Project FALCON

Dynamic Asset Rating Cables

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FALCON

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Executive Summary

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), and the introduction of new demand technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas.

WPD's Project FALCON has examined a range of innovative alternatives to conventional reinforcement that might be used to mitigate the impact of such energy usage. This was undertaken firstly through physically trialling four engineering and two commercial techniques. Secondly, innovative alternatives were examined through building and operating a software tool. This tool: models the real network under a range of energy use scenarios out to 2050; identifies network constraints that arise over time; employ the studied techniques to mitigate constraints; and assesses impact and benefit.

This report is one of a series describing the engineering technique trials, and focuses on dynamic asset rating of cables within networks. Dynamic Asset rating is the process of using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of for example, cold temperatures. Within the project, cable dynamic ratings were considered as an alternative to conventional reinforcement, the traditional engineering remedy to network constraints.

Recommendations resulting from this report are:

- A further DAR investigation of a single cable is conducted:
  - Where the cable is approaching thermal limits;
  - The ratings basis is cyclic;
  - Further improvements of soil parameter measurement are targeted; and
  - Full assessment is made of the actual cyclic load shape that the cable is experiencing is conducted.

Within this technique trial, the thermal model was validated by comparison with the industry accepted CRATER model [4], and by comparison to measured external cable temperatures. Comparisons with CRATER suggest that at modelled rated sustained currents the FALCON thermal models produces comparable results. Calculated cable temperatures from the thermal model also compared well to measured values over the load ranges experienced during the trials, even with measurement issues (temperature measurement placement and soil resistivity values).

For the trial 33kV cable, the estimated DAR was an average of 102% of the ENA ER P17 [2] seasonally adjusted sustained rating over the 14 month period. Gains over P17 were greater in the winter period, and it appears that there is a phase shift between the dynamic rating and the P17 seasonally adjusted rating (i.e. the peak in winter DAR occurs after the middle of the nominal winter period of October to March inclusive). Gains over

P17 for the period October to March (inclusive) averaged 107% of the seasonally adjusted P17 rating.

For the trial 11kV cable the estimated DAR was an average of 103% of the P17 seasonally adjusted sustained rating over the trial period; and again gains over P17 during the winter period were more pronounced. Gains over P17 for the period December to March (inclusive) averaged 107% of the seasonally adjusted P17 rating.

A new method has been described to look at prediction of cable ampacity and offers a potential opportunity to take advantage of slow changing soil temperatures. This allows a day ahead rating to be calculated that gives average winter benefits of 105% on the 33kV cable and 107% on the 11kV cable over P17 seasonally adjusted. It should be noted that this work has been done in the absence of good quality soil resistivity data and as such there is risk that rain impacting soil resistivity over a much shorter time period could revise results obtained.

The trial findings suggest that that this technique may be able to provide relief to cables hitting thermal limits in some circumstances (on the evidence that the trial DARs - sustained rating basis, suggests that average improvements over a winter period may be in the range 107% on average)

SECTION 1

Project Introduction[1]

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[1] This introduction to Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is common to all the engineering technique Final Reports.

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), coupled with the introduction of new technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas. This expected change in nature of customer demand and electricity generation will have an impact on networks nationwide and globally, and provides a significant challenge to WPD, and all electricity network operators.

Part of WPDs approach to this challenge has been look at new flexible ways to design, optimise and manage the network into the future. Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is designed to help answer these questions and is focussed on the Milton Keynes area 11kV network.

In the past network operators have used conventional reinforcement to deal with constraints but it can sometimes be over engineered to meet only peak demands; it can also be expensive, disruptive and inefficient. In project FALCON, WPD and its partners are trialling alternative techniques and will assess if they are more flexible, cost effective, quicker to deploy and more effective at managing these new demand requirements than conventional reinforcement. The techniques are:

- Dynamic Asset Ratings – Using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of for example, cold temperatures.
- Automatic load transfer – load is redistributed between 11kV feeders.
- Implementation and operation of a meshed (interconnected) 11kV network.
- Deployment of new battery technologies allow the flow of power on the network to be changed as the battery is charged or discharged.
- Demand Response services - the use of localised smaller generation and load reduction services that can be provided in the event of a local constraint.

Central to the project is the Scenario Investment Model (SIM) - a new piece of software being developed to assist long term network planning. The SIM performs load flow analysis for the network for 48 half-hourly periods during the day for different days of the week and different seasons of the year. Predicted load patterns extend as far as 2050. A network planner will operate the SIM to help with planning based on load forecasting. When a network planner is running the SIM and a voltage or thermal problem is found, the SIM will select the techniques that could help resolve the problem and determine how they could be applied to the network. The best solution can be selected using a weighted metric that combines elements such as installation and operating costs, network performance, losses and disruption to customers.

This report presents the work undertaken through project FALCON on the dynamic asset rating of Cables on the 33kV and 11kV networks.

SECTION 2

Introduction to Technique Trial

2.1 Presentation of Learning

Throughout the document, key learning is presented in a box as follows:

LP #	Brief description of learning.

Each piece of trials feedback is referenced as a Learning Point (LP) with a unique number.

2.2 General Overview of Dynamic Asset Rating Technique

Traditionally overhead lines (OHL), transformers and cables have been assigned capacity ratings intended to ensure operation within safe operating limits, and allow assets to achieve nominal service life. These ratings may be fixed for specific periods of time (e.g. summer and winter ratings of OHLs), or may relate to a load that has a daily cyclic characteristic (e.g. transformer and cables). However, these ratings essentially do not take the current/present environmental conditions into account, nor do they take into account the current/present thermal state of the asset. In this respect, the ratings are regarded as “static” – not responsive to the current thermal or environmental conditions of the asset. These “static” ratings make assumptions about prevailing environmental conditions (air temperature, wind speed and direction etc.) and set a limit on electrical current passing through the asset such that safety and service life of the assets are maintained.

Dynamic Asset Rating (DAR) seeks to allow operation of these assets beyond the static limits, through dynamic assessment of the asset’s actual thermal state (derived from preceding operating circumstances), and the present environmental factors. Whilst seeking to increase capacity, this technique can also identify periods where the dynamic rating is calculated as less than the static rating, thereby potentially reducing the asset’s rating under some circumstances. The dynamic rating is often referred to as ‘ampacity’ – the maximum current that can pass through an asset before the temperature limits are reached. The ampacity may be defined as either ‘sustained’ or ‘cyclic’ where sustained refers to the asset seeing a steady load, whereas as cyclic refers to the asset seeing an ever changing load following a set pattern.

This technique seeks to properly increase the capacity of assets during peak usage periods to alleviate constraints, whilst maintaining safety and managing impact on asset life. DAR can also constrain use of assets (e.g. generation) when environmental/load conditions are not favourable.

2.3 Overview of Cable DAR Technique

The static calculated current ratings of underground cables are based on the rise of temperature of the cable insulation (90^{0}C for cross-linked polyethylene (XLPE) insulation and 65^{o}C for oil impregnated paper or 75^{0}C for other paper insulation types [1]). The temperature is limited to avoid insulation breakdown leading to cable failure. The cable temperature increases by the passage of current through the cable. This current is limited to a static summer and winter current rating and a cyclic summer and winter rating as defined in UK Engineering recommendation P17 [2]. These values are reduced (the cable is de-rated) when the cable is ducted or in close proximity to other cables.

The ratings contained within P17 are typically calculated using representative values for soil characteristics, taking the thermal resistivity of soil as a set seasonal value. Although this is fine for a generalised answer that will fit the large majority of cables on the UK distribution network, it does not allow the full realisation of individual cables current carrying capability. The ratings within P17 have been used over 30 years by the majority of UK Distribution Network Operators (DNO's).

P17 consists of three documents relating to the rating of 11kV and 33kV solid paper insulated cables and polymeric cables. Parts 1 and 2 of the document were created in 1976 and introduced the concept of the 'distribution rating' based on a five day cyclic load. Using these documents an engineer had the ability to determine the distribution rating for a circuit or a group of circuits. [2]

The 'distribution rating' is the most common rating basis applied throughout the distribution network (the maximum current that can be carried for five days whilst keeping the insulation below a maximum temperature). In addition a cable has two static ratings throughout the year, 'summer' and 'winter'. The 'winter' rating takes into account the ability of the cables to carry larger currents and therefore power flows in winter months due to colder temperatures, and generally wetter ground. This rating is broadly independent of the laying depth of an underground cable, provided the burial depth is at least 600mm.

The Dynamic Asset Rating (DAR) technique looks to maximise network capacity usage by monitoring soil temperature and moisture. This data will be used to calculate 'real-time' asset capacity, potentially allowing for higher ampacity for limited periods rather than the current 'static rating' current used by distribution network operators. The DAR technique will allow the underground cable to be temporarily run above its continuous current rating providing it remains below the critical temperature set out by the manufacturer.

A dynamically rated cable would provide the option of running underground cables to incorporate short term increases in load that might defer capital expenditure on network reinforcement. Research into the dynamic capabilities of underground cables undertaken worldwide, has led to the development of a number of monitoring techniques and simulation software applicable to the transmission and distribution network.

In the UK, EA technology have carried out a number of detailed studies, notably by Graham Le Poidevin [4, 5] that have resulted in the development of the CRATER (Cable RATER) software modelling tool. The modelling tool is written in excel, with the program split into two, one that models the different constraints on the current carrying capability of a single core cable and that of a three core cable. The tool can broadly model three types of cable insulation, polymeric, paper and oil filled.

Three different types of rating (in accordance with P17) can be assessed with CRATER, the static rating, cyclic rating (at maximum conductor temperature) and the distribution rating.

In 2009 a report was published by Le Poidevin on the development of CRATER to study the dynamic asset rating of underground cables. The report included the addition of soil characteristics and ambient temperature to the CRATER model to allow it to be used for the calculation of a dynamic rating [5, 6].

In Finland a dynamic asset model for the rating of distribution cables has been developed by Helsinki University. The model predicted an increase in capacity of up to 1.52 times the static rating for normal operation and 2.6 times the normal rating for emergency operation. The model takes into account the loading history for the cable and requires data such as cable construction, thermal operational limits, installation and operational data and power loss data [7].

In Holland, KEMA have developed a dynamic thermal model for their domestic network. Initially designed for use with cables, it has now been extended to include overhead lines and transformers. The model uses the properties of the cable and soil to model the cable behaviour in time steps down to 5 minutes. The cable model was validated by measuring the behaviour of an underground cable with a fibre optic cable used as a thermal measurement sensor. The KEMA model notably takes into account thermal bottlenecks these are critical points in the cable and can act as additional heat sources [8, 9].

In 1990 the Electrical Power Research Institute (EPRI) in America undertook a detailed study (RP 3022-7) of the DAR of underground cables and carried out a physical trial of a section of network in Georgia. The study also looked at underground cables, overhead lines, transformers and switchgear.

EPRI developed a software program called ‘alternative cable evaluation’ with the ability to calculate a number of different ratings (24 hour continuous rating, 1-24 hour continuous rating, and 1-60 minute short term emergency rating). The model requires the thermal resistivity of the soil and conductor, insulation, jacket and duct of the cable along with the thermal capacitance of each cable component and the soil. [10]

In the UK, Alstom extended the functionality of their P341 relay to calculate a dynamic asset rating of cables [11]. Other more recent work includes that undertaken by LCNF Customer Led Network Revolution (CLNR) project into Real Time Thermal Rating (RTTR) [12].

2.4 Overview of approach to the technique trial

The high-level objectives of the technique trials (the deployment and testing of techniques) can be generically summarised as:

- to understand the implementation of the alternative techniques;
- to understand operational capability of the alternative techniques;
- to inform changes to the modelling of the intervention techniques within the SIM;
- to trial an innovative communications network to support the techniques; and
- to capture knowledge and disseminate learning.

Learning Objectives originally associated with this technique are listed in Appendix B

The overall process approach to the technique trial is shown in Figure 1

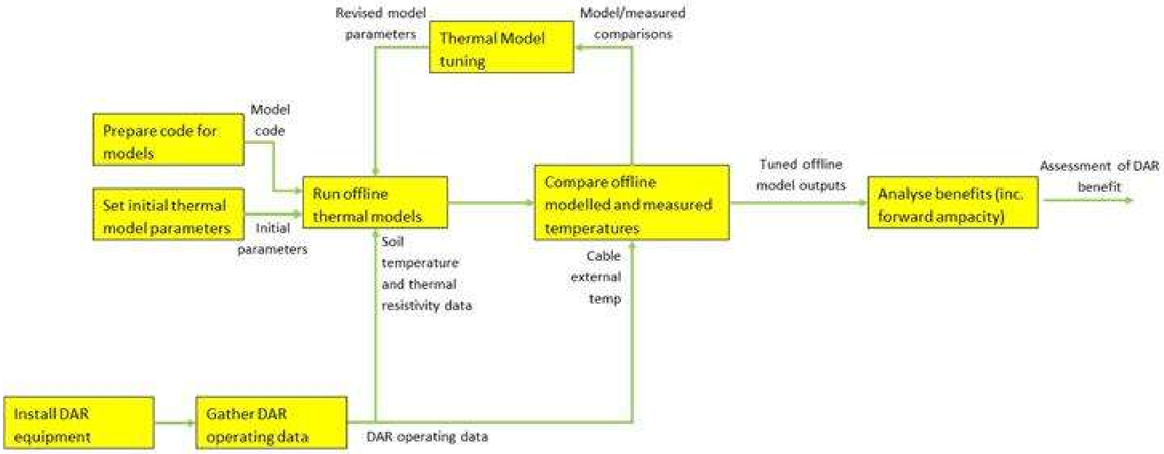


Figure 1: Overall process approach to the technique trial

The technique trial therefore had a number of key elements:

1. Installation and commissioning of online DAR relay plus associated input instrumentation;
2. Preparation of an offline thermal model
3. Analysis of thermal models
4. Assessment of the benefits of instantaneous/of-the-moment DAR benefits
5. Projection of future DAR, based on forecast environmental data;
6. Assessment of the benefits of forward DAR estimates

SECTION 3

Design, Construction and Commissioning

This technique trial sought to provide the data required for dynamic asset rating assessment of representative 33kV and 11kV cables, allowing an offline thermal model to be created and validated, and for cable dynamic asset rating values to be estimated.

3.1 Overview of selected cables

Monitoring of two cable locations was established:

- Bradwell Abbey to Newport Pagnell 33kV Circuits [Teed to Hanslope Park & Fox Milne] -2 x 33kV 185mm^2 3-core copper paper insulated cables; and
- Between Distribution substations Jonathans Coffee Hall and Lloyds Coffee Hall on an 11kV 185 mm^2 paper insulated corrugated aluminium sheathed (PICAS) cable.

3.1.1 Single line and geographic diagrams

The single line diagram for the 33kV cables is shown in Figure 2, and for the 11kV in Figure 3.

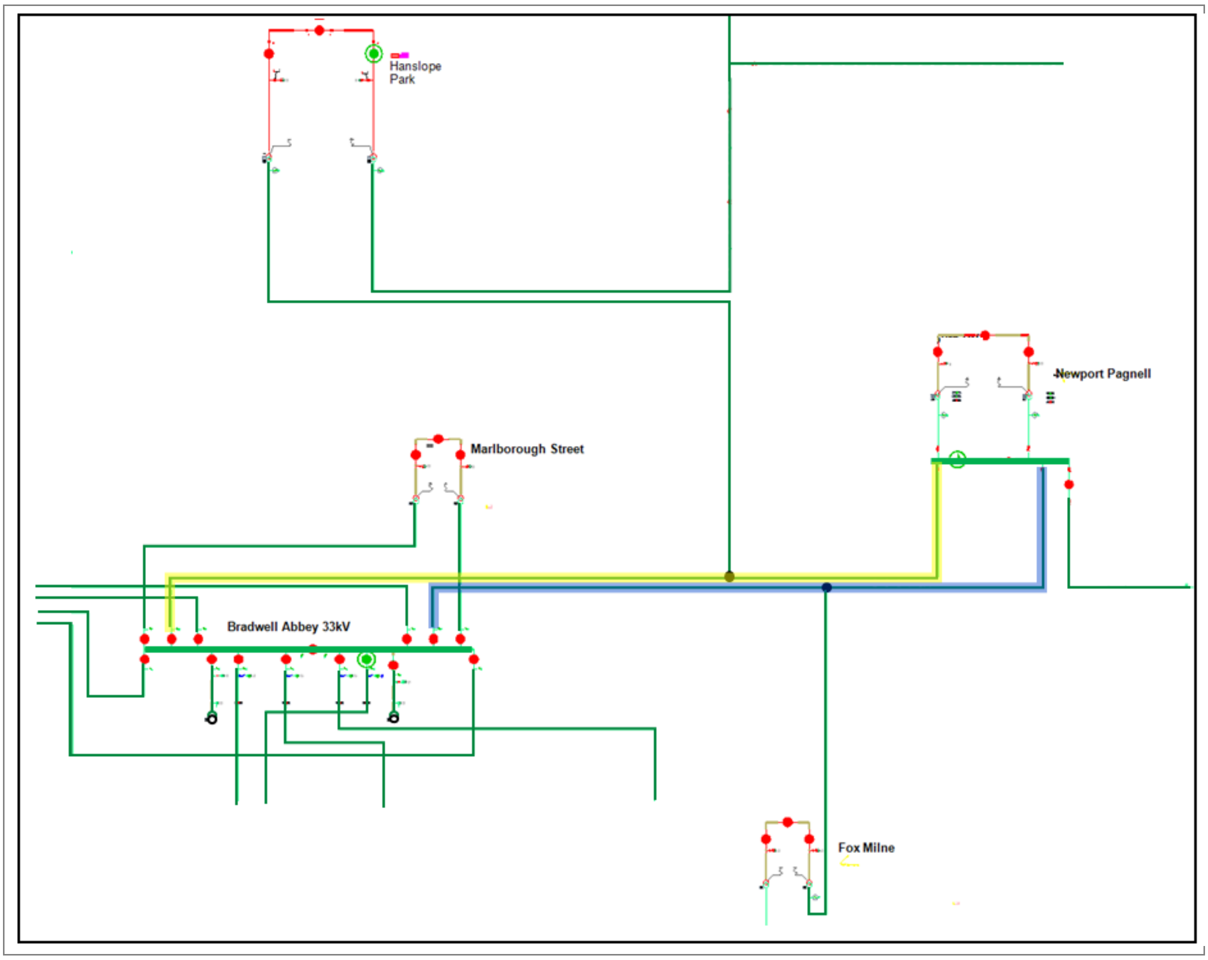


Figure 2: 33kV Cable schematic – larger format diagram in Appendix C.1

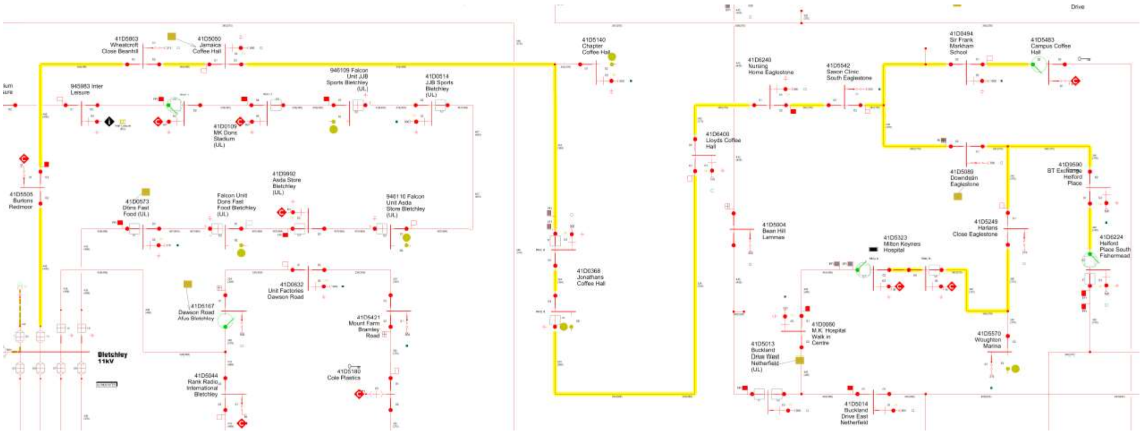


Figure 3: 11kV schematic – see larger format version in Appendix C.2

Geographic views of the cable routes are shown in Figure 4 (33kV cables) and Figure 5 (11kV cable.

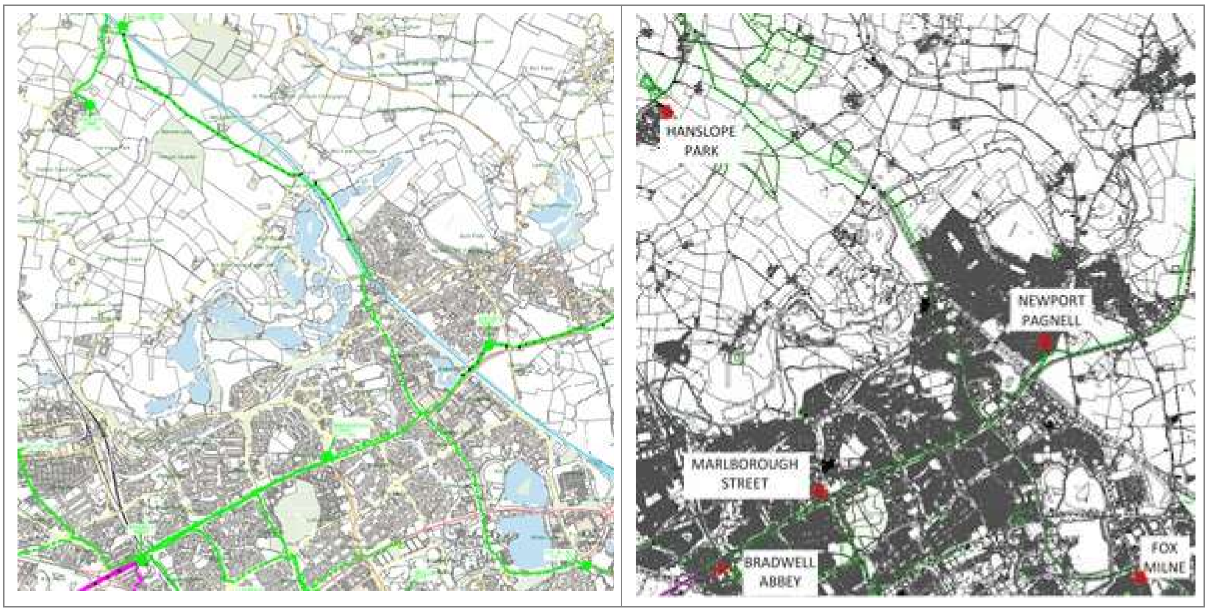
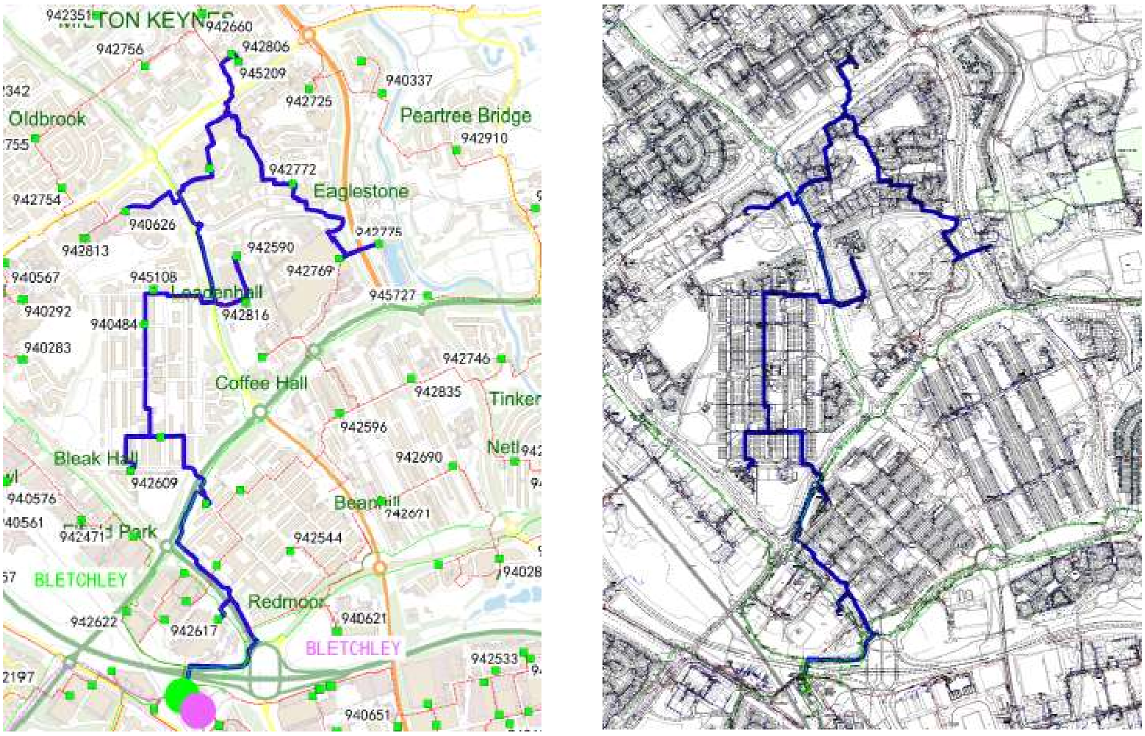


Figure 4: 33kV Cable geographic view



Small scale mapping

Main mapping

Figure 5: Geographic plots of cable route

3.1.2 Cable construction

33kV cable

The 33kV circuits between Bradwell Abbey and Newport Pagnell essentially comprise of 185mm^2 3 core, copper stranded conductor, screened, paper insulated, lead sheathed, steel wire armoured and served cables. A representative picture of the cable is shown in Figure 6.

Entry to Bradwell Abbey substation (the monitoring point) is completed in single core 185mm^2 copper XLPE cable, which is jointed to the 3-core cable with approximately 20m.

Figure 6: Representative picture of 33kV trial cable

11kV cable construction

The trial 11kV cable (Feeder 11, Burtons Redmoor, from Bletchley 11kV board) comprises of a number of cable types, outline construction details are shown in Table 1.

Cable identifier	Basic cable characteristics			
	Cores	Conductor	Sheath etc.	Conductor size
300Al PIAS	3 core cable	Aluminium	Belted, Corrugated aluminium, PVC covered	300mm^2
300 Al	3 core cable	Aluminium	Belted, lead sheath, SWA, PVC covered	300mm^2
3x300 1c Al XLPE	Single core cable	Aluminium		300mm^2
185 Al PIAS	3 core cable	Aluminium	Belted, Corrugated aluminium, PVC covered	185mm^2
185 AL	3 core cable	Aluminium	Belted, lead sheath, SWA, PVC covered	185mm^2
3x185 1c Al XLPE	Single core cable	Aluminium		185mm^2

Table 1: 11kV cable types and outline construction details

Table 2 provided nominal P17 ratings data for the cables in the feeder. From this it can be seen that the lowest rated cable types is the 185 Al PIAS, the monitored section of cable within the trial.

Cable identifier	P17 Reference	P17 Rating			Nominal GIS presentation - cyclic (distribution)
		Distribution	Sustained	Cyclic	
	Correction factors: Part 1 - Table 11		0.82	0.92	
300Al PIAS	Part 1 - Table 7c	490	402	451	451 (490)
300 Al	Part 1 - Table 4a	525	431	483	483 (525)
3x300 1c Al XLPE	Part 3 - Table 4-6 ,5-6 & 6-6	689	542	623	623 (689)
185 Al PIAS	Part 1 - Table 7c	370	303	340	340 (370)
185 AL	Part 1 - Table 4a	390	320	359	359 (390)
3x185 1c Al XLPE	Part 3 - Table 4-6 ,5-6 & 6-6	522	415	474	474 (522)

Table 2: Nominal P17 Cable Ratings for 11kV trial circuit.

A representative picture of the 11kV cable is shown in Figure 7.

Figure 7: Representative picture of 11kV trial cable

3.2 As-installed equipment

3.2.1 Overview of as-installed equipment

Each cable (two 33kV cables and one 11kV cable) was monitored for load current, soil temperature and soil moisture, as inputs to the thermal modelling/DAR assessment. In addition, cable (external sheath) temperature monitoring was installed to provide measurements for validation of the thermal models.

Schematic overviews of the measurement and data collection arrangements are shown in Figure 8 (33kV cables) and Figure 9 (11kv Cable).

