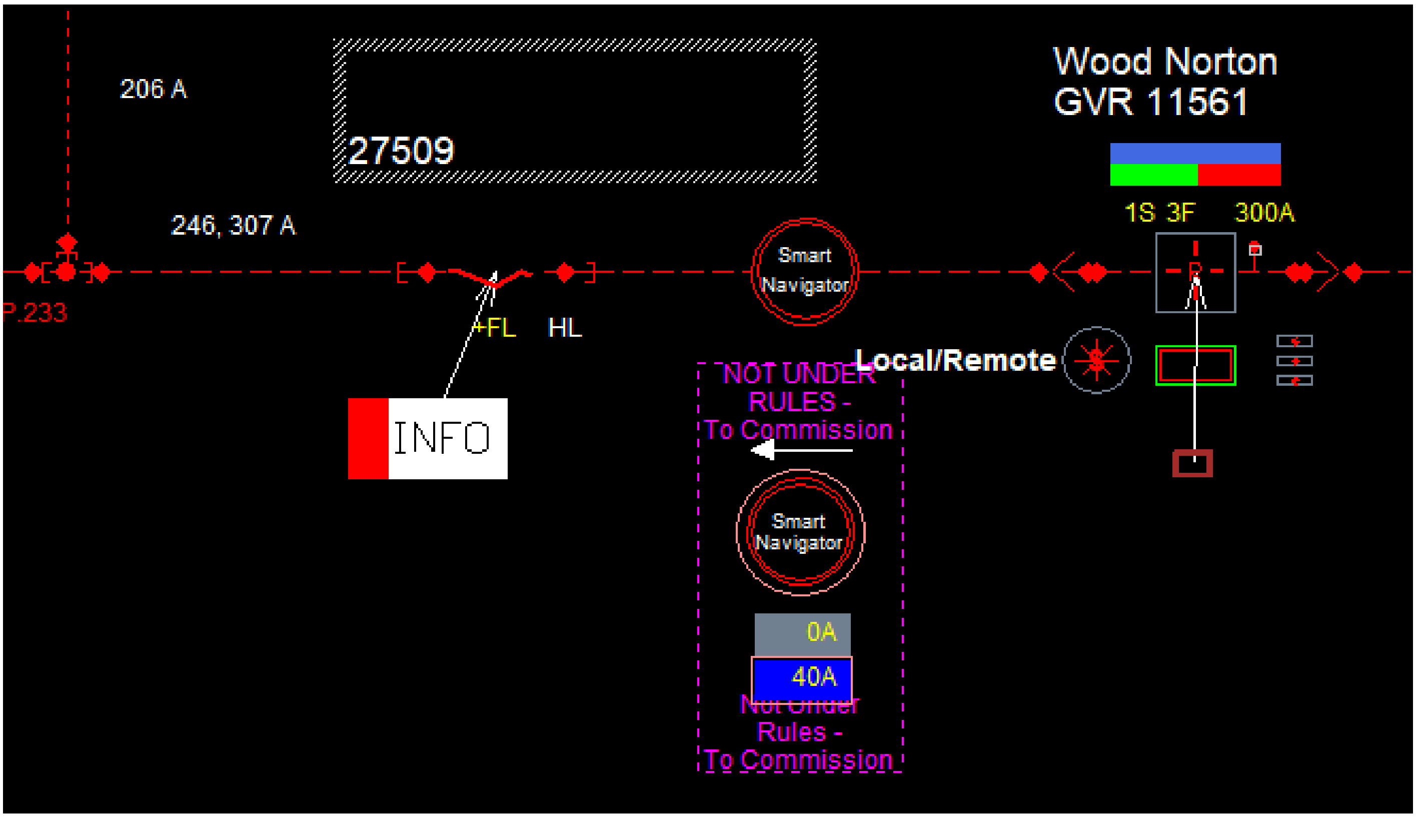

Figure 5-6: Smart Navigator 2.0 symbol in NMS diagram

5.3. Case Study – Commercial Road - 11kV OHL Circuit

The Gloscat / Over Hosp. 11kV feeder supplied from Commercial Road substation is located within the Gloucester area. The high-level characteristics for the selection of the feeder as a candidate trial area included frequent historical fault activity and the connection of a small-scale solar array at the remote end of the feeder. The OHL Power Pointer monitoring solution was installed at eight trial sites along the feeder, and the spurs to provide fault passage indication and localised monitoring of directional power flows. The section monitored by Site #216 was undergrounded during the field trials and the monitoring was removed.

A schematic diagram of the feeder and the respective trial locations is presented in **Figure 5-7.**

