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OHL Power Pointer - Report on Method 5

Method 5: Conductor Temperature Monitoring

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Western Power Distribution 2022

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1. Executive Summary

Distribution networks are evolving to accommodate more utility-scale generation connections. Under the current regulatory regime, generators carry responsibility for the cost of connection and (often expensive) costs of reinforcement to the upstream network (where required). There is a finite limit to the available capacity across the higher voltage (33kV, 66kV and 132kV) distribution networks, indeed several regions across the distribution licence areas are already operating towards the limits of capacity. In order to accommodate further connections to the distribution network, without the significant costs of reinforcement, the distribution system operator (DSO) currently offers constrained connections to new connectees. However, this can result in a significant volume of lost-generation throughout the year and deter development of further generation connections due to the adverse impact of lost-generation on the developer's business case.

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 5: Conductor Temperature Monitoring.

Witness testing at the manufacturer's facilities has confirmed that the conductor temperature monitoring solution is accurate to within ±3°C during steady state conditions, when compared to an independent thermocouple in a laboratory environment.

Conductor temperature data has been recorded at 120 trial locations along 11kV, 33kV, 66kV and 132kV overhead circuits. Seasonal variations in the temperature of the conductor have been analysed and illustrated in the report. Variation in conductor temperature has been assessed in response to the line current loading of the conductor, with no notable effect during normal loading conditions, but a loose relationship observed during higher conductor loading, typically above 80% of pre-fault rating.

The application of a short-term post-fault rating method has been developed and demonstrated. This method considers the adiabatic heating of the conductor to derive a maximum current rating suitable for use over short (10-minute) periods. A comprehensive conductor library has been prepared which considers common conductor types from ENA Engineering Recommendation P27 and is suitable for use across all distribution networks.

Case studies for the following trial areas have been presented in the report which support the key findings of the short-term post-fault rating method:

1. Alverdiscott SGP and Indian Queens SGP, 132kV double circuit K-Line, South West
2. Hereford BSP and primary network, Kington to Lower Chadnor Tee 66kV circuit, West Midlands
3. Shrewsbury BSP and primary network Shrewsbury BSP to Weir Hill 2 33kV circuit, West Midlands

The project has demonstrated that it is possible to further exploit the available thermal capacity of OHL distribution circuits using conductor temperature monitoring measurements to derive a ‘10 minute’ short-term post-fault rating, with the potential for increase in headroom capacity in higher-voltage OHL circuits by up to 18.5% and 48.1% where ACSR and AAC are utilised, respectively. There was no notable uplift in capacity observed where copper conductors were installed.

Active Network Management (ANM) schemes are currently active in areas of our network where headroom capacity is limited. ANM schemes interface with distribution control systems to monitor the limits of the network and allocate maximum amount of capacity to customers in the area. The application of a short-term post-fault rating in ANM schemes offers the potential to provide an immediate ‘boost’ to post-fault network capacity and deliver savings our potential future costs of network reinforcement.

By improving the overall capacity of the distribution network, we can look to accommodate more clean embedded generation connections, which would lead to a reduction in the overall carbon intensity of energy delivered to customers and thereby help to deliver and achieve ‘decarbonisation and Net Zero’ – a priority area in our Innovation Strategy.

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 networks 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

In this section the findings of the conductor temperature monitoring method are presented. The implementation of a short-term post-fault rating, trialled using real-time data captured during the conductor temperature monitoring solution, is also evaluated.

5.1. Conductor Temperature Monitoring

The design temperature of a conductor is the thermal limit at which the conductor can be continuously operational without degradation or damage to the materials. Conductors can be operated at higher temperatures for shorter periods without risk of permanent damage, however higher temperatures can increase the sag of overhead lines. It is important to maintain a minimum clearance to prevent the breakdown of insulation between the conductor and earth.

Conductor heating is generally proportional to the square of the load current passing through the conductor:

$$Ohms\ Law: V = IR \qquad\qquad Power: P = IV$$

$$Conductor\ heating: \boldsymbol{P} = I(IR) = \boldsymbol{I^2R}$$

A useful 'high-level' rule (in the context of this report) is to assume that the loading of the conductor with full rated current elevates the conductor temperature to its design temperature rating. Half the rated current, given the square proportionality, will only produce a quarter of the heating necessary to reach the design temperature. A quarter of the rated current will only produce one sixteenth of the heating necessary to reach the design temperature.

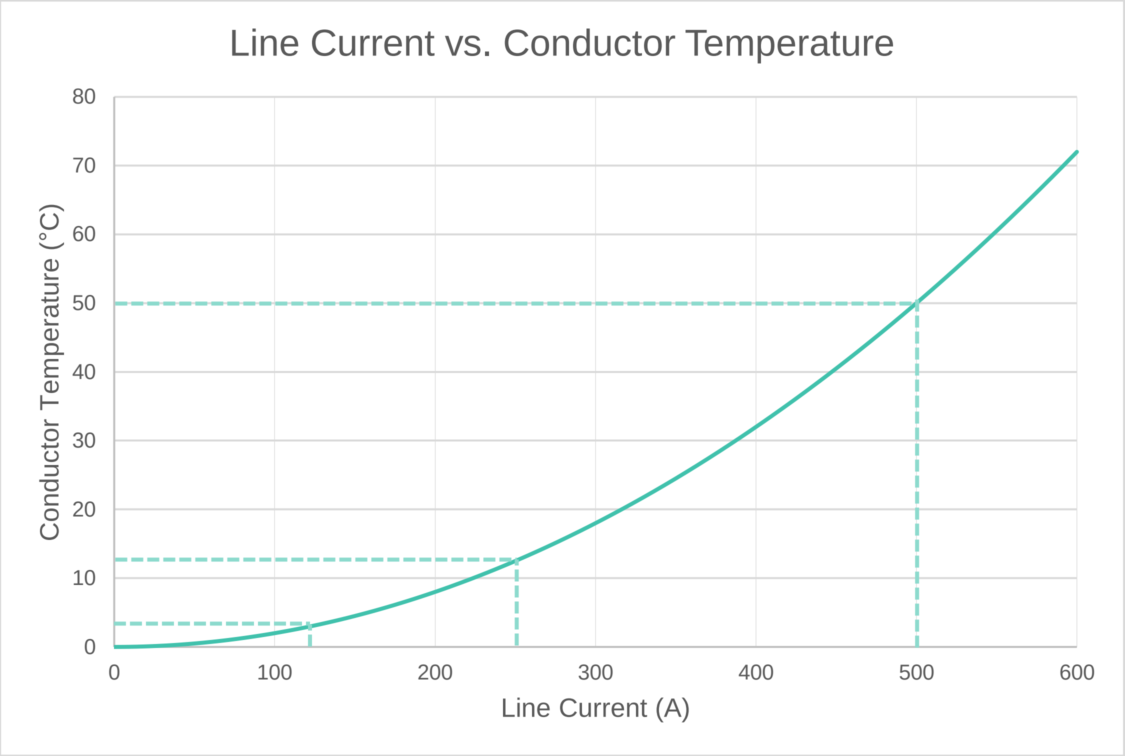


Figure 5-1 – 'Ideal' relationship between line current loading and conductor temperature

Figure 5-1 illustrates the 'ideal' relationship between line current loading and conductor temperature that could typically be observed if external factors were excluded. Of course, in distribution networks the relationship is not 'ideal', the net change in the temperature of a conductor is affected by external factors such as ambient temperature, wind speed, wind direction and solar irradiance.

It should be noted that the distribution network is designed in such a way that the circuits are normally loaded to a fraction of their design rating. Higher loading towards the thermal limits of the conductor generally occurs infrequently, mostly during abnormal network configurations such as in response to fault events on the wider network.

5.1.1. Validation of Data Captured by the Conductor Temperature Monitoring Solution

The project team witnessed the factory acceptance testing of set of Smart Navigator 2.0 sensors, a clip-on solution that contains a thermocouple for measuring the surface temperature of conductors. The sensor is secured to the conductor using a clamping mechanism. The technical datasheet for the sensor indicates that the accuracy of the conductor temperature measurement is ±5°C.