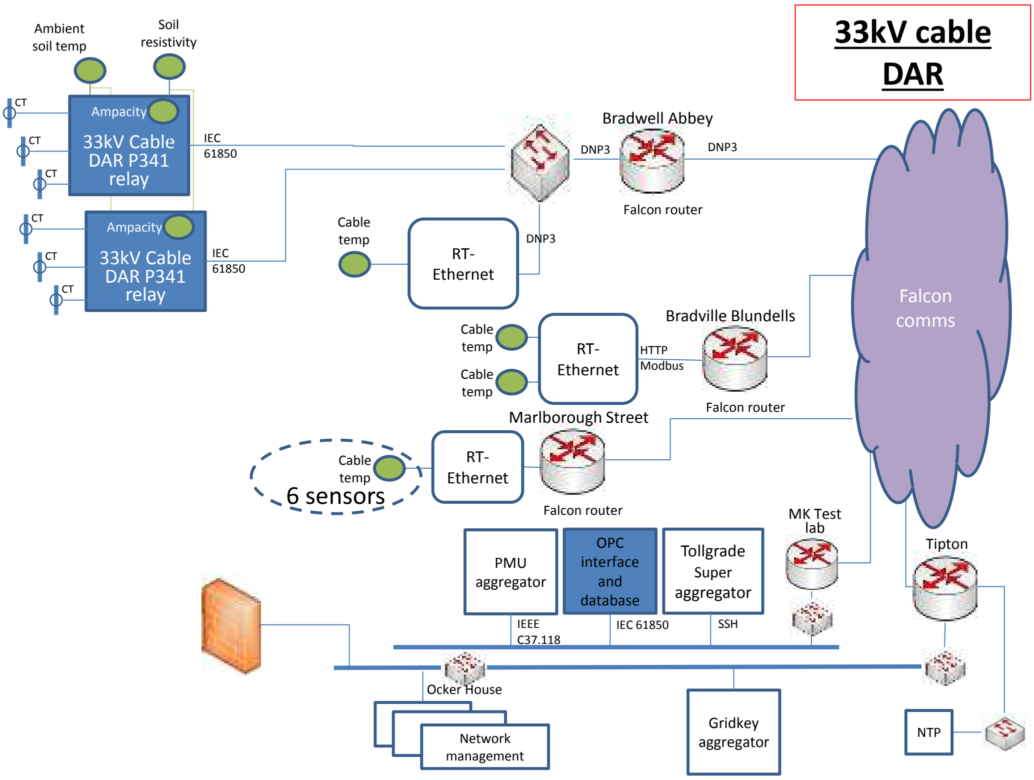


Figure 8: Schematic of installed 33kV Cable DAR scheme

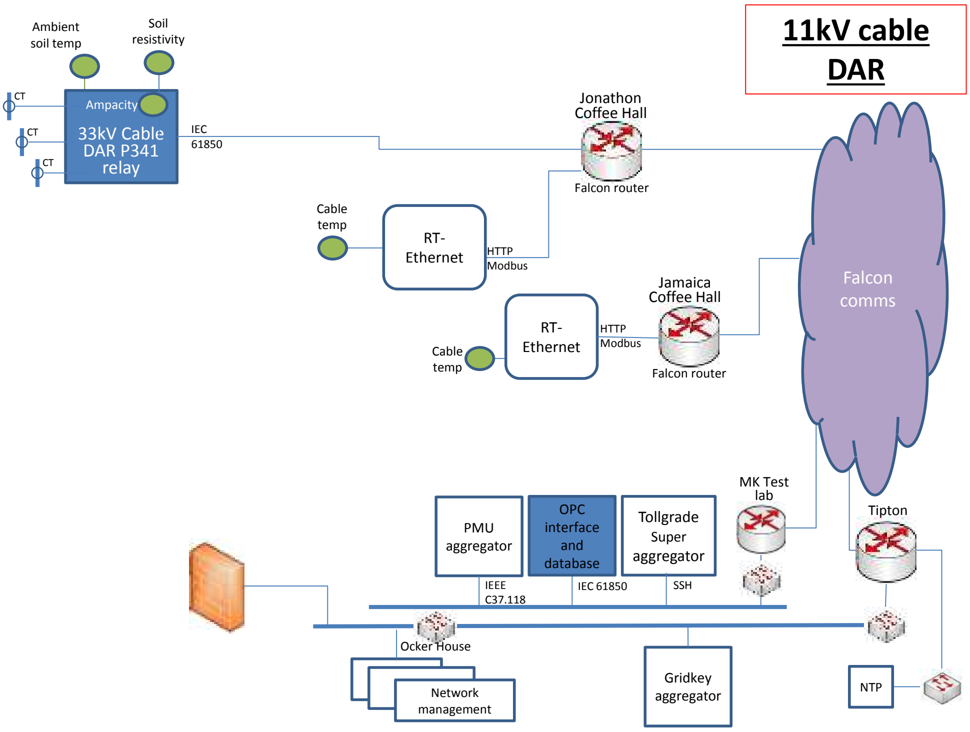


Figure 9: Schematic of installed 11kV Cable DAR scheme

For the 33kV, the installed equipment comprised of:

- One Alstom P341 DAR relay (model P34131BB6M0800J, running software P341____6__800_A) per cable, headline real-time calculation of modified rating of the cable based on soil temperature and moisture (proxy for soil thermal resistivity), communicating via IEC 61850 over IP network;
- Use of existing feeder current transformers at Bradwell Abbey to provide current measurement directly connected to the P341 relays;
- PT100 resistance thermometer measuring soil temperature connected to iSTAT400 transmitter providing 4-20mA output signal fed to P341 relay;
- Decagon Devices MAS-1 soil moisture sensor providing 4-20mA output signal fed to P341 relay;
- Nine PT100 resistance thermometers with Status Instruments' SEM203/P 4-20mA transmitters independently measuring sheath/joint temperatures at points along the cable route. 4-20mA signals are fed to Exemys RME1, which in turn communicate via Modbus over the IP network.

The 11kV trial cable is monitored with identical equipment, though additional CTs were installed to ensure that the correct current was being monitored, and only one PT100 resistance thermometer was installed to monitor cable temperature.

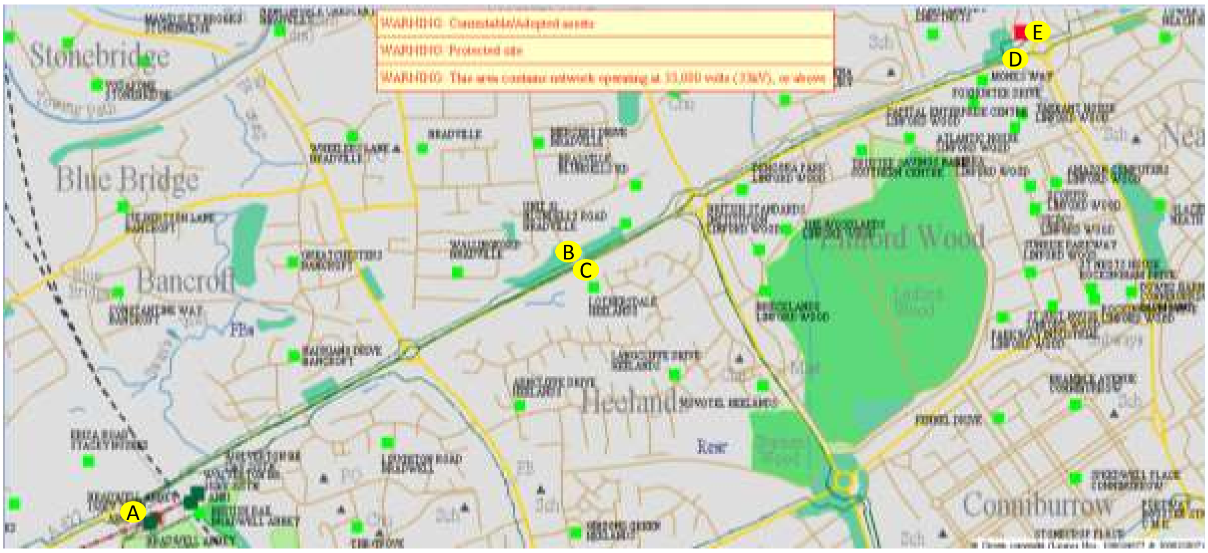
3.2.2 Planned locations of Cable temperature monitoring

33kV cable temperature monitoring

Monitoring of the 33kV cables was planned as described below and as shown in Figure 10:

- 1 cable temp sensor is marshalled at Bradwell Abbey monitoring general congested route cable sheath temp
- 2 cable temp sensors are marshalled at Blundells Road Bradville, sheath temperature of both the passing 33kV cables
- 6 cable temp sensors are marshalled at Marlborough St

Significant problems were encountered with cable temperature measurement. These are described in Section 3.2.3 below.



Location A 1 sensor on congested cable route.
Location B and C 1 sensor placed on cable sheath of each circuit.
Location D and E sensors placed on cable sheath, cable joint and in duct run.

Figure 10: Location of 33kV temp sensors

11kV cable temperature monitoring

Monitoring of the 11kV trial cable temperature was carried out adjacent to the substation. Figure 11 shows the installed sensor prior to backfill.

Figure 11: 11kV cable temperature measurement sensor

3.2.3 Trial measurement issues

Four issues arose with measurement data associated with cable DAR.

Soil temperature

As the technique trial progressed, disparities were identified between the two key soil temperature measurements taken at Bradwell Abbey substation, and at Jonathans Coffee Hall substation. Cross-checks with other FALCON measured soil temperatures at Marlborough Street and Childs Way substations were made, and also comparison against other sources external to the project. This resulted in an appreciation of the complexities of soil temperature and its measurement within the project that emerged over the course of the project:

- Soil temperature varies over time:
  - At the surface it is quickly influenced by changes in ambient air temperature and solar radiation, and is affected by the nature of ground cover/vegetation;
  - At depths of up to around 1 metre the soil temperature is influenced by diurnal variation (tempered by ground cover and moisture) and also seasonal variation in ambient air temperature/solar radiation;
  - Seasonal variations in temperature show a time lag with respect to ambient conditions (i.e. reductions in soil temperature over Autumn and into Winter lag behind the corresponding ambient air temperatures); and
  - At depths greater than around 10 metres the soil temperature is largely constant, fixed by the average annual ambient air temperature.
- Soil temperatures vary spatially - at depths associated with cable laying, soil temperature can be expect to vary with location; this variation is due to differences in:

  - Ground surface (e.g. black tarmac compared to dense vegetation);
  - Shading;
  - Variation in soil characteristics; and
  - Variation in soil moisture.
  - This applies along the route of a single cable, and between different cables.
- Single point soil temperature measurements (as implemented by the project) are therefore prone to being unrepresentative due to specific measurement-site factors such as:
  - Ground cover;
  - Extent of shading;
  - Measurement depth;
  - Extent to which the characteristics of the soil at the measurement point are representative of a wider area; and
  - Moisture.

As a result of this, finalised modelling of cable temperatures and resultant dynamic asset ratings for both the 33kV cable and the 11kV cable were based on the soil temperature measurements taken at Bradwell Abbey Substation. These values were judged to be the best available, and acceptable, considering measurement point depth, extent of shading and broad character of the soil.

Soil resistivity

Issues were also encountered with soil resistivity values derived within the technique trial.

As noted in Section 4.2.1, the model input value of soil resistivity was sourced from the Alstom online DAR relay. In turn, the relay derived this based on a calculation that used a number of soil characterising parameters, and an analogue (4-20mA) signal representing the soil moisture.

Figure 12 shows a trace of values logged for soil resistivity from the 3 relays. The Bradwell Abbey values overlay each other, as would be expected as the two relays are fed from the same soil moisture instrument

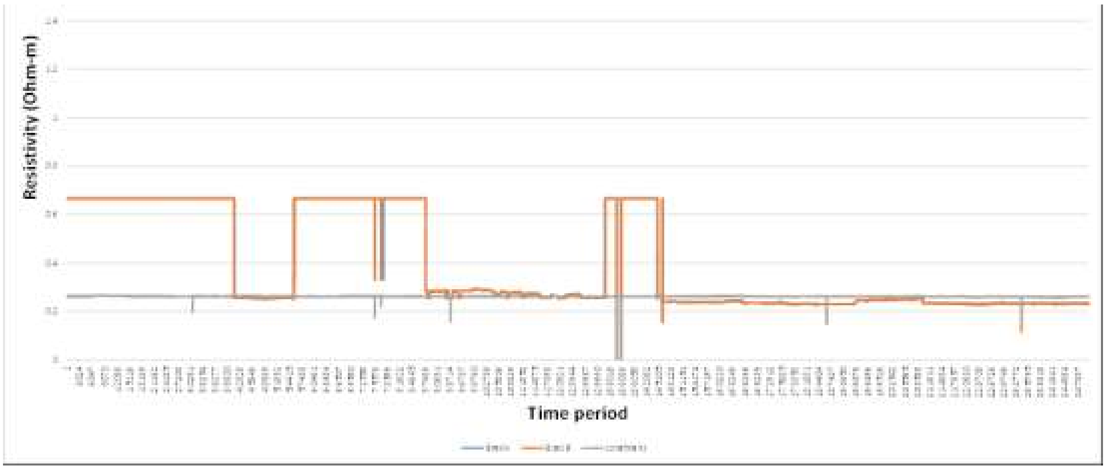


Figure 12: Reported soil resistivities

The values for resistivity, effectively from two sources, lie outside what may reasonably be expected. P17 considers a range of values for soil resistivity, allowing correction of ratings based on this variation. This range is between 3 and 0.7 Ohm-m. This along with the values reported in the Customer led Network revolution project [12] has meant that the confidence in the measured value on FALCON is low. Therefore fixed values of 0.9 and 1.2 were chosen for use with the models as a fixed seasonal time in-variant value to allow for comparison between winter and summer standard defined values.

Current measurement at 11kV Jonathans Coffee Hall substation.

Issues were also encountered with the position and calibration of the current measurements at the 11kV Jonathans Coffee Hall substation. For the period beginning December 2014, through to early March 2015, the current measurement was positioned upstream of the substation (including current associated with the substation load), whilst the cable temperature was being monitored downstream of the substation, see Figure 13.

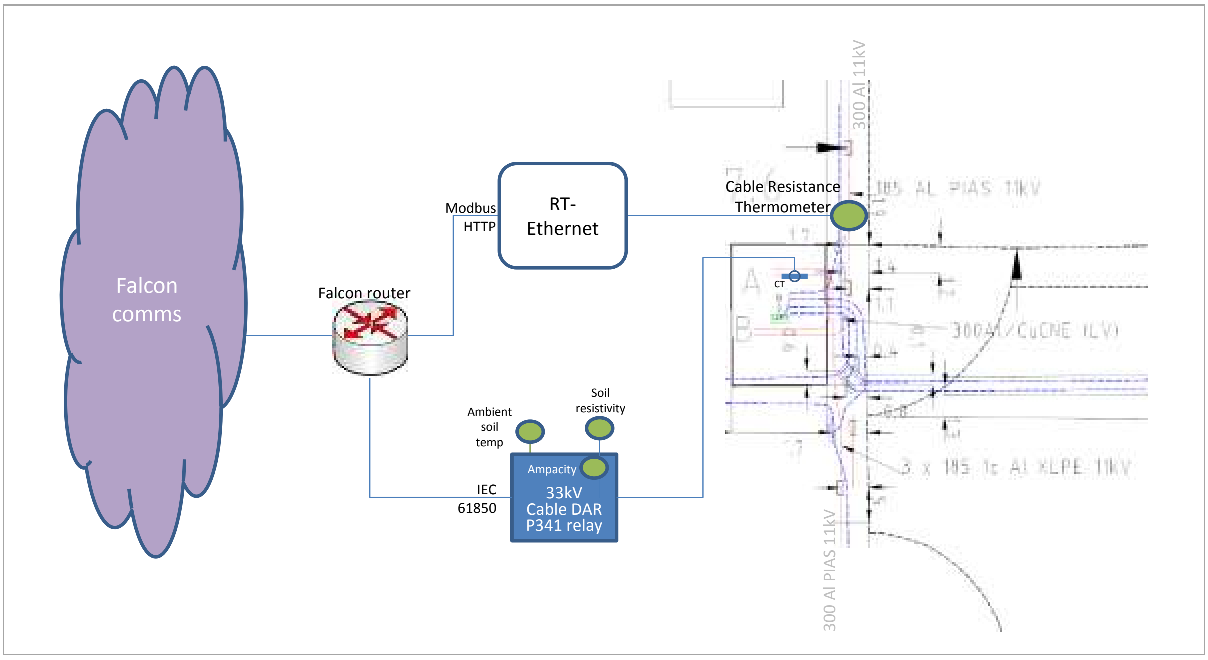


Figure 13: Initial construction and measurement positions

During early April 2015, new CTs were fitted that correctly aligned current measurement with cable temperature measurement, see Figure 14. However, during the period early April to late May 2015 the newly fitted CTs were incorrectly registered on the online DAR relay. This was subsequently corrected.

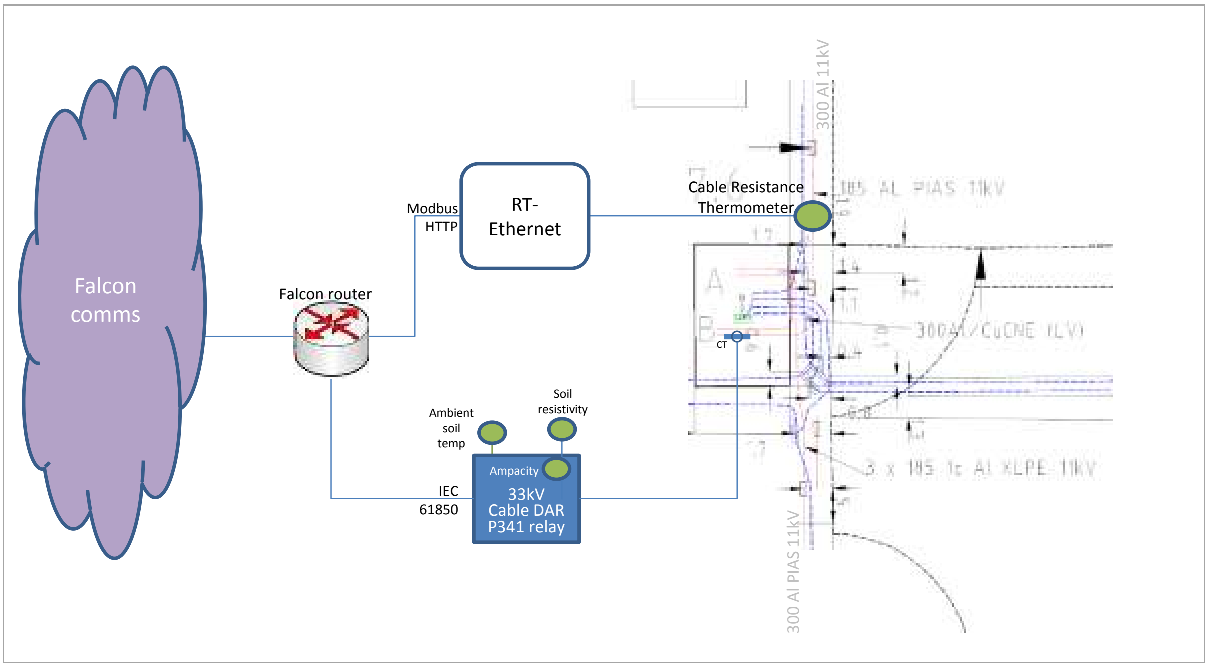


Figure 14: Final construction and measurement positions

These issues were all corrected for in the current arrays taken into the offline modelling.

33kV cable temperature measurement

The technique trial design included nine cable (external) temperature measurement points. All used the same design of resistance thermometer with housing and 4-20mA transmitter. Some months passed between installation and commissioning of the sensors, and at the time of commissioning only two of the nine sensors were found to function.

Investigations of reasonably accessible identical measurement devices showed that the gland/cable arrangement was not adequate, and substantial water ingress to the housing containing the transmitter occurred, see Figure 15.

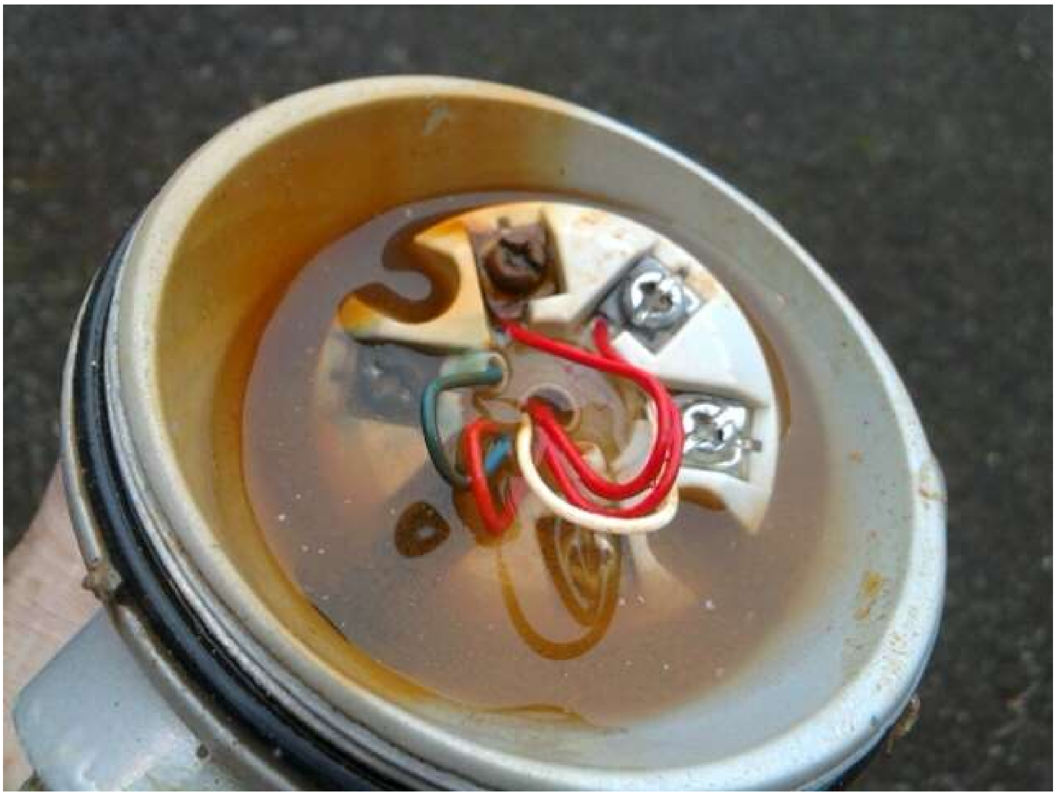


Figure 15: Damaged transmitter due to housing water ingress

This water ingress was found to have caused the failure of the two identical units that it was reasonably practicable to investigate. It was assumed that water ingress occurred on seven of the nine installed measurement points. Their electrical behaviour was consistent with the investigated units.

The technique trial continued with limited cable temperature measurement points to compare to calculated temperatures.

3.3 Data and data transfer

The high level trial data collection and transfer processes used within the trial are shown in Figure 16.

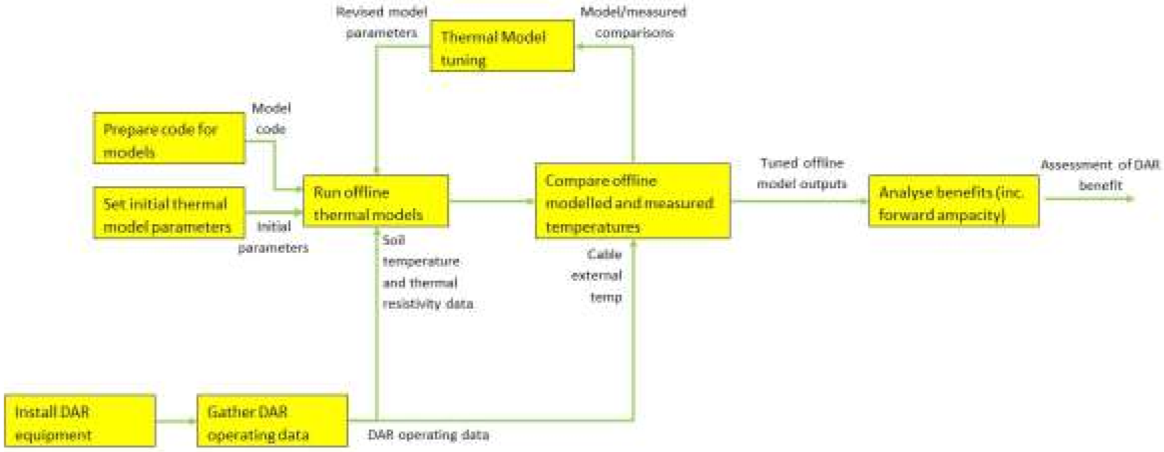


Figure 16: Data collection for offline modelling

These processes can be summarised as follows:

- Electrical current and soil data (temperature and moisture) are measured and passed as analogue 4-20mA signals to the Alstom P341;
- These inputs are transmitted by the P341 relay and stored for offline analysis via a Matrikon 61850OPC server. Data is passed to the offline model via .csv files as key input parameters; and
- Cable temperature measurements are collected via the DT80 data logger and made available via .csv file to allow comparison between the offline model and measured cable temperatures.

3.4 Key Learning from Implementation

3.4.1 Technique-Specific Learning

LP 1.	This project experienced difficulties in getting good soil temperature and soil resistivity measures. The use of advisors with specialist experience in optimised soil parameter measurement arrangements should be considered.

- As discussed in Section 5, issues with soil parameter measurement have been worked around, and it is judged that key findings (validation of the thermal model and assessment of DAR benefits) are valid.

LP 2.	The P341 relay reports a dynamic rating based on an adjustment factor that the relay calculates (based on soil temperature and moisture), and a static rating for the cable (entered as a relay parameter). The calculation algorithm associated with cables therefore has a significantly different approach compared to OHL and transformer algorithms contained in the same relay.

LP 3.	Whilst not immediately clear, the cable rating parameter required by the relay must be the Winter rating.

- The relay output appears to work by using a pre-entered static rating of the cable and increasing this, for example, when the soil temperature is colder than the assumed value from the static rating calculation.

LP 4.	The relay reports a dynamic rating but no temperatures (as are reported for OHL and transformers by the relay). The relay does not actually calculate any modelled temperatures, so from the relay it is not clear how close to limits the cable is being operated.

- The relay does not actually calculate any modelled temperatures for cables, so from the relay it is not clear how close to limits the cable is being operated.

LP 5.	Manufacturer software status needs to be known in advance so expectations on functionality can be managed:

- Version 80, P341 software, trial software is not on general release and appears to be less developed than the version of software supplied for the OHL implementation.

3.4.2 Generalised and Cross-Technique Learning

In a generalised form, a number of learning points have been found across more than one technique. Those applicable to the cable DAR technique trial are presented below, with examples specific to this technique.

LP 6.	Design and specification work stopped at a high level (as is usual for 11kV distribution equipment), leaving a significant and initially unrecognised volume of work and problem solving for the commissioning/early operation phase. This applied to all the engineering techniques. Sophisticated equipment at Distribution Substations may require similar levels of engineering design to the primary system. These functions may need expanding to cope with additional volumes.

- Design issues were identified with the soil moisture sensor
  - Design of the connection of the soil moisture sensor to the P341 relay was initially incorrect and required field modification agreed with the supplier

  - The soil moisture sensor outputs a signal that is proportional to soil dielectric constant not moisture content, and an additional signal conditioning card was installed providing a linear approximation of the non-linear relationship between soil dielectric constant and moisture content (required input to the relay), based on assumptions about soil type

LP 7.	FALCON established that conventional approaches to 11kV equipment factory acceptance tests (FAT) may not be adequate for innovation projects. The use of FAT approaches may necessitate rework at the install / commissioning stages.

- The relays, although issued with a FAT test certificate were inconsistently configured for operation. For example, CT ratios were correctly entered, but cable ratings were not.

LP 8.	FALCON demonstrated the importance of establishing measurement and data strategies as part of the programme design phase to help (dis)prove the technique hypothesis being trialled.

- Initial design work anticipated the wide-spread use of the central SCADA system for collection and dissemination of data (e.g. cable temperature measurements). Throughout final installation and during commissioning it became clear that alternative data collection systems would provide greater operational flexibility in the context of an innovation project. This led to the Installation of a single data logger that collated all plant temperature measurement data.

LP 9.	Control room interaction with the technique was light. More complicated control room interaction would be required if this were adopted as a BAU technique.

LP 10.	Limited training of operational staff was undertaken to allow the trial to take place. Additional more widespread training would be required if this were adopted as a BAU technique.

SECTION 4

Thermal models

All DAR assessment is predicted on a thermal model, and confidence in that model. These models include calculation algorithms, and parameters that are specific to each asset. This section describes the work undertaken within the project to prepare thermal models for cables that gave acceptable coincidence to an industry accepted thermal model of cables, and measured external cable temperature values, and the learning that resulted.