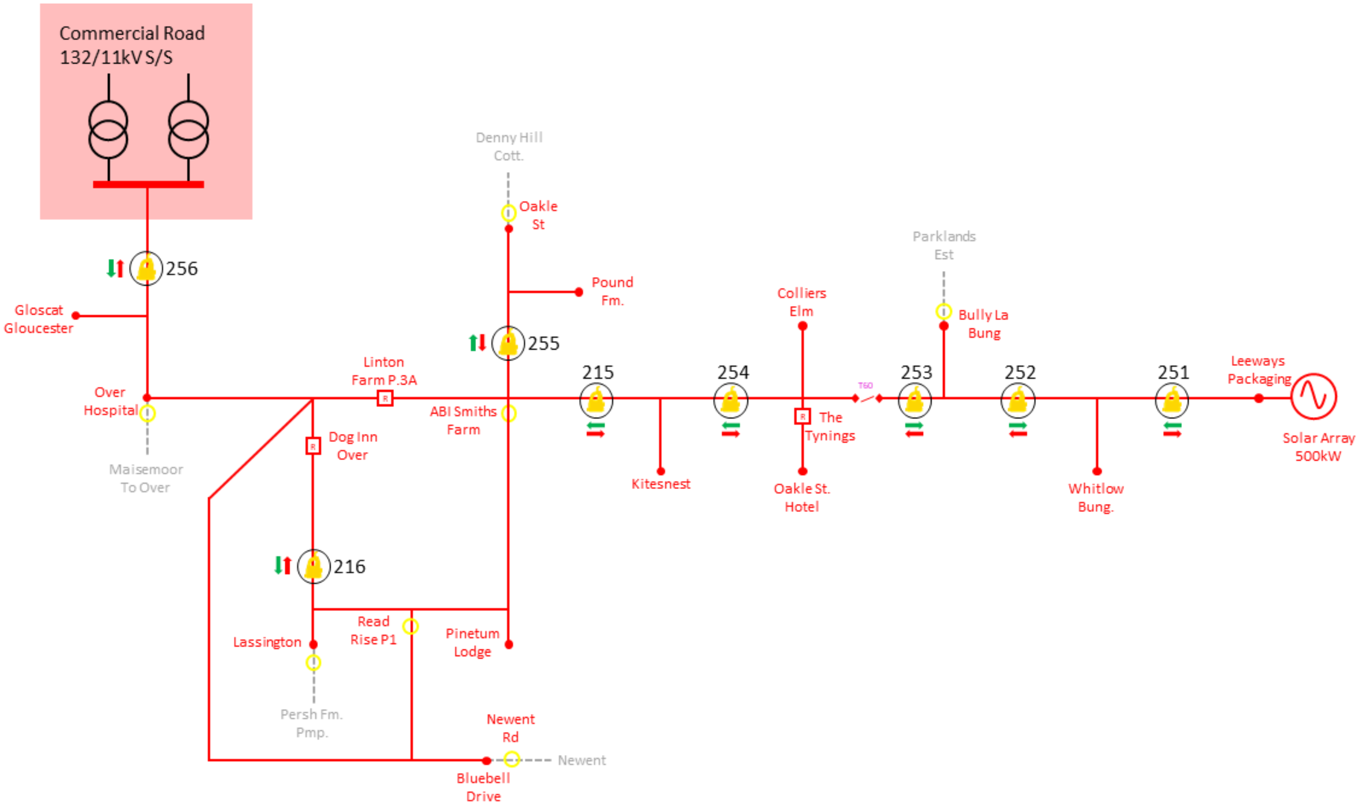

Figure 5-7: Schematic of the Gloscat / Over Hosp. 11kV from Commercial Road substation

The peak load on the feeder was observed to be approximately 160A (c. 3MVA) which closely correlates to the maximum day-time demand extracted from historical records, indicating that the feeder was likely to be operating in the normal running arrangement. The load current magnitude at the feeder head-end was recorded at trial site #256, a typical daily profile of the current load is captured in **Figure 5-8**.

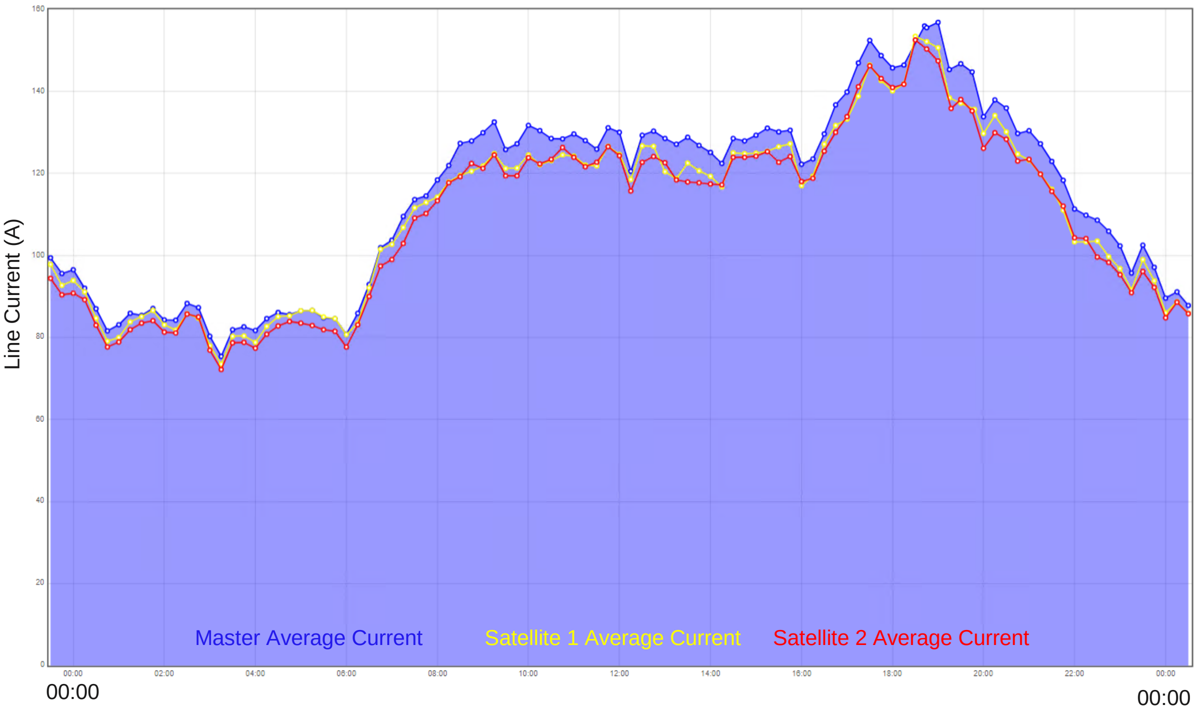

Figure 5-8: Load current magnitude at trial site #256 recorded on 28th October 2021

The 500kW solar array is connected at an industrial consumer's premises at the remote end of the feeder. On particularly sunny days, for example, 4th November 2021, localised monitoring detected reverse power flows as far as the midpoint of the feeder (site #215). The solar array supplied a large portion of the distributed demand of the total feeder. The overall demand on the feeder observed at the feeder head end (site #256) shows a local minimum at midday on 4th November 2021, with a higher ratio of the maximum to minimum load observed compared to other days.

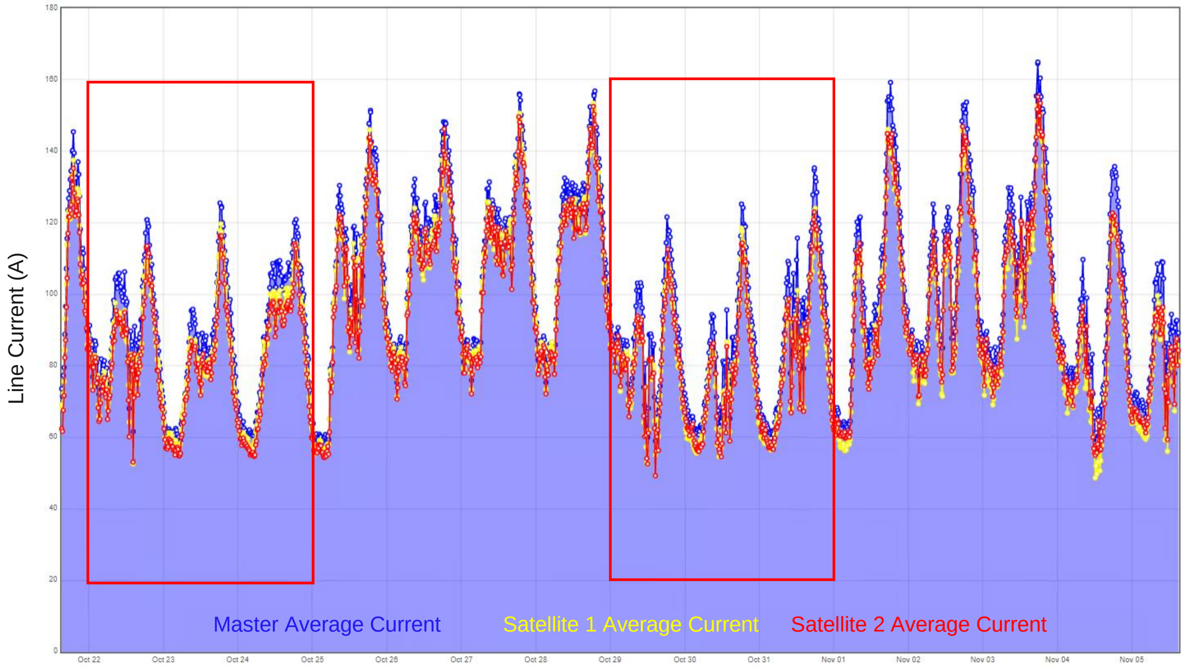

Figure 5-9: Load current magnitude at trial site #256 recorded on over two-week period