Acceptance testing was carried out in a laboratory environment to demonstrate the accuracy of the sensor by measuring of the surface temperature of a test conductor. The tests were carried out in a laboratory environment in accordance with an approved test specification. The testing platform was configured to provide step changes in load current at half-hourly intervals and hold the conductor at a steady-state temperature in order to obtain measurements. These results confirmed the accuracy of the sensor measurement to be within ±3°C of an independent thermocouple reading.

The transient behaviour of the conductor temperature was also studied, which noted maximum differences of 9°C between the thermocouple control and the Smart Navigator 2.0 readings when a large step change in load current weas applied. Due consideration should however be given to the relatively low thermal inertia of the short span of conductor and the relatively high thermal inertia of the Smart Navigator 2.0 for the laboratory test. The gradient of temperature rise would be less precipitous in a system with higher thermal mass (representative of a general overhead line installation) as this would have a balancing effect on the relative thermal inertias.

5.1.2. Configuration of the Conductor Temperature Monitoring Solution

The Smart Navigator 2.0 sensors were configured to sample the conductor temperature at 15-minute intervals. Sensors can operate in different power modes depending on the rate of power harvesting from the available line current to maintain the charge of the onboard back-up battery. The sensors were configured to operate in 'full-power' mode enabling a continuous connection to be established to the iHost monitoring platform (for the reporting of real-time data) when the line current was above approximately 25 Amps. The field trials confirmed that sensors were operating in 'full power' mode at the majority of the trial locations where they were installed on 33kV, 66kV and 132kV circuits.

The sampling rate of the conductor temperature is a user-configurable parameter, with the fastest supported rate of new samples every 5 minutes. This functionality was tested, successfully, during the main trials to confirm correct operation and reporting should more frequent sampling be required for future applications of conductor temperature monitoring.

5.1.3. Conductor Temperature Monitoring Trial Locations

Trial locations were identified on 33kV, 66kV and 132kV networks to carry out conductor temperature monitoring. The 33kV primary network at Shrewsbury was selected as a candidate network since it is operated in a ring configuration, where parallel circuits are often broken for routine maintenance. This presented an opportunity to potentially observe higher line current magnitudes through circuits. Similarly, the Hereford 66kV network was selected due to presence of intermittent wind generation which was anticipated to cause significant changes in line current magnitude through circuits which were observed to be operating towards the limits of rated capacity. The 132kV K-Line in the South-West licence area was identified as a thermally constrained circuit, in accordance with published constraint maps, an extract is presented in **Figure 5-2**. Smart Navigator 2.0 sensors were installed at intervals of several spans on each side of the double circuit (red) between Alverdiscott and Northmoor Solar Park, the aqua shading indicates a thermal constraint.

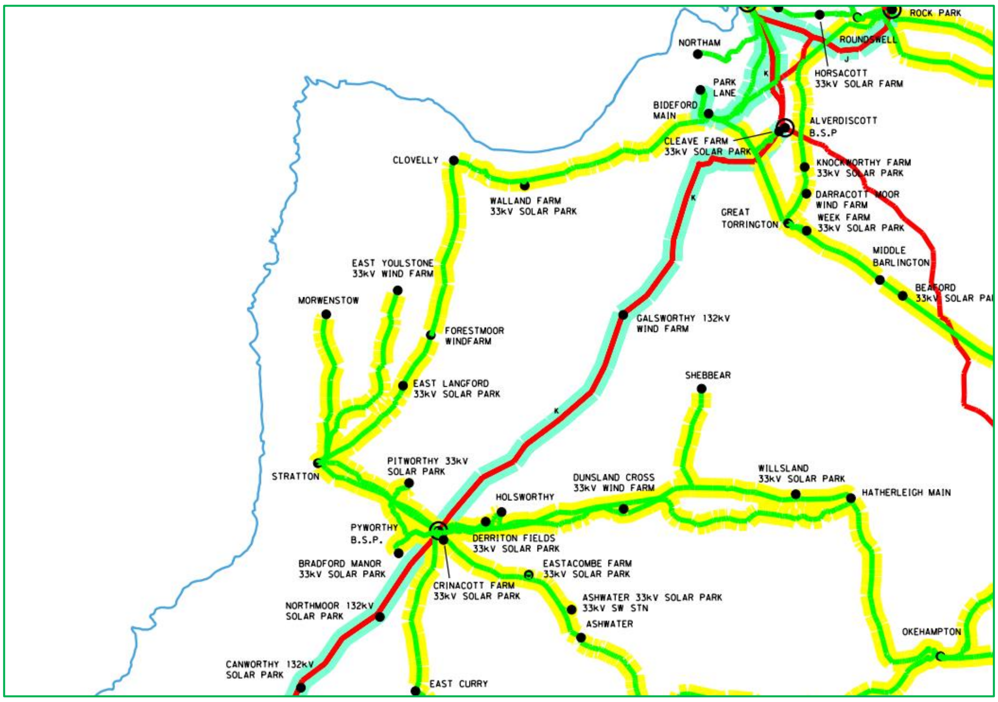


Figure 5-2 – Extract from WPD South-West Licence Area - Constraint Map

CIGRE Technical Brochure 601 summarises that convective cooling is a major issue for line ratings, particularly when the conductors are operating at high temperatures. The exposure of the conductor to convective cooling forces, such as wind speed and wind direction can be highly influenced by the local topography. **Figure 5-3** presents the elevation profile of the trial locations where conductor temperature monitoring was along the 132kV K-Line double circuit.

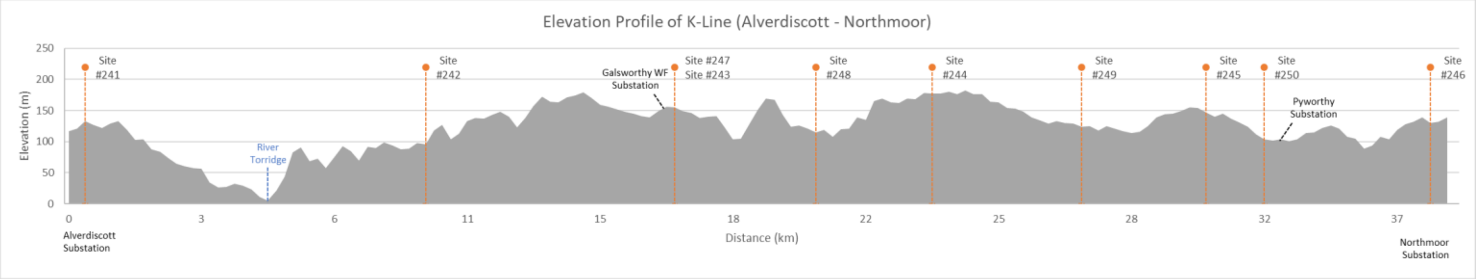


Figure 5-3 – Elevation Profile of the 132kV K-Line Circuit

Table 5-1 provides a summary of the conductor types that were studied during the field trials, where conductor temperature monitoring sensors were installed. Note that the table excludes conductor temperature monitoring locations where covered conductors were present and 11kV trial locations, which are less prone to capacity issues resulting from the thermal limits of conductors. Standard Technique SD8A/3 documents the current ratings for conductors with design temperatures of 50°C, 65°C and 75°C. Ratings for alternative design temperatures, including 70°C, were made available by a request to the Policy department.

Table 5-1: Summary of Conductor Types at Trial Locations

Area / Conductor Type	Conductor Design Temperature (°C)	Trial Locations
Lydney (Gloucester) (33kV)		**4**
175 mm2 Lynx (30/2.79mm + 7/2.79mm) ACSR	50	4
Meaford (Stoke) (33kV)		**11**
100 mm2 Dog (6/4.72mm + 7/1.57mm) ACSR	50	5
175 mm2 Lynx (30/2.79mm + 7/2.79mm) ACSR	50	3
200 mm2 Poplar (37/2.87mm) AAAC AL3	50	3
Shrewsbury (Telford) (33kV)		**10**
175 mm2 Lynx (30/2.79mm + 7/2.79mm) ACSR	50	4
200 mm2 Poplar (37/2.87mm) AAAC AL3	50	4
400 mm2 Centipede (37/3.78mm) AAC AL1	50	2
Hereford (66kV)		**10**
100 mm2 Dog (6/4.72mm + 7/1.57mm) ACSR	50	6
175 mm2 Lynx (30/2.79mm + 7/2.79mm) ACSR	50	1
200 mm2 Poplar (37/2.87mm) AAAC AL3	50	1
70 mm2 (7/3.55mm) HDC	50	2
South West (K-Line) (132kV)		**10**
175 mm2 Lynx (30/2.79mm + 7/2.79mm) ACSR	70	10
Grand Total		**45**

5.1.4. Conductor Temperature Monitoring Data

The conductor temperature data is stored locally in the Smart Navigator 2.0 and pushed to the iHost monitoring platform periodically (or instantaneously if operating in ‘full-power’ mode). The iHost platform offers interactive trending of data for post-event analysis.

