Customer-Led Network Revolution

Lessons Learned Report

Real Time Thermal Rating

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Executive Summary

The Customer-Led Network Revolution has successfully implemented Real Time Thermal Rating (RTTR) systems on all of Underground Cables, Overhead Lines and Transformers at voltages ranging from LV to 66 kV. The Real Time Thermal Ratings are calculated at resolutions of up to 5 minutes and accessed by the CLNR Active Network Management System. The calculated Real Time Thermal Ratings have been used by the Active Network Management System to coordinate the operation of the CLNR Smart Grid technologies in dispatching real power (on different circuits) to demonstrate how they could be used to avoid overloading the distribution system.

For Underground Cables, Overhead Lines and Transformers the Real Time Thermal Rating trials have demonstrated that under certain conditions the distribution system assets can be operated above their present - static - ratings without exceeding the design parameters of the assets. Learning from RTTR trials monitoring can be incorporated into existing procedures to relieve assets of thermal loading (e.g. Ensuring adequate air flow or the use of better backfill on cables).

With the introduction of Low Carbon Technologies such as heat pumps and electric vehicles, and increased penetration from distributed renewable generation, it is vital that Distribution Network Operators are able to operate their networks with confidence and that load management systems are in place. The trialled systems are expected to provide information allowing Distribution Network Operators to minimise cost by showing where unused network capacity can be released.

Furthermore, trial results have shown that RTTR can show locations where the distribution network may be unexpectedly constrained due to operational or environmental conditions. Capacity releases can be expected in the use of RTTR on bespoke circuits on location specific instances (i.e. a wind farm connection).

For Overhead Lines, RTTR has been installed on HV lines at 20 kV and EHV lines at 66 kV. The RTTR system used weather conditions including temperature, wind speed and direction, in addition to load and static properties of the line. The trial results showed significant increases in thermal capacity compared to static ratings calculated under P27, particularly for double circuits. However, in particularly sheltered areas, combinations of low wind speed and high ambient temperatures resulted in ratings which were lower than the static ratings for a small proportion of the time. In order to maximise the benefits of RTTR on Overhead Lines, an Active Network Management System or alterative back up protection is required to avoid reducing the static ratings because of these periods.

For transformers, RTTR systems measured transformer load, ambient and transformer temperatures to assess the real time rating based on the equations set out in IEC 60076. The CLNR work has shown potential for a significant increase in transformer capacity because of the low thermal constant. However, further work is needed to establish the relationship between temperature, load and time. The window over which transformer RTTRs are calculated is recommended to be around 180 minutes to ensure that the transformer would reach steady state with constant load. It is also

recommended that transformers are procured to include fibre optic temperature sensors to ease implementation of RTTR in future.

For Underground Cables, the CLNR project developed and commissioned a concept design for RTTR. This trial design has proven the efficacy of the concept design and collected data over 17 months on the LV system and over 9 months for the EHV/HV systems. Significant learning has been achieved in understanding the parameters which influence cable thermal performance. This will lead to increased effectiveness of future RTTR systems and has shown a requirement for a modest revision downwards in the present static ratings calculations set out in Engineering Recommendation P17.

CLNR has demonstrated that RTTR can be deployed on distribution systems, across a range of asset classes and voltages, to increase reliability across the distribution system and to identify assets which have additional capacity, reducing the requirement for costly reinforcement.

A selection of the key lessons learned is listed in the table below:

Item	Details	Reference
1	Early engagement with Health and Safety stakeholders and working groups proved highly beneficial, especially in the development and approval of procedures to install equipment using our hot glove techniques. The learning achieved has identified periods where calculated results fall below static ratings for short periods, though capacity gains are released for much of the time. Acceptance of the systems outputs requires acknowledgement of the associated risk and coordination with backup protection mechanisms and a system to control powerflow, such as demand response.	RTTR LL 3.1 RTTR LL 3.3 RTTR LL 5.17 RTTR LL 5.23 RTTR LL 5.24 RTTR LL 5.25 RTTR LL 5.26
2	Managing change and integrating combinations of novel technologies onto the network, required a higher degree of specialist input than anticipated. Application and maintenance of the RTTR systems on the existing network was completed using our existing operational teams and procedures, maintenance and surveying requires significant attention should the system roll out on any scale. RTTR and the detail gathered about its proposed uses require integration into the business, particularly from control, design and technical services.	RTTR LL 5.25 RTTR LL 5.4 RTTR LL 5.5 RTTR LL 6.10 RTTR LL 6.10 RTTR LL 6.20

3	Communications infrastructure and GPRS communications in particular have identified that GPRS is insufficient in most cases for control and thermal rating purposes, especially in rural locations most likely for its application. The future roll out of smarter grid equipment is likely to be a telecommunications burden for DNO's. Enhancements using roaming SIM contracts had a major impact in both communication service provision and reliability for little extra cost. Thermal rating measured and controlled at source can ease the communications burden and infrastructure required.	RTTR LL 3.6 RTTR LL 3.7 RTTR LL 3.9 RTTR LL 4.8 RTTR LL 6.11

Glossary

ADC	Analogue to Digital Converter
ADSL	Asymmetric Digital Subscriber Line
ACSR	Aluminium-Conductor Steel-Reinforced
BaU	Business as Usual
BS	British Standards
CDF	Cumulative Distribution Function
CI	Customer Interruption
CIGRE	International Council on Large Electric Systems
CLNR	Customer-Led Network Revolution
CML	Customer Minutes Lost
CRATER	Cable Rating Software
CT	Current Transformer
DNO	Distribution Network Operator
DNP	Distributed Network Protocol
DTS	Distributed Temperature Sensing
EAVC	Enhanced Automatic Voltage Control
EES	Electrical Energy Storage
EHV	Extra High Voltage
ENA	Energy Networks Association
ER	Engineering Recommendation
ESQCR	Electricity Safety, Quality and Continuity Regulations
GE	General Electric
GPRS	General Pack Radio Service (Mobile Data Service)
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
GUS	Grand Unified Scheme (Control Infrastructure)
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institution of Electrical and Electronics Engineering
IP	Internet Protocol, Ingress Protection
LAN	Local Area Network
LCNF	Low Carbon Network Fund
LCT	Low Carbon Technology
LL	Lessons Learned
LTE	Long-Term Evolution (high-speed mobile data standard)
LV	Low Voltage
NPADDS	Network Planning and Design Decision Support
NPg	Northern Powergrid
NPS	Network Product Specification
OHL	Overhead Line

OPPC	Optical Phase Conductor
PD	Partial Discharge
PILC	Paper Insulated, Lead Covered (Cable)
PRT	Platinum Resistance Thermometers
PSU	Power Supply Unit
PV	Photovoltaic
RDC	Remote Distribution Controller (part of the GUS, installed in a substation).
RMS	Root Mean Squared
RTTR	Real-Time Thermal Ratings
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition (System)
SLD	Single Line Diagram
SSE	Scottish and Southern Energy
TR	Thermal Resistivity
UGC	Underground Cable
UKPN	UK Power Networks
UTC	Coordinated Universal Time
VPN	Virtual Private Network
VT	Voltage Transformer
WTI	Winding Temperature Indicator
XLPE	Cross-Linked Polyethylene

1 Introduction

1.1 Customer-Led Network Revolution Project

The Customer-Led Network Revolution (CLNR) Project is a four-year project, led by Northern Powergrid (NPg) trialling Smart Grid solutions within the NPg distribution network as well as creating smart-enabled homes to give customers more flexibility over the way they use and generate electricity. The results will help the industry to ensure the electricity networks can handle the mass introduction of solar PV panels, electric cars and other low-carbon technologies.

The objective of the CLNR project is to understand five Learning Outcomes, which are:

- **Learning Outcome 1** – What are the current, emerging and possible future customer (load and generation) characteristics?
- **Learning Outcome 2** – To what extent are customers flexible in their load and generation, and what is the cost of this flexibility?
- **Learning Outcome 3** – To what extent is the network flexible and what is the cost of this flexibility?
- **Learning Outcome 4** – What is the optimum solution to resolve network constraints driven by the transition to a low carbon economy?
- **Learning Outcome 5** – What are the most cost effective means to deliver optimal solutions between customer, supplier and distributor?

The CLNR project aims to understand the value of the different technologies in terms of being able to balance supply and demand while deferring investment in conventional reinforcement of the distribution network, and so facilitating the transition to a low-carbon economy while avoiding additional reinforcement costs. This is achieved by incorporating three network based technologies: Enhanced Automatic Voltage Control (EAVC), Real Time Thermal Ratings (RTTR) and Electrical Energy Storage (EES); in addition to customer flexibility solutions.

This report documents the lessons learned about RTTR from the process of initial design, through commissioning, to operation and maintenance and is intended to support organisations considering implementing RTTR on the transmission or distribution network.

1.2 Real Time Thermal Ratings

In the UK, thermal headroom for network assets is determined using static ratings which are based upon probabilistic methods and are representative of peak worst case scenarios. RTTR, using real-time data on weather conditions and usage rather than assumptions, could potentially release additional thermal headroom.

As part of the CLNR project, RTTR has been implemented for the following assets:

- Ground mounted primary transformer
- Ground mounted secondary transformer
- EHV and HV Overhead Lines
- EHV, HV and LV Underground Cables

The RTTR utilises measurements including asset operational temperature, ambient temperature, wind speed, voltage, current and asset location. Calculations based on these inputs feed into the GUS which then makes decisions based on ratings and performance.

1.3 Process and methodology for gathering lessons learned

Lessons learned for each of the network based technologies (EAVC, EES and RTTR) were gathered via a series of structured workshops, complemented and supported by a small series of site visits. In the case of the RTTR review, these comprised a series of visits in the installation of the Underground Cable RTTR system in 2012/13 by EA Technology (as system provider) together with a visit to the operational Overhead Line RTTR sites in Northumberland area in March 2013.

The Lessons Learned Workshops allowed staff working on all aspects of the project - ranging from procurement to health and safety, commissioning and project management - to reflect on the progress of the project and any aspects which challenged or showed learning opportunities.

This report principally documents the outcomes of the structured RTTR Lessons Learned Workshop supported by additional inputs from other sources, including the analysis performed by the CLNR project's academic partners, and follow-up with key staff.

2 Real Time Thermal Rating

2.1 General description of RTTR

Real Time Thermal Rating is a methodology to assess operational thermal rating of equipment such as Underground Cables, Overhead Lines and Transformers using real-time data of environment conditions and loading rather than conservative assumptions. RTTR could provide further information on thermal headroom; indicating whether areas are stressed (overheated) or in fact have more capacity than originally anticipated.

The temperature of an asset itself is key for RTTR as this should not increase above it design limits. It can be measured continuously if equipment has a Distributed Temperature Sensing (DTS) system, or can be estimated based on installation condition information and load data for assets without a DTS system.

RTTRs for Underground Cables with DTS can use direct measurements of the cable temperature, RTTR for Underground Cables without DTS must use environmental measurement, sheath temperature and loading. For a large proportion of existing underground distribution networks, a DTS system cannot be retrofitted cost effectively. Therefore, RTTR estimates cable temperature using a thermal model of the cable, based on real time cable environmental conditions and real time loading. A trial project of environmental based RTTR for Underground Cables was carried out as a part of CLNR project.

2.2 Objectives of RTTR

In the UK, thermal headroom is determined using static ratings which are based upon probabilistic methods and are representative of worst-case scenarios. The "static" design calculation methods provide simple and conservative estimates of network capacity.

In reality, networks can be complex and operational rating can be influenced by multiple factors including weather conditions and loading. Additionally for underground equipment, soil condition, burial depth, burial configuration, cable size and type must be considered. These factors often vary along routes, even for the same circuit. As a result, network capacity determined by “static” design calculation methods could be overly conservative. It is difficult to know whether equipment is being operated significantly below capacity, or being overloaded inadvertently which can cause premature ageing and failure.

With the introduction of Low Carbon Technologies (LCTs) such as heat pumps and electric vehicles, and an increased penetration from distributed renewable generation (i.e. photovoltaic panels, wind farms etc.), it is vital to increase the level of confidence for DNOs to operate their network more efficiently in a controlled manner.

RTTR can determine actual thermal headroom indicating whether some unused network capacity can be released or locations where networks are constrained; especially in the complex environment containing multiple cables, complex topology and different assets.

Note that the time constants for Underground Cables, Overhead Lines and Transformers are different and therefore the ideal shape for the load curve could conflict for the different assets.

3 Lessons common across technologies

A number of lessons have been raised across the different RTTR systems, principally on communications and thermal time constants of the systems.

3.1 Thermal Time Constants

The thermal time constant of the assets is an important parameter for RTTR as it governs:-

- The necessary speed of response for re-configuring an overloaded network
- How quickly the ratings can alter with changing conditions
- The extent to which the real-time rating is dependent upon previous events
- The amount and duration of short term overload current that can be applied to the line.

Given the different time constants of different assets, the impact of the whole of a circuit may need to be taken into account and a compromise achieved to ensure no asset becomes overloaded because of the implementation of RTTR on another asset on the same circuit.

3.2 Communications

Communications technologies have proved vital to successfully delivering all of the RTTR trials described here. However, the CLNR project did not set out to trial any novel communications technologies, and there were no specific communications outputs for the project. This section aims to collect the learning related to this rather than repeating it through the whole report.

3.2.1 Solution Design

All of the RTTR systems procured for the CLNR project required real-time communication of monitoring data from the measurement sites to some form of central Calculation Engine, with the results then being passed on to the Active Network Management System for real-time control. This architecture placed considerable strain on the public communications networks used for the project, both because large volumes of data were being transferred, and because data had to be transferred promptly in order to facilitate real-time control. This meant there was no opportunity to re-send failed communications, with a significant increase lost data occurring as a result.

In future changes to this structure should be considered, to reduce the volume of data transferred over communications networks, and to increase the opportunity to re-transmit missing data during idle periods.

Where the volume of monitoring data substantially exceeds the volume of RTTR results (for example Underground Cable and Transformer RTTR) then the location of the Calculation Engine in an RTU in the substation will greatly reduce the volume of data to be transmitted. This has the disadvantage that it is usually impossible to obtain the raw input data to scrutinise and develop the RTTR algorithms, so will only be possible once the RTTR algorithms are sufficiently mature to operate autonomously. For business-as-usual applications with proven RTTR algorithms local Calculation Engines should be used.