Figure 5-10, **Figure 5-11** and **Figure 5-12** present annual heatmaps of the intensity and direction of power flowing through the circuit at the various monitoring points along the feeder. The seasonal variation of the demand (January to December) is captured in the vertical plane and the daily variation in demand is captured in the horizontal plane (midnight to midnight). The charts are representative of the year 2021, with green indicating power flowing from the feeding substation along the feeder, and red flowing in the reverse direction.

Typical characteristics of a daily demand curve can be seen in **Figure 5-10**, with lower intensity during the night, higher intensity during the morning, and peaking during the evening. The selected area identifies a pattern of lower intensity to higher intensity loading through each week, reflected as stripes on the diagram. This is reflected in the two-week load curve presented in **Figure 5-9.** The pattern is more pronounced towards the industrial connection towards the end of the feeder between each Friday and Sunday.

The selected area in **Figure 5-11** indicates a significant reduction in consumption of power along the feeder for several hours over the 24-hour period Monday to Thursday, where the industrial connection adjusted operations in response to Government restrictions imposed during the COVID-19 pandemic. A subsequent increase in load resumed once the Government restrictions were relaxed.

The selected area in **Figure 5-12** indicates the presence of reverse power flows through the feeder, which is most prominent during the weekend period when the industrial demand on the feeder is minimal. The reverse power flows are from the solar generation and contribute to masking of the load at the feeder head-end where there is a significant correlation between the loading intensity (Site #256) and reverse power flow (Site 252) during the middle of the day.

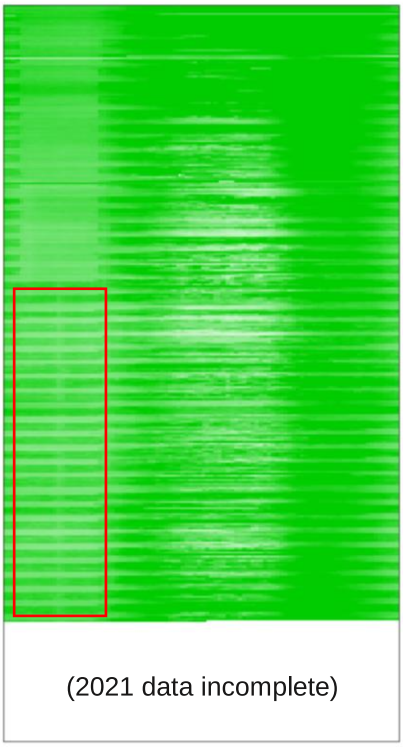

Figure 5-10: Site #256

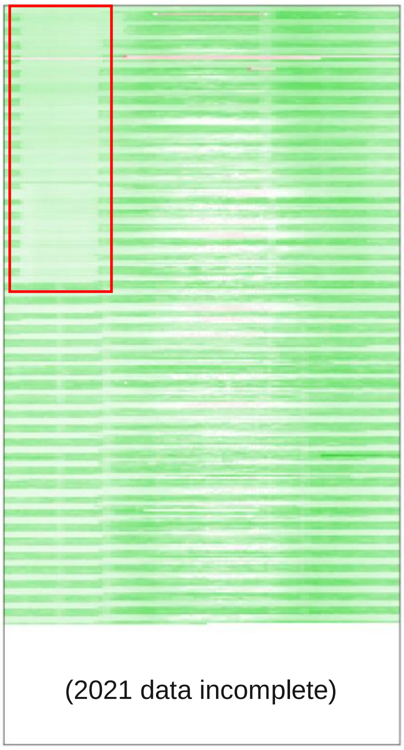

Figure 5-11: Site #254[4]

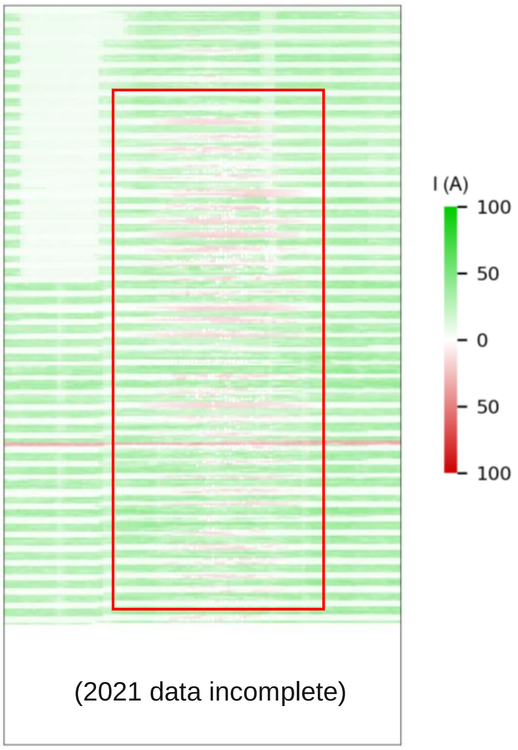

Figure 5-12: Site #252

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[4] Power flow direction notation inverted for the purposes of reporting.

This case study has demonstrated that when witnessed from the feeder head-end the demand has been masked, which could construe data used in typical planning resources, leading to underinvestment if conventional planning methods are followed.

As more generation is connected and electric vehicle uptake increases, there will be a marked shift in power flows through 11kV networks, with a risk of significant loading on conductors if coincidence of both local generation and demand is not carefully interpreted.

Localised monitoring provides a solution to this issue, ensuring visibility of the network further downstream from traditional substation sensors and enabling both planning and operations teams to determine whether there is sufficient latent capacity in the network to secure existing and new customers.

Once the demand on the feeder becomes smarter and more flexible, localised monitoring will be a valuable tool available to control algorithms to balance the network and ensure safe operation within statutory limits.

5.4. Case Study – Meaford - 33kV

The OHL Power Pointer monitoring solution was installed at eleven sites on the Meaford 33kV network for the duration of the main field trials. **Figure 5-17** presents the schematic of the network with the monitoring locations identified.