4.1 Overview of thermal models

Model basis

Initial review of available potential methodologies for preparing cable thermal models identified IEC 60853-1 and IEC 60853-2 as potential approaches. IEC 60853-1 standard was taken forward as the basis for FALCON modelling, the reasons being:

- IEC 60853-2 covers HV cables including those running above 36 kV, whereas the FALCON project only includes cables rated up to 33 kV, which is covered by IEC 60853-1;
- IEC 60853-2 has significantly longer run times than IEC60853-1 when based on the 3-month cycle recommended in the CRATER documentation [16].
- IEC 60853-1 is substantially simpler to implement (and is a special case of IEC 60853-2), where cable thermal capacitances are ignored.
- For cables relevant to the technique trial, better correlations were obtained between the results from initial FALCON algorithms when using IEC 60853-1, and CRATER (the accepted industry indicator).

It should be noted that whilst acceptable correlations to CRATER were achieved, the FALCON code did not exactly reproduce CRATER results. This is to be expected as the CRATER algorithm is documented as implementing IEC 60853-2, with several deviations noted.

Thermal model algorithm

The offline model algorithm introduced in this section (and described in detail in Appendix D) gives the transient temperature response of a cable to an arbitrary input function of current. The algorithm does this by modelling the thermal impedances formed by the constituent parts of the cable itself and its surroundings as shown in Figure 17.

The model is based on a thermal model of the system where W_c and W_a are the thermal power produced by losses in the system such as the conductor loss and armour losses. R_1 to R_4 are the thermal resistances of the layers of insulation and effect of soil and T_c is the conductor temperature while T_e is the external cable temperature (compared to the measured value) and T_s is the ambient soil temperature. According to IEC 60853-1, for cables up to 33 kV, the thermal capacitances of the cable components are neglected.

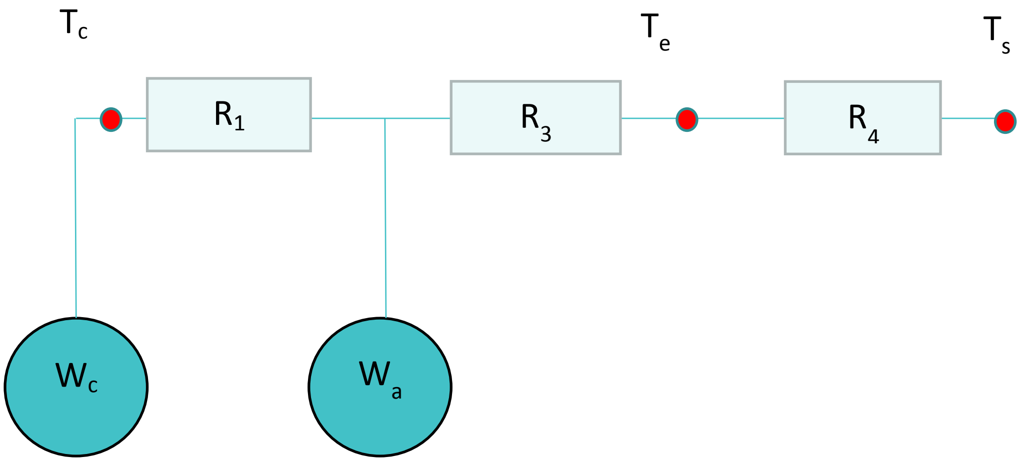


Figure 17: Cable thermal circuit

Model parameters

A number of input parameters are passed into the main FALCON offline model algorithm, for example, cable manufacturer's specification data, the cable layout, environmental parameters and a load curve. To allow for non-zero initial conditions at the start of the period, a pre-history term is used, which is based on the Loss-Load Factor (*LLF*) for the cable duty cycle.

The inputs include:

- *layout* : cable configuration, 1=Trefoil, 2=Flat laid
- L : cable depth of burial (m)
- D_e : cable or duct diameter (m)
- D_s : external diameter of screen (m)
- D_i : external diameter of insulation (dielectric) (m)
- d_c : external diameter of conductor (m)
- A_s : cross-section area of screen (m^2)
- d_c : external diameter of conductor (m)
- R_{dc20} : conductor dc resistance at 20°C (Ω/m)
- α_{20} : temperature coefficient of conductor resistivity (m/W)
- *spacing_factor* : spacing factor for flat laid configuration as integer multiple of D_e
- f : supply frequency (Hz)
- ρ_{cu} : resistivity of copper at 20°C (m °C/W)
- α_{cu20} : temperature coefficient of copper resistivity (m/W)
- δ : soil thermal diffusivity (m^2/s)
- ρ_{soil} : soil thermal resistivity (m °C/W)
- ρ_{dielec} : insulation (dielectric) thermal resistivity (m °C /W)
- ρ_{cover} : outer cover thermal resistivity (m °C /W)
- ϑ_{max} : maximum absolute cable conductor temperature (°C)

- $\vartheta_{ambient}$: ambient temperature (°C)
- I : cable current vector where I has been normalised to the peak current, over a trial period
- t : time vector (s) corresponding to Y

The cable information for the 33kV and 11kV cable can be found in Appendix E.

In terms of the trial, the cable burial depth is set to 600mm from the Network Design Manual. It is assumed that the cable is direct lay in ground, not ducted or grouped and that the soil resistivity is fixed as the data relating to this is untrustworthy.

	33kV	11kV
resistivity	0.9 (winter) 1.2 (summer)	0.9 (winter) 1.2 (summer)
Soil depth	750mm	600mm
Soil diffusivity	5.3xs10^{-7} (winter) 4.3x10^{-7} (summer)	5.3xs10^{-7} (winter) 4.3x10^{-7} (summer)

Table 3: trial parameters where different from validation parameters

4.2 Implementation and validation of offline thermal models

4.2.1 Implementation of offline thermal models

A 33kV and an 11kV cable model were coded into MATLAB, based on the methodology described in Section 4.1. Details of the parameter values used are contained in Appendix E.

The required input data arrays were: soil temperature, soil thermal resistivity, and cable current. These inputs were derived from the installed online cable DAR relay, and passed to the model via Microsoft Excel files. It should be noted that the DAR relay itself derived an estimation of soil resistivity from a measurement of soil moisture.

Figure 18 shows the high level data flow and provision of data for validation of the thermal model outputs. The flow of data can be summarised as follows:

- The cable load data along with soil temperature and a measure of moisture content were input into an Alstom P341 relay;
- The moisture content was converted to a soil resistivity within the Alstom relay:
- External temperature measurements were taken of the external cable sheath:
- The cable models were run with the relay reported input data and produced arrays of calculated external temperature for subsequent comparison to measured trial data;
- The model was used to generate arrays of ampacity values based on the input data, for subsequent comparison to reference data.

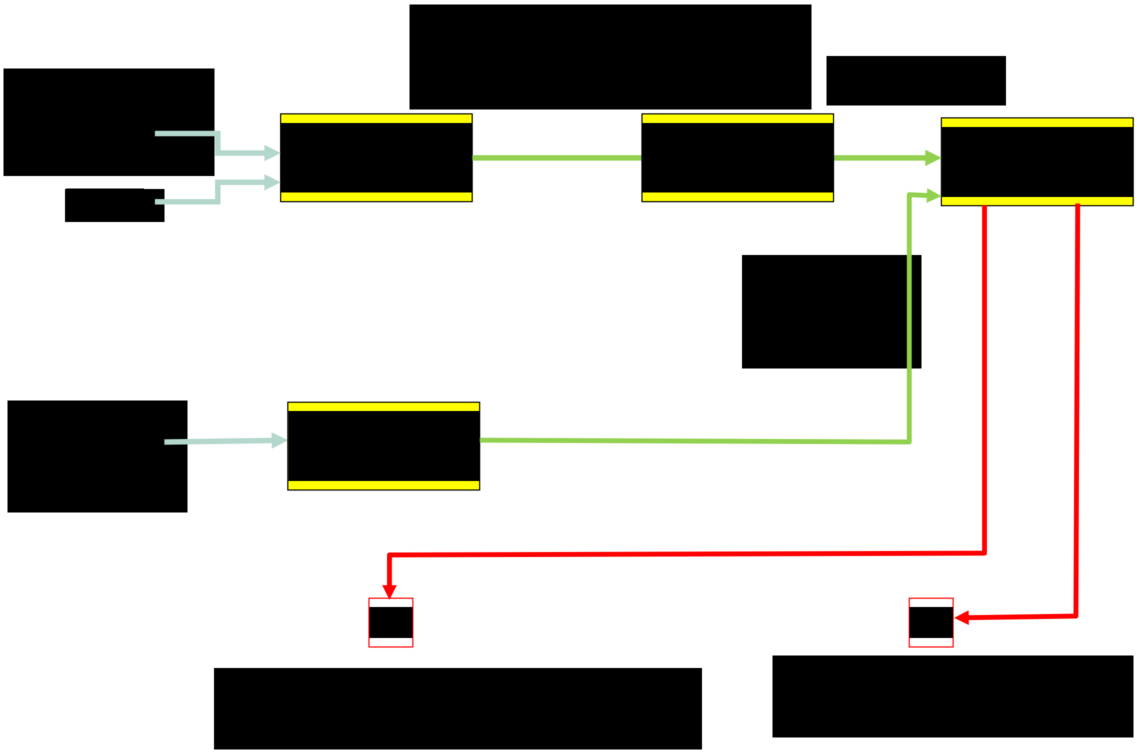


Figure 18: Data flow and measurement/calculation comparison for 33kV cable DAR

4.2.2 Introduction to FALCON Model validation

The FALCON cable thermal models were validated in two respects:

- Comparison of the cable temperature calculated by FALCON's cable models with CRATER under nominal rated sustained current conditions; and
- Comparison between FALCON modelled cable temperatures and measured cable temperatures

Comparison between available and modelled results is key to validating the accuracy of the prepared thermal models; however, within the technique trial this was achieved over relatively low levels of cable load.

Comparison to CRATER was therefore important in two respects: it confirmed that the FALCON model was producing results comparable to industry accepted results; and it tested the model at nominal full loads, mitigating the limited operating ranges achieved in operational testing.

4.2.3 Comparisons to CRATER

Comparisons between CRATER and the FALCON models using input currents equivalent to summer and winter sustained ratings (as defined in P17) are shown in Table 4.

	33kV (P17)	33kV MATLAB	33kV CRATER	11kV (P17)	11kV MATLAB	11kV CRATER
Sustained Summer	360A[2]	360A 64°C	360A 68°C	271A	271A 67°C	271A 68°C
Sustained Winter	403A	403A 60°C	403A 64°C	304A[3]	304A 64°C	304A 65°C

Table 4: CRATER/MATLAB code validation under fixed conditions

For the 33kV cable, Table 4 shows that for the nominal sustained summer rated current, CRATER calculated a cable temperature of 68°C, and the FALCON model calculated a temperature of 64°C. Therefore the FALCON model produces a value approximately 1°C lower than the nominally expected 65°C. This level of agreement is judged to be acceptable but on the 33kV cable MATLAB model might overstate dynamic rating by approximately 10A (2.5%). Similarly, values for 33kV cable winter rated current, and 11kV summer and winter rated current show acceptable correlation to the nominal 65°C limit, and good agreement to the accepted CRATER model.

Other key parameters used for model validation are shown in Table 5 - It is assumed that the cable is direct lay in ground, not ducted or grouped.

Season	Temperature (°C)	resistivity	Soil depth
winter	10°C	0.9[4]	11kV -0.8m (independent 0.6 -3m) 33kV – 0.9m
summer	15°C	1.2	11kV - 0.8m (independent 0.6 -3m) 33kV – 0.9m

Table 5: code validation parameters

Based on this work at was judged that the FALCON produced models gave acceptable results at nominal rated currents, with good agreement to accepted industry results from CRATER.

4.2.4 Comparison of calculated and measured cable temperatures

The data from the trial for each cable type was collected over a variety of periods as shown in Table 6.

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[2] This is from the Cable laying manual

[3] 334 A is the rating on the drawing – but it's not clear if this is distribution rating

[4] Diffusivity 5.3e-7 (winter) and 4.3e-7 (summer)

33kV – Bradwell Abbey	1st April 2014	20th June 2015
11kV – Jonathan’s	1st Dec 2014	30th July 2015
11kV - Jamaica	1st Dec 2014	30th July 2015

Table 6 : Cable trial period

The data collected up to July has been analysed using the offline thermal models and the key results are summarised in Section 5.

The model validation process compares the measured temperature of the cable with the calculated cable external temperature. As with other DAR techniques, sample one week periods, representing different seasons, have been used to assess the comparability of the calculated values to the measured values. The sample periods are shown in Table 7.

Season	Date (w/c)
Winter	5th Jan 2015
Spring	9th Mar 2015
Summer	8th Jun 2015
High Summer	21st Jul 2014
Autumn	3rd Nov 2014

Table 7 :Weeks for closer study

33kV cable

Long term traces of calculated and measured values of 33kV cable temperature are shown in Figure 19. In addition, results of the sample weeks providing a higher time resolution are shown in Appendix F.1.

From Figure 19 the results show that the measured external temperature and calculated temperature of the 33kV cable agree to within 5^{o}C over 98% of the time. This is despite the use of soil resistivity assumptions. The calculated and reported external sheath temperatures, vary depending on the time of year, but largely follow a curve similar to soil temperature variation.

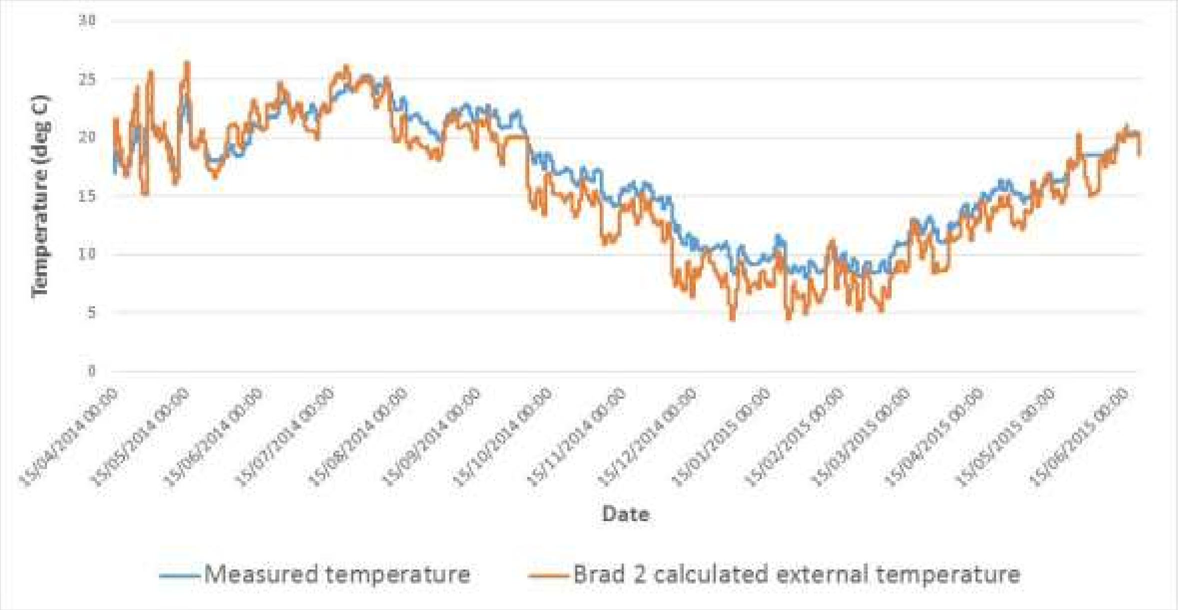


Figure 19 : 33kV measured and calculated temperature from April 2014 to June 2015 for 33kV Bradwell cable 2

A close up of Figure 19 is shown in Figure 20. The difference between the measured and calculated temperature of the 33kV cable is small. The two 33kV cables had similar results so only cable 2 values are presented here.

Also in Figure 20, the thermal time constant for the modelled external sheath temperature is lower than the measured, and the calculated value reacts more quickly to changes in load profile. This can be seen by the peaky nature of the calculated external temperature (referred to as Brad 2 External temp) that matches load curve shape compared to the smoother measured values.

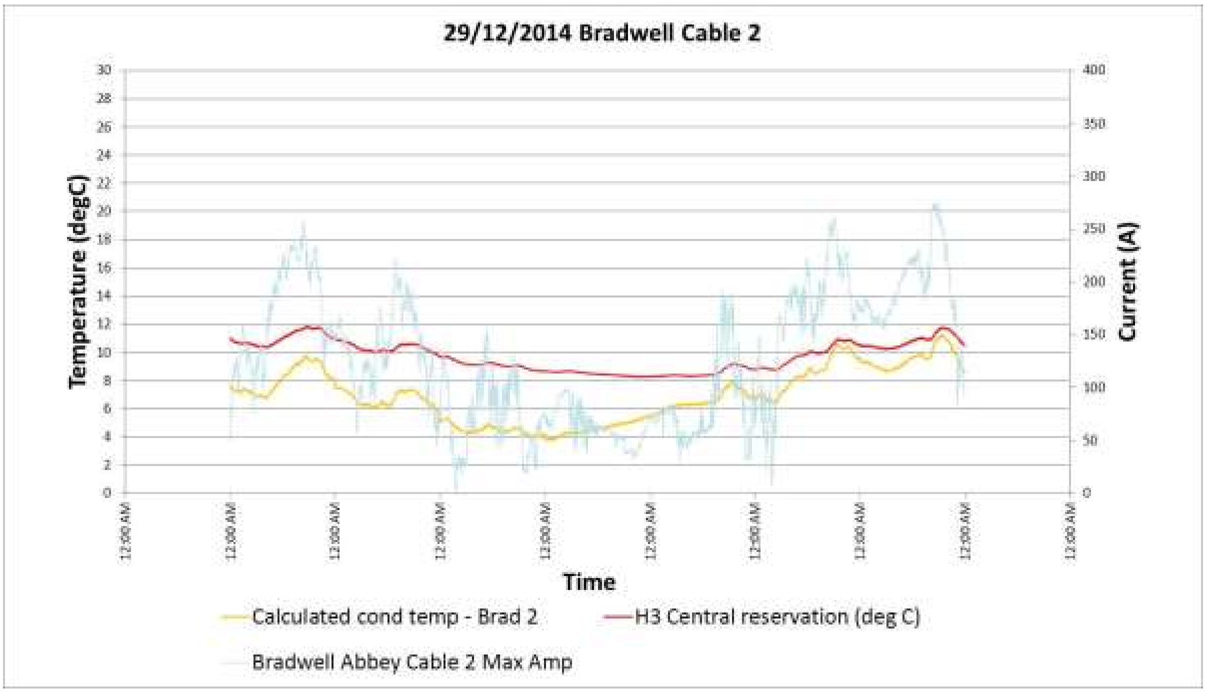


Figure 20 : 33kV measured and calculated temperature from 29/12/2014 for Bradwell Abbey cable 2

It should be noted that the value of external cable temperature is only just above soil ambient temperature and indicative of the low loading of the cables. It is assumed that this level of accuracy is present at higher loading from comparison to CRATER (section 4.2.3).

11kV cable

Long term traces of calculated and measured values of 11kV cable temperature are shown in Figure 21. In addition, results of the sample weeks providing a higher time resolution are shown in Appendix F.2.

Figure 21 shows good correlation between the calculated temperature of the cable and the measured value (5°C, 90% of the time).

Inspection of the sample week data for w/c 5th January 2015 (Figure 22) show a number of interesting features. The load curve can clearly be seen to sharply reduce during the traditional evening load pickup, which is believed to be due to a large connected load practicing triad cost reduction. This reduction in load can be seen to correlate to a measured reduction in cable temperature, which the model replicates (though to a slightly larger extent).

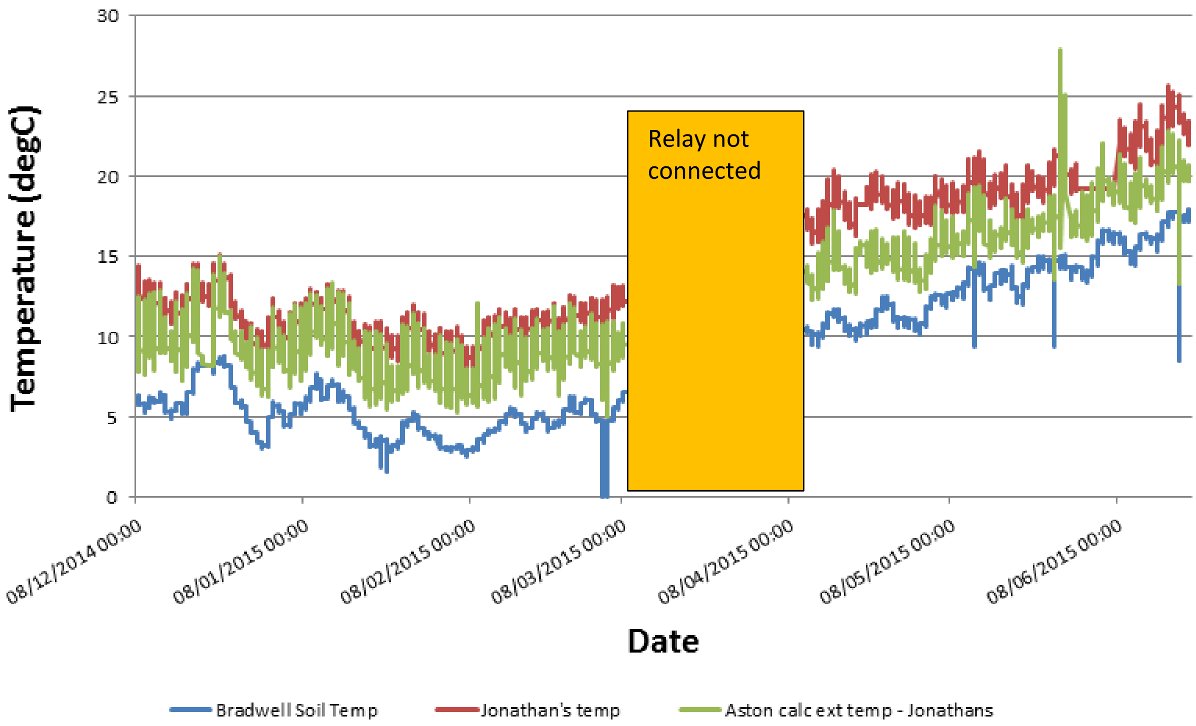


Figure 21 : 11kV measured and calculated temperature from Jan 2015 to June 2015 for Jonathan's

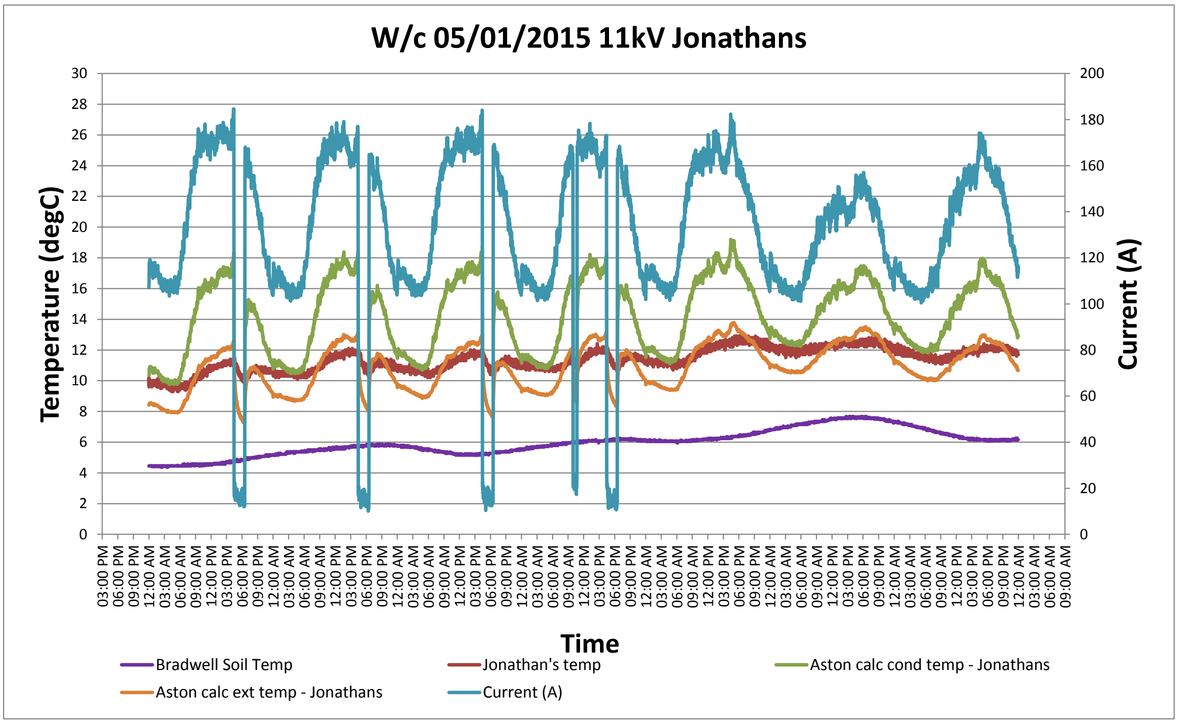


Figure 22 : 11kV measured and calculated temperature from Jan 2015 to June 2015 for Jonathan's

The results from this trial indicate that although the model is sensitive to soil resistivity, using a constant value throughout the year (as is the case in this modelling) it does not have a significant impact on the correlation between calculated and measured cable temperatures.

Based on the long term correlation (Figure 21), correlation in high-resolution traces (Figure 22), the modelling of the trial 11kV cable is regarded as fit for purpose.

4.3 Key learning from cable thermal modelling

Thermal models provide a good means of determining calculated external sheath temperature which largely matches measured conditions.

LP 11.	Cable thermal models were the most complex of the dynamic asset rating techniques to understand and code, construct, modify and validate. Future work in this area should make due resource allowance for this complexity.

LP 12.	Models appear to give good correlation to external cable temperature measurements. However the cable load is very low and temperature rises are consequently small.

LP 13.	Although modelling is sensitive to soil resistivity, using a constant value does not impact on the long term calculation of cable external temperature. This suggests that this measurement could be ignored and a constant value used.

SECTION 5

Dynamic Asset Rating

5.1 Approach to offline calculation of Cable DAR

5.1.1 Dependency on assumed load current profile

Cable DAR principally depends on:

- The heating effect of the cable load current;
- Soil characteristics that remain fixed over time (e.g. soil composition), and soil parameters that vary with time (e.g. soil temperature and soil moisture/thermal resistivity); and
- The high thermal inertia of the cable soil system:
  - Changes in heat input can happen quickly, (i.e. changes in cable load), but these take some hours to fully affect cable temperatures; and
  - Changes in the rate that heat is dissipated through the soil occur over weeks and seasons at typical cable burial depths.

Calculating the dynamic rating of an asset requires establishing the highest load current that could flow through an asset whilst not breaching key thermal limits. This current could be a fixed value or varying with time. For cables, because of the larger thermal time constants (described above), it is necessary to consider the profile of load that is assumed.

Different profiles can result in the same heating effect (over a given time period), but have markedly different values of peak current in the profile. For a given heating effect, a time varying (cyclic) load profile will have a higher peak value than the equivalent constant (sustained) load profile. The peak current for a given load current profile is the value quoted as “rated current”.

Similarly, a cable’s dynamic asset rating (i.e. rating that accounts for the prevailing thermal state of the cable, and the soil conditions) will tend to be higher if the load current profile has a varied (cyclic) character, compared to a load profile that is essentially constant (sustained) in character. This fundamental associated with the rating of cables is illustrated in P17 (Table 11), typically a 185mm2 cable’s sustained rating would be approximately 89% of the cyclic rating.

Therefore, for an array of experienced soil parameters (temperature etc.), the dynamic rating of a cable requires an assumed load current profile to be used. The assumed load current profile affects the resultant DAR. Throughout Section 5, a sustained load current profile will be used.

5.1.2 Look-up table approach to DAR calculations

Due to the time consuming nature of the cable code to run it is not feasible to calculate the ampacity in the same way that it was determined for the transformers and overhead lines. The offline model struggles to directly calculate a rating due to a matrix sizing issue. Therefore a different approach has been used. The developed FALCON thermal model has been used to produce a look-up table such that the rating of the cable at a particular soil temperature and resistivity has been calculated in advance using the model. The ampacity of the cable over the course of the trial can then be calculated using this look-up table to estimate the “of the moment” ampacity from the trial reported soil temperature data.

Further details of the resulting linear relationships between ampacity and soil temperature (for a fixed thermal resistivity) and ampacity and soil thermal resistivity (for a fixed soil temperature) are discussed in Appendix G.