3.2.2 Obtaining Communications

For the CLNR project, communications were provided over public communications networks, mainly 3G Mobile Data networks, with some sites having ADSL fixed lines installed. This reflects the fact that the majority of the CLNR equipment was installed at locations on the distribution network which have not historically been linked to electricity network private communications networks, and there is not always sufficient capacity to accommodate the volumes of data involved in these trials.

The project learning with 3G data was broadly in line with previous usage of similar GPRS data for fault passage indicators and the like:

- Network coverage is far from universal outside of urban areas, even with high-gain external antennas.
- Signal changes over time and from day to day. Sites which had good signal strength at commissioning may suffer from loss of signal subsequently.
- In some urban areas network congestion may result in very restricted bandwidth at peak usage times.

It was possible to mitigate (but not entirely resolve) all of these issues by employing roaming data SIM cards for connections. These are data SIMs issued by mobile operators outside the UK, but which can then roam to any of the UK mobile networks for coverage in the UK. Whilst this produces the useful technical result of a SIM which works seamlessly when it is within range of any of the four major UK mobile networks, it comes at the cost of high data charges for roaming. The UK Government has now consulted on ways to improve this situation[1]. A number of options, including some which would permit this sort of inter-network roaming at normal data rates, have been proposed and the outcome of this consultation is awaited.

Most of the 3G SIMs were procured on a contract basis. Whilst this involved an up-front commitment to a mobile network operator, often for 12 months or more, it has ensured that communications disruptions due to commercial issues have been avoided. Those SIMs procured on a 'pay as you go' basis encountered numerous problems with this, including running out of credit (not always a predictable event, due to varying data volumes and complex time-based expiry rules applied by operators) as well as intermittent coverage due to a lack of roaming facilities. The result was that all possible data was recorded at OHL RTTR sites, using these SIMs, for only 38.1 and 32.6% of the data collection period on the HV and EHV systems respectively.

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[1] 'Tackling Partial Not-Spots in Mobile Phone Coverage', 5th November 2014, https://www.gov.uk/government/consultations/tackling-partial-not-spots-in-mobile-phone-coverage. Accessed 11 December 2014

Whilst technical alternatives to 3G communications exist, they were not studied as part of this project, and are likely to have costs and limitations of their own.

The smaller number of ADSL communications links employed at sites where active network management interventions were installed have worked well, with very few data communications issues. The costs of communication are low, and performance adequate for any expected requirements. There were however delays in the installation of the fixed lines, and significantly the commissioning of the Virtual Private Network (VPN) scheme required in order to use them securely. These factors prevent the universal use of ADSL communications for future Smart Grid projects.

3.2.3 Communications Protocols

In the initial procurement specifications, discussion of communications protocols was restricted to 'The existing Northern Powergrid communications infrastructure uses DNP 3.0 protocol. Any new equipment should therefore support DNP 3.0.' In practice, things have not turned out to be quite that simple.

The majority of the equipment procured does use DNP 3.0, however it does not always use it in a manner which is interoperable with the other equipment which it has to communicate with. Some of the problems encountered have included:

- Incomplete implementation of the standard, e.g. no support for floating point values
- Lack of clarity over what DNP 3 data points the RTU will provide (e.g. confusion between real, reactive and apparent power)
- Inconsistent units for measurements (e.g. temperature as an integer in tenths of a degree)
- Endianness (bit order) of values not clearly specified leading to invalid values being read.

Modern software-defined Smart Grid equipment has a great deal of flexibility, but this can lead to a morass where nothing actually communicates because decisions have not been made on which mode to force each device to operate in, or in a particular order. A single design authority (or industry standard) for the various communicating systems that can make these decisions in a rational way (not dependent on any one supplier) is required.

To mitigate these problems, specification and procurement processes must be tightened, with suppliers providing detailed lists of available DNP3 data points, including the units, scaling factors and data types employed. This will allow the communications system design authority to determine whether the equipment is actually claiming to be interoperable in the required combinations, and allow the maximum time for resolving issues.

The new scenarios under which equipment has been operated for the CLNR trials have revealed various firmware bugs, even in already field proven equipment, wherever features have been used in anger for the first time. Not all of these bugs have been in 'Smart' features, e.g. firmware bugs were found (and fixed) in proven tap control relays related to paired mode operation, because previous deployments of this relay type had always been single relays. The only mitigation for this is careful testing of each new piece of functionality after commissioning and suitable commercial relationships with suppliers to ensure that the necessary after-sales support is in place.

3.3 Summary of lessons learned across technologies

RTTR LL 3.1 Developing a clear strategy and approach for the use of real time thermal rating systems requires significant effort across the business, safety and design issues are paramount and consideration of coordination with network protection systems is key

RTTR LL 3.2 Different thermal time constants and required inputs apply to RTTR of different asset classes. Therefore different monitoring intervals were required for Overhead Lines (5 minutes), Underground Cables (30 minutes) and transformers (xx minutes)

RTTR LL 3.3 Where a circuit employs RTTR, consideration is required for assets not fitted with RTTR to ensure no asset becomes overloaded because of the implementation of RTTR on another asset on the same circuit

RTTR LL 3.4 *RTTR systems should not monitor with sample intervals more frequent than is* required, to reduce the volume of data required

RTTR LL 3.5 Consideration should be given to data reduction (averaging) in RTUs so that only required data is transmitted over communications networks

RTTR LL 3.6 Where RTTR algorithms are sufficiently mature, location of Calculation Engines at the point of monitoring will substantially reduce the data to be transmitted.

RTTR LL 3.7 Significant reliability problems were encountered with communications based on GPRS.

RTTR LL 3.8 Mobile network SIM cards should be procured on a contract basis rather than 'Pay as you go' to avoid disruption when credit expires.

RTTR LL 3.9 Use of roaming SIMs able to access multiple mobile networks substantially improves the reliability of mobile communications, but also substantially increases the costs of communications.

RTTR LL 3.10 ADSL communications are reliable and cost-effective, but require a VPN for security which may be time consuming to set up, and will not be available at all sites.

RTTR LL 3.11 There must be a single design authority for communicating systems to deal with interoperability issues at the specification stage, rather than during implementation.

RTTR LL 3.12 Suppliers should be required to provide detailed listings of the data points supported by their equipment at the tender stage.

4 Underground Cable RTTR

4.1 Implementation of Underground Cable RTTR in the CLNR project

The CLNR project implemented the trial of RTTR systems on Underground Cable networks to dynamically assess and release capacity. The trial project only installed Underground Cable RTTR in the Urban High Density test cell at EHV, HV and LV levels.

4.2 Current status of the Underground Cable RTTR deployment in the CLNR project

In the initial stage of the project a design document was created, listing the constituent components required for UG Cable RTTR. The design document investigated the means and methods via which UG Cable RTTR could be introduced, reviewing technology choices, systems in practice on the electrical network today, equipment used, how solutions would work and what measurements and additional features would be required.

The Cable RTTR system at Darlington Melrose was commissioned in February 2013, and the systems at Darlington Rise Carr in November 2013.

At this stage, an initial detailed data analysis was carried out for the data collected in January 2014 and July 2014 representing winter and summer ground conditions, respectively. The purpose of the initial analysis was for a data sanity check and to develop the methodology for the further analysis work.

4.3 Lessons learned from design

4.3.1 UK Practice in Underground Cable Sizing and Rating Design

In the UK, ENA ER P17 Current Rating Guide for Distribution Cables Part 1 - 3 is used for Underground Cable sizing and rating design. The Guide provides a basis for estimating the ratings of cables for particular environmental and operational conditions, and gives tables of ratings for a stated set of conditions that have been selected as typical for distribution cables. The Guide also provides correction factors for engineers to make adjustment where the conditions are different from those assumed in the standard rating calculation.

DNO cable engineers use one of the following methods or a combination of some to base their cable sizing and rating design:

- Follow the Guide
- Using CRATER (a cable rating calculation software developed by EA Technology)
- Refer to manufacturer’s recommended ratings
- Use company specific tables collated using CRATER and manufacturer’s information.

While some DNOs selected the cable size based on cyclic rating or steady state rating, others use a limited time rating for their cable size design (cyclic rating). As a result, available capacity or headroom of Underground Cable networks varies depending on the methods DNOs employ for their cable sizing design.

It should be noted that while the "static" design calculation methods are likely to provide conservative estimates of cable rating, they do not completely rule out the possibility of local hot spots in a cable route, due to particular local conditions or mutual heating from cables installed in close proximity.

With the additional information from the trial, the company tables should be reviewed. In general the information from the trial shows that cable depth, soil type and the shape of load curve have a material impact on ratings and the actual worst case should be used when calculating static ratings.

4.3.2 Concept Design of RTTR

The concept of RTTR for Underground Cable networks is to monitor cable conductor operating temperatures and enable cables operated at their maximum rating capacity safely without overheating.

Cable operational temperature can be monitored and measured continuously along the length of the cable route if a Distribution Temperature Sensing (DTS) system is installed, or has to be estimated based on installation condition information and loading data for those cables without a DTS system.

For large proportion of existing underground distribution cables, a DTS system is impractical to retrofit, as this would involve excavating the entire length of the cable route. RTTR systems therefore have to use real time cable environmental information and real time loading to estimate cable operational temperature. The application of RTTR can be a desktop process which allows a DNO to re-assess their cable ratings using actual conditions and loading.

This trial project is an application of RTTR on existing cables without DTS installed. The thermal rating model for calculating cable RTTR should be based on an established methodology such as IEC 60287 and IEC 60853. The key inputs to the RTTR cable rating modelling are required as follows:

- Cable size and type, installation configuration (cable laying formation)
- Soil ambient temperature
- Soil thermal resistivity and cable backfill material thermal resistivity if used
- Real time loading

In the initial stages of the project a design document “CLNR Learning Outcome 3: Design of RTTR Solutions for Underground Cables” was created for the solution, listing the constituent components required for Underground Cable RTTR.

The design document was to address issues of Underground Cable RTTR solutions within the overall network context. The two test cells were the Rural Low Density and Urban High Density for which RTTR was to be designed for EHV (e.g. 66kV or 33kV), HV (e.g. 20kV, 11kV or 6kV) and LV (e.g. ≤1kV) Underground Cables (UG Cables).

In the trial project, RTTR was only applied to Urban High Density cell at EHV, HV and LV voltage levels. It was decided in the design that a single location was to be selected on the cable route for measurement of cable environmental conditions, and the equipment for the measurements was installed at substation sites for convenience.

4.3.3 Lessons Learned

During the trial project, lessons learned regarding the design concept are as follows:

- ***Cable installation environmental conditions can vary along the route***

Cable installation environmental condition can vary along a cable route as the cable circuit may travel through different types of soil, the cable may need to be buried deeper at some locations, or various neighbouring cables may join it to share the route or the trench at various locations, etc., therefore operational temperature of a cable circuit may vary at various locations along its route. The locations where the cable operational temperature is higher could be the hot spots in the cable circuit, and the cable rating can be constrained at one or more of these hot spots.

Without DTS, a RTTR system is unable to assess cable operational temperature continuously along its route, to increase accuracy of rating modelling, possible hot spots should be assessed and included in the modelling.

In the trial project, the cable installation condition was only tested at a substation site for the selected cable circuit, but it does not mean only one test location is required when applying RTTR to a cable circuit in Business-as-Usual in the future. Condition information from one location in a cable route cannot represent installation conditions of the cable circuit. RTTR modelling based only on one location condition could be insufficient and inaccurate. For Business-as-Usual in the future, installation condition from various locations should be assessed and included to enrich the model and make RTTR more accurate. The numbers of hot spots to be modelled are dependent on an assessment of the cable route condition and site accessibility.

- ***Hot spot selection***

Selecting hot spots is essential when conducting RTTR modelling for a cable circuit. Hot spots can be selected firstly based on a desk top study and then followed by a site visit. The desk top study is to use drawings (cable route plan, as built drawing etc.) to identify locations where the cable is buried deeper or with more neighbouring cables in proximity; and if a soil map is available, where the cable buried in an unfavourable soil type (for example sand) can also be picked up as a hot spot. The site visit is to investigate the accessibility of these potential hot spots, and to confirm the final selection of the hot spots which will be assessed to get the cable installation condition information for the RTTR application.

There are no rules for how many hot spots should be assessed for the RTTR modelling. The more hot spots are assessed, the more accurate results a model will produce, which will enhance confidence when operating the cable circuit based on its RTTR. On the other hand, the more hot spots used, the more expensive the cable rating assessment will be.

- ***Mutual heating cannot be disregarded***

Mutual heating from neighbouring cable(s) has critical impact on the rating of the cables. Without including the neighbouring cables in the cable rating modelling, the RTTR calculation for the selected cable can be misleading. This is also applicable to static ratings and leads to the recommendation that this be included in P17 (see Section 4.3.1). It should be noted that this is well understood by DNOs and is included in current NPg planning policy.

- ***Soil thermal resistivity testing***

Soil thermal resistivity was measured at two locations in the trial project but it was difficult and expensive to install sensors permanently on site. Thermal resistivity is one of the thermal properties of soil, which varies in different types of soil, and has a nonlinear correlation with moisture content of the soil. Compared with wind speed, soil thermal resistivity is more stable, especial when the moisture content in the soil is above a certain level. Figure 4-1 below shows soil thermal resistivity vs moisture curves for different soil types.