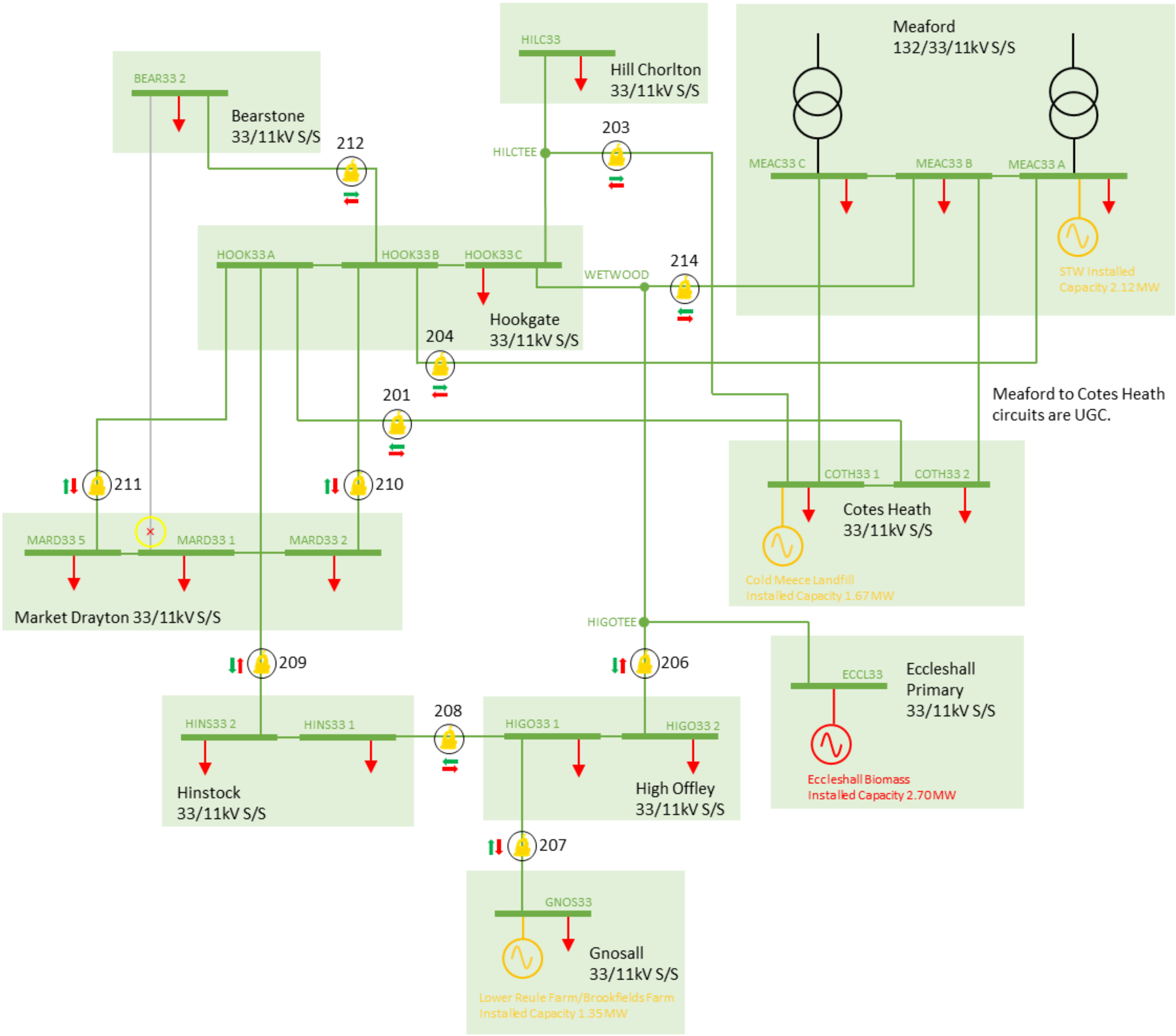

Figure 5-13 – Schematic of the Meaford 33kV network

Meaford 33kV network is a conventional network with small, embedded generation connections which have minimal impact on the direction of power flowing through the circuits that were monitored.

Figure 5-14, **Figure 5-15** and **Figure 5-16** present annual heatmaps of the intensity and direction of power flowing through circuits at several of the monitoring locations. Each figure demonstrates conventional power flows around the Meaford group of primary substations, with power flowing from the source (Meaford BSP) towards the load (Hookgate, Market Drayton and Bearstone primary substations). Site #208 was the exception to these observations, which power flow direction through the circuit between High Offley and Hinstock alternating frequently, although the circuit was relatively lightly loaded.

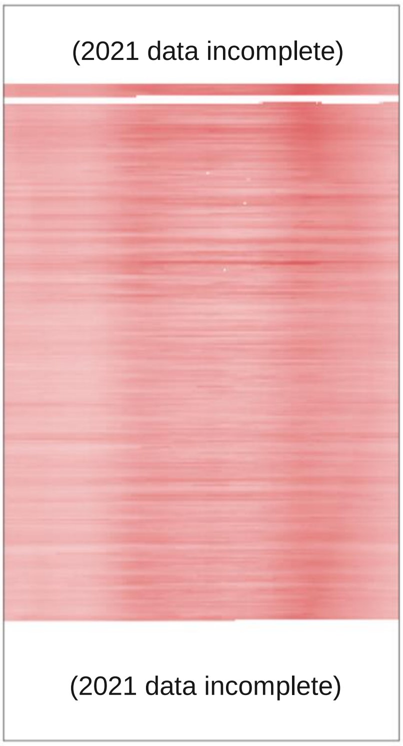

Figure 5-14: Site #204

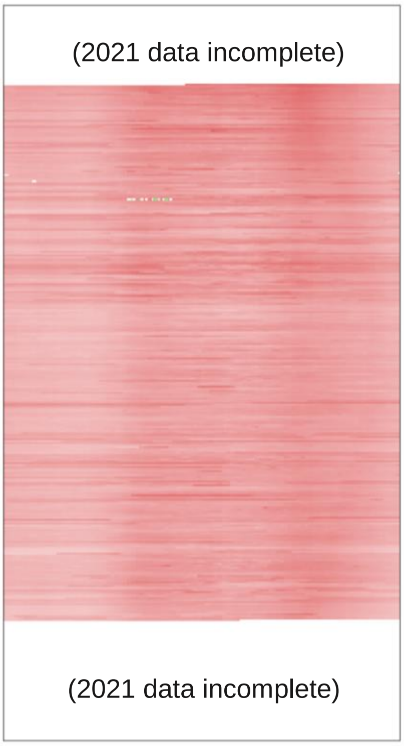

Figure 5-15: Site #211

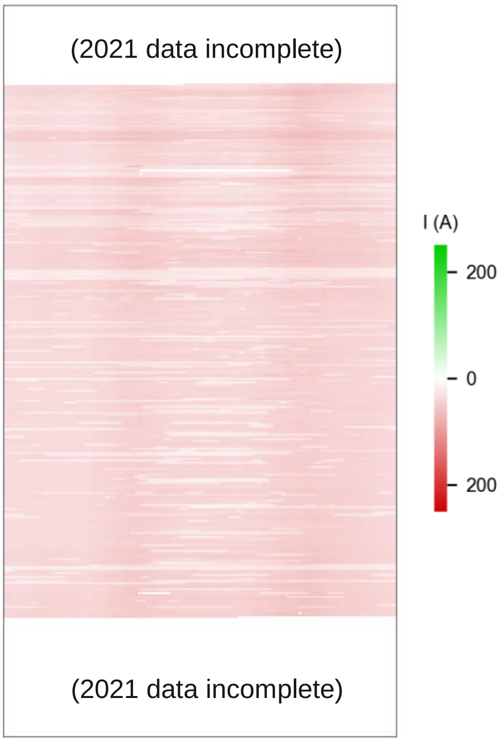

Figure 5-16: Site #212

This case study can be considered a control study of a historically conventional network with minimal DERs influencing changes in direction of power flow through circuits.