5.2 33kV cable offline DAR results

Calculated 33kV DAR results are shown in Figure 23 as a long term trace over time, with comparison to P17 seasonally adjusted static ratings.

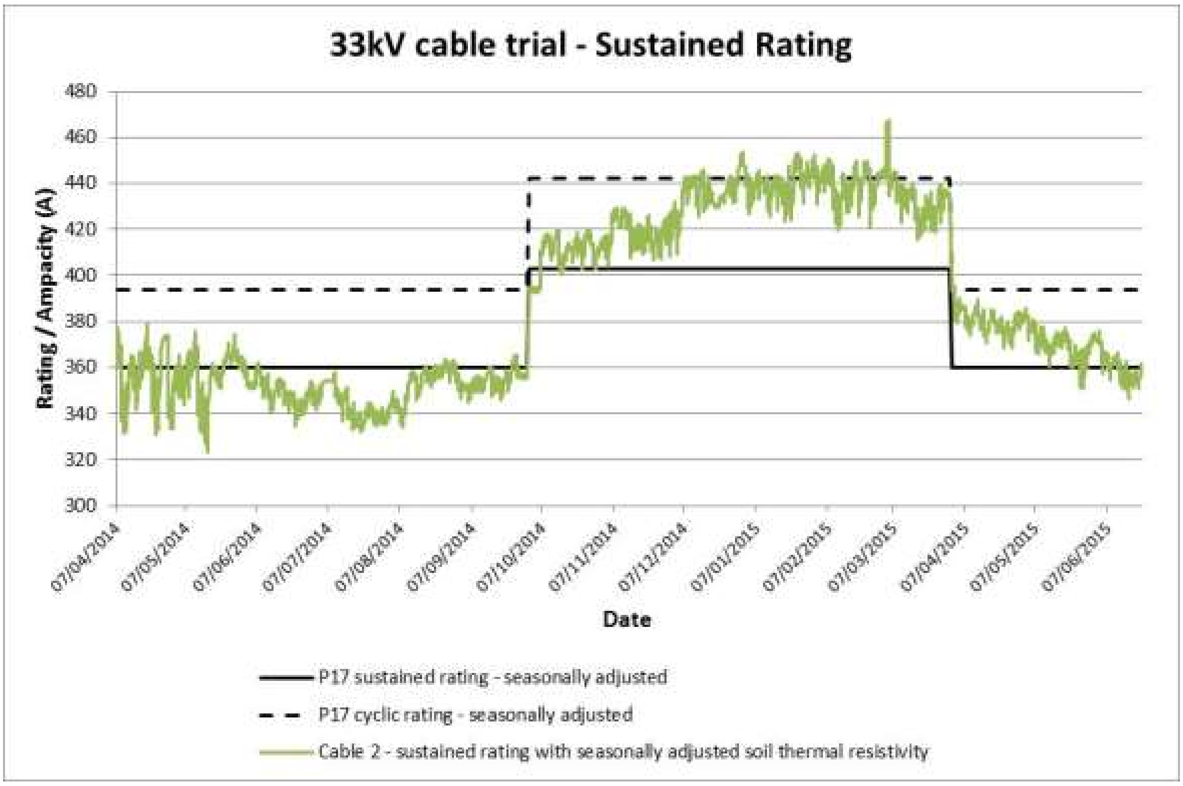


Figure 23 : 33kV cable DAR vs P17 seasonally adjusted ratings

From Figure 23 it can be seen that:

- Analysed data covered the period April 2014 to June 2015;
- DAR values are mostly below the P17 seasonally adjusted rating during the summer months, and mostly above the P17 rating in the winter months. Experienced summer soil temperatures are up to 5°C above the static value used within P17, therefore it could be expected that the DAR values are lower in summer than the static values;
- The calculated DAR is above the P17 seasonally adjusted sustained current rating in winter (as would be expected because the experienced soil temperature is mostly lower than the seasonally adjusted assumed value);

- It appears that there is a phase shift between the dynamic rating and the P17 seasonally adjusted rating.

The same underlying DAR data is presented in Figure 24, averaged over month periods, with maximum and minimum DAR values shown as error bars.

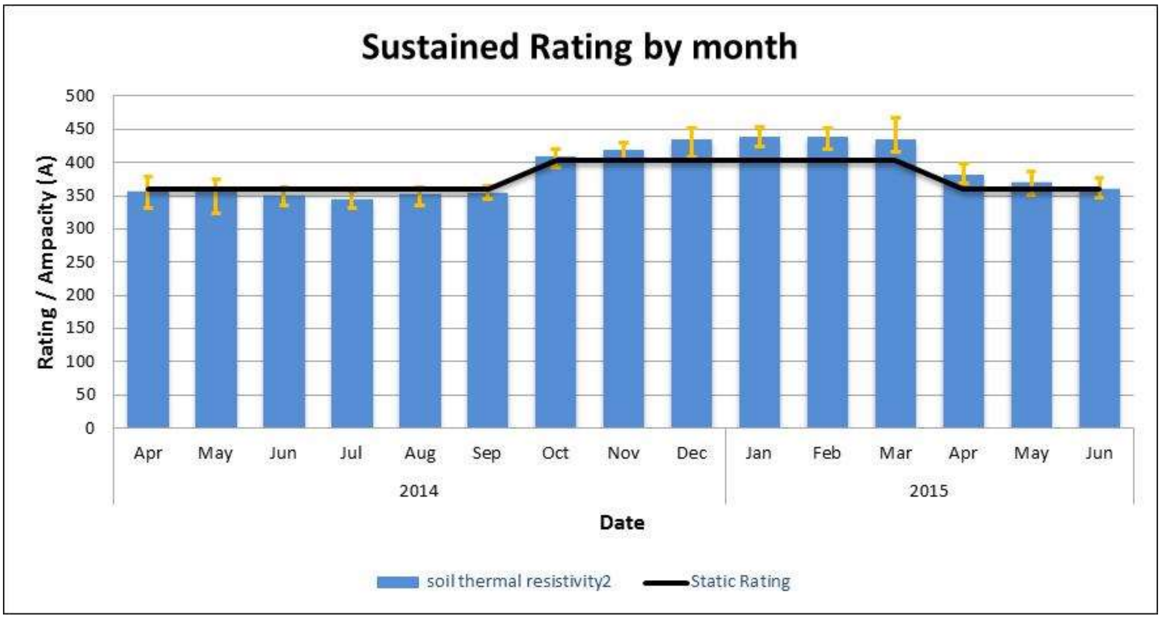


Figure 24 : 33kV Trial Cable Dynamic Asset Rating, averaged by month

From Figure 19 and the underlying data it can be seen that:

- The presented mean monthly DAR is mostly above the P17 seasonally adjusted rating. It should be noted that September 2014 was unseasonably warm (as noted in other DAR reports) which arguably delayed the ordinary seasonal reduction in soil temperature leading to a mean in October that is close to seasonally adjusted rating;
- Cable DAR is 102% of the P17 seasonally adjusted sustained rating over the 14 month period; and
- Gains over P17 for the winter period, October to March (inclusive), averaged 107% of the seasonally adjusted P17 rating

Further comparisons between the 33kV trial cable’s dynamic rating (using sustained current profiles) and relay ratings are presented in Appendix H.

Some investigation of cyclic ratings has been carried out. The work suggests that any cyclic rating taken from P17 may be overestimated, unless adequate account is taken of the experienced load curve shape. This is because P17 cyclic ratings are based on load curve G. The 33kV trial cables all experienced a load curve shape similar to that shown in Figure 25, where the minimum experienced load was greater than the load curve G minimum current. These differences in load current profile can be quantified through Loss Load Factors as shown in Table 8.

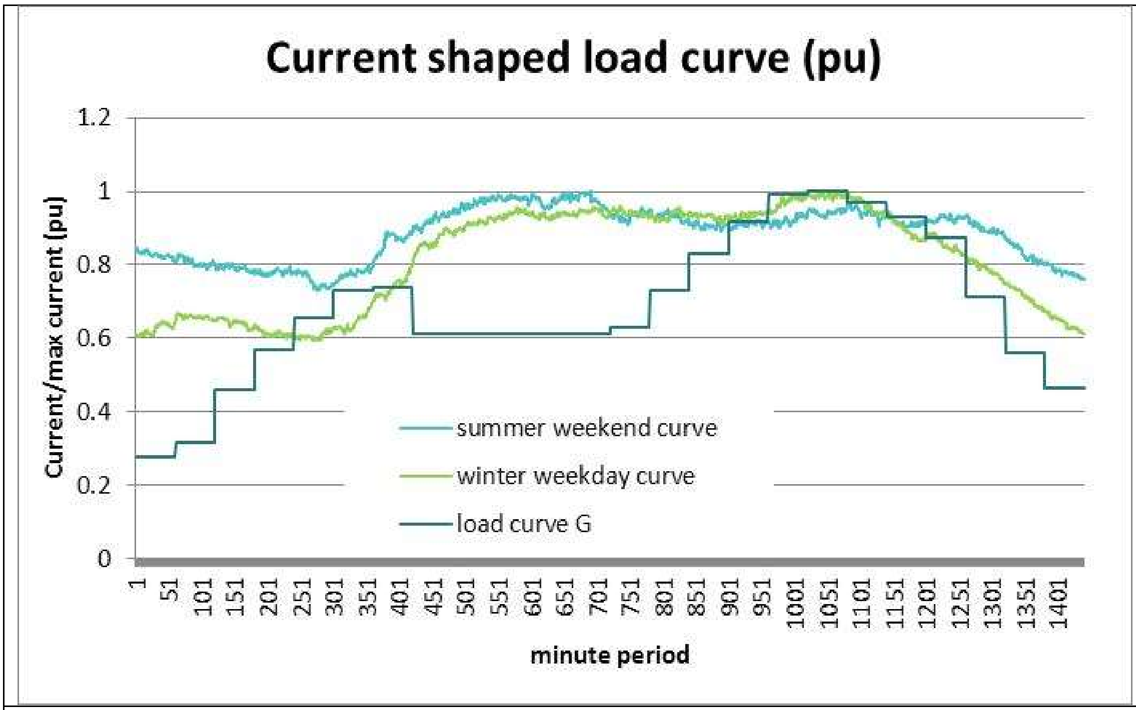


Figure 25 : 33kV Load curve shape

Load shape	Loss load factor
Load Curve G	0.51
33kV Cable Summer Weekend Curve	0.79
33kV Cable Winter Weekday Curve	0.70

Table 8 : 33kV load shape against loss load factor

Within P17, correction factors based on loss load factor indicate that the rating should be modified by a factor of 0.94 (for a winter weekday load shape) and 0.91 (for a summer weekend load curve shape).

5.3 11kV cable offline DAR results

Calculated 11kV DAR results are shown in Figure 26 as a long term trace over time, with comparison to P17 seasonally adjusted static ratings.

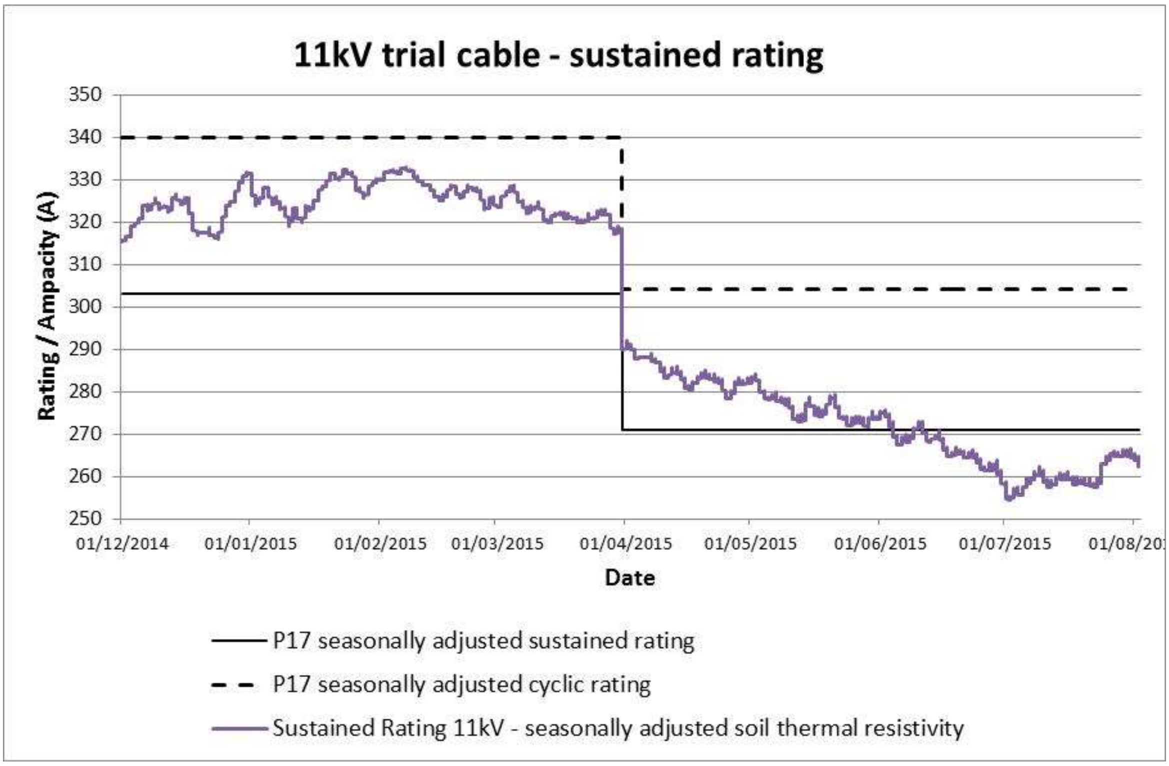


Figure 26 : 11kV cable DAR vs P17 seasonally adjusted ratings

From Figure 26 it can be seen that:

- Analysed data covered the period April 2014 to July 2015;
- The calculated DAR Sustained rating (with seasonally adjusted soil resistivity) is above the P17 static sustained current rating in winter (as would be expected because the experienced soil temperature is mostly lower than the seasonally adjusted assumed value);
- The calculated DAR Sustained rating (with seasonally adjusted soil resistivity) summer rating is below the P17 static sustained rating throughout the warmer months as the soil temperature exceeds that used in the P17 calculation. This is similar to the 33kV results from the previous year.

The underlying DAR data associated in Figure 26 is alternatively presented in Figure 27, with DAR values averaged over month periods, and showing maximum and minimum DAR values shown as error bars.

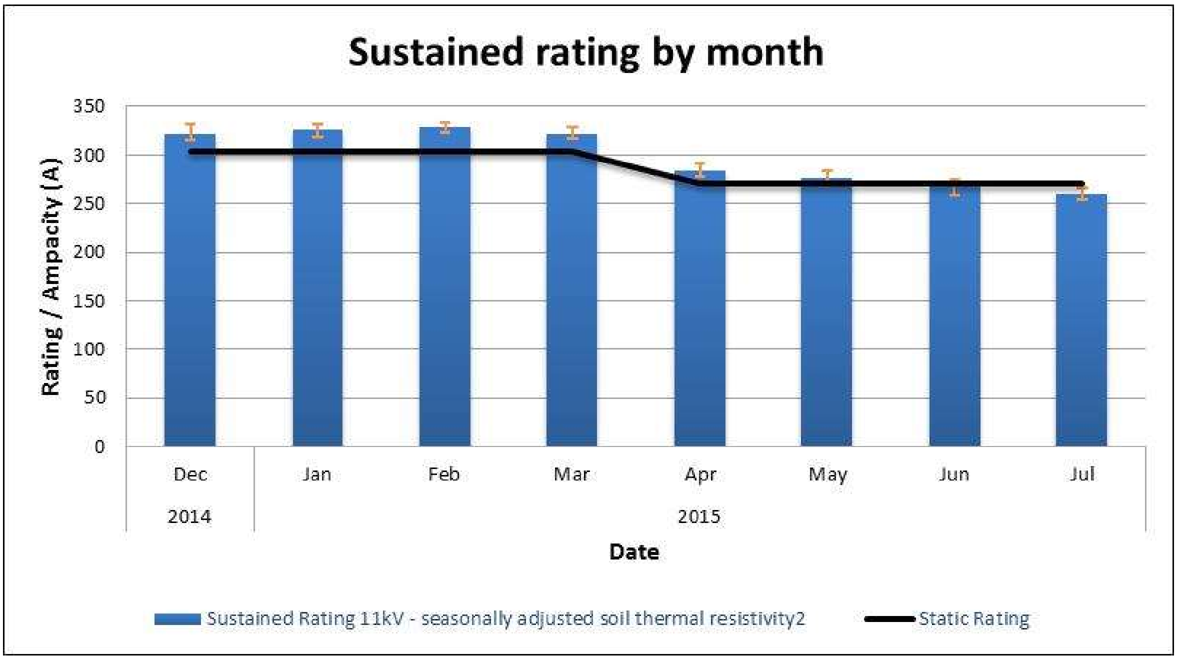


Figure 27 : 11kV Trial Cable Dynamic Asset Rating, averaged by month

From Figure 27 and the underlying data it can be seen that:

- The mean monthly DAR Sustained rating (with seasonally adjusted soil resistivity) based on the Winter load profile is always above the P17 seasonally adjusted rating;
- Cable DAR Sustained rating (with seasonally adjusted soil resistivity) is 103% of the P17 seasonally adjusted sustained rating over the 8 month period.
- Cable DAR Sustained rating (with seasonally adjusted soil resistivity) is 107% of the P17 seasonally adjusted sustained rating over the winter period.

Some investigation of cyclic ratings has been carried out. The work suggests that any cyclic rating taken from P17 may be overestimated, unless adequate account is taken of the experienced load curve shape. This is because P17 cyclic ratings are based on load curve G (a typical load curve shape used to help set cyclic ratings). An interesting difference in the 11kV winter weekday load curve shape (compared to 33kV load curve shape) can be seen in Figure 28, where the effect of the large load reduction changed the load curve shape and brought the Loss Load Factor for the winter more in line with that of Load curve G as shown in Table 9. The implication of this is that manipulating load curve shape is possible, e.g. through some demand management strategies, and can be used to impact the cyclic rating of the cable.

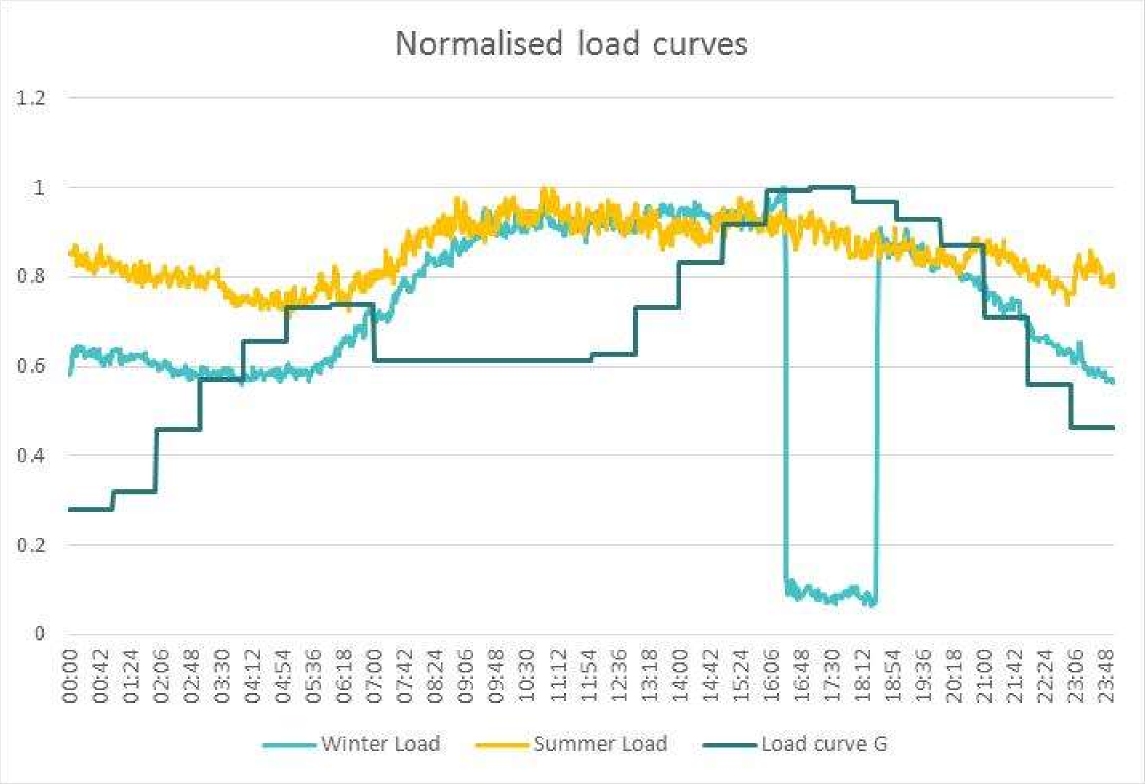


Figure 28 : 11kV Load curve shape

Load shape	Loss load factor
Load Curve G	0.51
11kV Cable Summer Weekend Curve	0.74
11kV Cable Winter Weekday Curve	0.56

Table 9 : 11kV load shape against loss load factor

Within P17, correction factors based on loss load factor indicate that the rating should be modified by a factor of 0.97 (for a winter weekday load shape) and 0.92 (for a summer weekend load curve shape).

5.4 Comparisons between offline and online relay DAR

The rating of the cable generated by the Alstom relay was compared against that generated by the Offline model and P17. The relay output appears to work by using a pre-entered static rating of the cable and increasing this, for example, when the soil temperature is colder than the assumed value in from the static rating calculation. However, only one value of rating is entered (which aligns to either summer or winter rating, but not both). It should be noted that the Alstom relay doesn't directly calculate external cable temperature only a new rating value and consequently there is no thermal model behind the Alstom relay – only an adjustment.

5.5 Key Learning

The following lessons have been learnt in the process;

LP 14. Static sustained summer rating calculations are based on a soil temperature of 15°C. However, the results in July show a soil temperature that is 5°C above this value. This may therefore results in a loss of calculated capacity compared to static capacity depending on soil resistivity. This is in keeping with the results from the modelling which suggests that the gains in ampacity are mostly realised in winter at low soil temperatures.

LP 15. Load curve shape can have an impact on cyclic ratings. However the load curves typically seen on a Network have a higher minimum load and as such the ampacity is lower than for a standard load curve shape G.

LP 16. Load curve shape used to calculate cyclic ratings should be reviewed in line with more up-to-date typical Network data.

LP 17. The load curve shape means that there is less benefit to cyclic rating than sustained rating over the winter months. Further investigation is needed.

LP 18. Knowledge of temperatures at a single location is not sufficient to set the full cable rating as the worst case (ducting/adjacent cables/burial depth etc.) needs to be known to ensure the rating of the cable is correct.

LP 19. There is scope to manipulate the load curve shape through alternative techniques such as demand side response to help with cyclic rating.

SECTION 6

Forward Ampacity

6.1 Overview of forward ampacity

“Of the moment” ampacity may not be useful from an operations perspective as to take advantage of ampacity it is necessary to know what this is going to be in future time periods. Estimation of future dynamic ratings, forward ampacity, involves forecasting future operating conditions, applying these forecast conditions to the established DAR estimation process, and retrospectively assessing the accuracy through comparison with “of-the-moment” ampacities based on the actual conditions that were experienced. Potentially, forward ampacity estimation requires the introduction of a probabilistic approach to manage the key risk of exceeding a thermal limit due to the inherent uncertainty that forecast operating conditions did not match experienced operating conditions.

6.2 Approach to estimation of forward cable ampacity

Given cable DAR’s dependence on relatively slow moving (at depth) soil parameters, it was anticipated that estimation of forward ampacity would not be as challenging as for overhead lines, and unlikely to require the incorporation of probabilistic approaches (as required for OHLs).

However, soil temperature forecasts are not widely available (as general ambient weather conditions are); they are usually only of interest to small specialised groups of people such as farmers or ground source heat designers. Therefore predictions of soil temperature tend to be from specialist providers, and were not reasonably available to the project.

Given the relative unavailability of forecast soil temperatures, the feasibility of estimating forward ampacity, over relatively short forward periods (up to 48 hours), using measured soil temperatures was investigated. Initial inspection of soil temperature data from the trial showed that soil temperatures changed by only up to 1^{o}C per day. This magnitude of variation in soil temperatures leads through to only small changes in cable ampacity.

Therefore, estimates of forward cable ampacity were prepared on a daily basis (at 10:00am), for a period of 24 hours ahead and 48 hours ahead, based on the soil temperature measurement at the time that the forward ampacity estimate was made.

The results of these estimates are presented and discussed in Section 6.3.

It should be noted that all of the experienced issues with soil temperature measurement still apply to the estimation of forward cable ampacities, as discussed in Section 3.2.3.

6.3 Estimated forward cable ampacity

6.3.1 33kV cable

Figure 29 and Figure 30 show the predicted sustained ampacity against the of-the-moment ampacity based on actually experienced soil temperatures. There is no obvious benefit in the summer months – but the benefit within winter months remains largely unchanged.