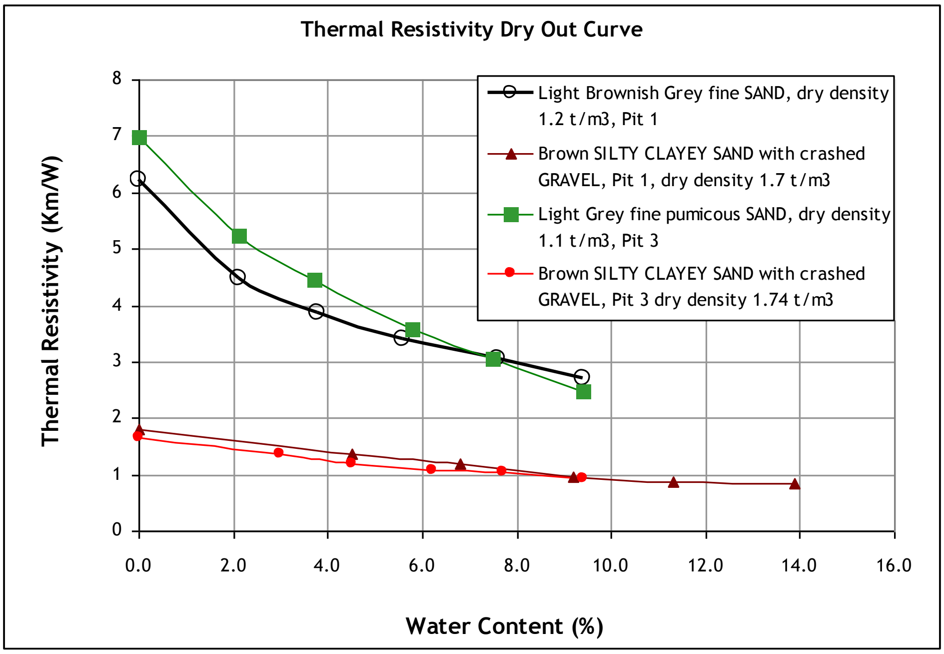


Figure 4-1: Soil thermal resistivity vs moisture curves

As illustrated in Figure 4-1, soil thermal resistivity increases as soil moisture content drops, increasing more rapidly below a certain level when the soil starts drying out. Correlation between thermal resistivity and moisture content varies in different soil types, so the turning point (start of drying out) and the maximum thermal resistivity value which is reached at soil fully dried state are different in different types of soil.

As soil thermal resistivity is primarily influenced by soil type and moisture content of the soil and it is unlikely to be unstable when moisture content level is high in the soil, it is not necessary to measure soil thermal resistivity continuously.

It is suggested that for Business-as-Usual, a soil thermal resistivity survey be carried out in a DNO's underground network area. The survey is to identify soil types and develop soil thermal resistivity vs moisture curves by laboratory testing for the soil types found. Soil thermal resistivity at a selected hot spot site can be obtained from a typical thermal resistivity moisture curve which matches with the soil type at the site, based on soil moisture content measured in the site.

Continuous monitoring measurement of soil thermal conductivity in this trial project has helped to back up the recommended approach of doing offline soil samples.

- ***Mutual heating from neighbouring cables***

Mutual heating from neighbouring cable(s) has a critical impact on the cable circuit selected for RTTR. Without including the cables in close proximity to the selected cable circuit for rating modelling, the RTTR calculation for the selected cable can be misleading.

In the trial project, when temperature sensors to monitor cable sheath temperature for the selected cable circuit were installed, other cables were found installed close to the selected cable. It is not possible to thermally model a single cable in isolation, if it runs in close proximity to other cables or heat sources. The trial specifications attempted to pick a circuit or feeder for RTTR based purely on the electrical connectivity of the distribution network, paying no attention to the physical location of the cable or what other cables were in close proximity. No provision was made to measure the loading on other cables which affect the circuit for which the rating was to be calculated.

In future, the whole cable situation should be considered when designing RTTR UGC systems, so that the loading and construction of all physically relevant circuits is measured and available to the model. Doing so will avoid the need for additional soil temperature sensors (used in the CLNR trial to compensate for elevated soil temperatures caused by cables not being modelled) and significantly improve the system accuracy.

- ***Emergency rating***

Underground cables have emergency current carrying capacity for defined period. The amount of extra current that can be conducted through the cable during an emergency event is dependent upon how the cable has been loaded before the emergency event, usually 6 hours prior to the emergency event, and the period required for the emergency event. In a situation where multiple cable circuits sharing a common trench, switching off one cable circuit doesn't always mean the remaining cable circuits can take increased load instantly, especially when these cable circuits are loaded highly before the event of emergency as the heated soil needs time to cool down.

- ***Static input parameters to RTTR***

Static input parameters to RTTR are mainly cable construction data. They do not change over time but may vary at different locations along the cable route as the cable type and size change. For the trial the general cable type was found using historical records from Northern Powergrid, and the numerous cable dimensions required to model the cables obtained from EA Technology's collection of cable data, built up from standards (BS and ENA) and manufacturer's data sheets. This process was not altogether straightforward, and it was necessary in some cases to make assumptions based on 'usual' historic practice where detail was not available. This was mostly dependent on the knowledge of experienced NPg staff rather than written down, and may become an issue in the future as these staff leave the business.

For Business-as-Usual it is suggested that a GUI software package is used to provide a data-base of these parameters and enable the correct parameters to be applied more easily. It will be important to document alongside this the historic design practices of the network operator so that appropriate (or at least most likely) choices can be made when calculating cable ratings. This is particular important when cable designs or practice for new installations changes, but large amounts of historic network remain constructed using older designs, which are more likely to be the subject of RTTR schemes.

- ***RTTR Model Outputs***

With a Business-as-Usual approach to the Underground Cable RTTR, operators only require the information that allows them to make operational decisions and monitor cables. For this reason it is recommended that there are only three types of output required; the ampacity of the cable for 1, 3, 6, 12 hours, the time the existing load can be carried under the present conditions and health alerts in case of system failures.

The calculated 30 minutes ampacity is to indicate the maximum cable operational rating for the next half hour. It is largely dependent upon the cable loading prior to the "30 minutes" event should it occur.

- ***Calculation Engine***

A dedicated server was hosted at EA Technology and linked to the iHost server at Northern Powergrid over the internet via a VPN. This ensured the server was easily accessible at EA Technology for initial setup and configuration.

It is envisaged that for BaU, the calculation engine will be hosted on the Northern Powergrid network removing the need for unnecessary internet traffic. The RTTR calculation model can be packaged for execution on individual RTUs (e.g. Nortech Envoy) at each site location to reduce data charges and data transmission error risk. Alternatively, the data collected from all sites can be hosted in a dedicated centre service.

- ***Cable Condition Assessment***

Underground Cable condition needs to be assessed using off-line or on-line cable PD testing before proceeding with RTTR application. This is unlikely to be an issue with HV cables, but it would be a challenge to check health condition of LV cables. Increasing the rating of a cable circuit based on the RTTR result without checking the cable condition, including PD, could increase the risk of cable failure.

- ***RTTR Process Scheme***

In summary, the application of an RTTR for the existing cables without a DTS is a process of re-assessing cable operational rating based on real time environmental and load conditions. This process will help DNOs to increase certainty the capacity their cables, and to improve the level of confidence in operating and managing their Underground Cable networks.

Figure 4-2 below provides a simple scheme for the RTTR process.

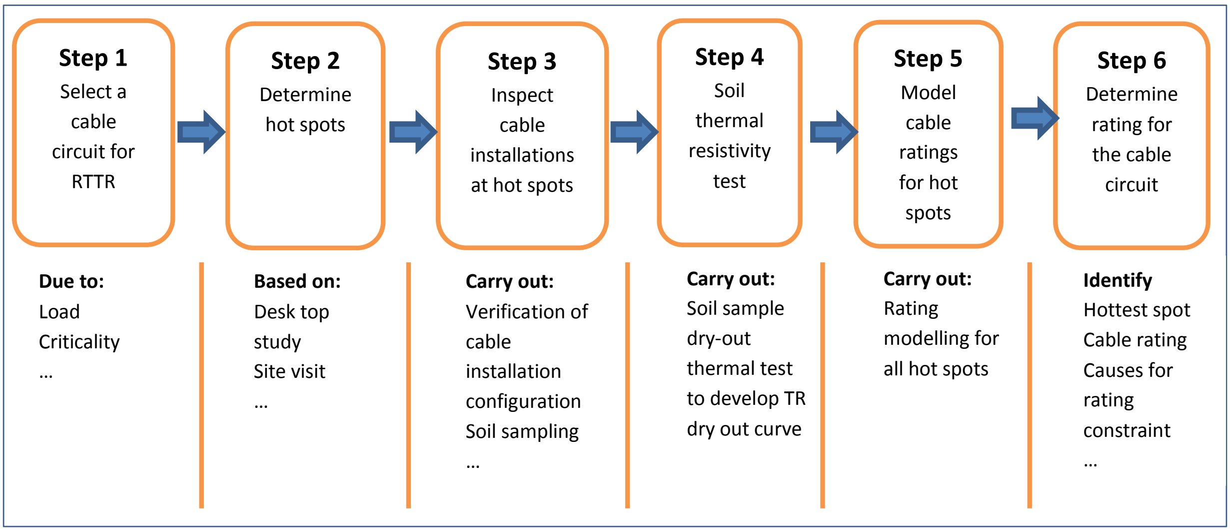


Figure 4-2: RTTR process scheme

The modelling process can be used in a number of ways:

- A desk top study, when planning, to understand the existing capacity and whether it is sufficient for a particular new load type. In this case the closest weather data and loading data would be used and soil resistivity curves.
- A desktop study to understand whether a cable is actually overloaded using the closest weather data and loading data and soil resistivity curves.
- RTTR with real time measurements to manage loads on a feeder to prevent overloads or reduce CIs and CMLs under outage conditions.

For desktop studies, this capability should be built into NPADDS.

4.4 Lessons learned from procurement and installation

The equipment requirements highlighted within the design document for Underground Cable RTTR, were used to create an equipment specification document. The document was used for the procurement of equipment in the trial. The following are the findings and the lessons learned:

4.4.1 Market Analysis

The design document reported that other than the use of fibre-optics within the cable, there are few off the shelf options to measure soil or cable conditions that can be applied for RTTR purposes.

At the design stage, we found that there were no off-the-shelf systems that were suitably mature and could be used on the existing cable asset, and therefore the RTTR procurement solution would be bespoke.

A solution based on the IEC cable ratings standards similar to CRATER was used for the Underground Cable RTTR.

4.4.2 RTTR System Components

The initial procurement document outlined system components required for RTTR applications as follows:

- Temperature sensors for soil temperature and cable sheath temperature measurement
- Thermal resistivity sensors for soil resistivity measurements
- Ambient temperature sensors
- Pyranometers for solar irradiance measurements
- CTs and VTs

The specification component has been revised as follows:

- Keep temperature sensors for soil and cable sheath temperature monitoring,
- Keep CTs for cable loading monitoring,
- Add communications system requirements
- Remove Pyranometers for solar irradiance and VTs for voltage measurement
- Reconsider the methodology of soil thermal resistivity measuring.

4.4.3 Communications System

Communications were required between:

- Measurement devices and a Local Controller; this was implemented using RS-485 Modbus RTU serial links, as these can cover distances up to 1200m in noisy environments, and are widely supported by the meters and ADCs used,
- Local Controller and a Calculation Engine; these communicated over public IP networks, using ADSL lines at the substation ends to connect to the Local Controller,
- Calculation Engine and the GUS; this was achieved via a VPN connection between the Calculation Engine at EA Technology Capenhurst and the GUS at Northern Powergrid.

A schematic of the Underground Cable RTTR communication system in the trial is given in

Figure 4-3.

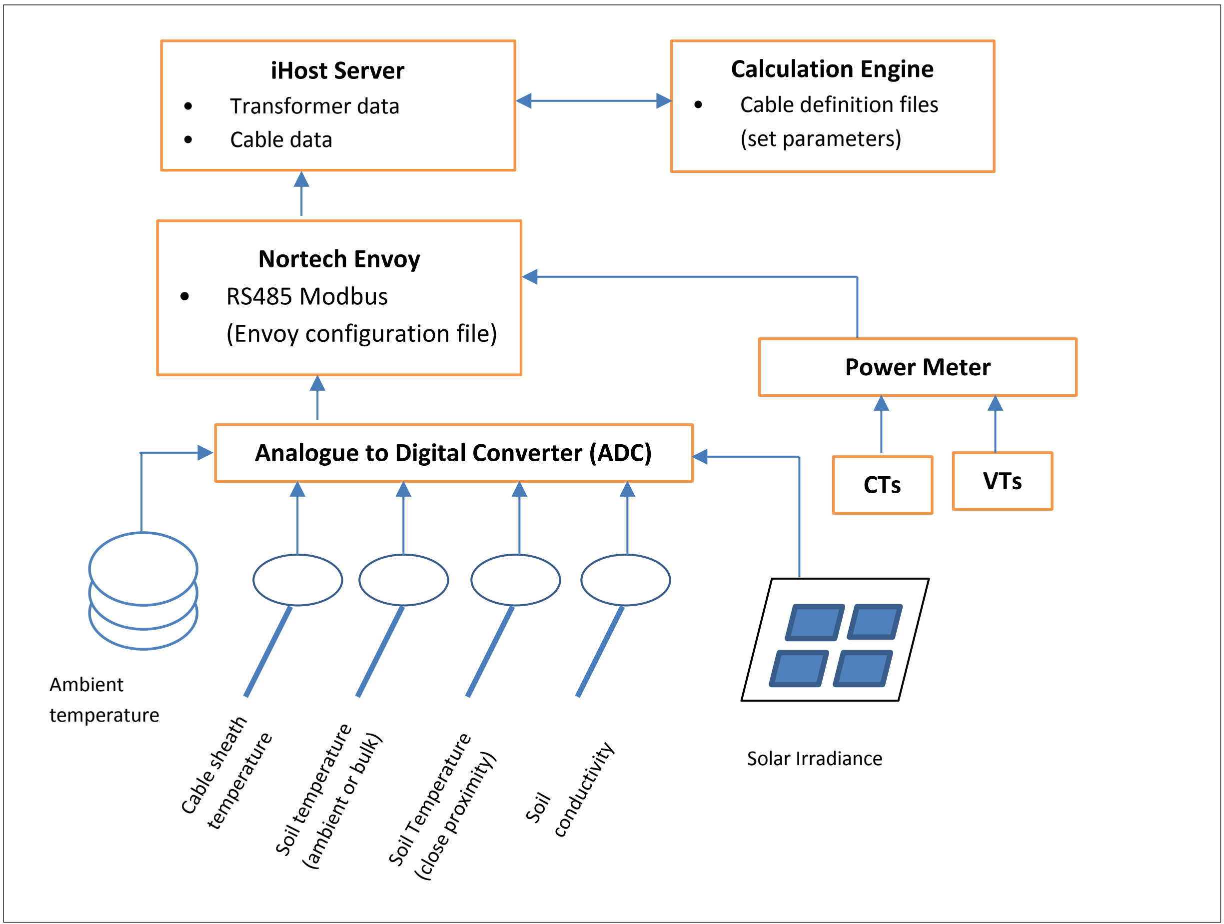


Figure 4-3: Simple schematic showing system components of an UG Cable RTTR system

Time-series parameters were sent from measurement devices to a server (iHost server) located on Northern Powergrid's Network. A Calculation Engine executed on a dedicated server at EA Technology obtained these time-series inputs from the server over the internet via a Virtual Private Network (VPN). The calculation engine server contained the static parameter files required to represent each of the cable networks being modelled in the CLNR project. The calculated Underground Cable RTTR values were stored on the dedicated server at EA Technology and sent back to dedicated channels on the iHost server where they could be accessed by users.