5.5. Case Study – Hereford – 66kV

The OHL Power Pointer monitoring solution was installed at ten trial sites on the Hereford 66kV network. The network is operated in a meshed arrangement, with a loop of circuits supplying primary substations selected as a trial area for the project. **Figure 5-17** presents the schematic of the network with the monitoring locations identified.

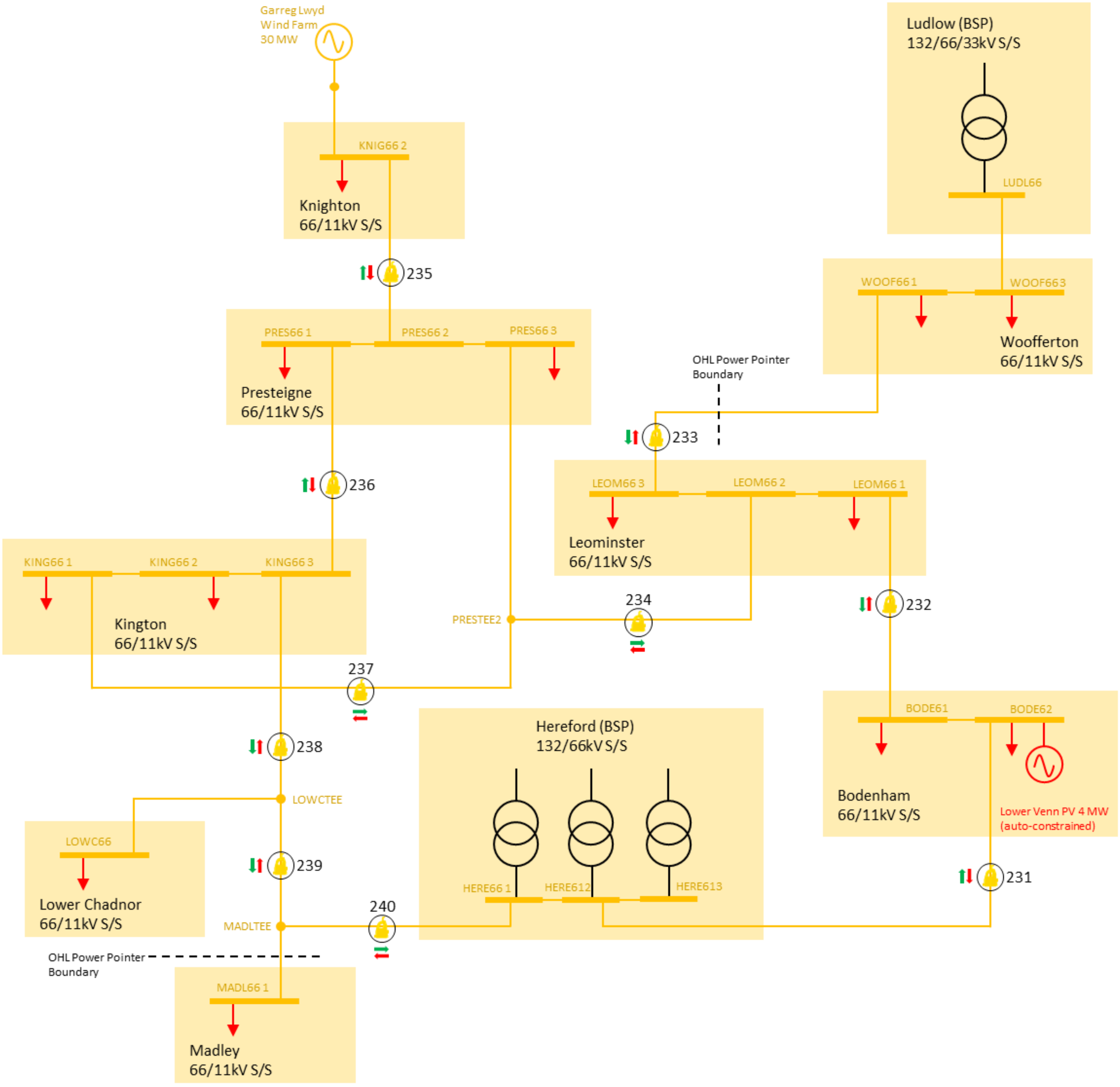

Figure 5-17 – Schematic of the Hereford 66kV network

Power flow direction changes are prevalent at the monitoring locations across the Hereford 66kV network. The typical daily demand profile is apparent at most of the monitoring locations, with a morning peak and early evening peak in load.

Figure 5-18, **Figure 5-19** and **Figure 5-20** present annual heatmaps of the intensity and direction of power flowing through circuits at several of the monitoring locations. Power flows through the circuit at monitoring Site #236 are heavily influenced by wind generation output from Garreg Lywd. The periods of high intensity green shading are indicative of periods of high power injection into the network from the Garreg Lywd wind farm. It can be seen from **Figure 5-19** and **Figure 5-20** that these intense periods of power injection influence the direction of power flows across the network. Similarly, the impact of a circuit outage between Leominster, Kington and Presteigne substations is observed in changes in directional power flows through adjacent circuits.