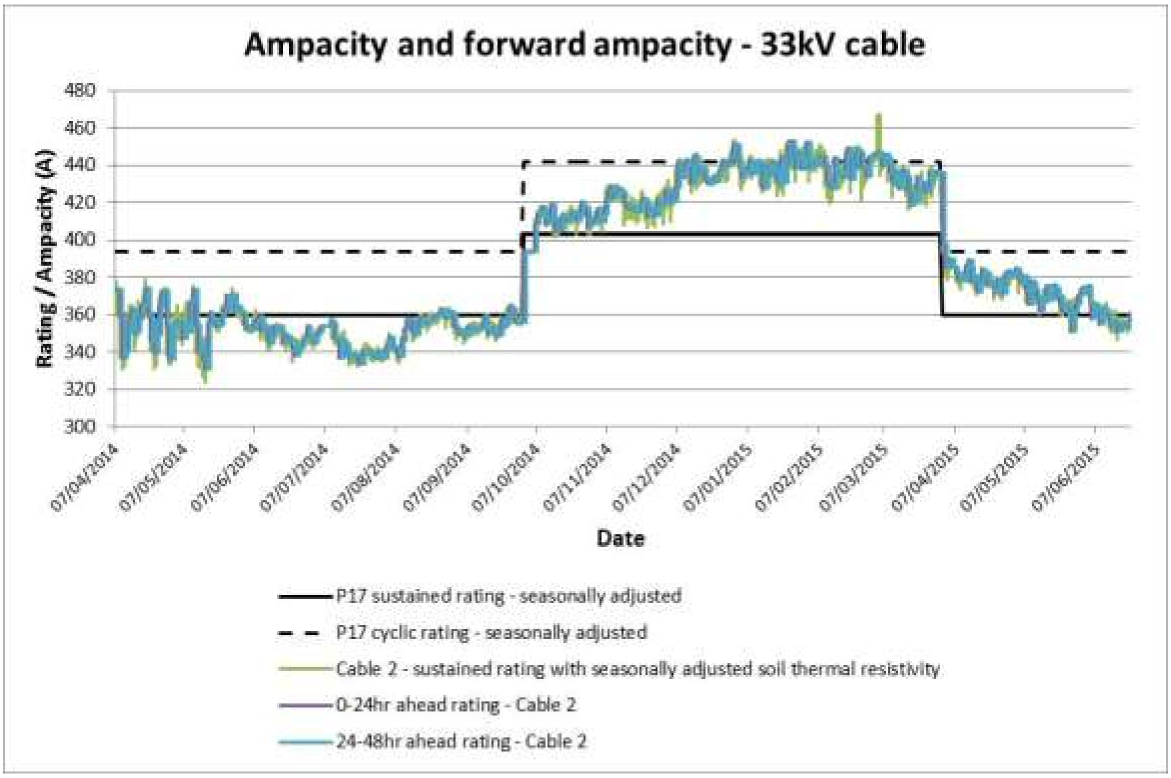


Figure 29 : Ampacity and forward ampacity for 33kV trial cable

From Figure 29 it can be seen that:

- The forward ampacity values can be seen to be less variable than the of-the-moment ampacity, as would be expected (the forward ampacities have a fixed soil temperature of the 24 hour period ahead)
- Overall correlation between of-the-moment and forward ampacities is very good, indicating that fixing soil temperature for the purpose of estimating forward ampacity provides a strong forward indicator;

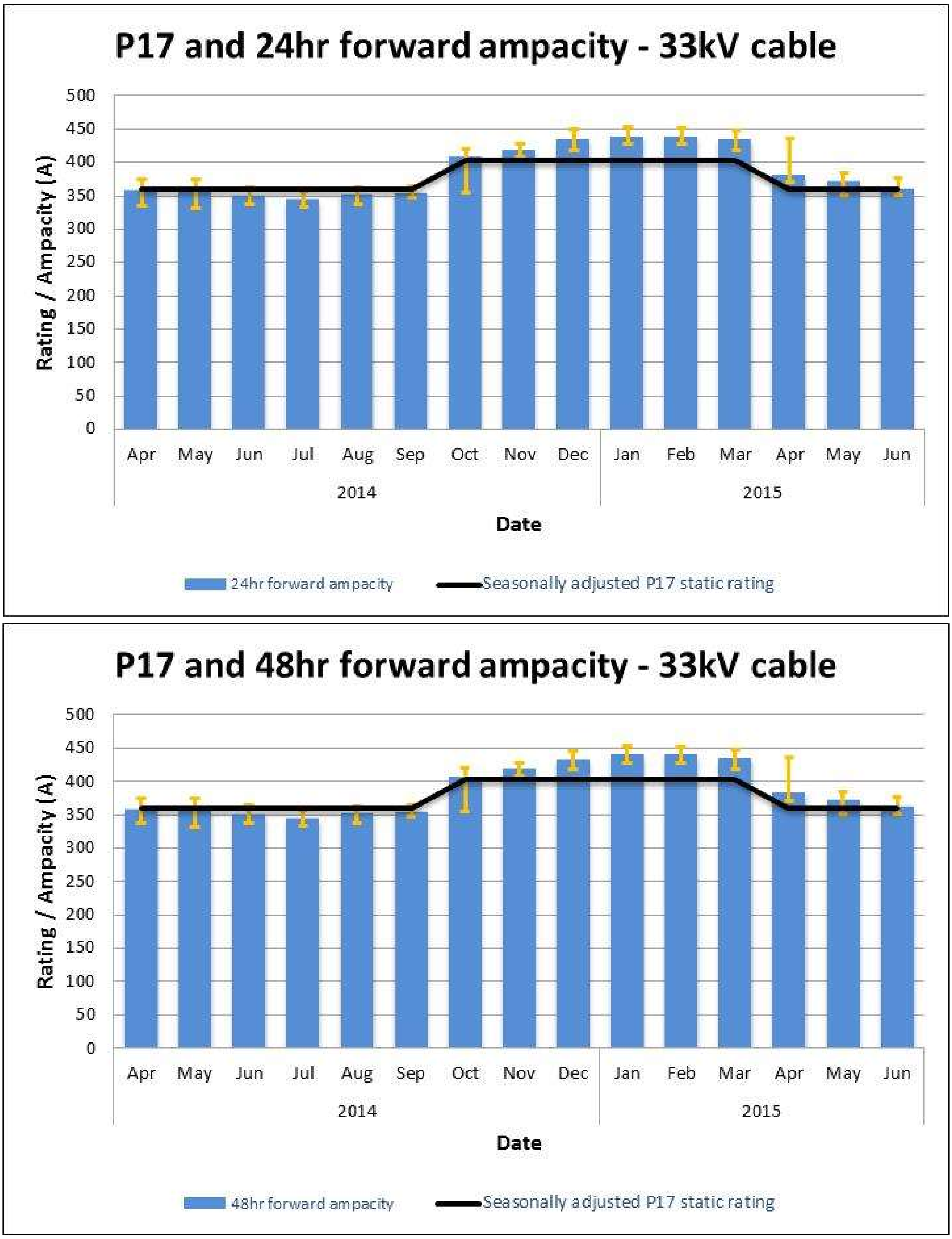


Figure 30 : 24hr and 48 hr forward ampacity – Cable 2

From Figure 30 and the underlying data it can be seen that:

- The presented mean monthly DAR is mostly below the P17 seasonally adjusted rating during the summer months, and mostly above the P17 rating in the winter months (following the trend of the of-the-moment ampacity);
- Cable DAR is 102% of the P17 seasonally adjusted sustained rating over the 14 month period; and
- Gains over P17 for the period November to April (inclusive) averaged 107% of the seasonally adjusted P17 rating

In order to guarantee that the predicted ampacity is within 95% of the of-the-moment ampacity it is necessary to include an error margin on the predicted ampacity. Figure 31 shows the difference between the of-the-moment ampacity and the forward predicted ampacity. This can be used to determine an error margin to be subtracted from the forward predicted ampacity to guarantee a 95% confidence that this rating is not over estimated. The value of error margin is 8A for the 24 hour ahead prediction and 12A for the 48hr ahead prediction (this is higher in keeping with the greater uncertainty resulting from predicting further into the future). This reduces the available benefit to an average of 105% and 104% for 24hr ahead and 48hr ahead predicted ampacity respectively over the winter period as shown in Figure 32.

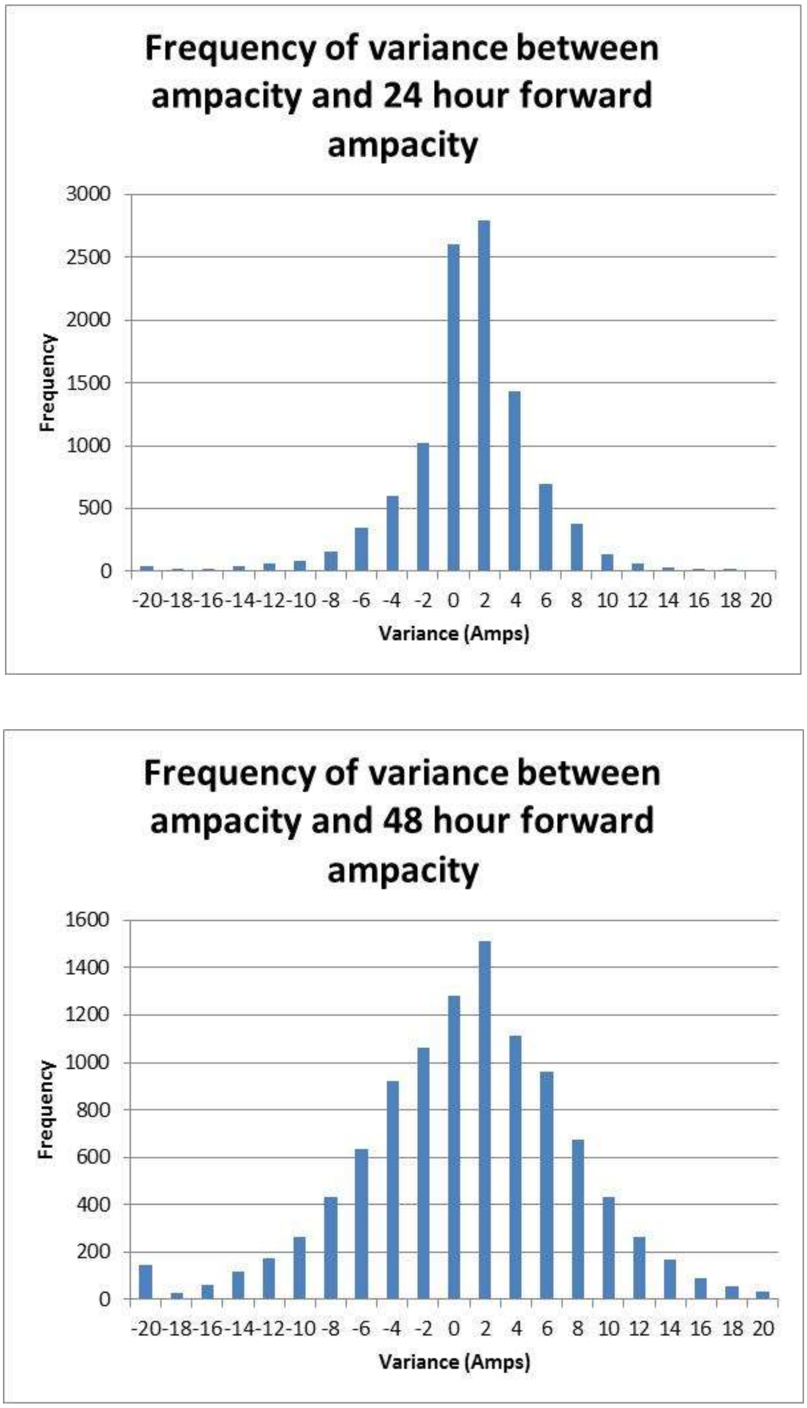
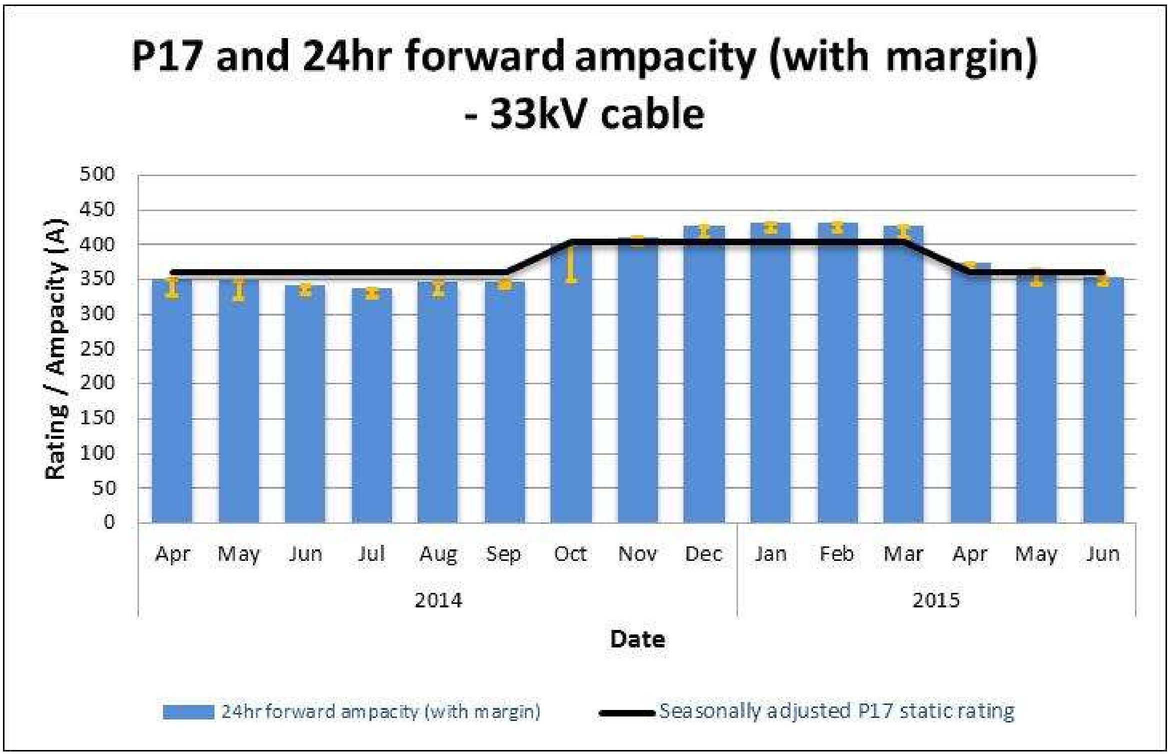


Figure 31 : Frequency of variances between ampacity and forward ampacities – 33kV trial cable 2



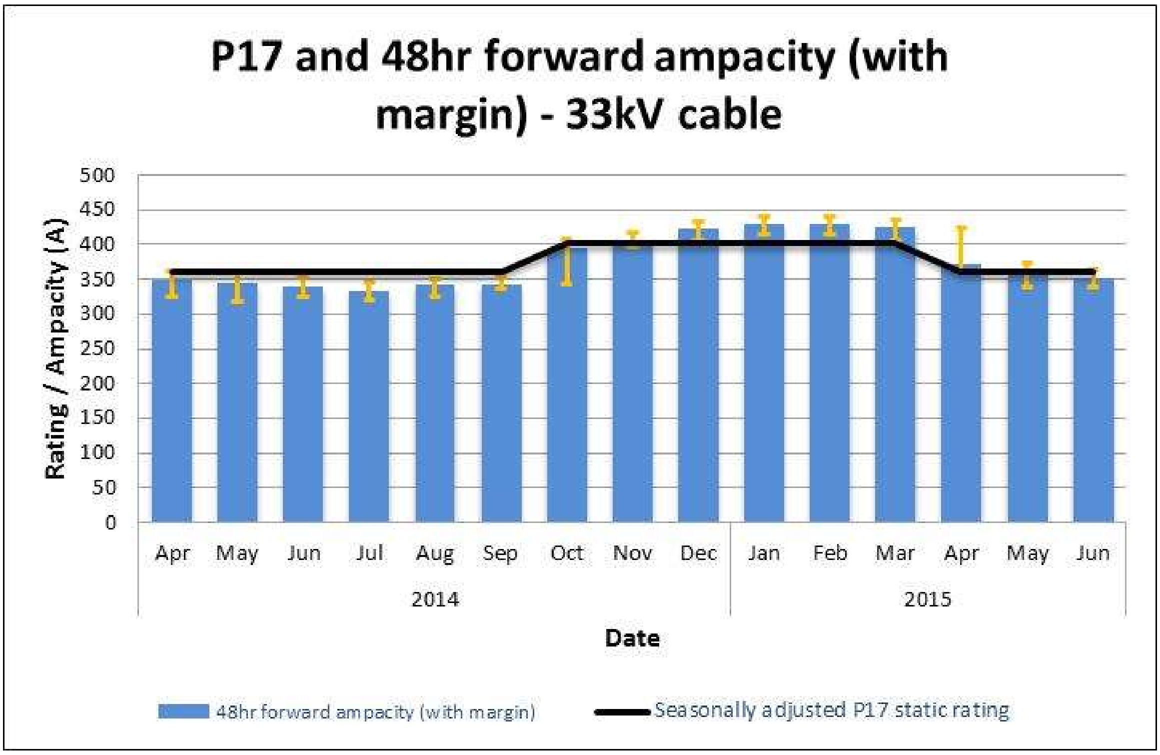


Figure 32 : 24hr and 48 hr forward ampacity – Cable 2

6.3.2 11kV Cable

A similar set of results were produced for the 11kV cable.

Figure 33 shows the predicted sustained ampacity against the of-the-moment ampacity based on actually experienced soil temperatures. There is no obvious benefit in the summer months – but the benefit within winter months remains largely unchanged.

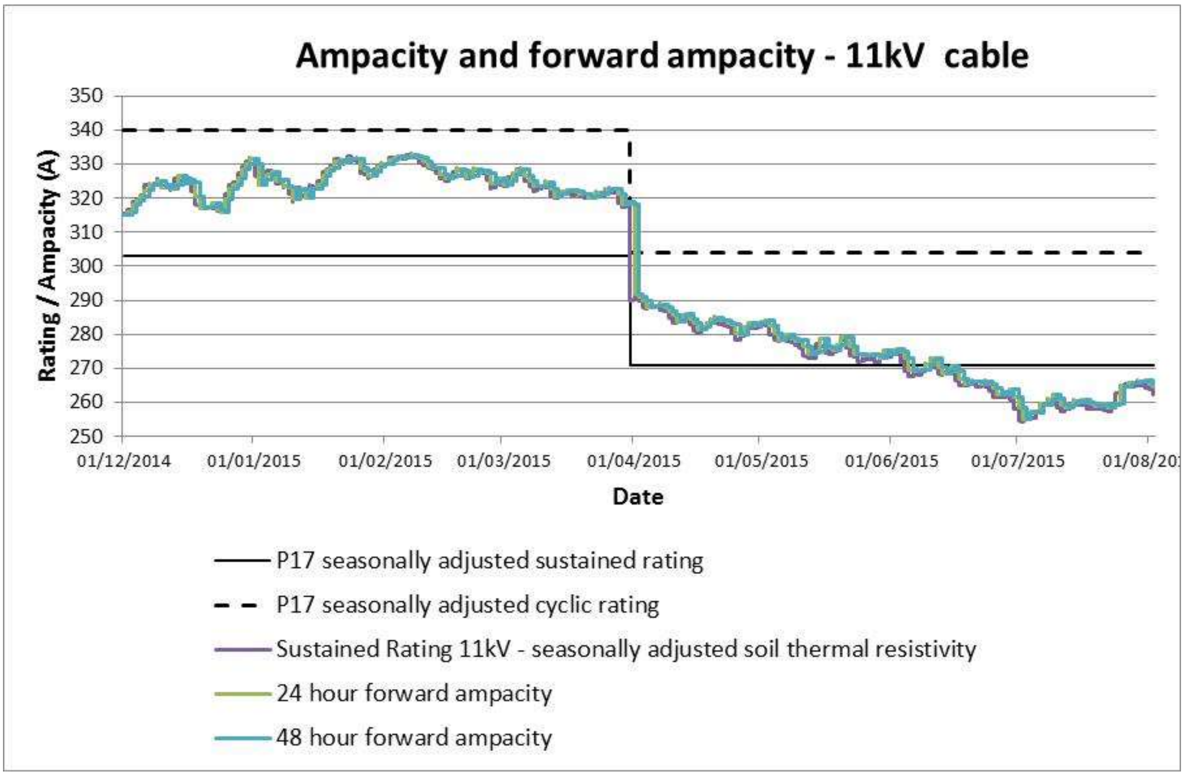


Figure 33 : Ampacity and forward ampacity for 11kV trial cable

From Figure 33 it can be seen that:

- The forward ampacity values can be seen to be less variable than the of-the-moment ampacity, as would be expected (the forward ampacities have a fixed soil temperature of the 24 hour period ahead)
- Overall correlation between of-the-moment and forward ampacities is very good, indicating that fixing soil temperature for the purpose of estimating forward ampacity provides a strong forward indicator;

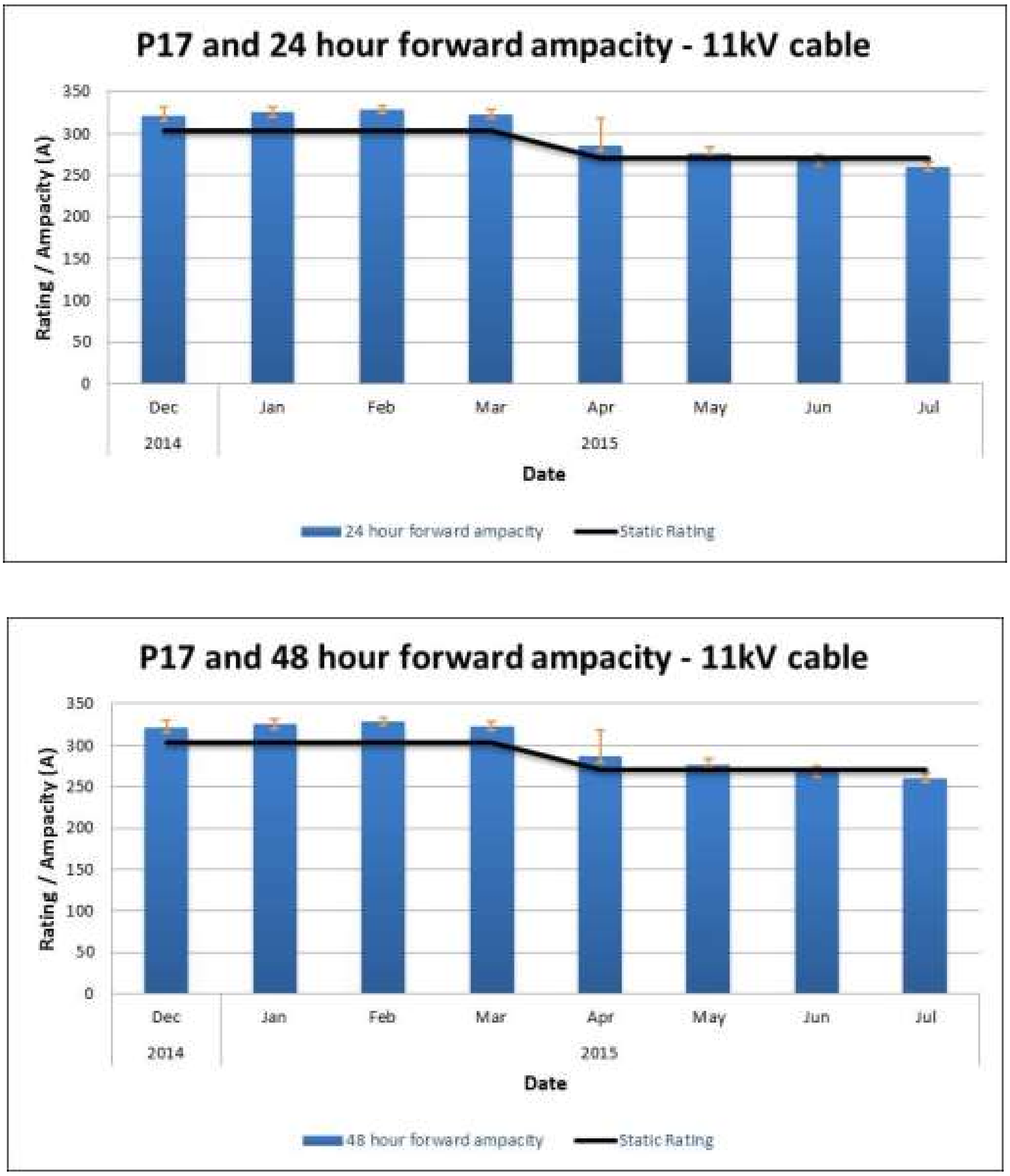


Figure 34 : 24hr and 48 hr forward ampacity – 11kV Cable

From Figure 34 and the underlying data it can be seen that:

- The presented mean monthly DAR is mostly below the P17 seasonally adjusted rating during the summer months, and mostly above the P17 rating in the winter months (following the trend of the of-the-moment ampacity);
- Cable DAR is 103% of the P17 seasonally adjusted sustained rating over the 8 month period; and
- Gains over P17 for the period December to March (inclusive) averaged 107% of the seasonally adjusted P17 rating

In order to guarantee that the predicted ampacity is within 95% of the of the moment ampacity it is necessary to include an error margin on the predicted ampacity. The value of error margin is 3A for the 24hour ahead prediction and 4A for the 48hr ahead prediction (this is higher in keeping with the greater uncertainty resulting from predicting further into the future). This reduces the available benefit to an average of 107% and 106% for 24hr ahead and 48hr ahead predicted ampacity respectively over the winter period.

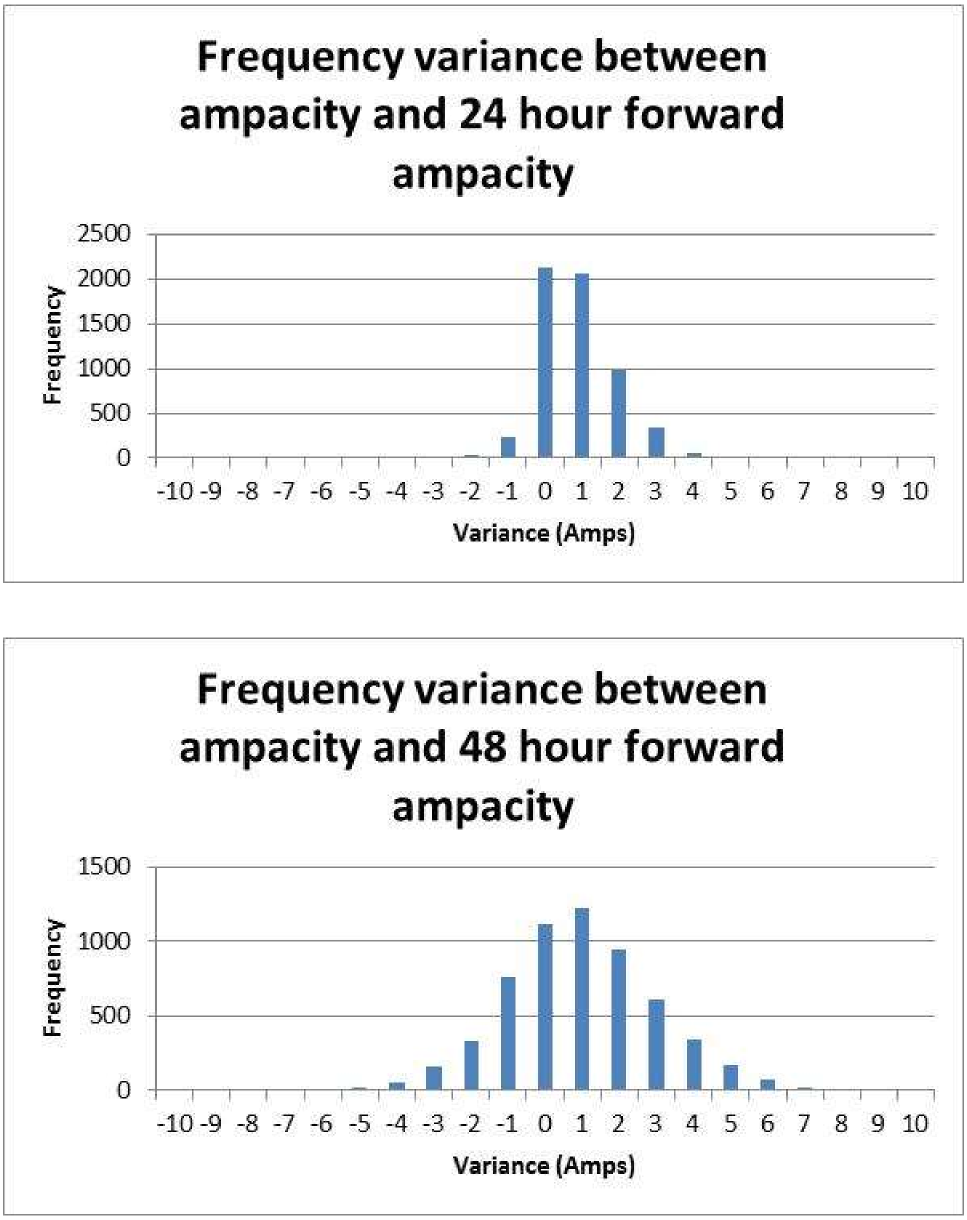


Figure 35 : Frequency of variances between ampacity and forward ampacities – 11kV trial cable

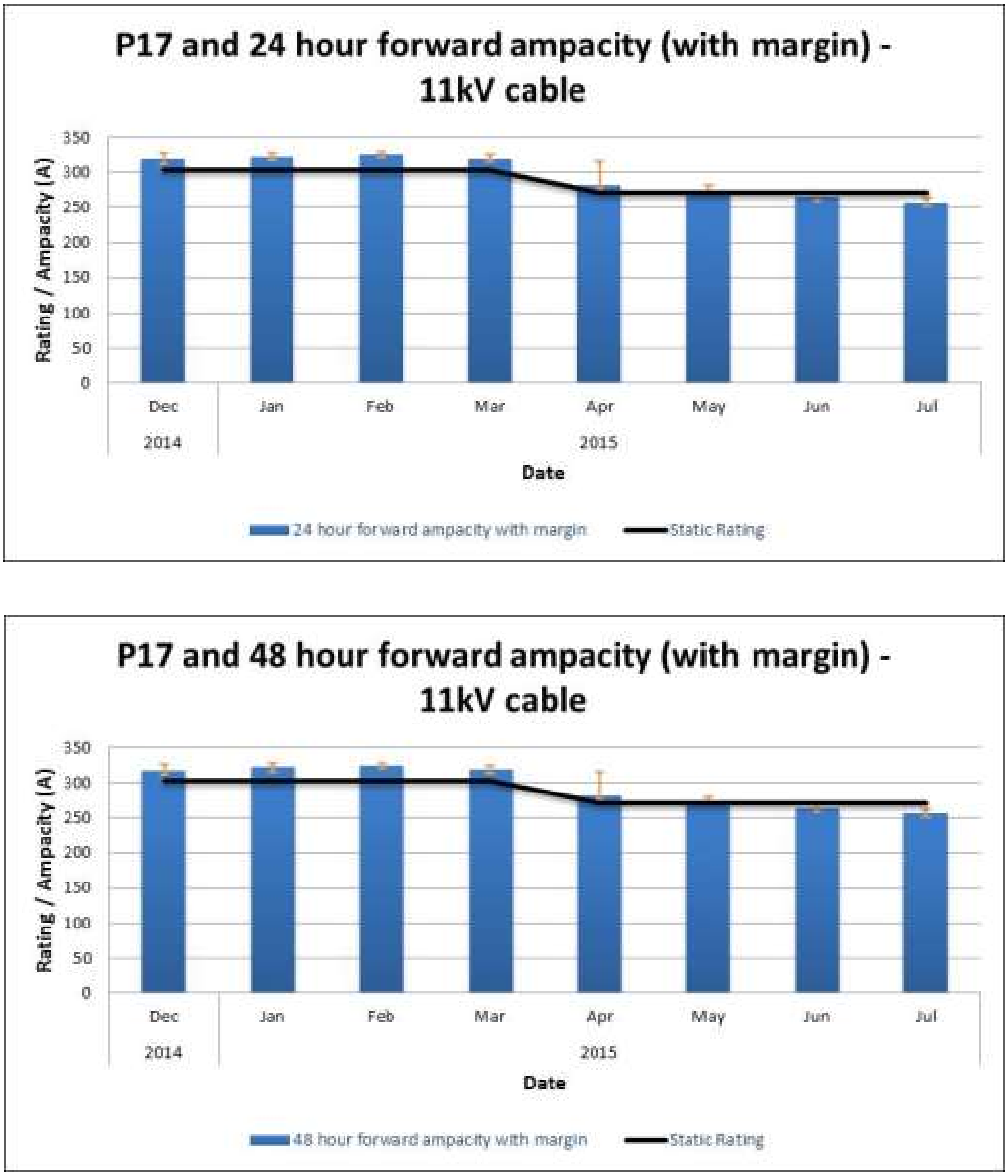


Figure 36 : 24hr and 48 hr forward ampacity – 11kV Cable

6.4 Key learning

LP 20.	It is difficult to use forecast data to obtain a forecast ampacity because of lack of data available at the soil depth required

LP 21.	A new method of estimating ampacity based on previous readings has been theoretically trialled and offers a promising means of predicting the ampacity up to 48 hours ahead based on "of the moment" data. Further investigations would

	be required to assess this for business as usual suitability with better instrumentation of soil resistivity.