It is likely that a calculation engine would be hosted on the DNO's network in the future, removing the need for unnecessary internet traffic. Alternatively, the RTTR calculation model can be built into the Remote Terminal Unit (RTU), so the calculations can be carried out locally at each site and only the results need to be sent to the control centre.

The resultant RTTR provided both the length of time that the existing load could be carried, and the different capacities that could be available for different periods of time into the future. The cable sheath temperature was measured to compare with the predicted temperature within the model.

4.4.4 Equipment Procurement

Based on experience gained through equipment procurement, it is suggested that improvement and modification are required in specifying the following equipment:

Temperature sensors

Temperature sensors for both soil ambient temperature and cable sheath temperature measurements were required for this application of RTTR. While cable sheath temperature is used for the purpose of verifying the cable rating calculation, the soil temperature is used as a key input for RTTR modelling. Specific requirements should be provided for sensors with different purposes of use.

In the trial project, Platinum Resistance Thermometers (PRT) temperature sensors were chosen due to their capability of meeting the accuracies specified for the trial, and they could be purchased off-the shelf with a weatherproof sheath. Silicon chip sensors could provide an alternative. If silicon chip sensors were available with adequate weather protection, use of these would be preferential as they have a digital output and the calibration is achieved internally. For the PRT sensors used within trials, all Analogue-to-Digital channels had to be calibrated to get the accuracy required.

Current measuring devices

CTs are required for cable circuit current measurement. For HV and EHV systems, secondary CTs need to be connected to the protection wiring to avoid the need for an outage. Specific requirement should be provided for procurement document to ensure the equipment purchased matches with the cable protection systems. It is necessary to involve protection engineers from the DNO to ensure the equipment is acceptable to them. Full Root Mean Square (RMS) measurements shall be specified for all the current measurements.

The original procurement specification requirement was confirmed, i.e., current measurements shall be taken using split-core CTs or Rogowski coils for each of the three-phases from protection CTs currently in-situ. When procuring equipment the full-scale secondary current of the CTs installed at the specific substation site must be included in the supplier information so that suitable equipment can be supplied.

The sampling rate of devices should be less than the smallest time constant within the thermal models used to calculate RTTR. Within the models, the thermal time constant is the time dependent step change of the heat of Underground Cables and is of the order of hours to days depending upon the cable location and surroundings.

To calculate the temperature of the cable, the total heat input over a period of time needs to be calculated. Instead of using an average current between time T_0 and T_1, a Full Root Mean Square (RMS) measurement is required to get more accurate results.

A sampling period of 10 minutes is considered suitable as it is less than the thermal time constant of distribution cables and practically achievable in terms of power requirements and typically available communication bandwidth in remote locations.

General requirements

General requirements for equipment specified in the procurement specification were tested in the trial project. It is suggested some modifications required on the following items:

- Lifetime of the devices

Lifetime of the sensors can be reduced to not less than 10 from 15 years specified in the original specification, if the recommended approach is used in the future as the soil temperature and thermal resistivity are not required to be monitored continuously.

- Ingress protection rating

It was required in the procurement specification, that all equipment shall be environmentally tested to a minimum IP68. In fact it was discovered that equipment installed in different environments should meet different environment protection ratings. Equipment ingress protection ratings should be specified as follows:

- All outdoor housing for equipment shall be environmentally tested to a minimum IP55
- All indoor equipment to IP52 in accordance with BS EN 60529.
- Equipment for permanent installation below ground shall be tested to a minimum of IP68

- Accuracy Requirement

The procurement document for the trial project sets up a high standard requirement on equipment accuracy. We found that the requirements on accuracy were unnecessary and impractical. It is recommended to use accuracy class of 0.5 (traffic kWh metering) or 1.0 (commercial kWh metering) for CTs.

4.4.5 Equipment Installation

Lessons learned through temperature sensors installation are provides as follows:

- Soil ambient temperature should be measured at approximately 1000 mm and 500 mm below ground level as HV and LV cables are likely buried at these depths respectively. Sensors should be installed in a cable route with minimum 2 metres space from the power cable or in vicinity without power cables.
- Cable sheath temperature sensors should be tied to the cable surface using standard nylon cable ties, instead of metallic clips to minimise the risk of cable surface damage.
- Where temperature sensors are buried, the cable heads must be accessible for future maintenance and calibration. To mitigate potential hazards from human interference, it is suggested that earth rod boxes or access chambers are used to house cable heads rather than leaving heads protruding from the ground.
- Temperature sensors need to be encased in ducting to protect them from the surrounding environment. It is suggested that plastic flexible ducting is used in all future installations.
- An installation manual with precise installation locations is required for the future projects.
- To fit secondary CTs personnel were required with site specific knowledge - knowing which conductor to fit them to - and with appropriate authorisation to work on relevant protection systems. The CT installation work is carried out on protection equipment, but the project is focused on potential benefits to existing cables, which are generally maintained by a different business section. This is an example of a typical “smart grid” or research and development learning cutting across traditional DNO silos. This indicates a future need for multi-skilled staff.

4.5 Lessons learned from testing and commissioning

The Cable RTTR system at Darlington Melrose was commissioned in February 2013, and the systems at Darlington Rise Carr in November 2013.

4.5.1 Darlington Melrose

The Nortech Envoy RTU to provide communications at Darlington Melrose was already installed when the Cable RTTR project was commenced. This RTU was communicating over GPRS and so there was no delay in having communications available at this site.

After commissioning significant issues were encountered with the reliability and bandwidth of the GPRS data link, which regularly dropped out. As the Nortech Envoy was not configured to store data during these outages, significant numbers of readings were lost. This will have had an adverse impact upon the accuracy of the RTTR calculations, especially for fast-changing inputs like load current on LV networks.

This was resolved at this site by the installation and commissioning of an ADSL line and VPN link to replace the 3G system, since which time the data reliability has greatly improved.

4.5.2 Darlington Rise Carr

Installation at the Rise Carr substation was significantly delayed by the procurement and installation of the Nortech Envoy RTU, ADSL line and VPN router required to connect the RTTR instrumentation to the iHost server. This emphasises the importance of specifying, designing and implementing the communications to support RTTR systems alongside the RTTR equipment itself.

Consideration should be given to RTTR systems which can use a single cable (or cable loom) to distribute both power and communications to their various components in order to reduce significantly the wiring work required.

Another challenging part of the commissioning process was installing the secondary CTs used to measure the load currents in the cables being modelled. Whilst the split-core CTs used had been accepted and the correct protection CT circuits identified on the substation single line diagram without incident, it took time to arrange for a suitably authorised Northern Powergrid Senior Authorised Person to be on site, with the correct documentation as to which numbered wires within the panels needed to have the CTs attached to them. The CT installation itself was not problematic and did not take long to undertake once on site. Future projects will ensure that suitably trained and authorised staff is available, aware and supplied with accurate information before any RTTR installation takes place.

During commissioning at both sites it was essential to have access to the iHost server display screens so that readings from the instrumentation could be checked, as there was no facility available to read the measurement values locally from the Envoy RTU. Access to the iHost server web interface was achieved via a laptop with a 3G data dongle for internet access, carrying a VPN connection to the iHost server at Manor House. This worked well, but depended on 3G mobile data service being available on site.

It may be beneficial in the future to consider arrangements for local access to data during commissioning that do not depend upon the communications infrastructure on site. This should allow the commissioning engineer to read the measured data values from the RTU directly, so that each sensor can be commissioned without the communications links to be working if necessary. This is especially important if RTTR algorithms are being implemented locally in the RTU.

4.6 Lessons learned from data analysis

4.6.1 Background

In the trial project, the RTTR equipment has been installed at two substation sites to measure and monitor the ground soil conditions for the following three selected cable circuits:

- EHV circuit: three 33 kV XLPE 240 mm^2 AI conductor, single core cables
- HV circuit: a three core 6.6 kV PILC 0.2 in^2 copper conductor cable
- LV circuit: a 4 core PILC 185 mm^2 Cu conductor cable

The EHV and HV circuits have been monitored at Darlington Rise Carr substation site since November 2013, and the similar monitoring for the LV cable has been stared at Darlington Melrose substation site since February 2013. The following cable installation and operational conditions have been measured for the three cable circuits.

- Soil ambient temperature
- Soil thermal conductivity
- Cable sheath temperature
- Cable loading

An initial detailed data analysis was carried out for the data collected in January 2014 and July 2014 representing winter and summer ground condition respectively. The purposes of the initial analysis are for data sanity check and methodology development for the further analysis work, detailed below.

4.6.2 Initial Data Analysis

Darlington Rise Carr substation site

<u>Temperature measurements</u>

The soil temperatures were measured at three locations including 900 mm and 450 mm depth away from the cable, and close to the cable. The data shows that the ground soil temperature varies in depth and correlates to the change of seasons. In winter, the soil temperature is lower at 450 mm deep than at 900 mm, but in summer the soil temperature is higher when closer to the ground surface.

The cable sheath temperature would be higher than the soil ambient temperature and the temperature of the soil around the cable, but the trial data seems to exhibit a calibration offset. As different temperature measurement systems are used for soil and cable sheath, it is important to calibrate the systems to align the data. The figures below illustrate the measured temperatures for the EHV cables in January and July 2014:

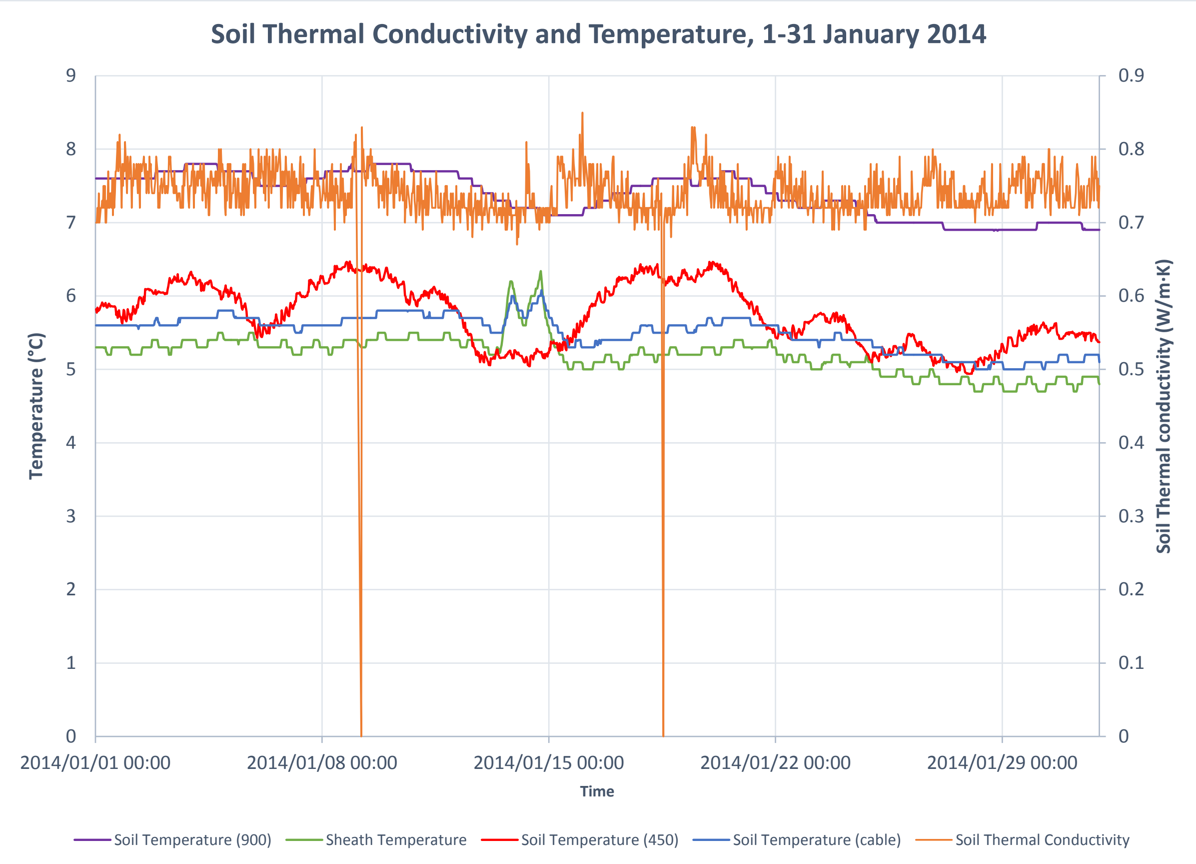


Figure 4-4: Measured temperatures and soil thermal conductivity for EHV cable at Rise Carr in January 2014

In Figure 4-4, Soil Temperature (900) is the soil temperature measured at 900 mm depth away from the cables, Soil Temperature (450) is the soil temperature measured at 450 mm depth away from the cables, Soil Temperature (cable) is the soil temperature measured above the cable. Sheath Temperature is measured on the cable sheath. The Soil Thermal Conductivity is measured at a depth of 450 mm. The same clarification should be applied the following similar figures.