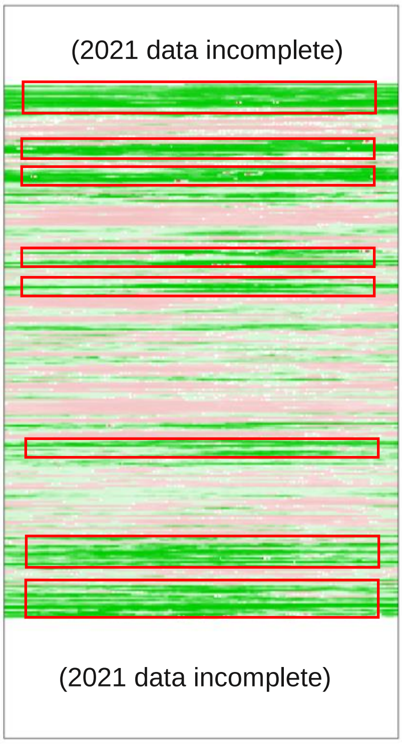

Figure 5-18: Site #236[5]

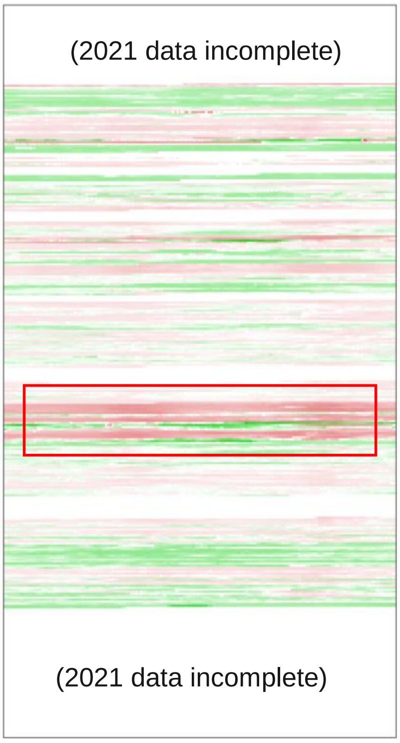

Figure 5-19: Site #238

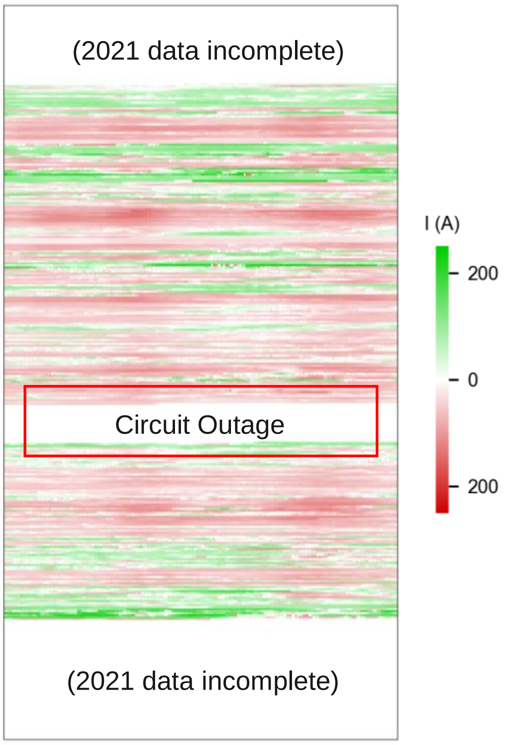

Figure 5-20: Site #234

Figure 5-21 presents the power flow direction and intensity through the 66kV circuit between Hereford BSP and Bodenham substation. Lower Venn photovoltaic solar farm, 4MW capacity, is connected to the 11kV network at Bodenham. This appears to contribute to the typical solar profile (reverse power flow) observed in green shading through the middle of the day in **Figure 5-21**. The red shading indicates the normal operating arrangement of power flowing in the direction of Bodenham substation from Hereford BSP. **Figure 5-22** presents the heatmap of directional power flow through the 66kV circuit between Bodenham substation and Leominster. It is apparent from the heatmap that the load at Bodenham substation is partially supplied from Hereford BSP, and partially from Ludlow BSP. There is also a distinct correlation with the output from Garreg Lywd wind farm illustrated in **Figure 5-18**, which demonstrates the depth of penetration of the wind generation through the 66kV network. The green shading in **Figure 5-23**

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[5] Power flow direction notation inverted for the purposes of reporting.

illustrates how Ludlow BSP supplies power through the circuit monitored between Woofferton to Leominster. The selected areas demonstrate when outages are likely to have occurred between Woofferton and Ludlow substations, with adjacent circuits through Hereford to Leominster recouping the additional load.

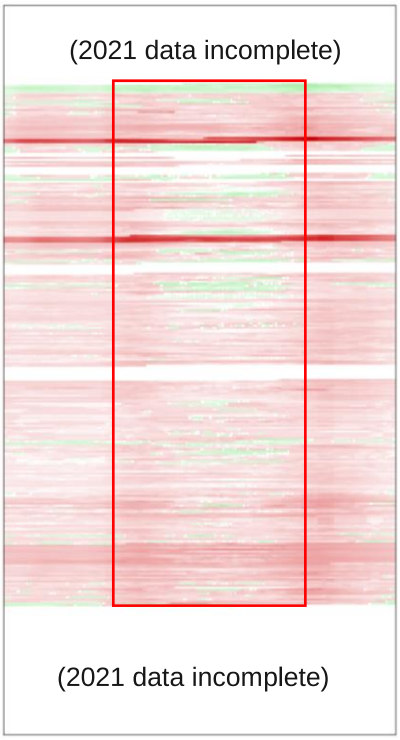

Figure 5-21: Site #231[6]

Figure 5-22: Site #232

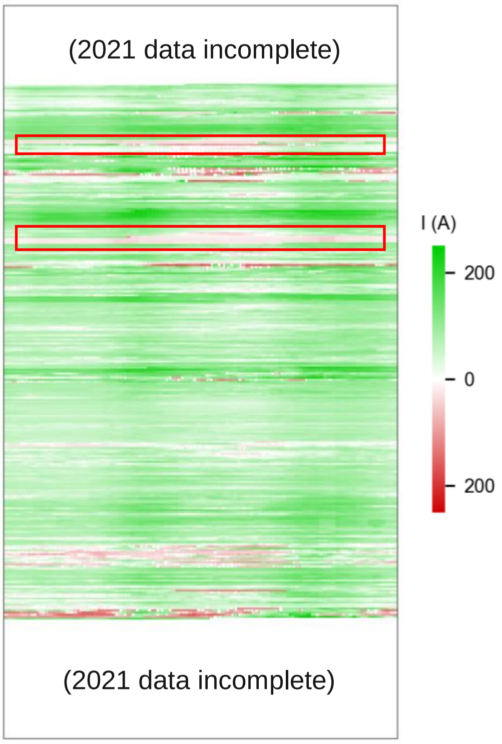

Figure 5-23: Site #233

This case study has illustrated how large intermittent power injections into the 66kV network can penetrate the network and influence the direction of power flows at remote nodes. The case study has also examined the effect of outages in circuits connected in a looped arrangement on the direction of power flows through adjacent circuits.

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[6] Power flow direction notation inverted for the purposes of reporting.

5.6. Case Study – K-Line (South-West) – 132kV

Visibility of the 132kV network is generally already well established, with directional power flow and fault flow information available locally and in the control room. This case study utilises the available directional power flow data from the Smart Navigator 2.0 to document trends in changes in power flow direction through circuits in response to large penetration of renewable energy connections, capturing seasonal periods over year.

Smart Navigator 2.0 devices were installed at intervals on each side of the double circuit K-Line in the South-West licence area. A representative network diagram is given below which shows the extent of the study area and the positions of the monitoring locations.