LP 22.	Predicted average forward ampacity benefits (inclusive of correction factor) over winter of 105% and 107% for the 33kV and 11kV trial cables respectively have been calculated.

LP 23.	The predicted forward ampacity requires a modest correction for variance experienced between the “forecast conditions” and “experienced conditions”.

SECTION 7

Cross-technique Comparison[5]

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[5] This section is common to all the engineering technique Final Reports.

Table 10 provides a high level summary of which techniques impact what network metric, with the remainder of the section providing comparison of the DAR Cable technique with other trials, on a network-metric basis.

	DAR - OHL	DAR-Tx	DAR-Cables	ALT	Mesh	Energy Storage
Thermal limits /capacity headroom	✓	✓	✓	✓	~	✓
Voltage limits	No impact	No impact	No impact	✓	~	✓
Fault levels	No impact	No impact	No impact	No impact	×	×
PQ	No impact	No impact	No impact	~	~	✓
Enablement of DG	✓	✓	✓	✓	✓	✓
Losses	×	×	×	✓	✓	×
CI/CMLs	No impact	No impact	No impact	~	~	No impact
Grid/ network services	No impact	No impact	No impact	No impact	No impact	✓

Key: ✓Positive impact; ×negative impact; ~ network dependant, may have positive or negative impact

Table 10: Cross-technique comparison of impact.

Network capacity:

- All techniques altered capacity on the network;
- DAR evaluates capacity more accurately than static ratings which may suggest additional or in some cases less capacity. OHLs are predominately affected by wind speed/direction meaning significant variations occur both across seasons and within short time scales (minutes). When this variability of rating is combined with the low thermal capacities of OHLs (i.e. the OHL temperatures respond rapidly to the environmental changes), taking advantage of this technique is limited to particular circumstances. The dynamic ratings of both cables and transformers are dependent on ambient temperatures, meaning diurnal (for transformers only) and seasonal variations are clearly present, and the larger associated thermal capacities means short-time duration changes in ambient conditions cause less short term variability in asset ampacity;
- ALT and mesh shift load from one part of a network to another, thereby potentially relieving constraints. ALT offers a far more intuitive mechanism, whilst mesh is continually dynamic by its very nature. The extent to which benefits exist is highly dependent on the connectivity of any candidate network, and loads/generation connected to the network, and the extent to which the loads vary relative to each other; and
- Energy storage shifts load in time, reducing load at a capacity constrained key point in time, only to increase the load at a less critical point in time. The specified power and storage energy capacity clearly need to be appropriately matched to the network load; and adaptive triggering is required to deal with individually daily variations in load, to optimise the impact that the installed system can have on the network.

Energy Storage may complement DAR by providing a mechanism to alter load patterns such that constrained assets might make the best use of available ampacity.

Voltage:

- Three of the techniques offer some potential for benefits (ALT, Mesh, ES);
- ALT demonstrated the largest benefit (4%), on some of the rural circuits that were trialled, but no significant benefit was found on urban circuits;
- Mesh considered a small urban network and for this example there was no significant impact on voltage;
- In general the voltage benefit of the ALT and mesh techniques networks will depend on the voltage difference across pre-existing NOPs, and does not directly address voltage issues at the end of branches
- The installed energy storage systems achieved little impact. In general, the reactive power capacity in relation to the magnitude and power factor of the adjacent load is modest, and can be expected to be expensive to deliver for this benefit alone.

Fault level:

- As is clearly already recognised, introducing generation (including ES) to a network will ordinarily increase fault level, in this instance the ES were small compared to pre-existing fault levels, and so had negligible impact. Meshed networks will also increase fault level due to the reduced circuit impedance. For the mesh technique trial, this was within the ratings of all circuit equipment.

Power Quality (PQ):

- Mesh trials showed no discernible impact on power quality. Super-position theory and the feeding of harmonic loads via different sources means that harmonics presently fed from one source could be fed from two sources (depending on Network impedances), however, it is unlikely that larger scale trials will show any marked appreciable benefits as the majority of loads are within limits defined by standards and as such it will be difficult to differentiate small changes;
- The installed energy storage equipment did not specifically have functionality aimed at improving PQ. At one site, improvement was noted, however this was a beneficial coincidence arising from the nature of a local (within standards) PQ disturbance and the inductance/capacitance smoothing network in the Energy storage system;
- More targeted studies of a network that has a known PQ issue could be identified to further examine the potential of mesh/ALT techniques to beneficially impact this issue.

Enablement of DG:

- This was not specifically studied as part of the engineering trials (e.g. interaction between the engineering techniques and DG was not designed into the trials);
- Whilst not a direct focus of the FALCON trials, it is clear that DAR systems may offer potential benefit to distributed generation, but is highly dependent on circumstances.

For example, OHL DAR can increase export from OH connected wind farms on a windy day; but solar farm output peaks occur on clear summer days when DAR OHL is less likely to provide additional benefit;

- ALT may facilitate the connection of more distributed generation. However, this needs to be looked at on a case-by-case basis as the location of the generation along the feeder, in relation to the ratings and load, can have an impact. Where the generation is close to the source (such as in the FALCON ALT OHL trial), there is scope to add a significant amount of generation so that the feeder is able to export at the Primary and also meet the load requirements along this feeder. The nominal location for the open point may well be different between when the generation is running or is off and this may impact other metrics such as losses and voltage regulation if generation operating condition is not considered.
- Meshing may facilitate the connection of more distributed generation by providing a second export route in certain scenarios, thus saving on line and cable upgrades. Modelling also indicates that there may be cost savings from reductions in feeder losses when meshing a network with DG connected to one feeder. However, the benefits of reduced losses would have to be compared on a case-by-case basis with the costs of more complex protection required for meshing (potentially necessitating replacement of existing protection relays as well as new relays).
- ES systems offer potential benefit to distributed generation. Examples of this include: peak generation lopping - storage of peak energy production (say above connection agreement levels) for later injection to the grid; and storage of energy to allow market arbitrage.

Losses

- As discussed in the preceding technique-trial specific section, ALT and Mesh offer some potential, though the magnitude is network specific.
- The trialled ES systems increased losses, and DAR will tend to increase losses if higher circuit loads are facilitated.

CIs and CMLs

- ALT changes NOP positions and consequently affects numbers of connected customers per feeder. The trial algorithms:
  - Increased one feeder numbers by 15% (whilst optimising capacity headroom) on a rural/OHL network; and
  - Increased one feeder numbers by 50% (whilst optimising losses/voltage) on an urban/cable network.
- Meshing networks does not improve customer security as such; the improvement only occurs if additional automatic sectioning/unitising occurs beyond that offered by the pre-existing NOP. Due to communication system limitations, the implemented trials did not increase the number of sections, essentially maintaining the pre-existing customer security.

Grid/network Services:

Whilst these trials have demonstrated that frequency response is possible with the ES technique, a marketable service is not fully delivered by the installed equipment. In addition, further work would be required to put DNO owned energy storage on an appropriate commercial basis.   Refer to the WPD Solar Store NIA project.

Grid/network Services:

Whilst these trials have demonstrated that frequency response is possible with the ES technique, a marketable service is not fully delivered by the installed equipment. In addition, further work would be required to put DNO owned energy storage on an appropriate commercial basis. Refer to the WPD Solar Store NIA project.

SECTION 8

Conclusions and recommendations

Dynamic asset ratings of cables are dependent on an accurate cable thermal model and a set of soil temperature/ resistivity measurements to allow conductor temperature to be calculated and a dynamic asset rating set that limits this conductor temperature to 65^{o}C.

Within this technique trial, the thermal model was validated by comparison with the industry accepted CRATER model, and by comparison to measured external cable temperatures. Comparisons with CRATER suggest that at modelled rated sustained currents the FALCON thermal models produces comparable results. Calculated cable temperatures from the thermal model also compared well to measured values over the load ranges experienced during the trials, even with measurement issues (temperature measurement placement and soil resistivity values).

For the trial 33kV cable, the estimated DAR was an average of 102% of the P17 seasonally adjusted sustained rating over the 14 month period. Gains over P17 were greater in the winter period, and it appears that there is a phase shift between the dynamic rating and the P17 seasonally adjusted rating (i.e. the peak in winter DAR occurs after the middle of the nominal winter period of October to March inclusive). Gains over P17 for the period November to April (inclusive) averaged 107% of the seasonally adjusted P17 rating.

For the trial 11kV cable the estimated DAR was an average of 103% of the P17 seasonally adjusted sustained rating over the trial period; and again gains over P17 during the winter period were more pronounced. Gains over P17 for the period December to March (inclusive) averaged 107% of the seasonally adjusted P17 rating.

A new method has been described to look at prediction of cable ampacity and offers a potential opportunity to take advantage of slow changing soil temperatures. To ensure that the predicted ampacity does not exceed the of-the-moment ampacity a correction factor has to be added to the predicted Ampacity. This reduces the forward ampacity benefits by 2%. It should be noted that this work has been done in the absence of good quality soil resistivity data and as such there is risk that rain impacting soil resistivity over a much shorter time period could revise results obtained.

The trial findings suggest that that this technique may be able to provide relief to cables hitting thermal limits in some circumstances (on the evidence that the trial DARs - sustained rating basis, suggests that average improvements over a winter period may be in the range 107%)

It is therefore recommended that a further DAR investigation of a single cable is conducted:

- Where the cable is approaching thermal limits;
- The ratings basis is cyclic;
- Further improvements of soil parameter measurement are targeted; and
- Full assessment is made of the actual cyclic load shape that the cable is experiencing is conducted.

Appendices

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B Learning Objectives

	A	B	C
1	A1 - Understand thermal models of assets	B1 - Define the boundaries or limits of safe operation	C1 - Define the effect of ambient temperature on assets
2	A2 - Understand changes in maintenance required for all components	B2 - Define the effect of solar irradiation on different asset types	C2 - Define the effect of wind speed and direction on different asset types
3	A3 - Applications of pre-emptive transformer cooling	B3 - Define the granularity of ampacity values required by control	C3 - Communications template/model for technique
4	A4 - Benefits of using MET office data versus real-time data	B4 - Validity of external data, e.g. MET office and own internal predictions/assumptions	C4 - Applications of forward predictions of ampacity values versus load required
5	A5 - Benefits comparison of sensor types and location of placement	B5 - Template for sensor installation on asset types	C5 - Analysis of relationships between different sensor values
6	A6 - Variability of conditions across an asset/confidence in data obtained	B6 - Analysis of effectiveness of assumptions versus real-time obtained values	C6 - Required post-fault running conditions
7	A7 - Application of short term overload on different asset types	B7 - Running conditions required during adjacent outages	C7 - Analysis of probabilistic and deterministic ratings of lines
8	A8 - Future policy for application of dynamic asset ratings across the network	B8 - Quantification of length of reinforcement deferral after implementation	C8 - Standard technique for retrofitting DAR on each asset class

Note: The Learning Objectives presented above were developed generally for the DAR technique (including overhead lines and cables). As such, not all of the objectives are directly applicable to Cables. The following Learning objectives do not apply:

- A3 - Applications of pre-emptive transformer cooling
- C5 - Analysis of relationships between different sensor values;
- C6 - Required post-fault running conditions;
- A7 - Application of short term overload on different asset types B7 - Running conditions required during adjacent outages.

C Large Format diagrams

C.1 33kV Single Line Diagram

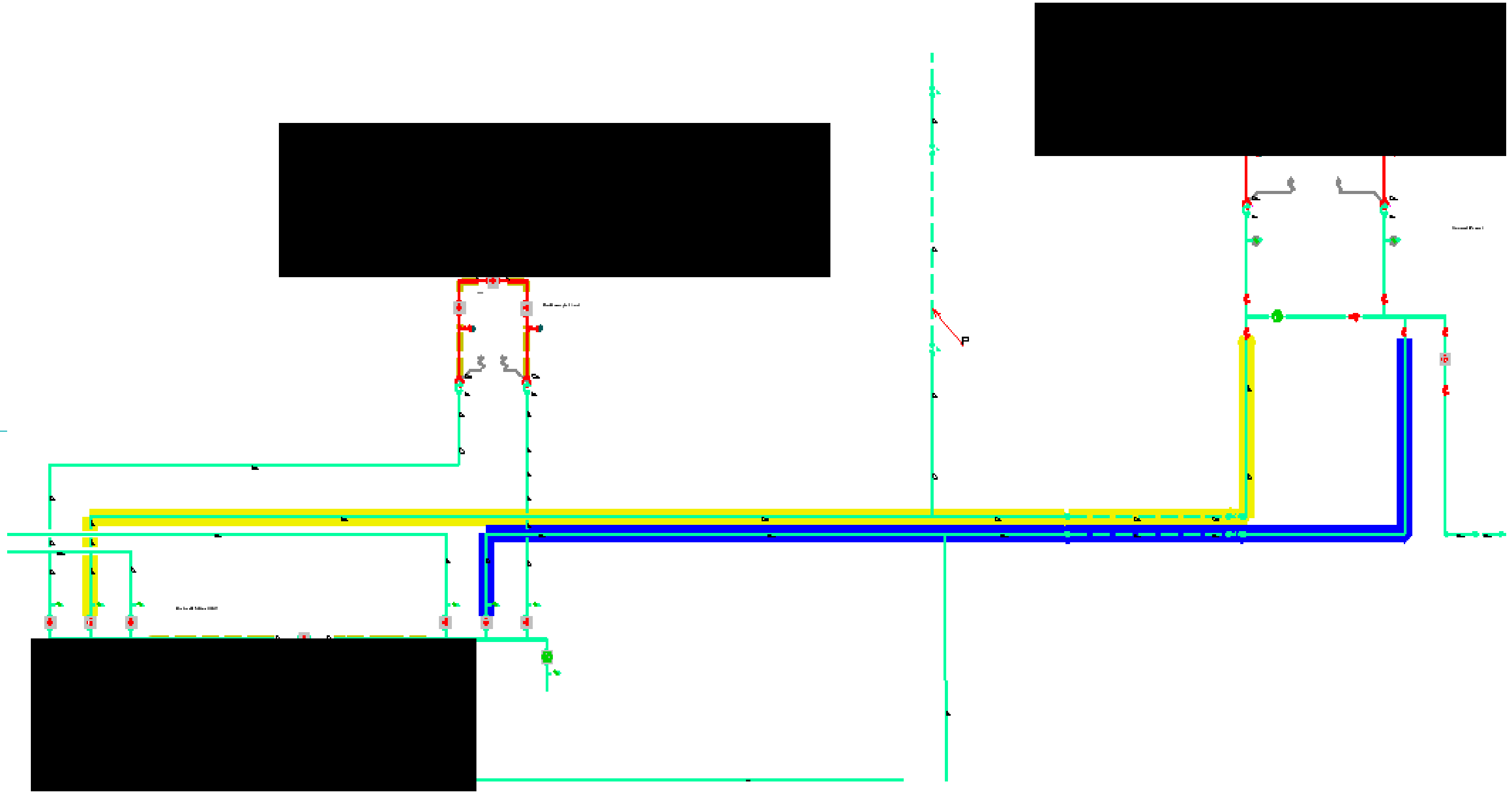

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Figure 37: Large format 33kV DAR cable Single Line diagram

C.2 11kV Single Line Diagram

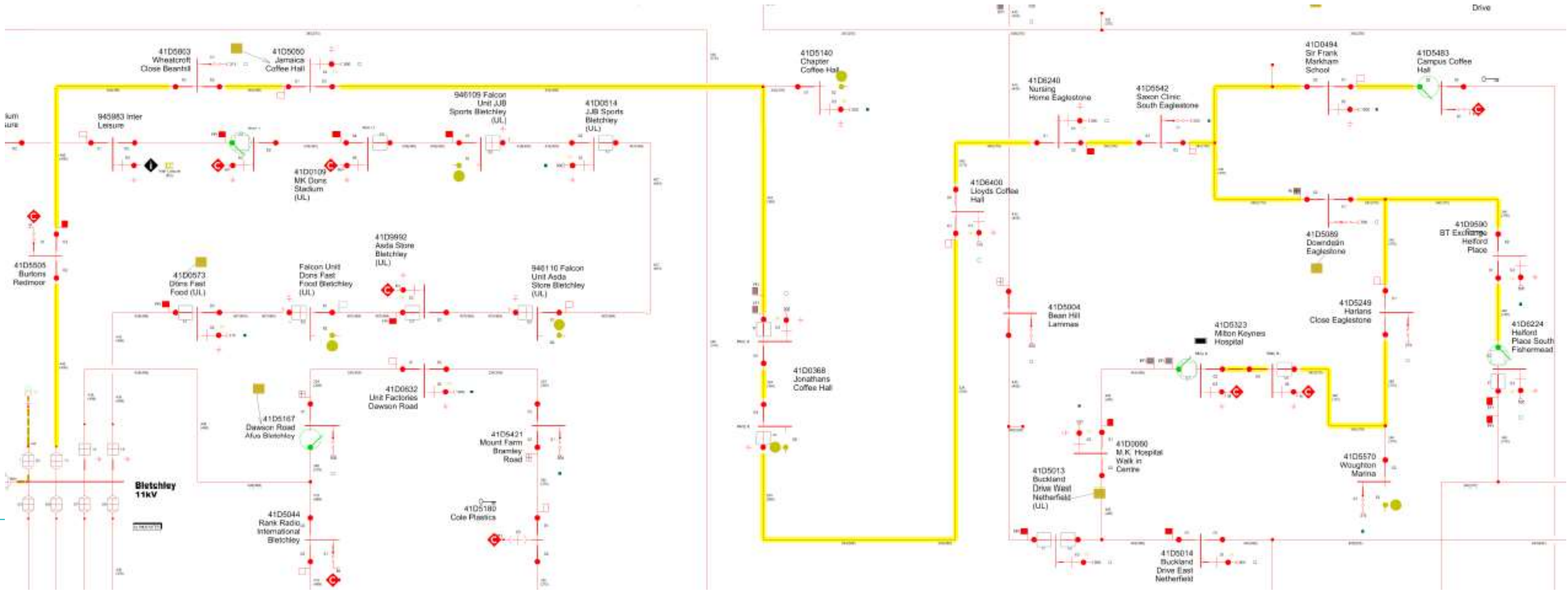


Figure 38: Large format 11kV DAR cable Single Line diagram

C.3 33kV Geographic Diagram - small scale mapping

Figure 39: 33kV cable, geographic plot of cable route – small scale mapping

C.4 33kV Geographic Diagram - main scale mapping

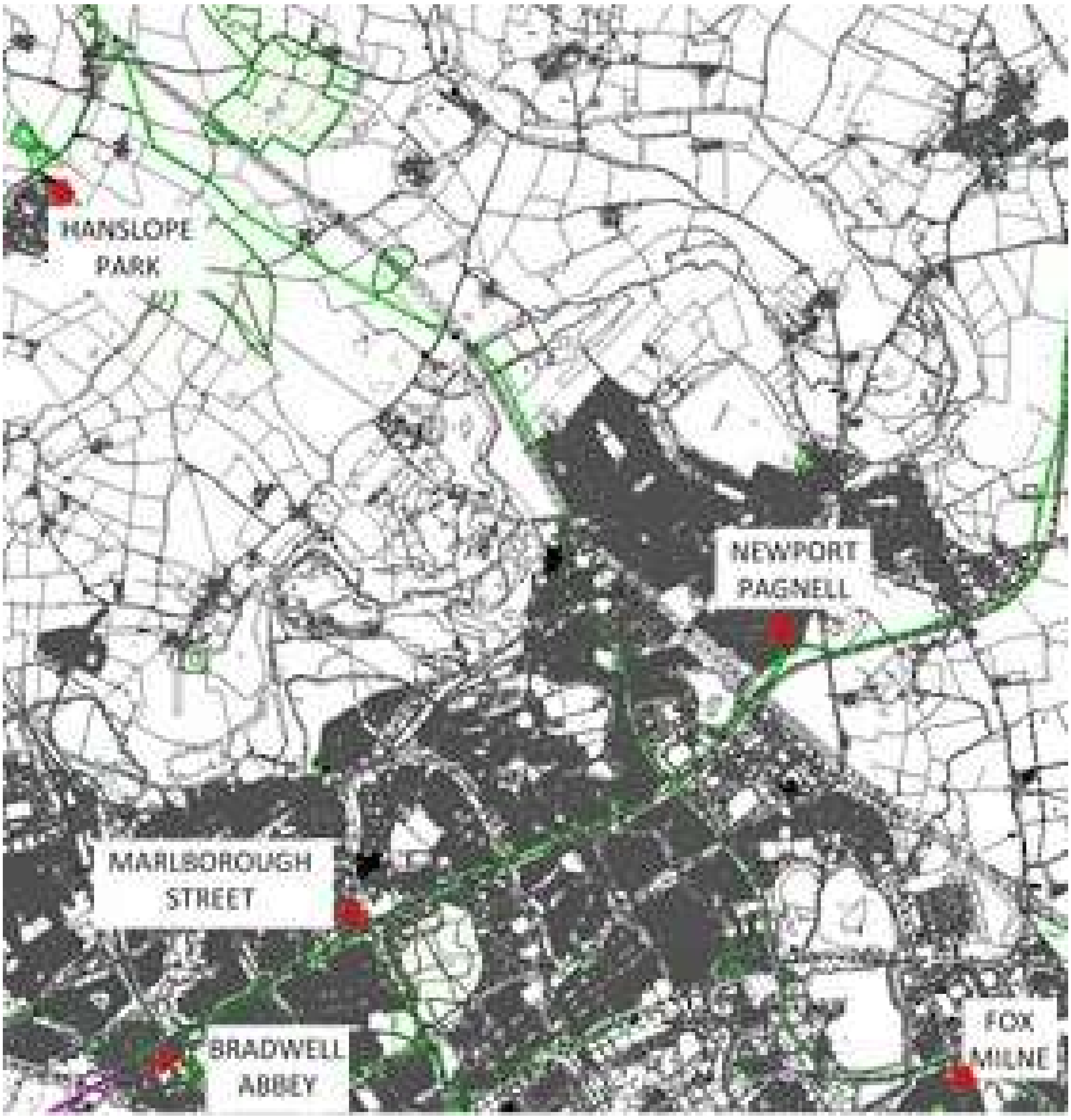


Figure 40: 33kV cable, geographic plot of cable route – main scale mapping

C.5 11kV Geographic Diagram - small scale mapping

Figure 41: 11kV cable, geographic plot of cable route – small scale mapping

C.6 11kV Geographic Diagram – main scale mapping

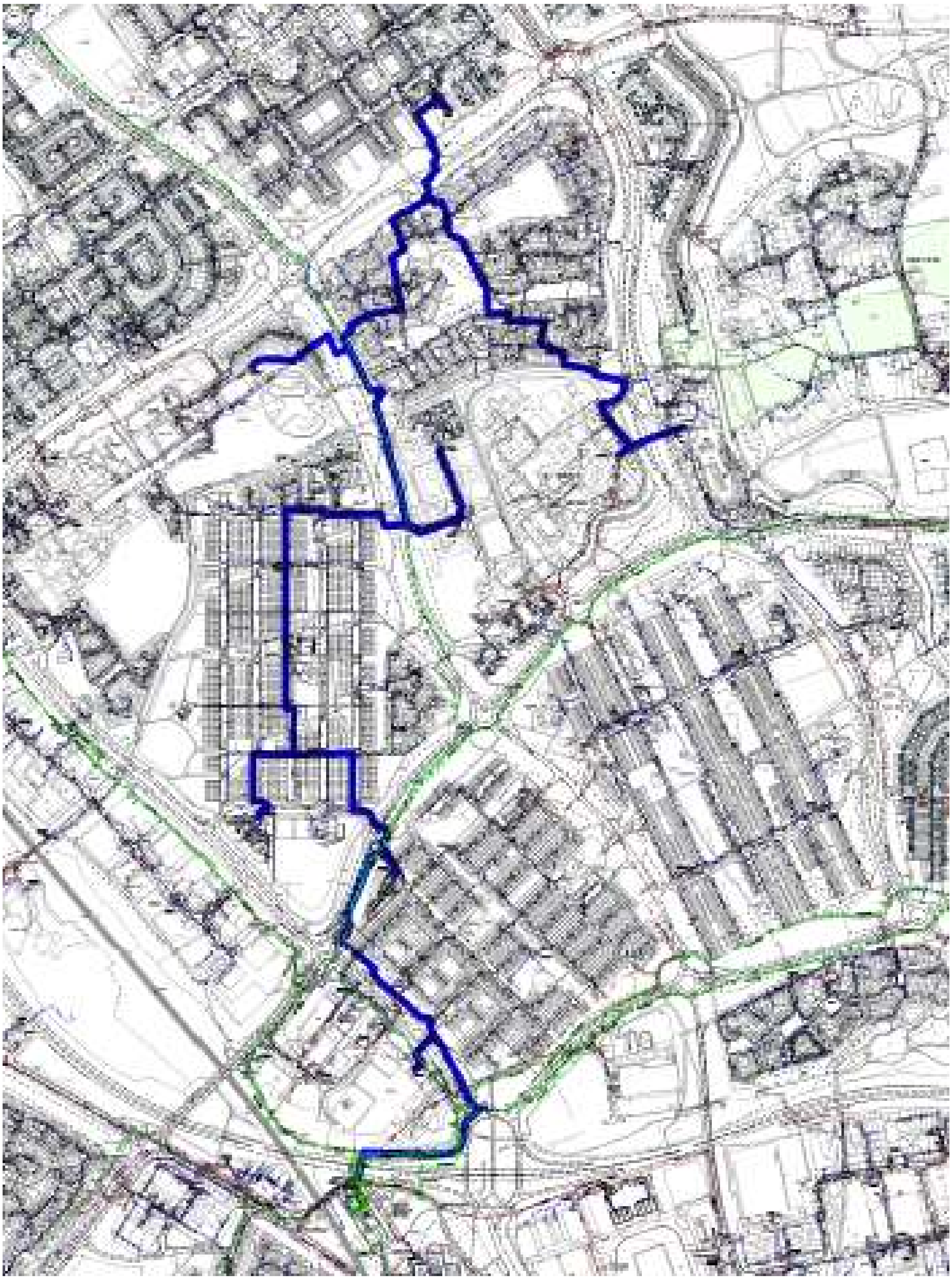


Figure 42: Geographic plot of cable route – main scale mapping

D Details of FALCON thermal modelling

Thermal model algorithm

The derivation of the offline model algorithm discussed in this section gives the transient response of a cable to an arbitrary function of current; the algorithm does this by modelling the thermal impedances formed by the constituent parts of the cable itself and its surroundings as shown in Figure 17.

The model is based on a thermal model of the system where W_c and W_a are the thermal power produced by losses in the system such as the conductor loss and armour losses. R_1 to R_4 are the thermal resistances of the layers of insulation and effect of soil and T_c is the conductor temperature while T_e is the external cable temperature (compared to the measured value) and T_s is the ambient soil temperature. According to IEC 60853-1, for cables up to 33 kV, the thermal capacitances of the cable components are neglected.