Figure 5-4 presents an example of a chart generated in iHost which displays a typical daily summer profile of phase conductor temperature (shaded blue background) which was captured on 1st July 2021 at trial site #106 on the Bayston Hill – Weir Hill/Longwood 33kV circuit, near to Shrewsbury. Each phase temperature is plotted, with a maximum variation in temperature between phases of 1.8°C observed at 15:15. The maximum conductor temperature observed was 23.7°C, and the minimum observed was 9.1°C. The average line current is plotted in orange for reference, the magnitude varies between 109A and 27A throughout the day.

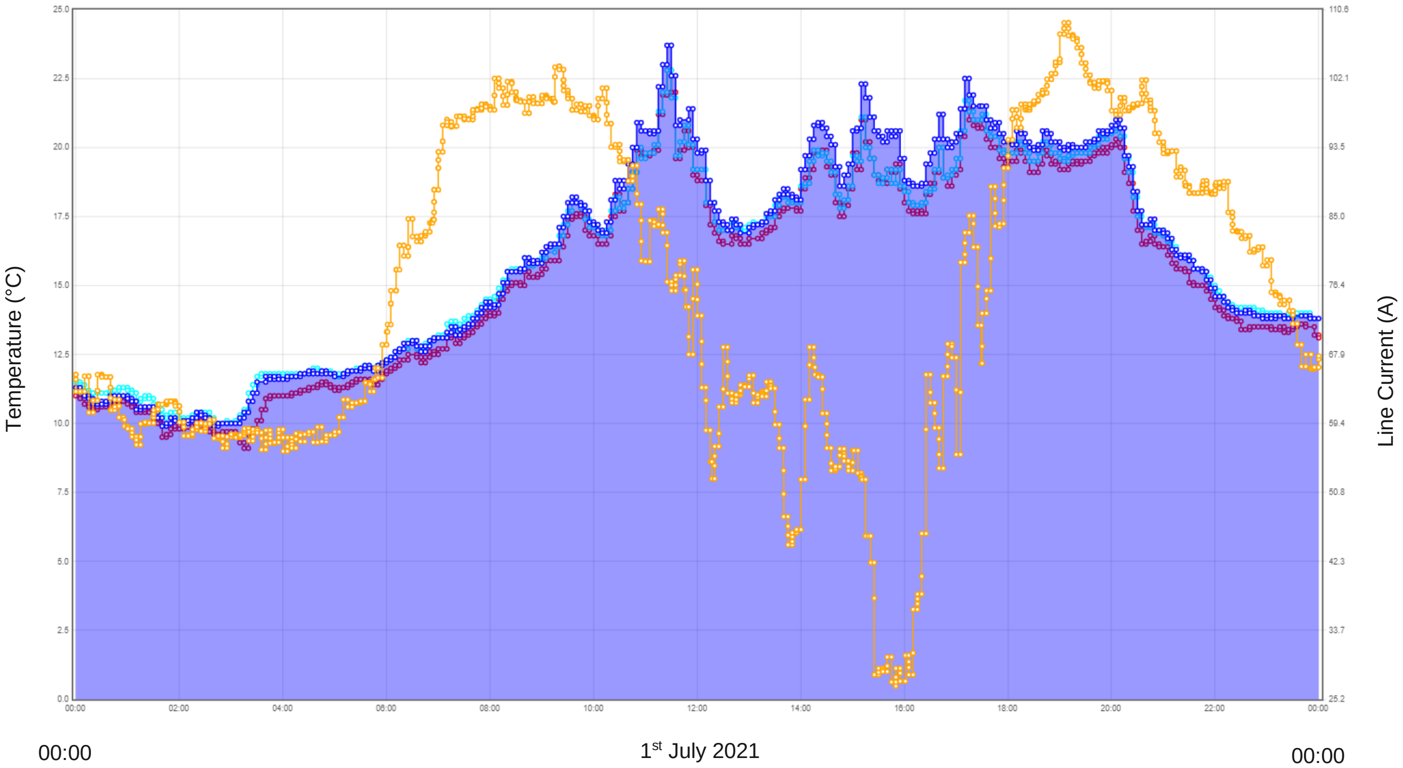


Figure 5-4 – Phase Conductor Temperatures - Site #106 (Bayston Hill – Weir Hill 33kV circuit, Shrewsbury)

The conductor temperature monitoring data recorded by the Smart Navigator 2.0 equipment through the main trials has been stored in our West Midlands iHost server.

5.2. Conductor Temperature Analysis

The main field trials have completed and the conductor temperature data has been captured from trial locations along 11kV, 33kV, 66kV and 132kV circuits. The analysis in this report is focused towards the higher distribution voltages (33kV, 66kV and 132kV) where visibility of conductor temperature could offer most benefit in terms of capacity uplift in OHL circuits. As a general rule, lower distribution voltages (LV, 6.6kV and 11kV) suffer from voltage constraints and higher distribution voltages suffer capacity constraints, this report therefore focuses on the latter.

This section presents analysis of conductor temperature data captured during the live operational field trials. Case studies are presented which present the variation in conductor temperature in response to steady state conductor loading, step changes in conductor loading and, variation in conductor loading between two circuits on opposite sides of a tower.

5.2.1. Temperature of the Conductor in Response to Normal Loading Conditions

Conductor temperature data captured by the solution at each of the trial locations was analysed to observe the seasonal variations in temperature over a period of a year, and understand whether a relationship between the line current and temperature could be observed under normal loading conditions. Normal loading conditions are where the conductor is loaded to a fraction of the seasonal pre-fault rating, normally when the network is operating in a normal running arrangement. Spare capacity is reserved from contingency, such as the transfer of load from the loss of an adjacent circuit.

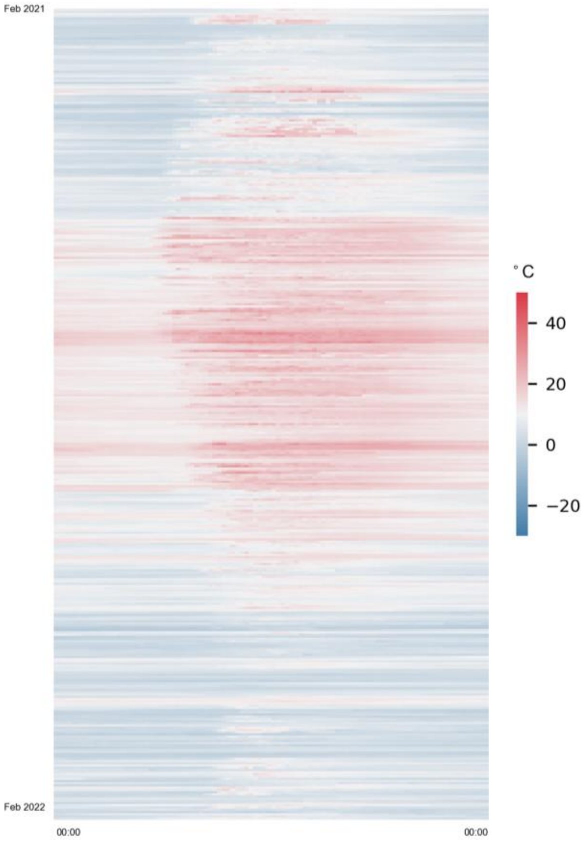
We can compare two trial sites on different 33kV networks where the daily demand through the year remained relatively consistent (i.e. no major network reconfiguration resulting in higher loading of the conductors). The conductors at both locations were comprised of type 200 mm^2 Poplar AAAC.