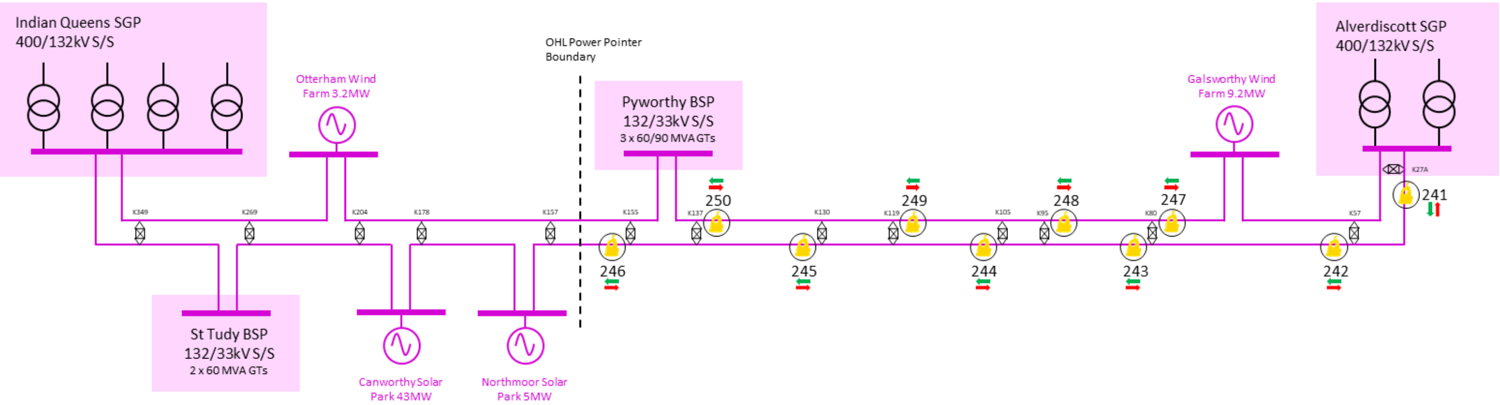

Figure 5-24 – Representative schematic of the K-line – South West licence area

The monitoring locations were primarily selected to observe the conductor temperature along the circuit, there is negligible variation in the data captured by the devices along each side of the K-Line circuit with regards to directional power flow. Therefore, selected results from Site #244 and #248 can be considered representative of directional power flow data captured at each site on either site of the double circuit, respectively.

The heatmaps in **Figure 5-25** and **Figure 5-26** illustrate the influence of connected solar generation on the direction of power flowing through both sides of the K-Line circuit. The red shading in **Figure 5-25** illustrates power flowing from the OHL Power Pointer boundary towards Alverdiscott SGP and is indicative of power export from solar parks connected at Canworthy and Northmoor during periods of daylight. There are also several solar parks connected to the 33kV systems at Pyworthy and St Tudy BSPs which perhaps explains the emergence of a similar solar profile on the adjacent K-Line circuit in **Figure 5-26**. The seasonal effect of higher solar output through the summer period is also evident in both charts.

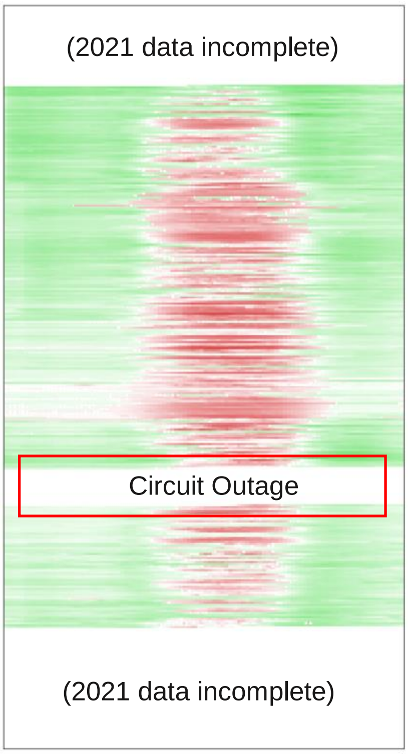

Figure 5-25 - Site #244[7]

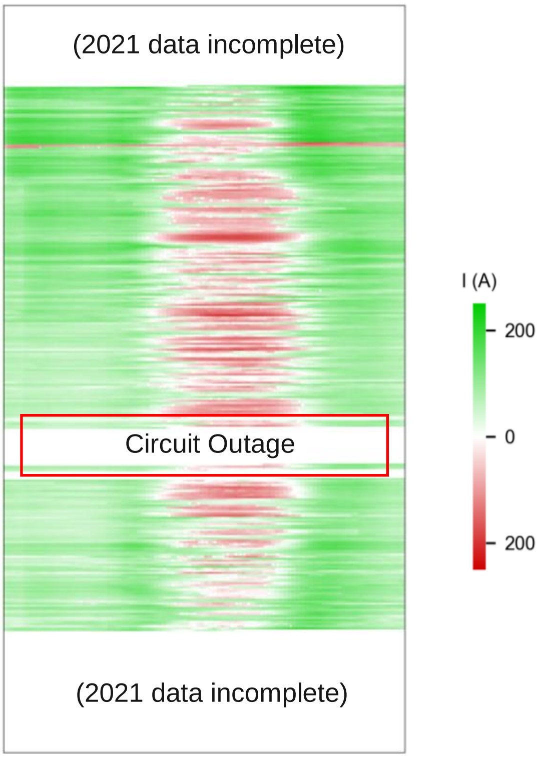

Figure 5-26 - Site #248

Figure 5-27 presents a load duration curve derived from the load current and power flow direction data captured at Site #248. The chart indicates that the peak loading on the circuit occurred during a period when the power was flowing in the reverse direction. This highlights a particular challenge faced by network planners and is likely a behaviour that will be observed across the various distribution voltages, as solar arrays become more prevalent in low voltage consumer connections.

Figure 5-27: Power flow direction load duration curve for Site #248

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[7] Power flow direction notation inverted for the purposes of reporting.

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 meets the objective of providing the control room with visibility of directional power flows through OHL circuits.

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 improve visibility of directional power flows across high-voltage distribution networks.

The performance of the solution has been scrutinised in the field trial reports and where recommendations have been identified, the project partner has engaged with the manufacturer to implement changes and deliver a proven product that instils confidence in the technology.

Changes in power flow direction have been observed regularly in circuits throughout the test trials and the main trials, often because of a shift in the balance of demand and generation along a feeder, and sometimes through switching in response to fault activity or planned maintenance by Network Services teams.

The devices were found to operate predominantly in boost-mode on 33kV, 66kV and 132kV circuits, where higher line currents (c. 25A) generally support ample power harvesting to keep the battery in a fully charged state. At these monitoring locations, the devices maintained a continuous communications connection to the iHost platform, reporting measurements immediately upon sampling. Changes in power flow direction through the circuit were observed to be updated in near real-time at these locations, with due consideration given to a small lag introduced by the minimum 3A threshold to determine phase angle, when crossing the zero current point.