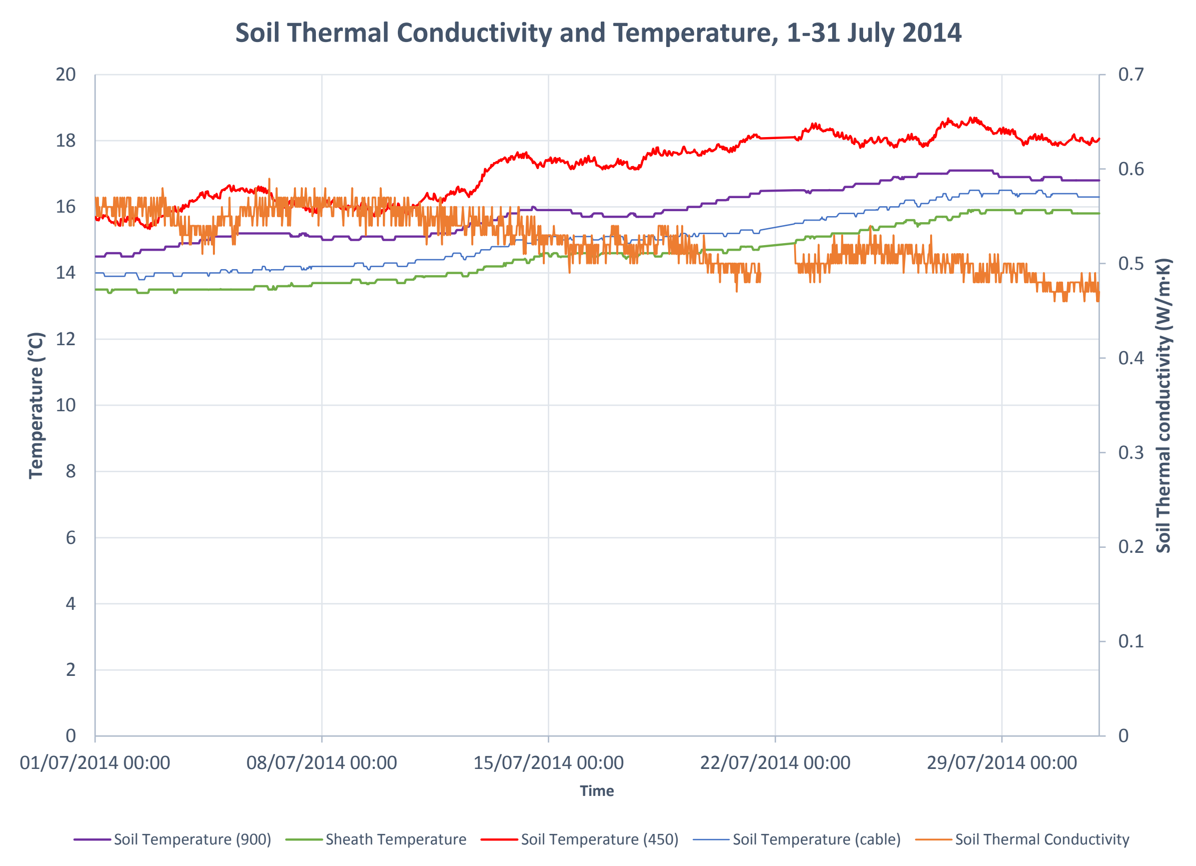


Figure 4-5: Measured temperatures and soil thermal conductivity for EHV cable at Rise Carr in July 2014

For the HV cable, temperatures are measured for the cable sheath and the soil 180 mm to the side of the cable, at the same depth as the HV cable. The ambient soil temperature is assumed to be the same as the EHV cable as they are at the same site.

Figure 4-6 and Figure 4-7 show the measured temperatures for the HV cable in January and July 2014.

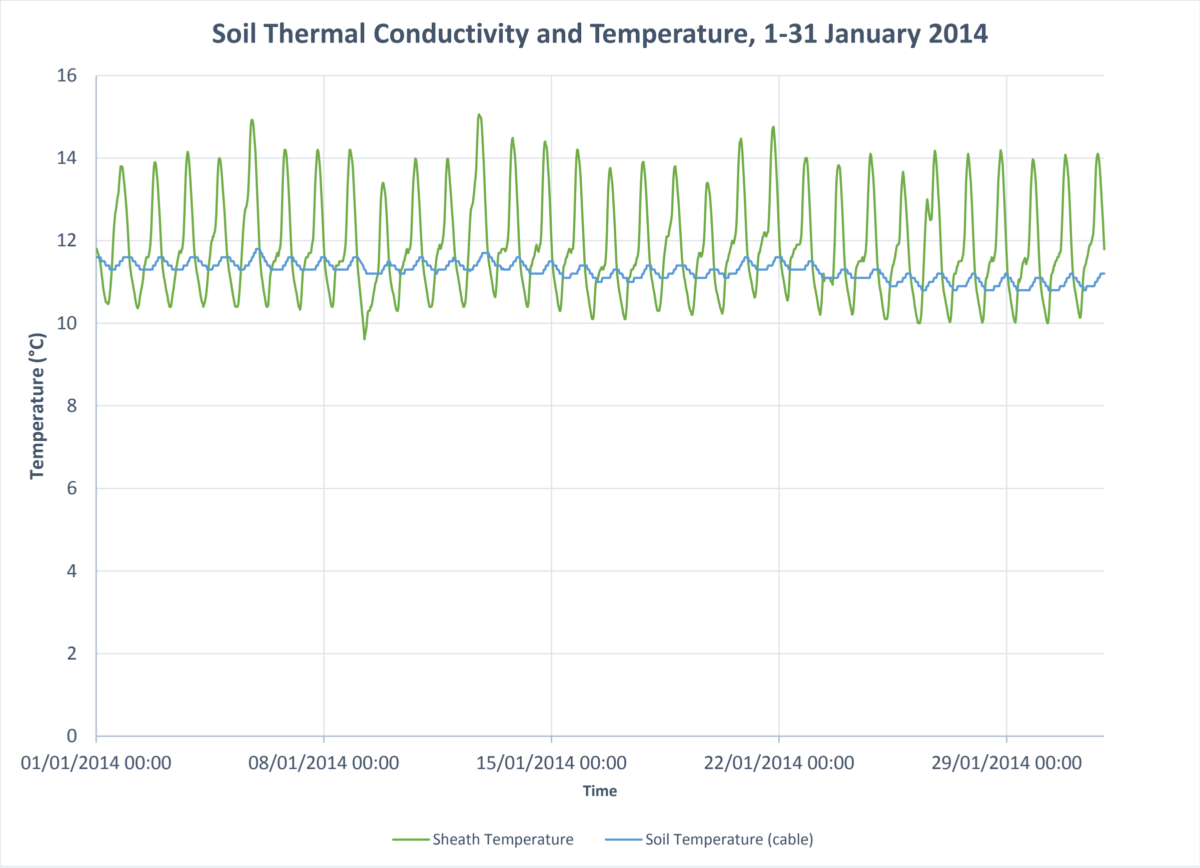


Figure 4-6: Measured temperatures and soil thermal conductivity for HV cable at Rise Carr in January 2014

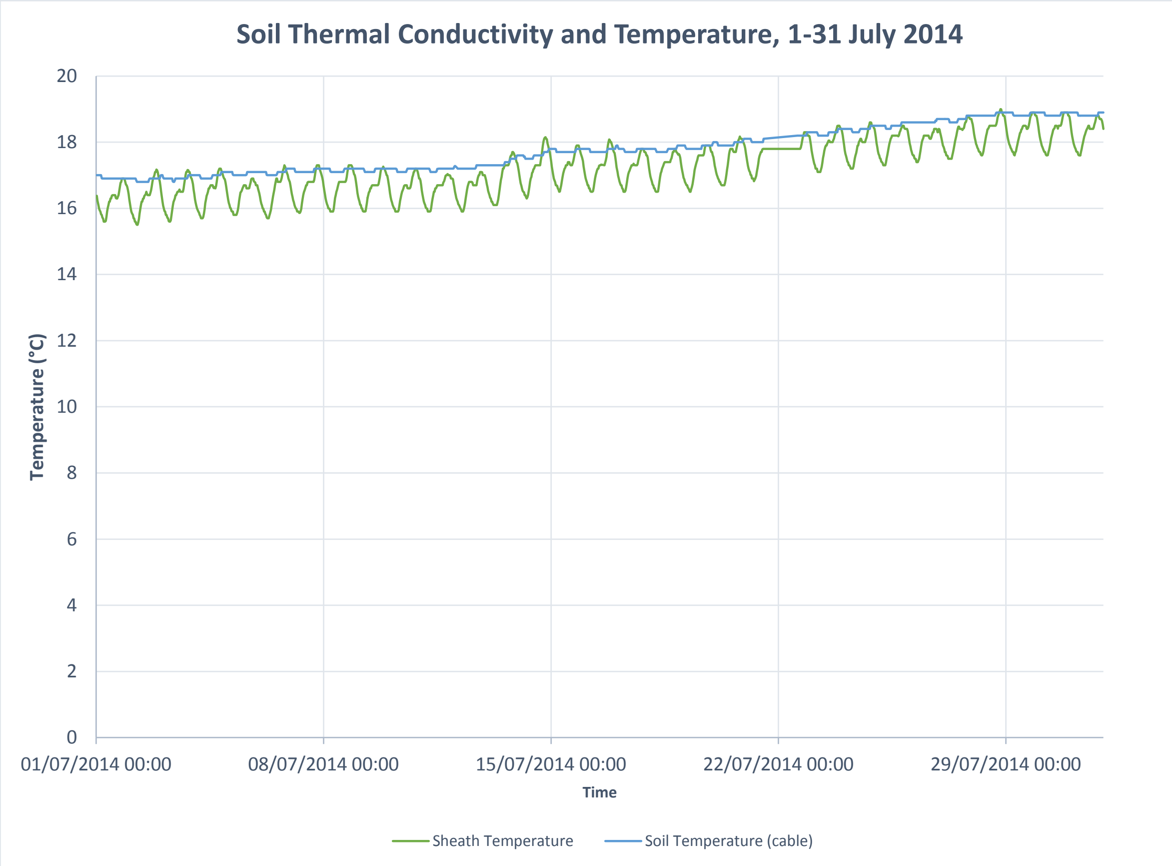


Figure 4-7: Measured temperatures and soil thermal conductivity for HV cable at Rise Carr in July 2014

In Figure 4-6 and Figure 4-7, it is shown that cable sheath temperature falls below the cable surrounding soil temperature. This indicates that calibration is required of the different temperature measurement systems used in the RTTR.

<u>Soil Thermal Conductivity and Resistivity</u>

Soil thermal conductivity data indicates that soil thermal conductivity is relatively stable within the months January and July, but can is clearly distinguishable between the two months. Soil thermal resistive is converted from thermal conductivity; therefore it shows the same behaviours. Figure 4-8 and Figure 4-9 below illustrate the comparison of soil thermal conductivity and resistivity for the Rise Carr substation site in January and July 2014 which are expected to represent winter and summer seasons.

In winter condition the thermal resistivity of the soil is more likely in a range of 1.25 - 1.45 K·m/W, and in summer condition the soil thermal resistivity is likely to fall in a range of 1.8 - 2.0 K·m/W.

It is indicated that the soil at Rise Carr substation site has a higher thermal resistivity than the default value of 0.9 K·m/W used in P17.

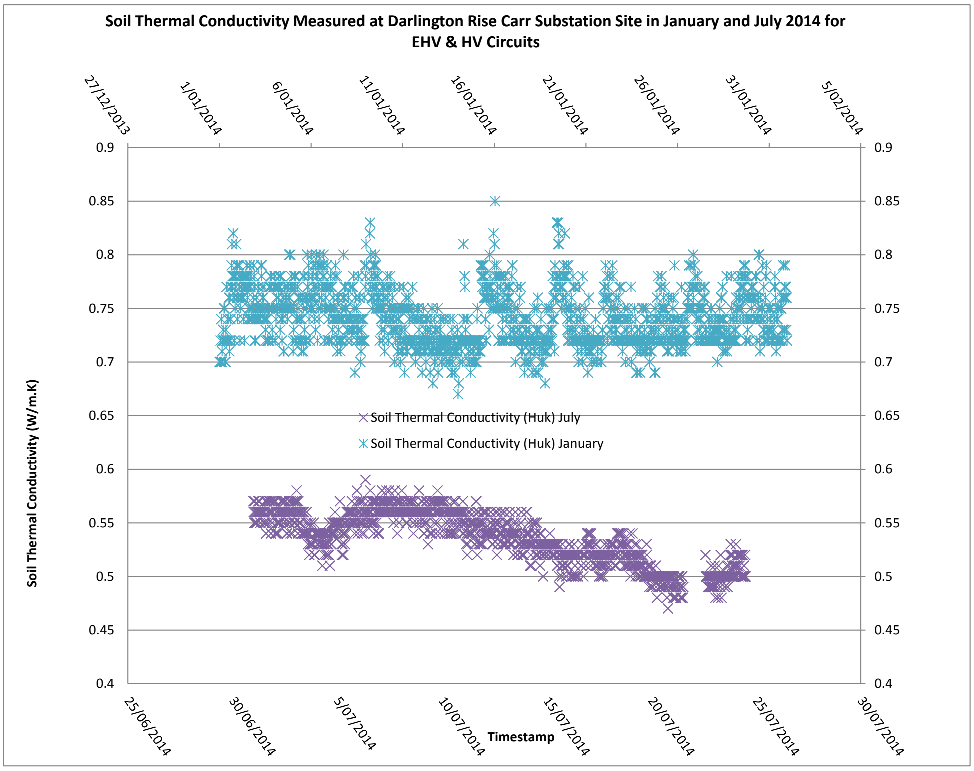


Figure 4-8: Soil thermal conductivity measured for EHV cable in Rise Carr site in January and July 2014

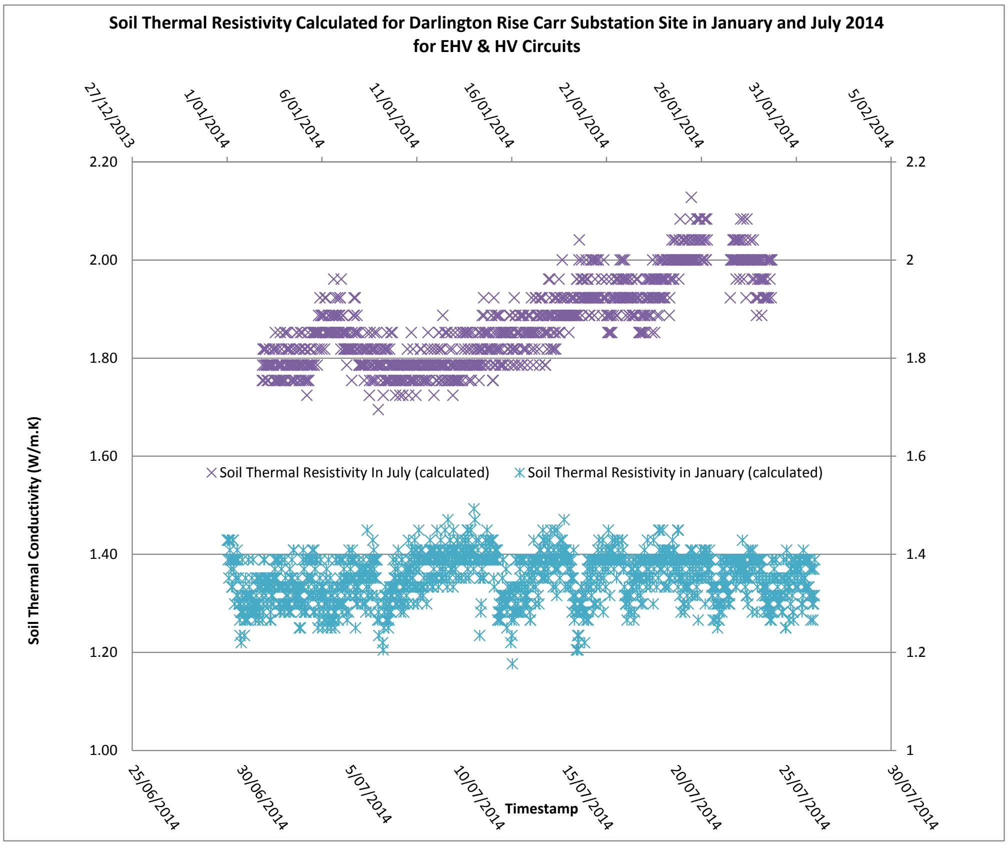


Figure 4-9: Soil thermal resistivity calculated for Rise Carr site in January and July 2014

Calculated ampacity, conductor temperature and sheath temperature

The calculated 30 minutes ampacity is to indicate the maximum cable operational rating for the next half hour. It is largely depending upon the cable loading prior to the "30 minutes" event should it occur.