Figure 5-5 presents the seasonal (and daily) variation in conductor temperature at trial site #201 on the Hookgate – Cotes Heath 33kV circuit, near to Meaford. The data indicates that the circuit was loaded to 23% of the seasonal pre-fault rating on average through the year (118 Amps). The maximum recorded conductor temperature was 33.4°C and the minimum was -3.8°C.

Figure 5-6 presents the seasonal (and daily) variation in conductor temperature at trial site #265 on the Weir Hill – Berrington 33kV circuit, near to Shrewsbury. The data indicates that the circuit was loaded to 4% of the seasonal pre-fault rating on average through the year (20 Amps). The maximum recorded conductor temperature was 33.4°C and the minimum was -3.8°C.

Data from further trial sites was analysed and reviewed for consistency, there was no noticeable change in conductor temperature in response to normal loading of the conductors.

Most conductors, where conductor temperature monitoring had been installed, were found to be loaded substantially below the seasonal static rating for the majority of the year. During these periods the temperature of the conductor was observed to loosely follow the ambient temperature at trial locations. This suggests that the line-current did not contribute to any observable, significant heating of the conductor.



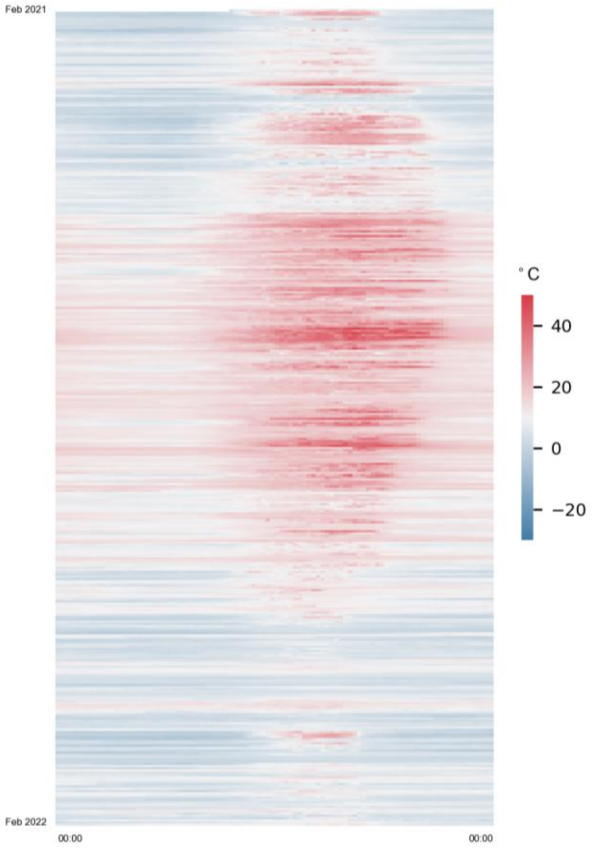


Figure 5-5 – Conductor temperature (Site #201)

Figure 5-6 – Conductor temperature (Site #265)

5.2.2. Temperature of the Conductor in Response to a Step Change Loading Conditions

Figure 5-7 presents a time-series plot with a notable step change in line current (12:20 on 22/02/2021) recorded at trial site #106 on the Bayston Hill – Weir Hill/Longwood 33kV circuit. The average 24-hour load current prior to the step change is 106A, and following the step change the average 24-hour load current is 213A. The average 24-hour recorded temperature during the period prior to the step change in line current is 8.4°C. The average recorded conductor temperature during the 24-hour period of increased line current the average conductor temperature was 8.8°C, an increase of 0.4°C.

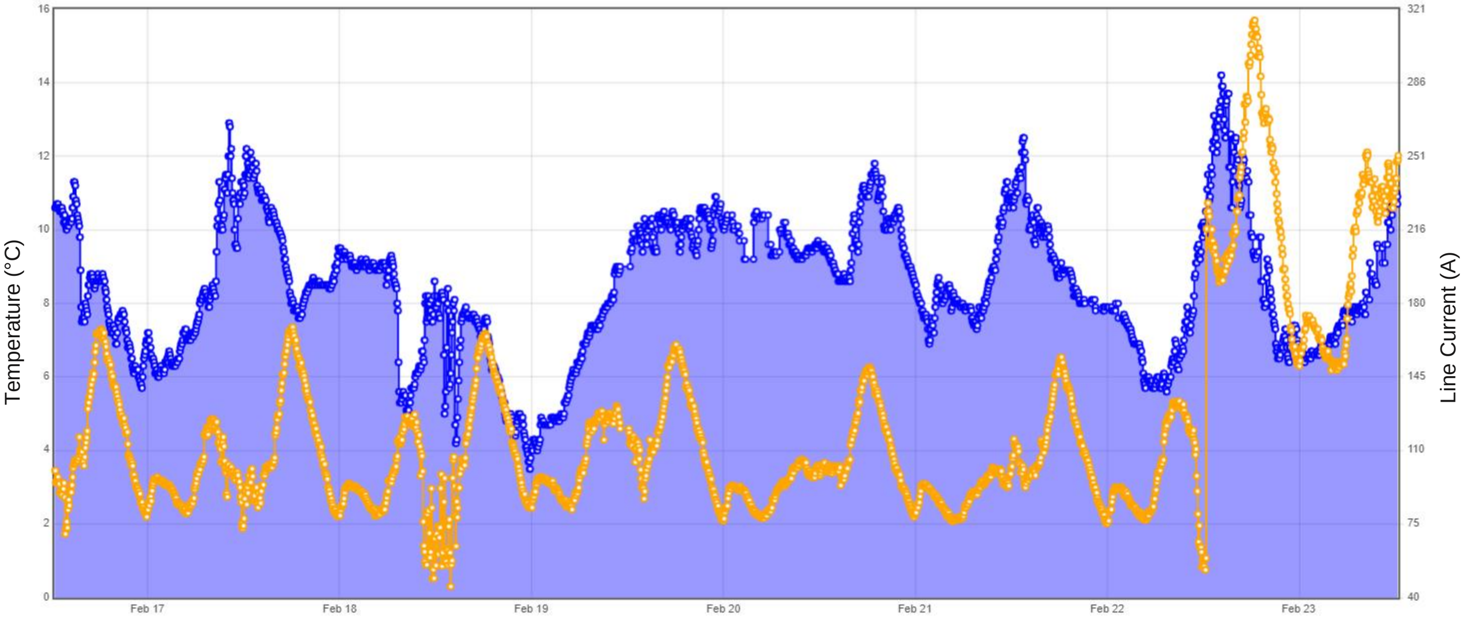


Figure 5-7 – Conductor Temperature Response to Step Change in Line Current

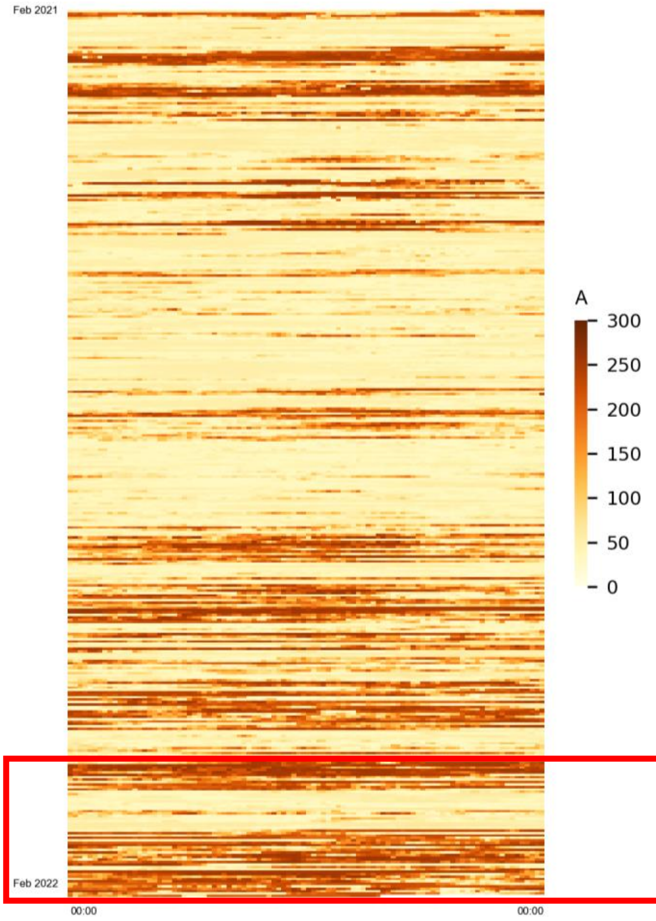
High-level analysis indicates that the doubling of line current within a normal load pattern has a minimal effect on the operating temperature of the conductor, however a recording of ambient weather conditions would be required to assess the true relationship between line current and recorded conductor temperature over a similar period. It should be noted that the conductor type is a 175mm^2 Lynx ACSR conductor with a pre-fault seasonal static rating of 492A, therefore the step change in line current of 107A was minor relative to the seasonal static current rating.