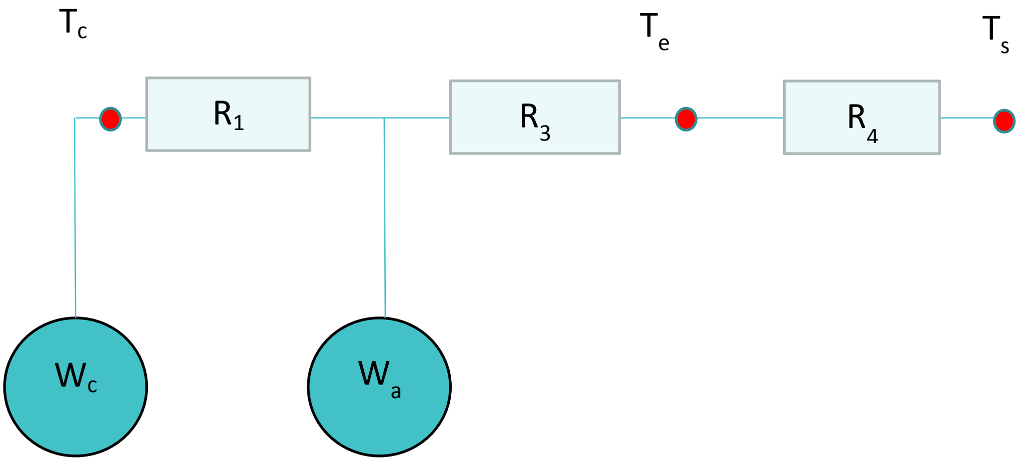


Figure 43: Cable thermal circuit

A cyclic rating factor of the cable (for use in the SIM) is denoted by *M*, and is the factor by which the permissible sustained rated current (100% load factor) may be multiplied to obtain the permissible peak value of current during a daily load cycle such that the conductor attains, but does not exceed the standard permissible maximum temperature during this cycle. The cyclic rating factor of the cable *M* is calculated from the following formula taken from IEC 60853-1 eq. (21).

$$M = \sqrt{\frac{\theta_R(\infty)}{\theta_{max}}} \quad (1)$$

Where $\vartheta_R(\infty)$ is the maximum permissible cable conductor temperature rise (for example $\vartheta_R(\infty)$ = 90-10, for XLPE insulation and a 10^oC (soil) ambient temperature. The term ϑ_{max} is the actual peak conductor temperature rise for a given cyclic load, and is given by (IEC 60852-1 eq. (20):

$$\theta_{max} = Y_0\theta_R(1) + \textstyle\sum_1^5 Y_i(\theta_R(i+1) - \theta_R(i)) + \mu(\theta_R(\infty) - \theta_R(6)) \qquad (2)$$

Where Y_i is the i^{th}, cable loss term, and μ is the Load loss factor (mean) of the *Y* values for the whole of a 24-hour cyclic period - IEC 60853-1 eq. (1). This equation is based on the cable loading profile being sub-divided into a finite number of step-functions (hourly in this case), and then summed over the six-hours (six samples) prior to the point of highest load. This equation can be substituted into IEC 60853-1 eq. (21) to give IEC 60853-1 eq. (22),

$$M = \frac{1}{\sqrt{\sum_0^5 Y_i\left[\frac{\theta_R(i+1)}{\theta_R(\infty)} - \frac{\theta_R(i)}{\theta_R(\infty)}\right] + \mu\left[1 - \frac{\theta_R(6)}{\theta_R(\infty)}\right]}} \qquad (3)$$

Substituting in IEC 60853-1 eq. (23) into this equation, where *α(i)=1* for cables rated less than 36 kV gives,

$$M = \frac{1}{\sqrt{Y_0[1-k] + Y_0 k\beta(1) + k\left[\sum_1^5 Y_i[\beta(i+1) - \beta(i)] + \mu[1-\beta(6)]\right]}} \qquad (4)$$

This is in the form that is coded in the FALCON algorithm. All that is required is to determine the values of *k* and *β*.

The equation for *β* depends on whether the cables are flat-laid or trefoil. However, IEC 60853-1 eq. (10) can be used for both arrangements – note the IEC specification changes the notation from *β* to *λ* between IEC 60853-1 eq. (9) and IEC 60853-1 eq. (23), the term *β* will be used here – by the addition of the term *p*:

$$\beta(i) = \frac{-Ei\left(-\frac{D_e^2}{16t\delta}\right) - p(N-1)Ei\left(-\frac{d_f^2}{16t\delta}\right)}{2ln\left(\frac{4LF}{D_e}\right)} \qquad (5)$$

The function *Ei* in (5) is the exponential function, *N* is the number of conductors (equal to 3 for trefoil and flat-laid) and the terms d_f and *F* are given by IEC 60853-1 eq (11)-(12):

$$s = \begin{array}{ll} spacing\_factor\ D_e & Flat\ laid \\ D_e & Trefoil \end{array} \qquad (6)$$

$$F = \begin{array}{ll} 1 + \left(\frac{2L}{s}\right)^2 & Flat\ laid \\ 1 & Trefoil \end{array} \qquad (7)$$

$$d_f = \frac{4L}{F^{1/(N-1)}} \qquad (8)$$

Equation (5) is identical to IEC 60853-1 eq. (16) for trefoil and IEC 60853-1 eq. (10) for flat-laid *if* the term *p* is set to zero and unity respectively. However, the CRATER document [23], eq. (50), suggest a modification to eq. (5) for flat-laid arrangements where unequal screen losses arise between the three conductors (the IEC specification assumes they are equal). In which case *p* can be used to take into account these different screen losses where for flat-laid:

$$p = \frac{1+0.5(\lambda'_{11}+\lambda'_{12})}{1+\lambda'_{1m}} \qquad (9)$$

The lambda loss terms in this equation are shown in Table 2 below.

The term *k* is the ratio of the cable external surface temperature rise above ambient to the conductor temperature rise above ambient under steady-state conditions and is given by for example IEC 853-1 eq. (4):

$$k = \frac{W_c(1+\lambda)T_4}{\theta_{max}} \quad (10)$$

where w_c are the conductor losses (W), λ represents the cable screen losses and T_4 is the soil thermal resistivity. Equations for λ and T_4 can be found in Table 2 and eq. (12) below. The conductor losses are found from

$$w_c = I^2 R_c \qquad (11)$$

where *I* is the sustained rating of the cable and R_c is the equivalent electrical resistance of the cable, taking in to account skin effect, proximity effect screen losses etc. Both *I* and R_c depend on whether the cables are flat-laid or trefoil. The sustained rating, *I* is also the second output of the of the FALCON algorithm and is important because it is needed to calculate the cyclic rating of the cable = *IxM*. Note that the exponential integral function *Ei* used in (5) above exists as a pre-defined function in MATLAB.

The sustained rating *I* is calculated from the thermal resistances of the cable arrangement and the cable losses. As such it uses equations from IEC 68287-2-1 [14], and also references IEC 68287-1-1 from the text by Anders [17].

The process of identifying the correct equations from the IEC specifications for use in the FALCON algorithm is quite involved and only a summary is given here for one cable type. These variables can change depending on cable construction.

Trefoil	**Flat-laid**
$I = \sqrt{\frac{\theta_{max}}{R_c\left(1.07T_1 + \lambda'_m(1.6T_3 + T_4)\right)}}$	$I = \sqrt{\frac{\theta_{max}}{R_c\left(T_1 + \lambda'_{1m}(T_3 + T_4)\right)}}$
1.07 & 1.6 factors BS 7769-2-2.1:1997, p.14	
$T_1 = \frac{\rho_{dielec}}{2\pi} ln\left(\frac{D_i}{d_c}\right)$	
IEC60853 eq. (4-1)	
$T_3 = \frac{\rho_{cover}}{2\pi} ln\left(\frac{D_e}{d_s}\right)$	
IEC60853 eq. (4-6)	

Trefoil	**Flat-laid**
$T_4 = \frac{3\rho_{soil}}{2\pi} ln\left(\frac{4L}{1.87761D_e}\right)$	$T_4 = \frac{\rho_{soil}}{2\pi}\left(ln\left(u + \sqrt{u^2 - 1}\right) + p\ ln\left(1 + \left(\frac{2L}{s}\right)^2\right)\right)$
BS 7769-2-2.1:1997, 2.2.4.3.2	*u=2L/*D_e BS 7769-2-2.1:1997, 2.2.3.2.3
$\lambda'_m = \frac{R_{scn}}{R_c}\left(\frac{1}{1 + \left(\frac{R_{scn}}{X_{scn}}\right)^2}\right)$	$\lambda'_{1m} = \frac{R_{scn}}{R_c}\left(\frac{1}{1 + \left(\frac{R_{scn}}{Q}\right)^2}\right)$
Anders [25] p. 45, 1.6.4.2 (1)	Anders [25] p. 46
$R_{scn} = \rho_{cu}\left(\frac{1 + \alpha_{cu20}(\theta_{max} - 20)}{A_s}\right)$	
Standard text	
	$Q = X_m - X/3$
	Anders [17] p. 46
$X_{scn} = 4\pi f 10^{-7} ln\left(\frac{2s}{d}\right)$	$X_{scn} = 4\pi f 10^{-7} ln\left(\frac{2\sqrt[3]{2}s}{d}\right)$
Anders [25] p. 44	Anders [17] p. 45 – denoted *X₁*
	$X = 4\pi f 10^{-7} ln\left(\frac{2s}{d}\right)$
	Anders [17] p. 44
	$X_m = 8.71x10^{-7} f$
	Anders [17] p. 45
	$\lambda'_{11} = \frac{\lambda'_{1m}}{4} + \frac{R_{scn}}{R_c}\left(\frac{3/4}{1 + \left(\frac{R_{scn}}{P}\right)^2} - \frac{2R_{scn}X_m/(PQ)}{\sqrt{3}\left(\frac{R_{scn}^2}{Q^2} + 1\right)\left(\frac{R_{scn}^2}{P^2} + 1\right)}\right)$
	Anders [17] p. 46
	$\lambda'_{12} = \frac{\lambda'_{1m}}{4} + \frac{R_{scn}}{R_c}\left(\frac{3/4}{1 + \left(\frac{R_{scn}}{P}\right)^2} + \frac{2R_{scn}X_m/(PQ)}{\sqrt{3}\left(\frac{R_{scn}^2}{Q^2} + 1\right)\left(\frac{R_{scn}^2}{P^2} + 1\right)}\right)$
	Anders [17] p. 46
	$P = X_m + X$
	Anders [17] p. 46

Trefoil	Flat-laid
$d = \sqrt{(D_s^2 + D_i^2)/2}$	
Anders [25] p. 42, 2nd para. RMS diameter of screen	
$R_c = R'\left(1 + y_s + y_p\right)$	
Anders [25] p. 39	
$R' = R_{dc20}\left(1 + \alpha_{20}(\theta_{max} - 20)\right)$	
Standard text	
$y_s = \frac{(x_s^2)^2}{192 + 0.8(x_s^2)^2}$	
Anders [25] p. 39	
$y_p = F_p\left(\frac{d_c}{s}\right)^2\left(0.312\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{F_p + 0.27}\right)$	
Anders [25] p. 39	
$x_s^2 = F_k K_s$	
Anders [25] p. 39	
$F_p = \frac{\left(x_p^2\right)^2}{192 + 0.8\left(x_p^2\right)^2}$	
Anders [25] p. 39	
$F_k = \frac{4\ 2\pi f 10^{-7}}{R'}$	
Anders [25] p. 39 – typing error in Anders text, should read π rather than ω	
$K_s = 1$	
Anders [25] p. 40, Table 1-2	
$x_p^2 = F_k K_p$	
Anders [25] p. 39	
$K_p = 1$	
Anders [25] p. 40, Table 1-2	

Table 11: IEC equations used for the sustained current rating of Trefoil and Flat-laid cables

Note that the equation for λ that is required for the calculation of k in the previous section - equation (10) - is given by Anders [17] p. 45, 1.6.4.2 (1):

$$\lambda = \frac{R_{scn}}{R_c}\left(\frac{1}{1+\left(\frac{R_{scn}}{X_{scn}}\right)^2}\right) \quad (12)$$

for both trefoil and flat-laid. The variables on the right-hand side of this equation can all be obtained from Table 2 above.

E Cable modelling parameters

E.1 33kV Cable data

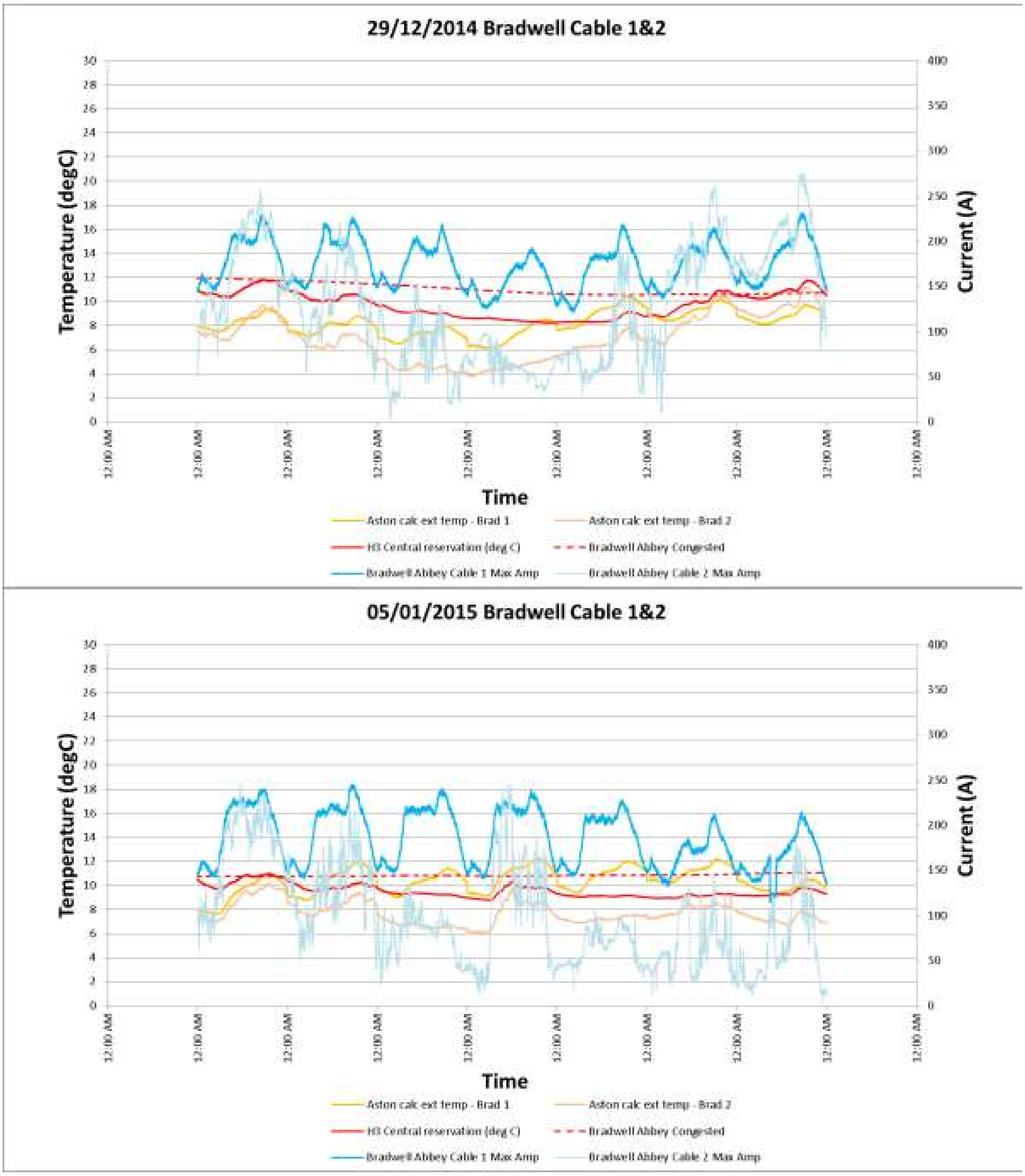
	Symbol	Description	Value from Cable etc Manual (mm/sq mm)	Other reference values	Calculated Value (inches/sq inches)	Calculated Value (m)	Calculated value (mm2 or mm)
Description of cable							
	11,00 Volt 3-core belted cable (table 15, BS480 part 1)						
Cable specific dimensions/materials							
		Conductor material	Cu				
		Sheath material	Pb				
		Armour material	Steel				
		Cross-section of conductors	185		0.287	1.850E-04	185.0
	t_ins	Thickness of insulation between conductors	13.6		0.535	0.0136	13.6
		Thickness of insulation between any conductor and sheath	6.8		0.268	0.0068	6.8
	ts	Thickness of sheath	2.7		0.106	0.0027	2.7
		Diameter of armour wire	3.15		0.124	0.0032	3.2
		Number of armour wires	67		67		
	Ds/doc/dit	Nominal diameter (over) [of] sheath - taken as external diameter	70.30		2.768	0.0703	70.3
	De/rm	External cable diameter - note: varies with type	83.6		3.291	0.0836	83.6
Calculated dimension							
	t3	Thickness of outer serving			0.262	0.0067	6.7
	R1	radius of circle circumscribing conductors					29.1
	dc	Diameter of circular conductors with same nominal x-sec area					15.3
	As	Area of screen [sheath]					573.4
	Di	External Diameter of insulation (dielectric)					63.6
	da	External diameter of belt insulation					64.900
		Internal diameter of sheath					64.9
	d	rms diameter of sheath					67.7
	darm	rms diameter of armour					73.4500
Other parameters used in thermal calcs							
		[Electrical] resistivity [Cu] at 20 deg C		1.7241E-08			
		Temp coefficience [Cu]		0.00393			
		[electrical] resistivity of [Al] at 20 deg C		2.8264E-08			
		Temp coefficient of [Al]		0.00403			
	rho_swa	[Electrical] resistivity [carbon steel]		1.69E-07			
		Temp coefficient of [carbon steel]		0.00393			
		[Electrical] resistivity [Pb]		2.20E-07			
		Temp coefficient of [Pb]		0.00393			
		Thermal resistivity [PVC]		6.0			
		Thermal resistivity [Fibre/biumen]		6.0			
		Thermal resistivity [paper insulation]		6.0			
		Thermal resistivity [PE]		3.5			
	Rcond_dc_20	DC resistance of [Cu] conductor at 20 degC (ohms)				9.319E-05	
	temp_coeff_cond	Temp coefficient of [Cu] conductor		0.00393			
	rho_sheath			2.20E-07			
	temp_coefficient_shreath			0.00393			
	f	Supply frequency (Hz)		50			
	delta	Soil thermal diffusivity		4.3e-7/5.3e-7			
	rho_soil	Soil thermal resistivity		1.2/0.9			
	rho_dielec/rho_t1	Conductor insulation/Dielec [paper] thermal resistivity		6.0			
	rho_cover/rho_t3	Thermal resistivity of [Fibre/bitumen] oversheath/cover		6.0			
	Tempmax	Maximum temp of conductor (deg C)		65			
	N	Number of cables [conductors?]		3			
	Aarm	Area of armour				5.22E-01	522.1
	Rarm_dc_20	DC resistance of [carbon steel] armour at 20 degC (ohms)		3.24E-07			
	I	Array of current values passing along conductor					
	Tsoil	Array of soil temperatures - note appears to be set to 15?					
Cross-check parameters			P17				
		P17 Distribution rating (10 deg C, 65 deg C, 0.9)	480				
		Factor for soil temp to 15 deg C - not size dependant, varies with nor	0.95				
		Factor for soil thernmal resistivity to 1.2 - varies with size	0.94				
		Factor to sustained rating - varies with size	0.84				
		Factor for cyclic ratings	0.92				
		Sustained winter rating					403
		Sustained summer rating					360
		Cyclic winter rating					442
		Cyclic summer rating					394
		Distribution winter rating					**480**
		Distribution summer rating					429

E.2 11kV Cable data

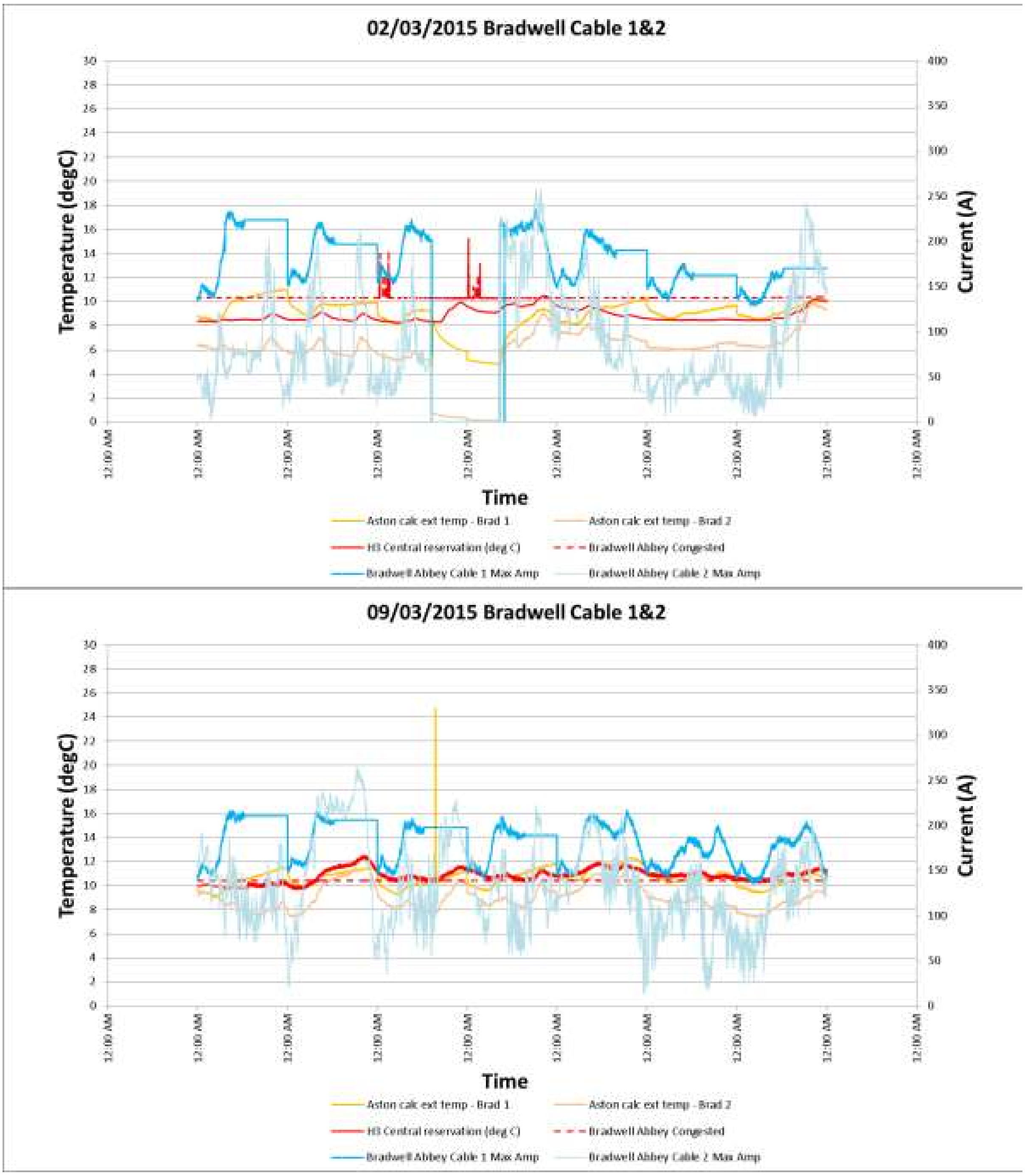
	Symbol	Description	Value from Cable etc Manual (mm/mm2)	Other reference values	Calculated Value (inches/sq inches)	Calculated Value (m)	Calculated value (mm2 or mm)
Description of cable							
	Three core shaped stranded aluminium conductors, paper insulated, belted, corrugated aluminium sheath, PVC sheathed, 6.35/11 kV PICAS cable to EA 09-12.						
Cable specific dimensions/materials							
		Conductor material	Al				
		Sheath material	Al				
		Cross-section of conductors	185		0.287	1.850E-04	185.0
		Nominal diameter of conductor (depth)	13.84		0.545	0.0138	13.8
		Mean thickness of paper insulation	3		0.118	0.0030	3.0
		Nominal depth over insulation	20.24		0.797	0.0202	20.2
		Nominal diameter over laid up cores	42.8		1.685	0.0428	42.8
		Nominal thickness of belt insulation	0.65		0.026	0.0007	0.7
		Nominal thickness of belt carbon screen	0.15		0.006	0.0002	0.2
	ts	Nominal thickness of corrugated aluminium sheath	1.6		0.063	0.0016	1.6
	dit	Nominal external root diameter	49.6		1.953	0.0496	49.6
	Ds/doc	Nominal external crest diameter	56		2.205	0.0560	56.0
	De/rm	Nominal diameter over PVC oversheath	63.2		2.488	0.0632	63.2
Calculated dimensions							
	t_ins	Thickness of insulation between conductors			0.236	0.0060	6.0
	t3	Thickness of outer serving			0.142	0.0036	3.6
	R1	radius of circle circumscribing conductors			0.724	0.0184	18.4
	dc	Diameter of circular conductors with same nominal x-sec area			0.604	0.0153	15.3
	As	Area of screen [sheath]			0.400	2.58E-04	257.8
	Di	External Diameter of insulation (dielectric)			1.685	0.0428	42.8
	da	External diameter of belt insulation			1.748	0.0444	44.4
		Internal diameter of sheath			1.953	0.0496	49.6
	d	rms [external] diameter of sheath			2.083	0.0529	52.9
Other parameters used in thermal calcs							
		[Electrical] resistivity of aluminium at 20 deg C		2.83E-08			
	Rcond_dc_20	DC resistance of [aluminium] conductor at 20 degC (ohms)				1.528E-04	
	temp_coeff_cond	Temp coefficience of [aluminium] conductor		0.00403			
	f	Supply frequency (Hz)		50			
	rho_al	[electrical] resistivity of aluminium		2.8264E-08			
	temp_coeff_al	Temp coefficient of aluminium		0.00403			
	delta	Soil thermal diffusivity		6.00E-07			
	rho_soil	Soil thermal resistivity		1.2/0.9			
	rho_dielec/rho_t1	Conductor insulation/Dielec [paper] thermal resistivity		6.0			
	rho_cover/rho_t3	Thermal resistivity of oversheath/cover - PVC		6.0			
	Tempmax	Maximum temp of conductor (deg C)		65			
	N	Number of cables [conductors?]		3			
	I	Array of current values passing along conductor					
	Tsoil	Array of soil temperatures - note appears to be set to 15?					
Cross-check parameters			P17				
		Distribution winter rating (10 deg C, 65 deg C, 0.9)	370				
		Factor for soil temp to 15 deg C	0.95				
		Factor for soil thernmal resistivity to 1.2	0.94				
		Factor to sustained rating	0.82				
		Factor for cyclic rating	0.92				
							P17 with factor
		Sustained winter rating					303
		Sustained summer rating					271
		Cyclic winter rating					**340**
		Cyclic summer rating					304
		Distribution winter rating					**370**
		Distribution summer rating					330