The initial data analysis, calculated over 30 minutes, was found to be incorrect as the results did not correlate to the cable load. The problem was identified and the RTTR calculation software updated in August 2014.

Cable rating

Cable ratings of the EHV and HV cable circuits have been modelled using CRATER programme by using the real time condition data. The calculated ratings and conditions used in the calculations are presented in **Table 4-1** and Table 4-2 for the EHV and HV cables respectively.

For the both EHV and HV cables, the rating calculation results indicate that the headroom given in ER P17 will be reduced as the ground soil condition is worse than the conditions assumed.

The ratings are calculated based on the soil conditions measured on site but without taking account of mutual heating from neighbouring cables. The distribution rating and cyclic ratings are calculated using the measured ground conditions and the assumed general load curve ('Load Curve G', as used in ER P17). In the future analysis, a typical load curve should be developed and used to verify the distribution and cyclic ratings.

As shown in Table 4-1, the loading on the EHV cable is very low. Compared with the real time cable rating, a significant spare rating capacity is still available, even after allowing for N-1 operation under post-fault conditions. It should be noted that this circuit contains a number of cable types, some of them with considerably lower ratings than the one modelled. As a result, the fully implemented circuit RTTR is likely to be significantly lower than the ratings given here, because of hot spots not taken into account by this project.

	ENA ER P17	Design Rating Calculated in CRATER (based 60287)	Calculated in CRATER Based on Real Condition Data			
			Summer - Best (July 2014 data used)	Summer - Worst (July 2014 data used)	Winter - Best (Jan 2014 data used)	Winter - Worst (Jan 2014 data used)
Distribution Rating (amps)	637	620	515	479	602	562
Cyclic Rating (load curve G)	574	548	442	405	527	486
Steady State rating (amps)	487	455	355	321	433	393
Maximum load (amps)			70	70	98	98
Installation condition	P17 part 3	Design input				
Maximum Cond Temp (°C)	90	90	90	90	90	90
depth of burial (m)	0.6 - 3.0	1	1	1	1	1
Ground Temperature (°C)	10	10	15	15	7.5	7.5
Soil TR (K·m/W)	0.9	1	1.69	2.12	1.18	1.49
Sheath bonding	both ends	both ends	both ends	both ends	both ends	both ends

Table 4-1 EHV cable rating comparison

Results of the HV cable are shown in Table 4-2 below. The ER P17 rating is reduced in all but the winter best case, as the ground soil conditions are worse than the standard assumptions, despite the average ground temperatures being cooler.

The loading on the HV cable hovers around 50% of distribution rating. Assuming the standard operating conditions (a ring main with the normally open point configured to split the load 50/50), then this cable is on the edge of being overloaded. If a fault were to occur at the far end of this ring main, moving the whole ring load onto this cable to restore supplies would overload this cable under even the best case winter conditions. Although the summer rating is lower, the load reduction is greater, and so there is just enough capacity available for post-fault operation up to the 5-day limit used in ER P17 part 1 under summer conditions.

In the actual Darlington network the cable being studied is part of a teed feeder with a complicated topology, so without a load flow study of the possible post-fault load flows, it is impossible to say if a real issue exists. If the ring main load split is known to be unequal such that this cable carries more than 50% load normally, or the fault restoration times are less than 5 days, then there may not be a problem with present loading. This highlights the importance of understanding the wider network operation context in order correctly define what rating the RTTR scheme should calculate.

	ENA ER P17	Design Rating Calculated in CRATER (based 60287)	Calculated in CRATER Based on Real Condition Data			
			Summer - Best (July 2014 data used)	Summer - Worst (July 2014 data used)	Winter - Best (Jan 2014 data used)	Winter - Worst (Jan 2014 data used)
Distribution Rating (amps)	385	384	326	311	378	356
Cyclic Rating (load curve G)	358	354	290	271	346	319
Steady State rating (amps)	323	318	250	230	307	277
Maximum load (amps)			147	147	244	244
Maximum load (% of Distribution Rating)			45%	47%	65%	69%
Installation condition	P17 part 1	Design input				
Maximum Cond Temp (°C)	65	65	65	65	65	65
depth of burial (m)	0.6 - 3.0	1	0.9	0.9	0.9	0.9
Ground Temperature (°C)	10	10	15	15	7.5	7.5
Soil TR (K·m/W)	0.9	0.9	1.69	2.12	1.12	1.54
Sheath bonding	both ends	both ends	both ends	both ends	both ends	both ends

Table 4-2 HV cable rating comparison

Darlington Melrose substation site

Temperature measurements

The same approach is applied at the Melrose site for the temperature measurements. Figure 4-10 and Figure 4-11 below provide information on temperatures measured for the LV cable site in January and July 2014 respectively.

The soil temperatures are relevantly stable within the month either in January or July, but are different between the two months as season changes. Soil at 900 mm depth is warmer than it is at 450 mm depth in winter, but cooler in summer.

The soil temperature measured near the cable is 60 mm to one side of the cable at the same depth, whereas the Soil Temperature (400 mm) measurement is some distance away and close to the substation foundations, which may affect the readings. At this site (a very heavily disturbed urban location, with multiple telecommunications ducts as well as power cables) finding suitable and replicable measurement locations was challenging, especially as other installation work was going on at the site simultaneously.

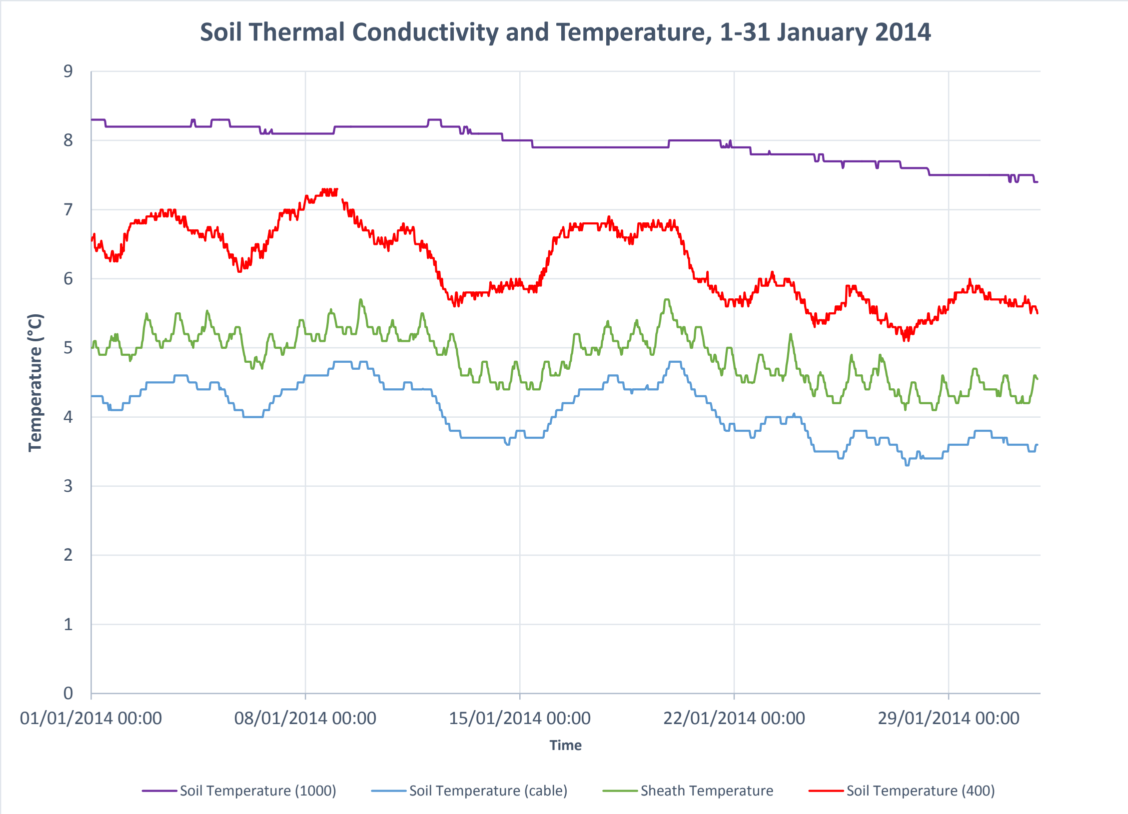


Figure 4-10: Measured temperatures and soil thermal conductivity for LV cable at Melrose in January 2014

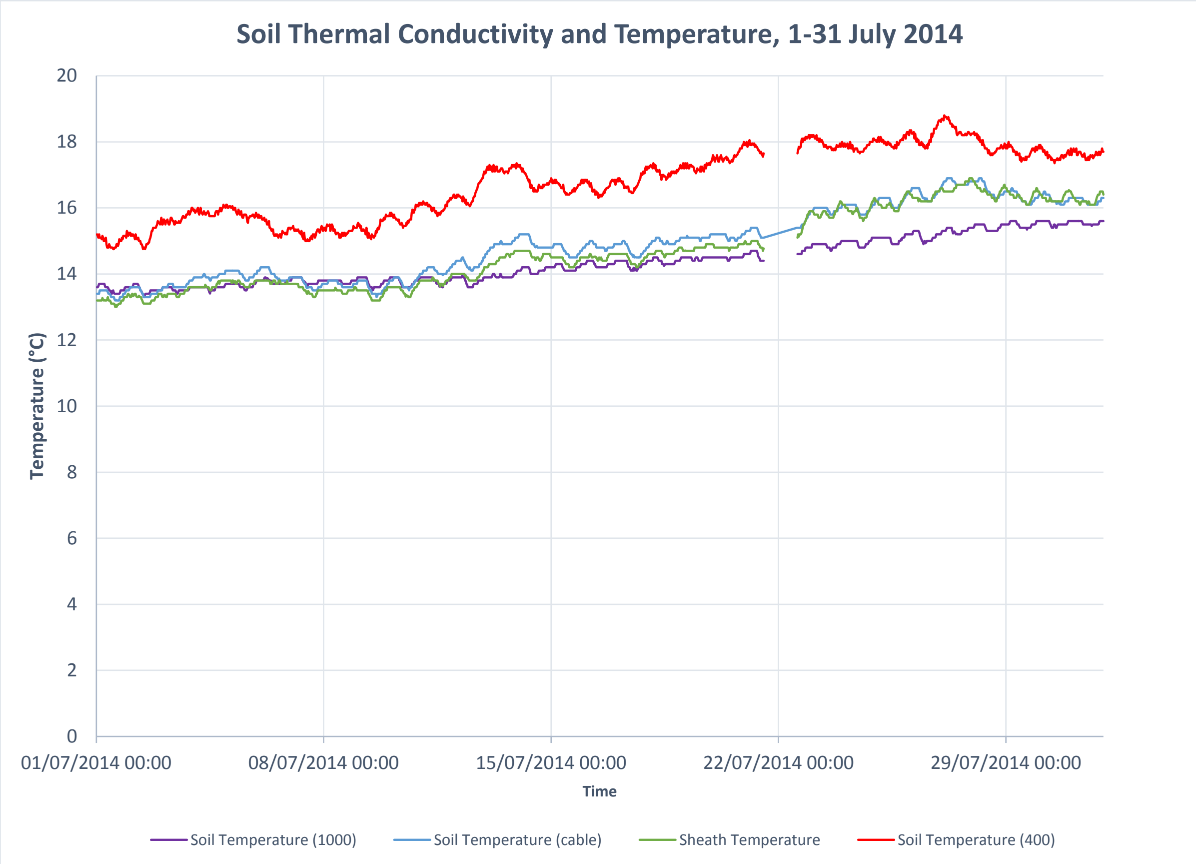


Figure 4-11: Measured temperatures and soil thermal conductivity for LV cable at Melrose in July 2014

Soil Thermal Conductivity and Resistivity

Soil thermal conductivity data indicates that soil thermal conductivity does not vary significantly within January or July, and between the two months. Soil thermal resistivity is converted from thermal conductivity therefore it shows the same behaviours. It is expected that soil type is different from Rise Carr substation site.

Figure 4-12 illustrates the comparison of soil thermal resistivity for the Melrose substation site in January and July 2014.

In both winter and summer the thermal resistivity of the soil is more likely within a range of 0.7 - 0.9 K·m/W, which confirms the standard value of 0.9 K·m/W used in ER P17.