5.2.3. Temperature of the Conductor in Response to High Loading Conditions

The data across all of the trial site locations was analysed to identify trial sites with the greatest step changes in current loading. Typically a step change in current towards the pre-fault rating indicates a transfer of load from an adjacent circuit under a contingency scenario. During the main trials there were no such contingency scenarios recorded at the trial locations where the step change in current approached 80% of the pre-fault rating, where we might expect to observe a response in the temperature of the conductor.

However, high loading above 80% of pre-fault rating was observed at trial site #235 on the Knighton – Presteigne 66kV circuit, near to Hereford. Power export from the Garreg Lwyd Hill Wind Farm (34MW) is the dominant contributor to power flowing through this circuit, the line current magnitude through the circuit was observed to regularly exceed 80% of the pre-fault rating.

Figure 5-8 illustrates the seasonal (and daily) variation in the line current magnitude passing through the conductor, this chart can be compared to the seasonal (and daily) variation in temperature of the conductor, illustrated in **Figure 5-9**. A direct comparison of the charts suggests that there are some minor, but significant, correlations between the data. An attempt has been made to establish a relationship between the datasets in the highlighted area of the charts where step changes in magnitude of line current are most prominent. A 2-day moving average was applied to the time-series data to more carefully examine the differences between the periods of low loading and high loading, this data is presented in **Figure 5-10**. There is evidence of a loose correlation between the conductor temperature and the magnitude of the line current flowing through the conductor.



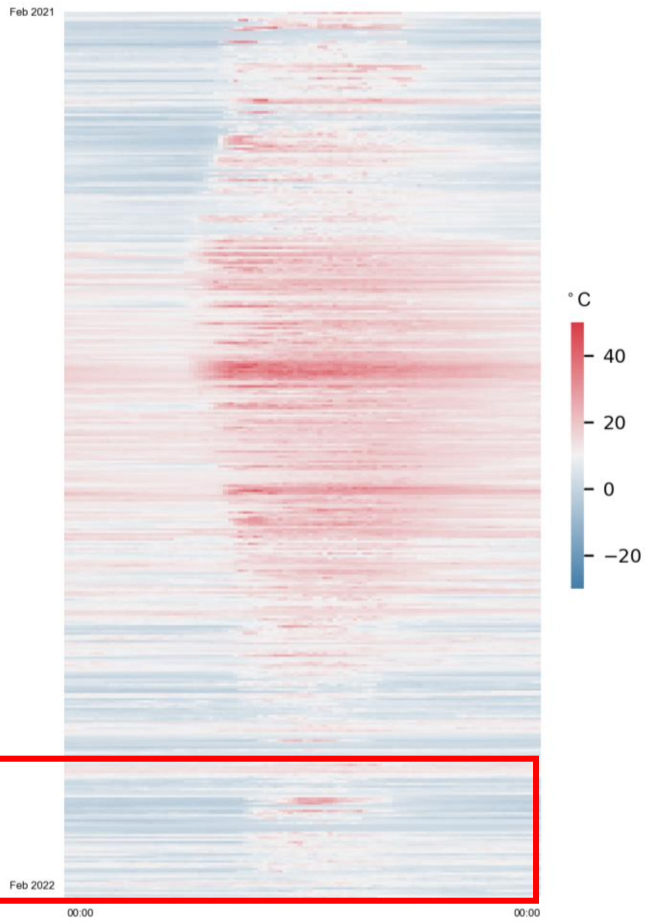


Figure 5-8 – Line current (Site #235)

Figure 5-9 – Conductor temperature (Site #235)

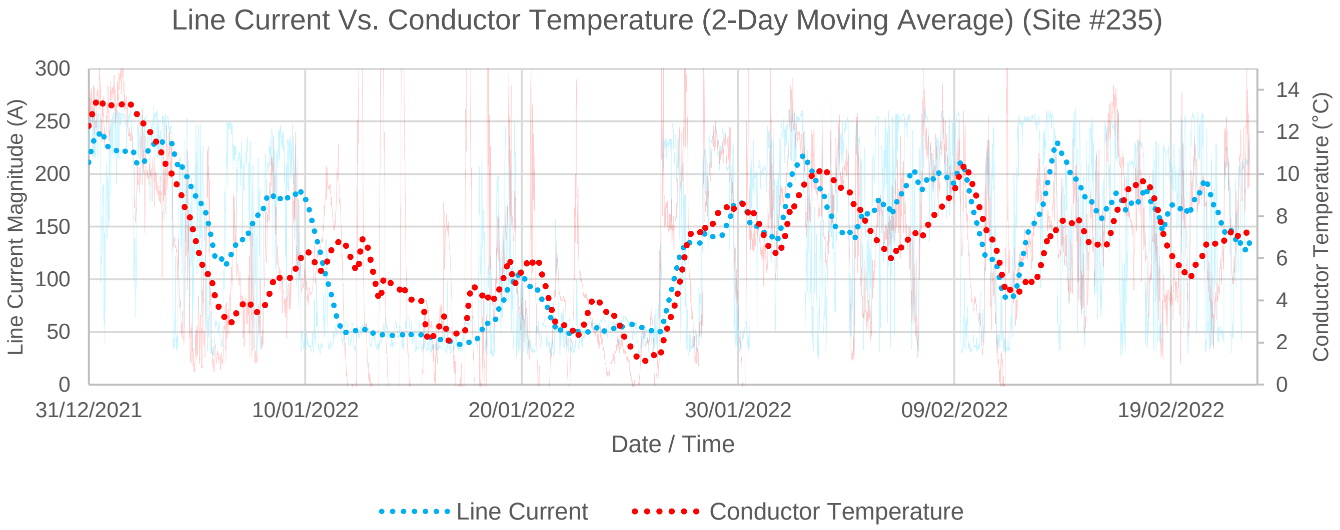


Figure 5-10 – Line current vs. conductor temperature (2-day moving average, raw data in shadow)

In this case study, the line current magnitude is approximately proportional to the wind speed, it should be noted that higher wind speeds normally result in higher convective cooling of the overhead conductors.

5.3. Demonstration of a Short-term Post-fault Rating

Prior to the project, the operating temperature of OHLs was not monitored directly, making it difficult to determine the available thermal capacity that can be utilised when during the operational response to the loss of a ‘worst circuit’ on the network. The short term rating of an overhead line exploits the thermal capacity of the material itself, with the rating not being dependent on any cooling conditions (such as wind) being available. A simple temperature measurement is all that is needed to provide a rating to cover short-term (around 5-minutes) events.

This section describes the methodology and presents the findings of a short-term post-fault rating calculation based on real-time conductor temperature measurements captured by sensors installed on OHL circuits.

5.3.1. Governance of Overhead Line Current Ratings for Distribution Networks

Overhead line current ratings were originally calculated using deterministic conditions, assuming that a conductor was carrying 100% load, and was subjected to a given set of conservative weather conditions, applicable across the UK. ENA Engineering Recommendation (ER) P27 Issue 1 introduced weather risk probability where conditions influencing the conductor’s operating temperature may be exceeded for a period of time (‘exceedance’), but assumed that the rated load applied remained constant at, or around 100%.