The devices were generally deployed to provide visibility of the extremities of the 11kV network where line currents are generally less than 25A. The devices were found to operate in smart-mode on these circuits, where the charged state of the battery is maintained to a satisfactory level to support reporting of unsolicited events (e.g. faults and loss of supply), and once per day reporting of routine logging data. At some of the low current monitoring locations, frequent changes in power flow direction (c. 100 times per day) were observed, unsolicited reporting of power flow direction was found to be undesirable, due to the heavy load on the battery required to repeatedly initiate the remote communications. The configuration of devices on 11kV networks was updated to disable unsolicited reporting of changes in power flow direction thereby reduce the priority of the events, instead capturing in routine data logging, reported once per day to iHost.

The accuracy and consistency of the solution has been assessed and quantified in a controlled laboratory environment and during the live field trials, the performance of the solution has been successfully tested against SCADA records, this has been demonstrated in section 5.1.3.

In accordance with the success criteria, power flow direction has been determined correctly at more than ten sites across 11kV and 33kV networks.

7. Potential for New Learning

The solution has been integrated into the NMS and provides visual indication of the direction of power flow through OHL circuits in the control room. Significant learning has been obtained through the project:

1. Directional power flow detection solution proven to be accurate and consistent without the requirement for a bonded reference to earth. This offers an option for cost effective monitoring of the overhead network, to maximise visibility of directional power flows in the Control room.
2. The directional power flow detection solution has been used to provide independent validation of the installed polarity of substation power transducers and assess conformance against the power flow direction convention given in our Standard Technique TP6F/1.

The following opportunities for new learning could be considered:

1. The NMS offers a Distribution Power Flow (DPF) module which aims to provide visibility of power flow direction through circuits to the Control room. The directional power flow detection solution could improve the accuracy of the DPF calculation along HV feeders, where it is assumed that uncertainties would exist due to limited availability of sensory feedback. Visibility of directional power flows will be important for preparing
2. The time-series data captured in iHost provides a rich resource for network planning teams to understand the utilisation of assets. Load duration curves can be developed for each locally monitored site to provide a summary of directional power flows at different points along feeders. This would provide planning teams with resources to assess and identify where latent capacity exists in circuits. Greater network visibility would provide network planning teams with an array of options, such as targeted flexibility products, to potentially mitigate seasonal constraints by balancing feeder loads, which could help to defer network reinforcement.
3. Monitoring of the reverse power flows through feeders could inform the dynamic configuration of feeders, feeding into soft-normally open point schemes which could manage the load on the feeders depending on the time of day.

8. Conclusions of the Method

In our RIIO-ED1 business plan and DSO Transition Strategy, we have made the commitment to improve visibility of distribution network power flows.

Ofgem's RIIO-ED2 methodology draws on the principle of a smart and flexibly energy system. Ofgem is clear that the use of data lies at the heart of the energy system transition, and that a shared understanding of what is happening to power flows and the status of network infrastructure will be key enablers for creative solutions to future challenges.

Our Distribution System Operability Framework identified the main drivers for increased monitoring and control:

- Making informed decisions about switching and network operation;
- Ratings of transformers, as they are dependent on power-flow direction;
- Running real-time analysis like Active Network Management (ANM) will necessitate this level of detail to ensure the control systems can represent the network accurately; and
- Enabling the network to be correctly represented in power system software as this is used to determine reinforcement requirements and network constraints.

The technology deployed within the solution has been proven during the field trials. The OHL Power Pointer solution offers benefits to several areas of the business, these are discussed in the sections below.

As the distribution network evolves to accommodate more generation connections, and adoption of electric vehicles accelerates, the direction of power flows through networks will become increasingly uncertain. By enabling greater visibility of the network, real-time system operations can react to wider system events to improve network performance and maintain a safe and reliable network. The benefit to maintaining a healthy system (within statutory limits) can often be quantified by a reduction in risk of incurring CIs and CMLs.

OHL Power Pointer has delivered a solution for the detection of power flow direction in circuits without the requirement for a grounded voltage reference. 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 of the data from the main trials has been completed, and the following conclusions have been drawn on the findings of Method 1: Directional Power Flow Monitoring.

The 11kV network is predominantly operated in a radial configuration. Changes in the direction of power flow were observed where embedded generation, such as clusters of rooftop and small commercial solar arrays are common. It was possible to observe the power flows from generation along the feeder towards the primary substation when solar irradiance was high during the day and the general demand was low over a weekend. Whilst these reverse power flows were not observed to back-feed primary substations during the main trials, the connected generation did provide power to supply large portions of demand on the feeder, which would have masked the measurements at the primary substation. This data could be utilised by planning engineers for investment appraisals. It could be argued that more localised monitoring in 11kV networks will be necessary to support customer connection appraisals, by using tools which evidence bi-directional power flows and time-series variation deep within the network.

The 33kV and 66kV networks are predominantly operated in a meshed configuration. The connection of utility scale solar and wind generation actively influences the direction of power flow through circuits during periods of peak generating output. The trials observed extensive periods during daylight hours where power flowing through the circuits was reversed, flowing back towards the bulk supply point.

At 132kV the network is already well instrumented, with sensors for detection of directional power flow available at grid substations. The Smart Navigator 2.0 has detected forward and reverse power flows through circuits for long durations through the day, primarily due to large solar and wind connections. It was also observed that the daily peak of the line current magnitude was recorded during the period of reverse power flow at one the studied trial locations.

A separate study of the sensor measurements available at each of the primary substations in the 33kV trial area was undertaken. It was found that approximately half of the 33kV circuits on the local system were instrumented with MW and MVAr sensors, providing visibility of power flow direction, other circuits were instrumented with non-directional measurements, and some circuits were not instrumented.

The number of devices deployed along the feeder should be determined on a topology basis and the requirements for visibility at key branches along the feeder. Up to eight devices were installed on 11kV feeders for the main field trials. In terms of network visibility, the main benefits were realised when an average of four sets of devices had been deployed along a feeder.

Consideration should be given to the role of mid-feeder monitoring in the planning of future networks. Visibility of power flow direction through circuits will enable planning engineers to accurately assess the available headroom in the system to inform planning applications for new generation connections. Without due consideration a saturation point could be reached prematurely when the limits of reverse power flow capacity of primary and grid transformers are approached. This would result in curtailment of distributed generation connections without major network reinforcement.

Consideration should also be given to the role of mid feeder monitoring in ANM schemes. Wider network visibility will lead to fewer conservative assumptions of the state of the network, which will ultimately improve decisions made by automated schemes. Improved decisions could include the relaxation of enforced constraints on generation, and more efficient dispatch of flexibility services. The overall benefit would likely be a reduction in the carbon intensity of the grid, where clean energy sources can be prioritised, release of headroom capacity to accommodate more connection of generation, and a more operationally efficient power system resulting in fewer technical losses.

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
TSDS	Time Series Data Store
WPD	Western Power Distribution

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