F Reported and calculated external temperature

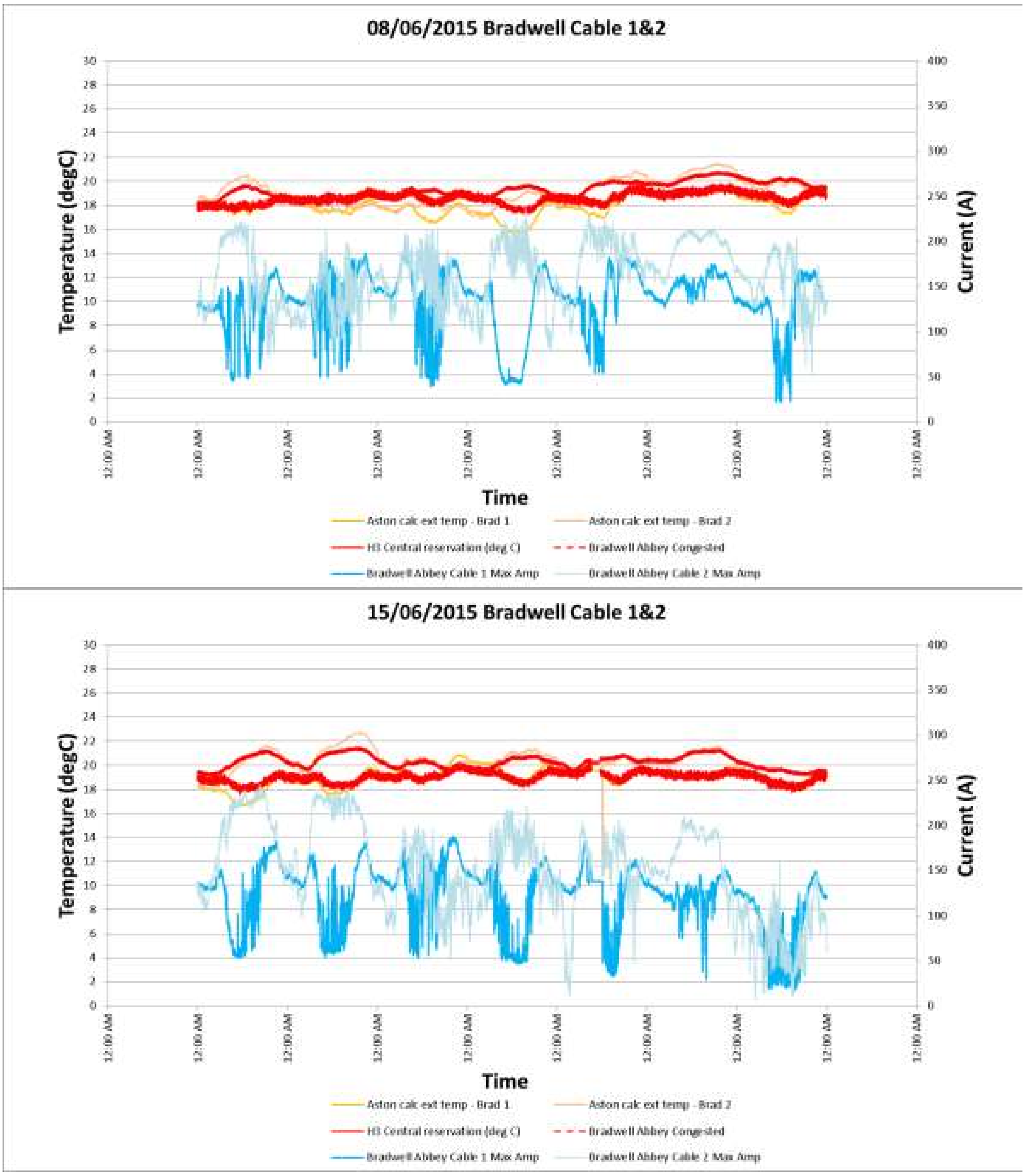
F.1 33kV Cable data



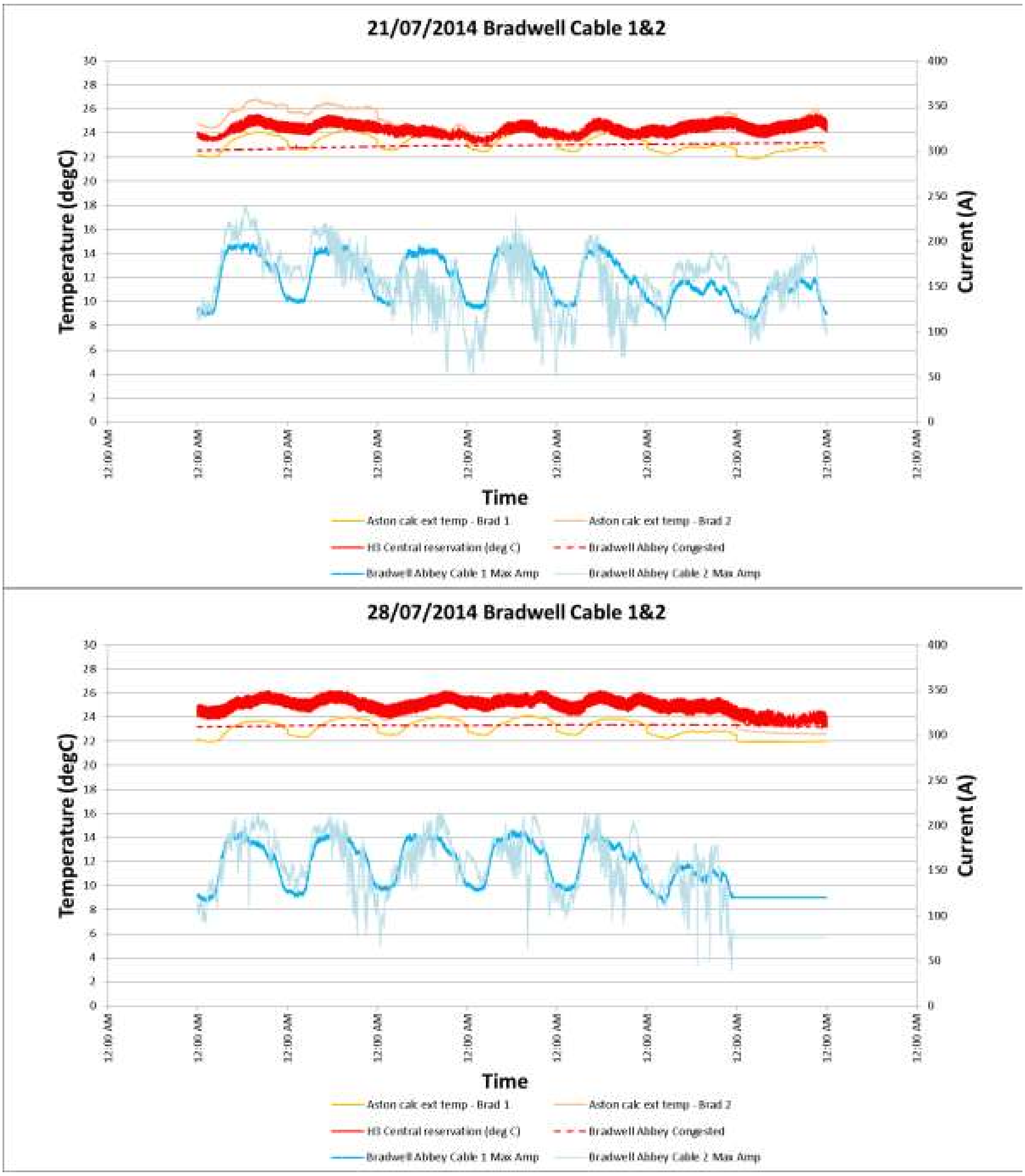
33kV Winter external temperature vs model temperature (w/c 29th Dec 2014 & 5th Jan 2015)



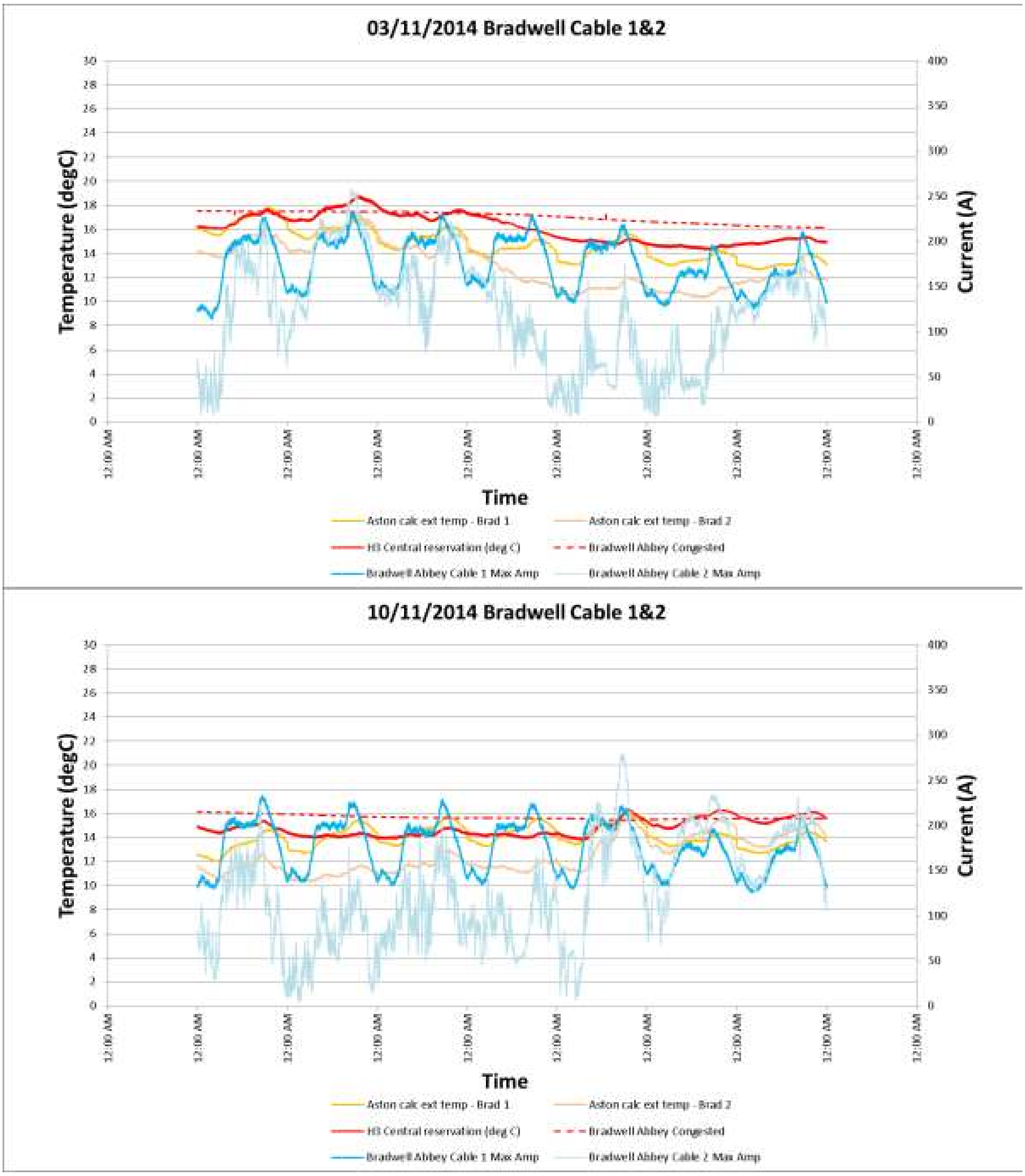
33kV Spring external temperature vs model temperature (w/c 2nd Mar 2015 & 9th Mar 2015)



33kV Summer external temperature vs model temperature (w/c 8th Jun 2015 & 15th Jun 2015)

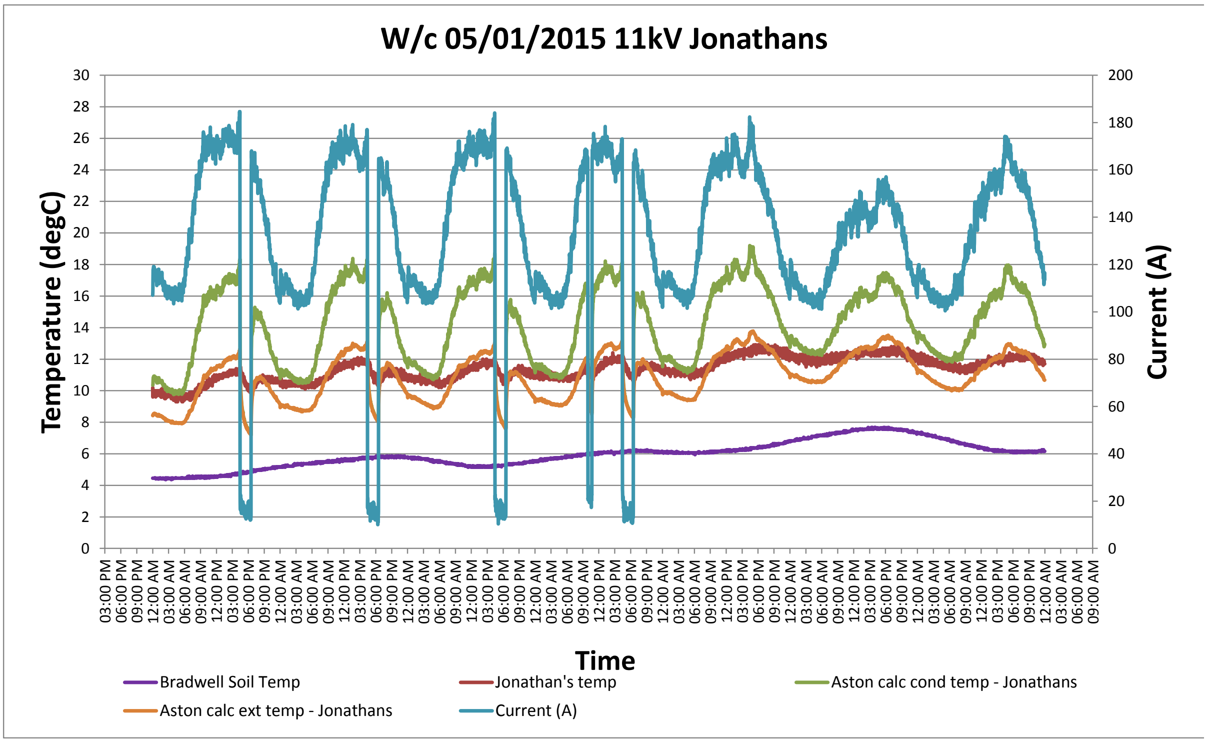


33kV High summer external temperature vs model temperature (w/c 23rd Jul 2014 & 28th Jul 2014)

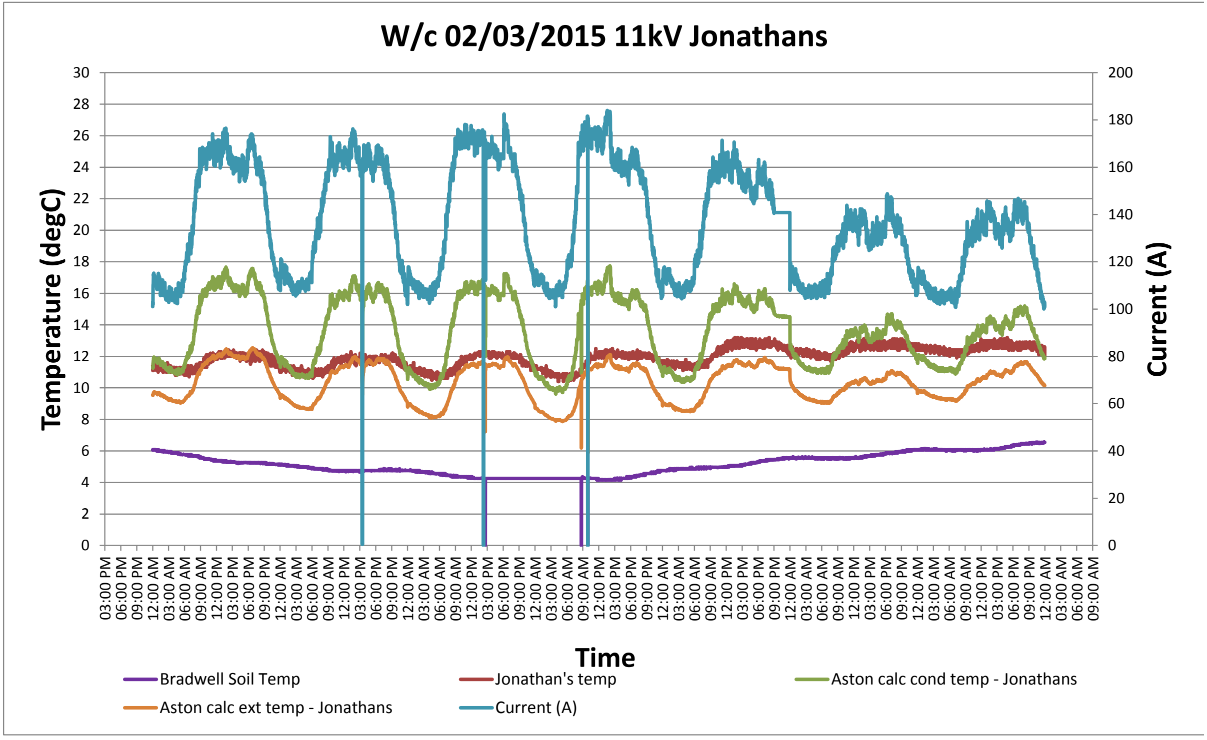


33kV Autumn external temperature vs model temperature (w/c 3rd Nov 2014 & 10th Nov 2014)

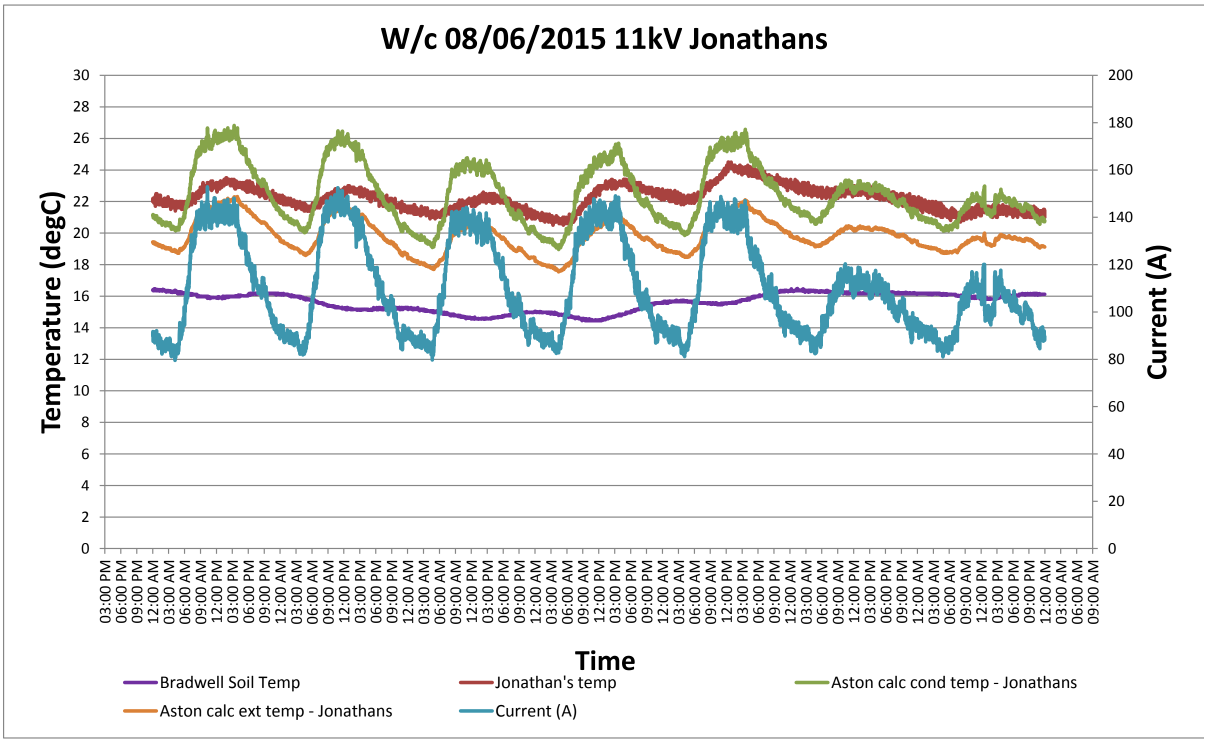
F.2 11kV Cable data



11kV Winter external temperature Jonathans vs model temperature (w/c 5th Jan 2015)



11kV Spring external temperature Jonathans vs model temperature (w/c 2nd March 2015)



11kV Summer external temperature Jonathans vs model temperature (w/c 8th June 2015)

G Linear relationships between ampacity and soil parameters

P17 includes tables to correct ratings based on factors such as soil temperature and soil resistivity to help give appropriate ratings.

These correction factors provide a useful cross check to dynamic rating, as calculated by the relay and the model calculations. "Of the moment" ampacity for the cable (using soil conditions from a moment in time to determine ampacity at that same moment) may be calculated directly from P17. An ampacity is produced directly from the Alstom relay without the use of an underlying thermal model but adjusting a static rating in-line with measured data. The offline model uses the reported measured data in conjunction with a thermal model to calculate an ampacity.

Due to the time consuming nature of the cable code to run it is not feasible to calculate the ampacity in the same way that it was done for the transformers and overhead lines. The offline model struggles to directly calculate a rating due to matrix sizing issue. Therefore a different approach has been used. The model has been used to produce a look up table such that the sustained rating of the cable at a particular soil temperature and resistivity has been calculated in advance using the model. The ampacity of the cable over the course of the trial can then be calculated using this lookup table to estimate the "of the moment" sustained ampacity from the trial reported soil temperature data. It is interesting to note that for a fixed resistivity, the relationship between rating and soil temperature is linear in nature – similar to the relationship in the relay and P17 as shown in Figure 44.

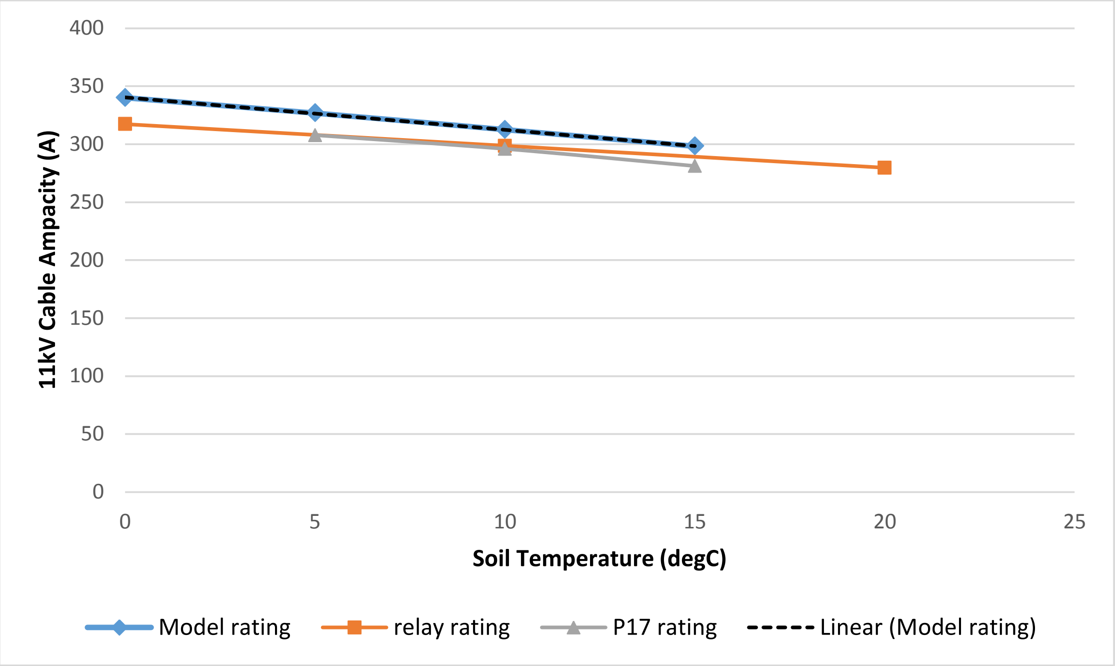


Figure 44 : Relationship between rating and soil temperature for fixed resistivity on the Jonathan's 11kV cable

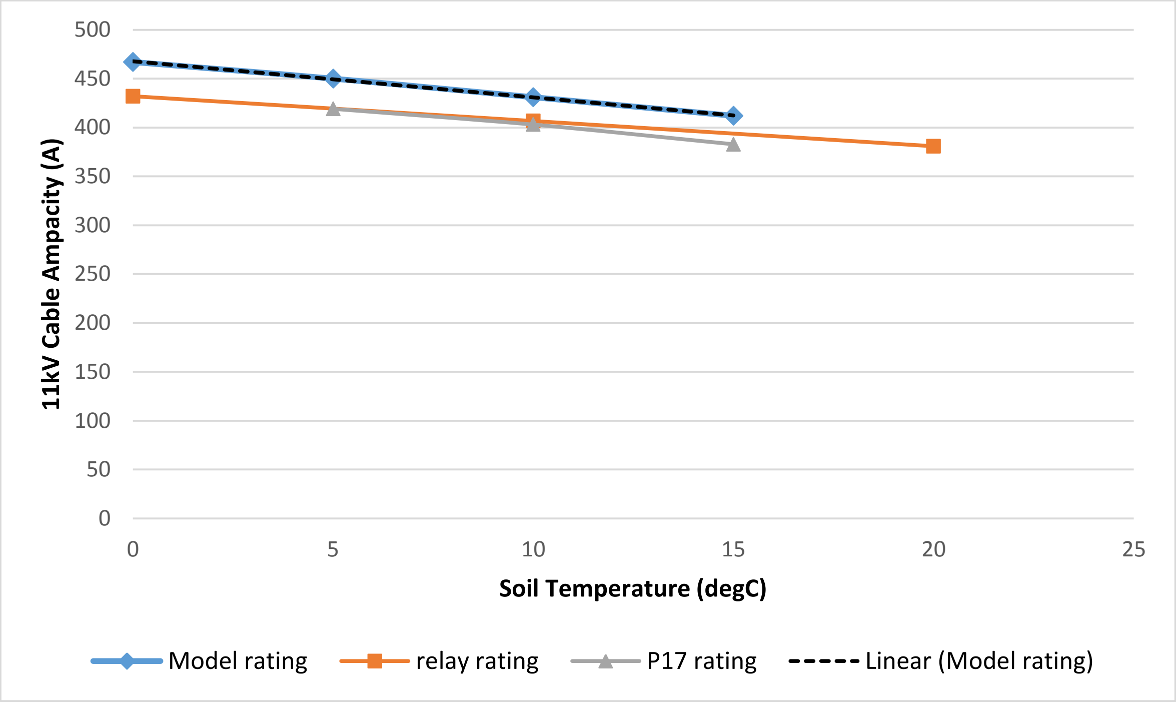


Figure 45 : Relationship between rating and soil temperature for fixed resistivity on the Bradwell 33kV cable

The graphs suggest that the linear relationship within P17 and the relay is appropriate and aligns to that calculated using a thermal model.

H Comparisons of 33kV Cable Sustained ratings

Figure 46 shows the calculated ampacity comparison between the model, relay and P17 calculation over the course of a year.

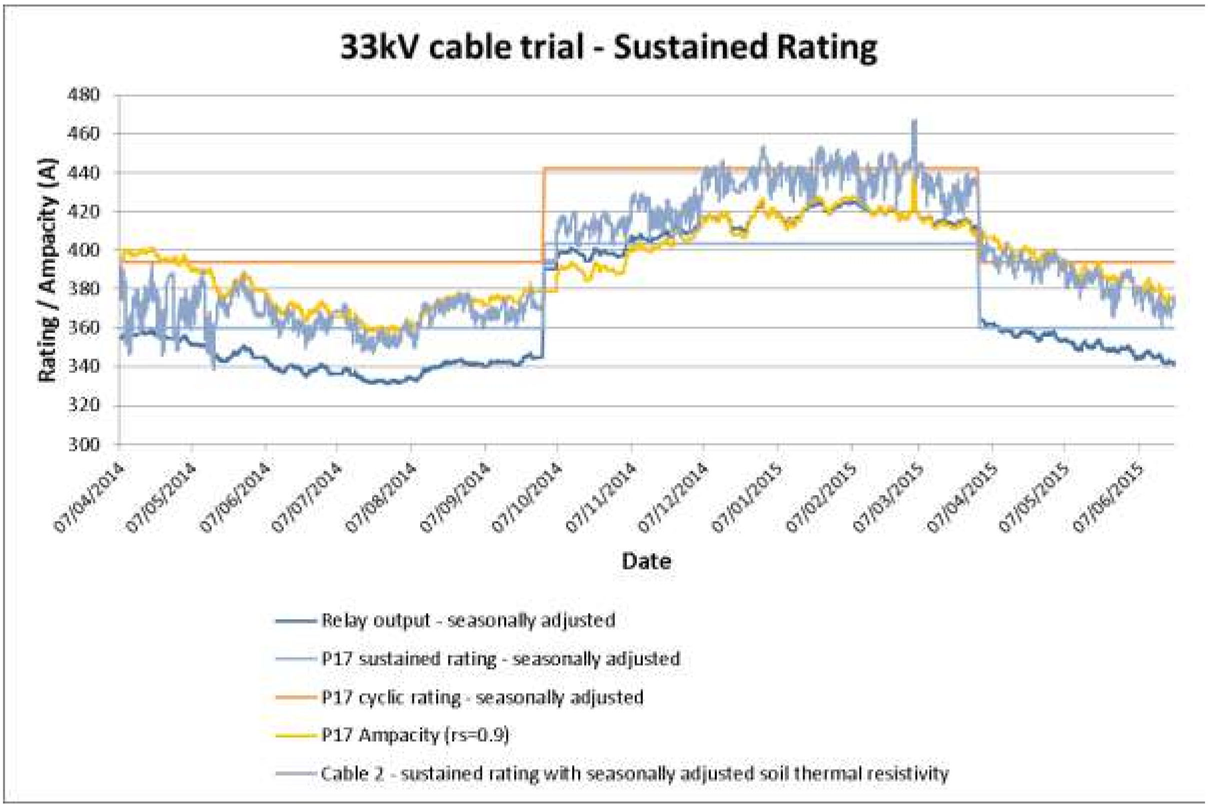


Figure 46 : Relayed reported and model calculated sustained ampacity for 33kV cable

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