ER P27 Issue 2[1] was released in February 2020 with major revisions to Issue 1 to reflect learnings from our Innovation Project “Improved Statistical Ratings for DNO Overhead Lines”. The work carried out under the innovation project confirmed the statistical relationship between an overhead line conductor deterministic rating and the associated risk of exceeding its design temperature under full rated load (the ‘exceedance’). The statistical relationship has been used to derive probabilistic thermal ratings for an overhead line where the conductor design temperature will be exceeded as a percentage of time averaged over a year. The seasonal boundaries for application of the ratings were also revised to reflect more accurate variation in modern weather conditions in the UK. Full details of the risk model are included in ER P27 Issue 2.

The recommendations from ER P27 Issue 2 have been incorporated into a revision of our Standard Technique SD8A/3[2], and overhead line ratings for application in our licence areas have been derived using the risk model. SD8A/3 provides; sustained load per-fault ratings (based on 0.001% risk of exceedance), variable load pre-fault ratings (based on 3% risk of exceedance) and post-fault ratings (based on 9% risk of exceedance) for a range of common conductor types installed across our networks.

5.3.2. Derivation of a Short-term Post-fault Rating from real-time Conductor Temperature Data

CIGRE Working Group B2.43 published a Technical Brochure 601 (TB 601) “Guide for Thermal Rating Calculations of Overhead Lines” in December 2014. TB 601 is referenced in ENA ER P27 with due consideration given to the thermal rating calculation model and an associated software program.

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[1] Energy Networks Association (ENA) Engineering Recommendation P27 Issue 2 - Current rating guide for high voltage overhead lines operating in the UK distribution system - 2020

[2] WPD – Standard Technique: SD8A/3 – Relating to Revision on Overhead Line Ratings – February 2020

TB 601 offers a model for calculating the thermal rating of OHLs. It provides typical input parameters used in the thermal model, including wind speed, wind direction, ambient temperature, solar radiation, conductor resistance, etc. TB 601 Annex E.3. details an example of a temperature tracking calculation, it describes a method to continuously calculate the conductor temperature, considering the weather and current data are provided in 10-minute time intervals. The method derives an estimated final conductor temperature based on the starting conditions and a given set of weather conditions and fixed current loading for the 10-minute period.

The OHL Power Pointer temperature-based post-fault rating is an adaptation of the TB 601 temperature tracking calculation. It has been implemented on the basis that the starting temperature of the conductor is known, the final temperature of the conductor is known (design temperature rating), and the current carrying capacity is to be determined from the capacity of the conductor to heat to the design temperature over the 10-minute period, assuming adiabatic conditions. The implemented method is given in Document D_003163 (Post-Fault Ratings Algorithm Technical Specification).

A prototype of the solution for two 10-minute intervals was prepared in spreadsheet format, using pseudo parameters from TB 601, and subsequently verified using a python script to demonstrate the performance offline using a dataset captured from the Smart Navigator 2.0.

5.3.3. Implementation of Temperature-based Post-Fault Rating in iHost

The iHost monitoring platform extends the functionality of remote field devices using logic points. Logic points are type of virtual data point which calculates its value using a logic expression. Logic expressions are a method of logically or mathematically gathering data from RTUs into a single datapoint. Under the OHL Power Pointer project, a series of special functions for logic expressions were developed to calculate a temperature-based post-fault rating using the temperature measurements from the phase conductors.

The special function considers the maximum of the last recorded phase conductor temperature, the conductor type, the maximum design temperature of the conductor, and the interval that the post-fault rating should be valid before new measurements become available and the rating recalculated. The algorithm embedded in the special function draws on the specific heat capacity and the mass (per unit length) of the conductor materials, and the AC resistance of the conductor at different operating temperatures. Conductor specific parameters are captured in a conductor library along with static seasonal ratings which have been transformed from our SD8A/3 document into a data file for interpretation by iHost. This enables static ratings to be trended alongside the real-time temperature-based post-fault rating for a direct comparison of the performance of the solution. The library is extendable to consider many different DSO policies for OHL ratings, the given in ENA ER P27 Issue 2 are included for default application.

5.3.4. Case Study – South-West 132kV - K-Line Circuit

Figure 5-11 presents the real-time short-term post-fault rating for a 175mm^2 Lynx aluminium conductor steel-reinforced (ACSR) conductor (design temperature rating of 70°C) monitored at trial site #247, along the 132kV K-Line circuit. The data comprises the period from 7th March 2021 to 8th March 2022, the pre-fault seasonal static rating (extracted from SD8A/3) is presented for comparison. The steps changes in the pre-fault rating are in accordance with the seasonal boundaries in ENA ER P27. The orange trend presents the line current magnitude recorded at the trial location.

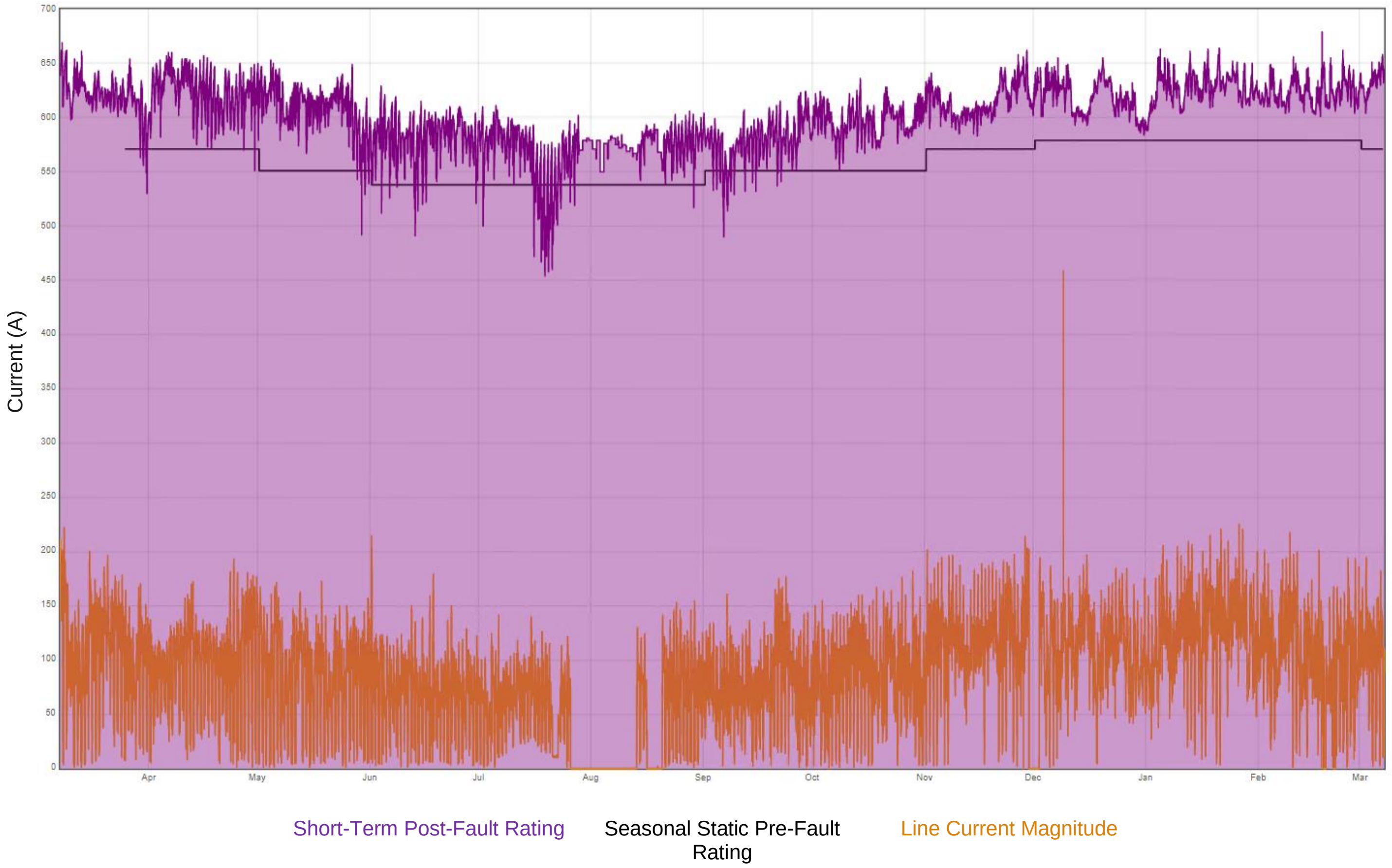

Figure 5-11 – Short-Term Post-Fault Rating – 175mm^2 Lynx ACSR Conductor

The data demonstrates that the short-term post-fault rating was greater than (or equal to) the pre-fault seasonal static rating for 97.7% of the period. On 4th May 2021 at 18:30 the short-term post-fault rating offered an additional 102A (18.5%) headroom capacity in the circuit, above the seasonal static pre-fault rating of 551A. The average increase in headroom capacity of the circuit across the year was 45A (8.1%) above the pre-fault seasonal static rating.