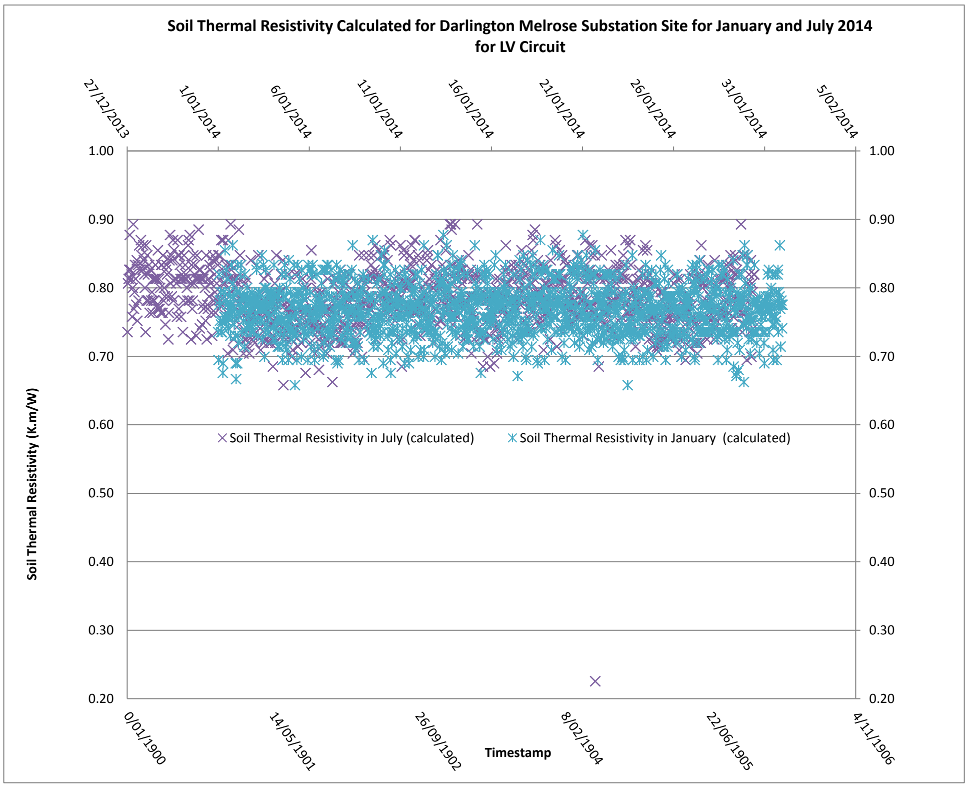


Figure 4-12: Soil thermal resistivity for LV cable in Melrose site in January and July 2014

Estimated Ampacity, Conductor Temperature and Sheath Temperature

The calculated 30 minutes ampacity is to indicate the maximum cable operational rating for the next half hour. It is largely depending upon the cable loading prior to the "30 minutes" event should it occur.

The calculated data of 30 minutes ampacity in this data initial analysis is incorrect as the results seem not to correspond to cable loading. This issue is identified and the RTTR calculation software has been updated since August 2014.

Cable Rating

Cable ratings of the LV cable have been modelled using CRATER programme by using the real time condition data. The calculated ratings and conditions used in the calculations are presented in Table 4-3 for the LV cable. As the load curve used for the cyclic and distribution ratings is composed of 1-hour RMS averaged segments, the maximum load figures are calculated on the same basis. The ratings assume balanced three-phase load with equal phase power factors, leading to no neutral current. As this is substantially not the case for this feeder, an equivalent balanced load giving rise to the same losses in the cable as the actual load has been calculated. This calculation was also used for the RTTR calculations, although it is not covered by the IEC standards. The maximum load given in Table 4-3 is the maximum value of this equivalent current, and so is directly comparable to the ratings shown.

The soil temperatures measured at the cable depth (400 mm) are significantly different to those used as defaults by ER P17. In the summer period, the soil temperature ranged from 14.8 °C to 18.8 °C, so was always equal to or higher than the 15 °C summer soil conditions used for summer loading calculations in ER P17. This reduces the summer worst case ratings

As this is a radial circuit, the Distribution Rating values are of no practical relevance but are included for completeness. ER P17 does not include LV cable ratings, but the approach of using the ground conditions from ER P17 for LV ratings seems well established in company specific LV cable rating tables.

Results of the LV cable rating calculation indicate that the rating headroom of the LV cable will remain broadly the same as the rating using ER P17 estimated ground conditions, as the reduced soil thermal resistance is counterbalanced by the higher ground temperatures.

The LV cable loading never exceeds 25% of the cable rated capacity, so there is no operational problem on this circuit.

	ENA ER P17	Design Rating Calculated in CRATER (based IEC 60287)	Calculated in CRATER Based on Real Condition Data			
			Summer - Best (July 2014 data used)	Summer - Worst (July 2014 data used)	Winter - Best (Jan 2014 data used)	Winter - Worst (Jan 2014 data used)
Distribution Rating (amps)		562	612	541	642	508
Cyclic Rating (load curve G)		537	594	519	622	567
Steady State rating (amps)		476	544	464	566	508
Maximum load (amps)			81	81	124	124
Installation condition		Design input				
Maximum Cond Temp (°C)	80	80	80	80	80	80
depth of burial (mm)	0.6 - 3.0	450	450	450	450	450
Ground Temperature (°C)	10	10	14.8	18.8	5.1	7.3
Soil TR (K·m/W)	0.9	1	0.6	0.89	0.66	0.88

Table 4-3 LV cable rating comparison

4.6.3 Lessons Learned

Through the initial data analysis the following was learned:

- *Sufficient data to reflect the ground seasonal conditions*

The data collection for the LV cable and EHV/HV cables has been over 17 months and 9 months respectively which is considered sufficient to reflect the ground seasonal conditions. It is expected that the analysis would establish a correlation patterns between the cable loading, soil condition and seasons.

- *Soil ambient temperature is relevantly stable but can be distinguished between summer and winter*

The soil ambient temperature varies insignificantly within the month in January or in July, but can be distinguished between the two months, i.e., winter and summer. At the EHV and HV cable test site, the soil ambient temperature is within the range of 6.9 – 7.8 ^{0}C in January, and 14.5 -16.7 ^{0}C in July. At the LV cable test site, the soil ambient temperature at cable depth changes between 5.1 – 7.3 ^{0}C in January and between 14.8 – 18.93 ^{0}C in July.

- *Soil thermal resistivity varies significantly at the two test sites*

The soil thermal resistivity is converted from the soil thermal conductivity measured in sites. At Melrose substation site (LV cable), soil thermal resistivity is low and stable with no notable difference in January and July, which indicates that the soil has the preferable thermal condition for cables. The maximum thermal resistivity of 0.89 K·m/W confirms that the standard design value of 0.9 used in P17 is conservative.

At Rise Carr substation site (EHV and HV cables test pit), the soil has different thermal characteristic compared with the soil at LV cable test site. The soil type at the two test locations are unknown, but is assumed that it would be different. At Rise Carr site, the soil thermal resistivity changes clearly in January and July, and the soil thermal resistivity is higher compared with the standard value used in P17 in the both winter and summer months. In summer (July) TR is 1.9 K·m/W, and in winter (January) TR is 1.3 K/m/W.

- *Estimated 30 minutes rating should not be used as a steady state rating continuously*

The calculated 30 minutes ampacity is to indicate the maximum cable operational rating for the next half hour. It is largely depending upon the cable loading prior to the “30 minutes” event should it occur.

The calculated data of 30 minutes ampacity in this data initial analysis is incorrect as the results seem not corresponding to cable loading. This issue is identified and the RTTR calculation software has been updated since August 2014.

- *Lessons Applicable to Static Rating Calculations using P17*

For the LV cable circuit, the rating remains broadly the same as the rating using ER P17 estimated ground conditions, as the reduced soil thermal resistance is counterbalanced by the higher ground temperatures. This circuit was very lightly loaded compared to its rating.

For the EHV and HV cables, unfortunately the thermal headroom needs to be reduced in both winter and summer compared with the standard rating provided in ER P17 as the soil thermal condition is worse than assumed standard condition in ER P17.

The EHV cable is very lightly loaded (note that changes in cable type are likely to cause hot spots elsewhere on this circuit and restrict its true rating). The HV cable, by contrast, is heavily loaded. This loading exceeds the default ER P17 50% utilisation under winter conditions, although the actual network may have more capacity in other assets to compensate for this. This illustrates that a good understanding of the network topology and load flow is required in order to correctly specify the outputs from an RTTR system.

4.7 Summary of lessons learned

This section provides the summary of the key learning gained throughout the project process - from initial design through to operation of an UG Cable RTTR system. It includes lessons learned from EA Technology through the project implementation, feedback from Northern Powergrid in the workshops, and outcomes of data analysis from Newcastle University. Detailed information is provided in the relevant sections of this report.

4.7.1 Underground Cable RTTR Concept Design

RTTR LL 4.1 CLNR has proven the RTTR concept design with the following input parameters required: Cable size, type and installation configuration; soil ambient temperature; soil thermal resistivity; and real time cable loading.

RTTR LL 4.2 Multiple hot spots should be assessed and included in Underground Cable RTTR modelling

RTTR LL 4.3 Mutual heating from neighbouring cable(s) cannot be disregarded for RTTR or static ratings

RTTR LL 4.4 Different soil thermal resistivity measurement methodologies, including modelling based on soil type, should be considered

RTTR LL 4.5 Further work is required to assess the impact of RTTRs on emergency ratings

RTTR LL 4.6 It is necessary to assess Underground Cable condition prior to installing RTTRs

4.7.2 Procurement and Installation

RTTR LL 4.7 No commercially available system for Underground Cable RTTRs is currently available.

RTTR LL 4.8 Future installations would use the DNO’s communication infrastructure or local RTUs to host the calculation engine

RTTR LL 4.9 Locally available sensor data significantly increases efficiency of the testing and commissioning process

RTTR LL 4.10 Soil ambient temperature is relevantly stable but varies seasonally

RTTR LL 4.11 Soil thermal resistivity differs significantly between sites and, where measured, it exceeded the “worst case” scenario assumed in Engineering Recommendation P17

RTTR LL 4.12 Cable sheath temperature measurements require calibration to account for variation in measurement equipment.

RTTR LL 4.13 Cable ratings calculated show a potential need for a modest revision downwards in the static ratings calculated using Engineering Recommendation P17. More data (especially on soil parameters) is required.

RTTR LL 4.14 Three primary uses for RTTR of Underground Cables have been identified: Desktop studies when planning or reviewing network loading; and managing load on assets during outage conditions to avoid both overload and unnecessary customer interruptions

RTTR LL 4.15 A software tool is required to calculate RTTR for Underground Cables (such as CRATER) in design and planning processes.

5 Overhead Line RTTR

5.1 Implementation of Overhead Line RTTR in the CLNR project

The CLNR project implemented the trial of RTTR systems on Overhead Lines to calculate capacity on a real time basis. The test cell was the Rural Low Density Cell for which OHL RTTR was to be designed for EHV (66kV tower) and HV (20kV wood pole) OHLs.

The HV network consists of a 0.1 in^2 Hard Drawn Bare Copper (HDBC) energised at 20kV and is of a single circuit rural, radial network topology. The EHV network is a 175mm^2 Aluminium-Conductor Steel-Reinforced (ACSR) conductor energised at 66kV and forms a double circuit to the Denwick primary substation.

The trial project, OHL RTTR systems were installed at “Whitehouse”, “Broxfield”, “Earle Mill”, “Scar Brae” and “Towers 49 and 131”. All of these sites are in Denwick in the North East of England in the project’s rural test cell.

5.2 Overhead Line RTTR deployment in the CLNR project

Data analysis was completed for the period March 2012to the end of June 2014 from the HV RTTR trials, and the period December 2012 to end June 2014 from the EHV RTTR trials.

5.3 Lessons learned from design

5.3.1 Present UK Practice for Overhead Line Ratings

The OHL ratings used in the UK are based on experiments carried out on transmission lines and are listed in Engineering Recommendation P27. Seasonal ratings for summer and winter are included, but do not cover all conductor types currently in use by DNOs.

Two approaches are used to estimate Overhead Line ratings: deterministic and probabilistic.

A deterministic rating is calculated on the worst case scenario that may occur, and ensures that the rating criteria are never exceeded in operation. This approach minimises risk, but produces very conservative ratings which increase the cost of network asset provision.

A probabilistic rating approach takes the pragmatic view that exceeding the design conditions for a very small fraction of the operating time (typically tens of minutes per year) is not a practical problem, and so develops ratings which will be exceed a stated (small) percentage of the time. The development of these ratings requires an understanding of the probability of different weather events affecting line capacity. ER P27 uses a probabilistic method for calculating ratings.

A probabilistic approach for RTTR with the same exceedance levels (e.g. 0.001% for single circuits and 3% for double circuits) as those used for static ratings in P27 is required. The probability of overload should take into account the probability of different weather conditions and corresponding different ratings. As the thermal constant of overhead Lines is short, the probability of different levels of loading and duration has little impact on the ratings themselves. However, the probability of different loads coinciding with different weather conditions will give the probability of an exceedance occurring. The probability of different loads will depend on the type and could vary over time (for example wind generation output will align with the variation of RTTR due to wind speed).

To calculate the probability of different loads and ratings coinciding, the probability distribution of a level of load/generation and the probability distribution of a rating is required. The rating will be dependent on wind and temperature. In the case of solar or wind generation they will be dependent on sunshine hours and wind respectively. The probability distribution of these parameters is therefore required.

The probability of a particular load/generation level occurring at the same time as a particular rating can be calculated via the convolution of the two probability distributions.

During design, analysis is required to understand how RTTR can be deployed, if active network management should be used and the amount of controllable load or generation that is required. The maximum controllable load that is required is the maximum difference between the load/generation and rating that may occur. This may not occur when the rating is lowest or highest.

5.3.2 Overhead Line RTTR Design

To calculate the capacity available on an OH Line, an RTTR system uses real-time weather condition data and loading to track the actual line temperature and indicate the available capacity which will typically be greater than the static rating under most conditions. Under all circumstances, OH lines need to be operated to within statutory clearance levels.

At present, on line measurement devices which determine line sag and line angle are more costly, in terms of procurement and installation, than other devices measuring temperature and current from which sag can be calculated. On line devices which measured temperature and current and calculated sag were therefore procured for trials.