5.3.5. Case Study – Hereford 66kV - Kington to Lower Chadnor Tee

Figure 5-12 presents the real-time short-term post-fault rating for a 70mm^2 Copper conductor (design temperature rating of 50°C) monitored at trial site #238. The data comprises the period from 7th March 2021 to 8th March 2022, the pre-fault seasonal static rating (detailed in Standard Technique SD8A/3) is presented for comparison. The steps changes in the pre-fault rating are in accordance with the seasonal boundaries in ENA ER P27. The orange trend presents the line current magnitude recorded at the trial location.

Period where conductor temperature monitoring solution was intelligently operating in a power saving mode (due to low line current) with routine communications to iHost once per day (instead of real-time)

Figure 5-12 – Short-Term Post-Fault Rating – 70mm^2 Copper Conductor

The data shows the short-term post-fault rating was lower than the pre-fault seasonal static rating for duration of the period. The average reduction in capacity was 64.1A (21.3%) when compared to the seasonal static pre-fault rating.

The implication is that the heat capacity of a copper conductor is insufficient on its own to provide the necessary rating, a cooling contribution will always be required. It should also be noted that 70mm^2 is a relatively small conductor in use on 66kV networks. Further offline modelling was undertaken to examine the short-term post-fault rating in larger copper conductors. Similarly, average reductions in short-term post-fault capacity were estimated to be 10-12% for 100mm^2 copper conductors, and 5-7% for 125mm^2 copper conductors.

The marked red area of the chart presents a period where there was no load current flowing through the circuit. The device discreetly moved into a power saving mode to preserve the charge of the back-up battery, and the frequency of communication of sampled data reduced from real-time to once per day.

5.3.6. Case Study – Shrewsbury 33kV – Shrewsbury BSP to Weir Hill 2

Figure 5-13 presents the real-time short-term post-fault rating for a 400mm^2 All-Aluminium (AAC) conductor (design temperature rating of 50°C) monitored at trial site #108. The data comprises the period from 7th March 2021 to 8th March 2022, the seasonal static pre-fault rating (extracted from SD8A/3) is presented for comparison. The steps changes in the pre-fault rating are in accordance with the seasonal boundaries given in ENA ER P27. The orange trend presents the line current magnitude recorded at the trial location.

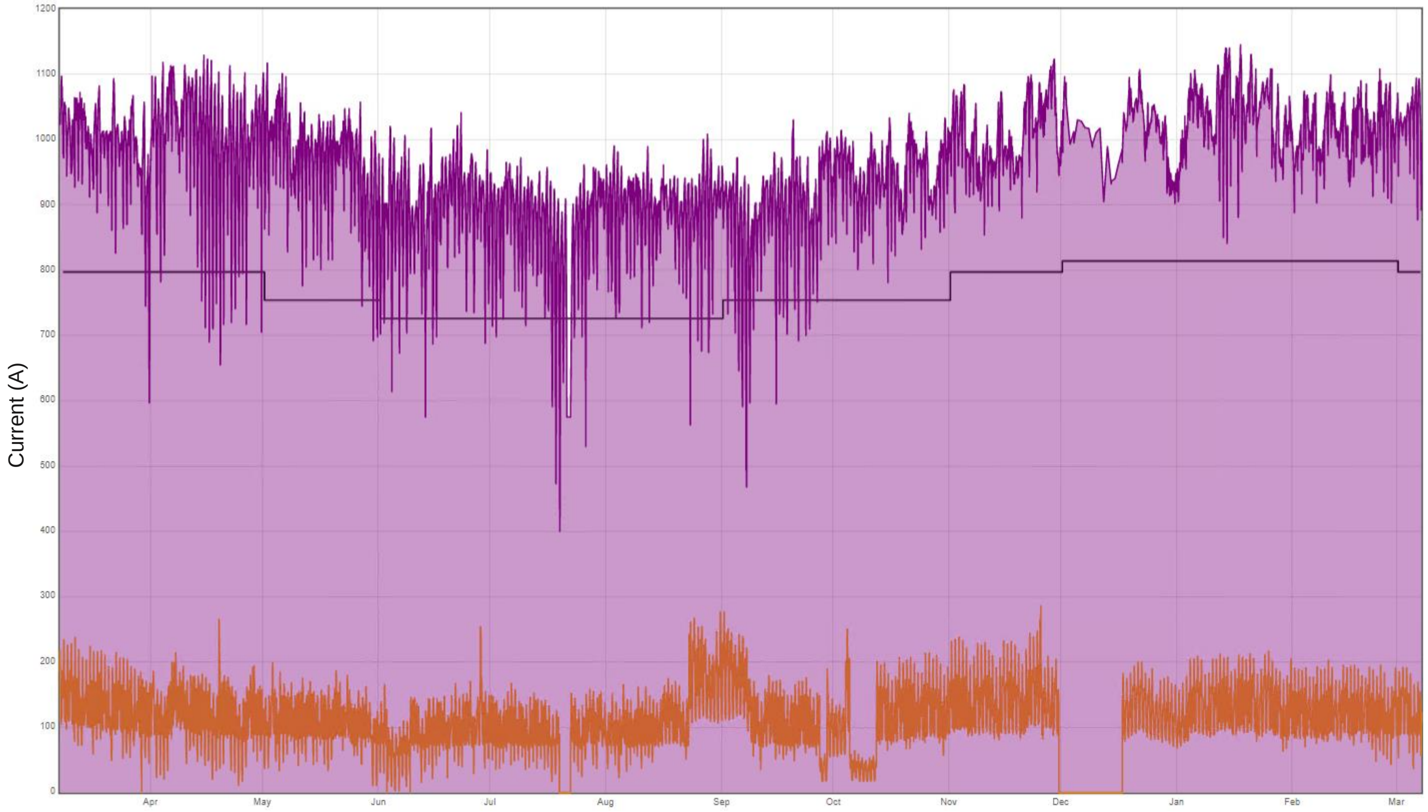

Figure 5-13 – Short-Term Post-Fault Rating – 400mm^2 AAC AL1 Conductor

The data demonstrates that the short-term post-fault rating was greater than (or equal to) the seasonal static pre-fault rating for 98.1% of the period. On 2nd May 2021 at 07:00 the short-term post-fault rating offered an additional 363A (48.1%) headroom capacity in the circuit, above the seasonal static pre-fault rating of 754A. The average increase in headroom capacity of the circuit across the year was 191A (24.8%) above the seasonal static pre-fault rating.

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 has demonstrated the application of short-term post-fault ratings based on real-time monitoring of the conductor temperature of 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 potential solution for the safe uplift in short-term post-fault capacity of conductors in high-voltage distribution networks.

The performance of the conductor temperature monitoring solution has been validated successfully during factory acceptance testing at the manufacturer's laboratory facilities, with accuracy demonstrated to within ±3°C of an independent thermocouple reading over a series of tests designed to mimic step changes in load through a sample of OHL conductor.

The monitoring solution supports real-time reporting of conductor temperature measurements (boost-mode) where the magnitude of line current flowing through the conductor provides sufficient power harvesting for the device to maintain a continuous GSM connection to the iHost platform. During the main field trials, the solution was found to operate in boost-mode on circuits with 25A minimum average line current, approximately 43 of the 45 trial locations on higher voltage circuits. The availability of real-time measurements from devices operating in continuously in boost-mode was observed to be 98.6%. The iHost platform recalculated (and made available) an updated short-term post-fault rating for the circuit (on average) within 4 seconds of receipt of new conductor temperature data.

The seasonal variation of the surface temperature of various conductor types has been illustrated in case studies. The maximum conductor temperature recorded (routinely) during the main field trials was 49.8°C which occurred on 19th July 2021 at 16:15 along the 33kV OHL circuit supplying Berrington primary substation. The temperature was close to the design temperature rating of the conductor.

A technical issue was observed in the devices during the test trials which caused infrequent anomalous measurements of -273.2°C (absolute zero) to be recorded. The issue investigated by the manufacturer and the cause was identified as a flaw in the production process. The production process has since been amended and the issue rectified by the manufacturer.

A real-time method for calculating a short-term '10-minute' post-fault rating based on the surface temperature of the conductor has been implemented and a library of common conductor types has been prepared which can be applied across the distribution network.

A short-term post-fault rating would require a new conductor temperature measurement to be reported at the beginning of each new '10-minute' period. A '10-minute' period is preferred by the control room since this provides a sufficient 'short-term' window to switch and divert load around the system to reduce the load transferred to conductors during the 'post-fault' period. The devices were configured (by default) to sample conductor temperature measurements once every 15 minutes. A configuration update was released over-the-air from iHost to a device installed on the Weir Hill – Bayston Hill 33kV circuit to increase the frequency of sampling to once every 5 minutes (the maximum supported by the device). The reconfiguration was successful and the data recorded in iHost confirmed that the solution is able to deliver a new short-term post-fault rating for an OHL circuit at up to 5-minute intervals.

An assessment of the application of a short-term post-fault rating algorithm was undertaken with results presented for ACSR, AAC and copper conductors. The findings from the main trials suggest that significant headroom capacity in OHL systems could be released for short periods when applied to ACSR and AAC conductors, but there was no observable gain when applied to copper conductors.

In accordance with the objectives and the success criteria of the method, short-term post-fault ratings have been successfully determined for each monitoring location on the higher voltage distribution network and the application of a real-time short-term post-fault rating has been demonstrated and made available to the control room.

7. Potential for New Learning

The conductor temperature monitoring solution has been installed and trialled and a short-term post-fault rating, derived from real-time conductor temperature measurements, has been demonstrated. Significant learning has been obtained through the project.

With regards to conductor temperature monitoring:

1. The conductor temperature monitoring solution has proven to be accurate and consistent in capturing the operating temperature of multiple standard conductor types used across our high-voltage distribution networks.
2. There was no noticeable increase in conductor temperature where the circuit was operating under normal loading conditions, typically 25% of the pre-fault rating.
3. There appeared to be a small, but noticeable, increase in conductor temperature where operating under high loading conditions, typically above 80% of pre-fault.
4. There was minimal variation between conductor temperatures recorded across the individual phase conductors of overhead line circuits, even where loading was observed to routinely exceed 80% of the pre-fault rating.
5. The availability of real-time conductor measurements from devices installed on 33kV circuits was evaluated, with 98.6% uptime demonstrated for the month of February 2022.

With regards to the short-term post-fault rating solution:

1. The potential uplift in (short-term) post-fault capacity of AAC and ACSR circuits has been demonstrated in a real-time environment using conductor temperature monitoring equipment during the main field trials.
2. The heat capacity of a copper conductor appears to be insufficient on its own to provide the necessary short-term post-fault rating – a cooling contribution will always be required.
3. The conductor temperature monitoring solution is not suitable for use with covered conductors (typically BLX). However the other functions of the solution (directional fault passage indication, power flow direction detection, voltage presence sensing, etc.) performed satisfactorily when installed on covered conductors.
4. When an overhead line is taken out of service (e.g. for maintenance), or consumer load is disconnected or low, the devices will often fall-back into a power saving mode to retain sufficient charge of the battery. This interrupts the real-time reporting of conductor temperature data. This was observed on a minority of circuits (2 out of 45 trial sites on the higher voltage distribution network), furthermore the average load current should be routinely available from substation metering equipment for consideration during the site selection procedure.

The following opportunities for new learning could be considered:

1. Consideration should be given to the installation of the conductor temperature monitoring solution on circuits loaded towards the maximum capacity to study the variation in conductor temperature and establish a direct comparison with the design rating of the conductor, particularly where circuits may be vulnerable to high-loading during programmes of major works.
2. Consideration was given to the common conductor types which were found to be most prevalent across the higher voltage distribution networks during the selection process for the field trial locations. The solution could be deployed to monitor other conductor types which were not studied during the field trials, this would enable full quantification of the potential benefits across the network.

8. Conclusions of the Method

Distribution networks are evolving to accommodate more utility-scale generation connections. Under present rules, new connectees to the distribution system must pay for the costs of sole use assets and make a contribution to the costs of wider reinforcement, this is considered a ‘shallow-ish’ charge where the contribution extends to the partial costs of reinforcement at one voltage higher than the connection voltage.

There is a finite limit to the available capacity across the higher voltage distribution circuits, and several regions across the distribution licence areas are already operating towards the limits of capacity. In order to accommodate further connections to the distribution network, without the significant costs of reinforcement, the distribution system operator (DSO) currently offers constrained connections to new connectees. However, this can result in a significant volume of lost-generation throughout the year, impacting the business case, and deterring often ‘clean’ generator from connecting to the distribution system.

Active Network Management (ANM) schemes are currently active in areas of our network where headroom capacity is limited. ANM schemes interface with distribution control systems to monitor the limits of the network and allocate maximum amount of capacity to customers in the area. The application of a short-term post-fault rating in ANM schemes offers the potential to provide an immediate ‘boost’ to post-fault network capacity and deliver savings our potential future costs of network reinforcement.

ANM schemes are currently active in the following locations, with several further schemes planned:

- Pembroke (South Wales)
- Swansea North (South Wales)
- Alverdiscott Indian Queens (South West)
- Staythorpe (East Midlands)

ANM schemes send signals to generators to constrain or relieve constraints on power export, depending on the available capacity of the network. According to a curtailment report[3] for the South West region a new 10MW wind farm connection can expect to have power export curtailed by over 60% (of projected output) over a given 12-month period, and present levels of curtailment are likely to increase as the network becomes more heavily congested.

However, In 2023 the regulatory landscape is expected to change. Ofgem’s minded-to position sets out that the voltage rule is amended such that new connectees only contribute to reinforcement at the same voltage level as their own connection. Under Ofgem’s minded-to position, we will become the bearer of costs for such reinforcement at 132kV in these cases, to ensure available capacity for 33kV generation connections. It is therefore in our interest to investigate alternative more innovative methods of introducing capacity at higher distribution voltages to accommodate such connections. The short-term post-fault rating solution provides an immediate retrofit solution for the safe release of capacity along 33kV, 66kV and 132kV OHL circuits, should we wish to adopt a DSO style of

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[3] Curtailment Assessment Report: Alverdiscott ANM system (from WPD’s website)

solution as an alternative to a (potentially) much larger investment in reconductoring and additional circuits to introduce new capacity across the system.

During this project field trials have been carried out at 120 locations on 11kV, 33kV, 66kV and 132kV networks to monitor the operating temperatures of various conductor types commonly used in UK distribution systems. Furthermore, the application of short-term post-fault ratings has been demonstrated at each trial location on the 33kV, 66kV and 132kV network, where thermal constraints are most prevalent.

This project has demonstrated that it is possible to fully exploit the available thermal capacity of OHL distribution circuits using conductor temperature monitoring measurements to derive a ‘10 minute’ short-term post-fault rating, with the potential for increase in headroom capacity in higher-voltage OHL circuits by up to 18.5% and 48.1% where ACSR and AAC are utilised, respectively.

By improving the overall capacity of the distribution network we can look to accommodate more clean embedded generation connections, which would lead to a reduction in the overall carbon intensity of energy delivered to customers and thereby help to deliver and achieve ‘decarbonisation and Net Zero’ – a priority area in our Innovation Strategy.

Glossary

Abbreviation	Term
AAC	All-aluminium Conductor
ACSR	Aluminium Conductor Steel-reinforced cable
APN	Access Point Name
ANM	Active network Management
CI	Customer Interruptions
CML	Customer Minutes Lost
DMS	Distribution 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
WPD	Western Power Distribution

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