It was proposed at the initial design stage that OH Line RTTR thermal ratings are calculated based upon calculations found within one of the industry recognised thermal models as follows:

- IEC/TR 61597 Ed. 1.0 b: 1995
- IEEE 738-2006
- CIGRE WR 22.12: 1992.

The RTTR model developed based on CIGRE WR 22.12: 1992 was used in this project, as this is based on the same experimental work as the UK industry standard for OHL ratings, ER P27.

The line rating is determined by direct measurement of the conductor's state. The actual conductor sag can be calculated using the predetermined relationship between the conductor position/tension and temperature.

The heat balance equation is used to determine the additional current that can be transferred before the reaching conductor's maximum operating temperature (design temperature). The time constant for distribution OHLs is in the order of five to ten minutes.

5.3.3 Communications Infrastructure

Manufacturers generally overstate their product's capability, which can influence the direction of the solution design. The communication methods should be specified to ensure the correct functionality is attained.

The existing Northern Powergrid communications infrastructure uses DNP 3.0 protocol. Any new equipment should therefore support DNP 3.0.

If load or generation is controlled from the RTTR system and communications is lost, it may need to trip automatically or rely on back up protection of the circuit.

5.3.4 Lessons Learned

- *Overhead line RTTR model*

OH Line RTTR should be based upon calculations found within one of the industry recognised thermal models including IEC/TR 61597 Ed. 1.0 b: 1995, IEEE 738-2006 or CIGRE WR 22.12: 1992.

The RTTR model based on CIGRE WR 22.12: 1992 was used for the trial project, as this was the model adopted by the chosen system vendor.

- *Thermal dynamics*

The thermal dynamics of an Overhead Line is directly related to the forced convection heat loss, radiation loss and solar radiation gain. In ER P27, forced convection heat loss and radiation loss are static values, and solar radiation gain is ignored. In OH Line RTTR, forced convection heat loss is variable calculated based on wind speed and angle, radiation loss is kept the same as ER P27, and solar gain is also ignored as in ER P27.

- *Key conditions for OH Line RTTR and location to install measurement devices*

The magnitude of wind speed and angle of incidence to the conductor are key conditions for OH Line RTTR, as they affect the thermal dynamics of the conductor.

If single measurement devices are used along an Overhead Line circuit section, they should be installed to the location likely to have the lowest rating i.e. an area heavily sheltered from the wind.

The location likely to have the lowest rating will need to be checked regularly (e.g. once a year) as tree growth or new buildings could determine the need for the installation position to change. Determining if there are new buildings could be difficult as they could occur anywhere on a line. Estimating the height of a building in relation to the distance from the line that may cause a shadow and hence a change to the rating will give an indication of what could be of concern. Checking Council planning portals could provide an alert to new buildings of concern.

- *Site dependent static parameters to the OH line RTTR model*

The same site dependent static parameters used in P27 are required in RTTR to calculate conductor operational temperature. These static parameters are:

- Conductor Resistance @ 20°C per unit length
- Temperature coefficient of resistance for conductor
- Diameter of conductors
- Span Length
- Conductor Type
- Design limits of the line (e.g. design temperature, minimum clearance).

- *RTTR Model calibration*

Conductor operational temperatures calculated from RTTR were verified with the measurements of actual conductor temperature.

- *Line temperature measurements*

The line temperature measurement is to be used to monitor the effective capacity in the line and the accuracy of the model in predicting the line temperature. Line temperature measurement at one point cannot be used as a direct means for rating an OHL as the temperature can vary in a span under critical conditions. The average temperature of the limiting span has to be used.

- *Thermal-time constant*

The thermal-time constant of OH lines is an important parameter for real-time thermal ratings as it governs the necessary speed of response for configuring an overloaded network.

The time constant for Overhead Lines used for distribution on the power network is in the order of five to ten minutes and therefore the sampling rate from equipment should less than or equal to 5 minutes.

- *Assumptions relevant to heating in ER P27 (or the underlying ACE 104)*

Heating mechanisms considered in ER P27 or ACE 104 are:

- Wind speed 0.5 m/s, wind angle to conductor is 12 degrees
- Radial conductivity is 4W/m·K
- Evaporative cooling from rainfall is specified as equal to 0.
- Absorptivity and emissivity specified as 0.9 and 0.8 respectively.

- *Real time parameters and assumptions used in the calculation of heating using RTTR*

Average temperature, wind speed and angle are measurements of the real weather condition. The other heating mechanisms used in ER P27 are also used in RTTR.

- *Wind angle*

To calculate the angle of attack of wind on a conductor requires knowledge of the orientation of each conductor along the circuit, requiring significant time to set up the system. The sensitivity of RTTR to wind angle is relatively small. Therefore, the effort required to measure wind angle is not justified and this value should be set to 12° (as in Engineering Recommendation P27).

5.4 Lessons learned from procurement and installation

The equipment requirements within the design document for Overhead Line RTTR, were used to create an equipment specification document. The document was used for the procurement of equipment in the trial. The following are the findings and the lessons learned:

5.4.1 Market Analysis

The majority of OHL RTTR systems in the UK to date have been installed to facilitate wind farm connections without costly reinforcement. Two demonstrations projects were found; one on SSE's Scottish distribution network in Orkney and the other on Western Power Distribution's (Central Networks) network near Skegness; both proved that windy conditions increase line ratings which coincide with the time of greatest wind farm output. Subsequently Scottish Power has carried out an RTTR trial on the North Wales 132kV network to accommodate additional wind farm connections.

At present constraint of a load would have to be included in the connection agreement and therefore at present could only be applied to large new loads. Therefore deploying RTTR with generation is probably the most straight forward application of RTTR.

For the CLNR project and in BaU it was recommended that complete 'off-the-shelf' systems are procured, with model and measurement devices provided by the same manufacturer. Note that this should not preclude normal competition between manufacturers for supply of the systems.

5.4.2 RTTR System Components

In this trial project, the RTTR was installed for ongoing capacity improvement. The system components were:

- Measurement devices (current, wind speed, temperature etc.)
- Communication (local wireless, cellular, licensed radio etc.)
- Local power supply
- Calculation engine.

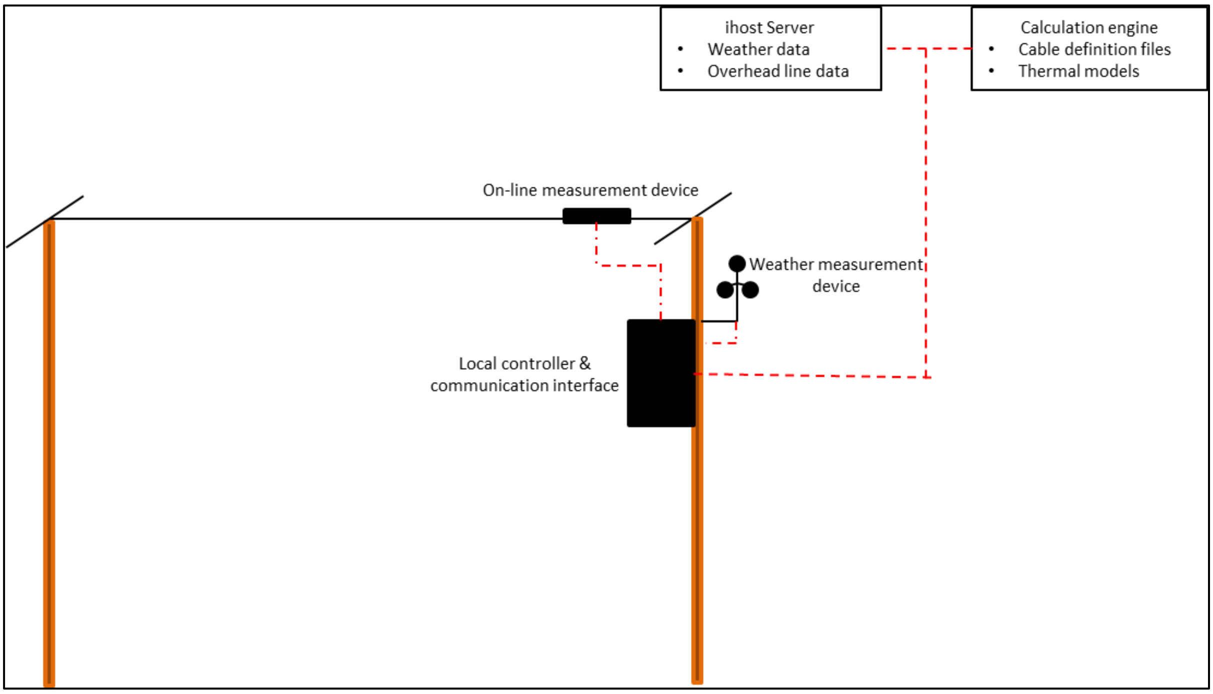


Figure 5-1: Simple schematic of OHL RTTR system and components

For the CLNR project and in BaU it is recommended that complete 'off-the-shelf' systems are procured, with both the model and measurement devices provided by the same manufacturer. Four possible line-mounted measurements are:

- Line Temperature
- Current
- Line Sag
- Line Angle

At present, line sag and line angle measurement devices are more costly than devices measuring temperature and current. However, if in future these devices are more cost effective then these solutions should be investigated.

Measurements of the following weather parameters may also be required:

- Ambient Air Temperature
- Wind Speed
- Wind Direction

It is difficult to accurately measure wind direction of low wind speeds, and it is likely that air flow at low wind speeds will be turbulent (and so have no clear direction) rather than laminar. For the purposes of developing a (static) rating standard, only the low wind speed cases are of interest, as they are the ones in which conductor temperatures are highest, and line ratings lowest.

This is not so obviously the case for RTTR systems, because ratings have to be calculated for a much wider range of weather conditions, including higher wind speeds. In these higher wind speeds, the air flow is likely to be less turbulent, and so its direction is important.

For the CLNR trial wind speed data was obtained from cup-type anemometers and moving vane direction indicators, installed on the tower or pole closest to the line-mounted measurement. For Business-as-Usual the total lifetime cost (including maintenance) of these should be compared to ultrasonic type anemometers (see Appendix 3 for more detail). The weather sensors were powered from, and fed data back to, the Local Controller, also pole mounted. From the Local Controller the various readings were fed back (over public GPRS networks) to the centrally located Calculation Engine (the software responsible for calculating line ratings and available headroom).

A single Calculation Engine would typically serve multiple points, and for the CLNR a single unit calculated ratings for all 6 sets of equipment installed. The system calculated the line temperature and capacity using the CIGRE model.

Given the short thermal constant of Overhead Lines, measurements are required each 5 minutes and an accuracy of 1-2% is needed.

5.4.3 Communications System

Various options for communication devices were discussed. The communications media possible will be dependent upon the sites chosen, however, options break down into three categories:

- Between Measurement Devices and Local Controller – short range wireless (6LOWPAN, ZigBee, WiFi, Bluetooth or similar);
- Between Local Controller and Calculation Engine – cellular (e.g. GSM, LTE, WiMax);
- Between Calculation Engine and GUS – hardwired or cellular (e.g. Asynchronous Digital Subscriber Line (ADSL), standard Local Area Network (LAN) or GSM).

Manufactures generally overstate their product's capability, which can influence the direction of the solution design. The communication methods should be specified to ensure the correct functionality is attained.

5.4.4 Available Products

Product available and their installation methods are:

- FMC-T6 sensor should be installed on a live line using hot-glove techniques, as the line mounted measurement devices were too heavy for hot-stick installation. The sensor measures the electrical current and delivers its data via an on-board 2.4 GHz radio transmitter.
- The sensor can be supplied with an optional temperature probe on a flying lead, which measures the surface temperature of the conductor. It weighs 6 kg and will sit on

conductors between 10mm and 28mm in diameter and power is obtained via induction from the conductor's magnetic field.

- Optical Phase Conductor (OPPC) is a fibre optic cable incorporated within an Overhead Line conductor. As well as communications, this allows continuous measurement of the temperature of the conductor along its length, as with a DTS for underground cables (typically a temperature for every metre of span length). OPPC is energized along with the line and therefore it requires specially adapted splice boxes and insulators to make the live line conditions.
- Power Donut is a self-powered sensor using energy harvested from the power line with a typical power consumption of 10 Watts. It weighs 9.2 kg and uses GSM, GPRS or Edge wireless data communications to transmit Current, Temperature and Inclination data

5.4.5 Equipment Installation

A number of lessons were learned from installation of the temperature sensors. As noted above, the sensors were too heavy for "hot-stick" installation. Therefore, online sensors were connected to each of the conductors by live line working engineers. This required that all the conductors were shrouded to provide insulation and ensure accidental phase-to-phase contact could not be made when installing sensors. If OHL RTTR becomes BaU, ideally the mass of sensors should be reduced to allow "hot-stick" installation, as it will remove the need for insulated buckets, reducing resource and cost requirements.

To avoid the expense of a step-down transformer on the pole, power for the local controller and communications was obtained from a solar PV panel mounted on the pole. To ensure maximum effectiveness, the bracket for the solar panel and hence the solar panel itself should be installed so as to ensure the panel is facing South. The bracket should be installed so that the panel surface is at an angle of 50° - 65° from the horizontal (dependent on the latitude, see the manufacturer's instructions for more details). The aim is for the output from the solar panel to produce enough power to operate the local controller throughout the year, rather than to produce the most annual energy. During summer months producing enough power is not expected to be a problem. However, in winter the sun will be closer to the horizon and therefore the installation should be at angles nearer to 60° from horizontal.

The On-Line Devices where powered by scavenging energy from the line load current, backed up by an internal re-chargeable battery. This scheme has worked reliably through the trial. See Appendix C for more details.

5.5 Lessons learned from data analysis

The data analysis covers data from the HV RTTR trials collected from the period March 2012 - end June 2014, and the period December 2012 to end June 2014 for EHV RTTR trials.

RTTR equipment was installed on two twin-circuit EHV towers, one in a sheltered location and one more open site. Both circuits on these towers were independently monitored. Four monitoring devices were installed on a wood-pole HV line. One of these units was re-located during the trial to give a total of five locations. Further details on both the HV and EHV sites can be found in the following section. An increase in headroom above the presently implemented P27 ratings has been observed at all sites, although there are large differences between both the magnitude of the uplift and the percentage of time for which the RTTRs were greater than the P27 ratings (Figure 5-2 to Figure 5-4).

CDF – Cumulative Distribution Function

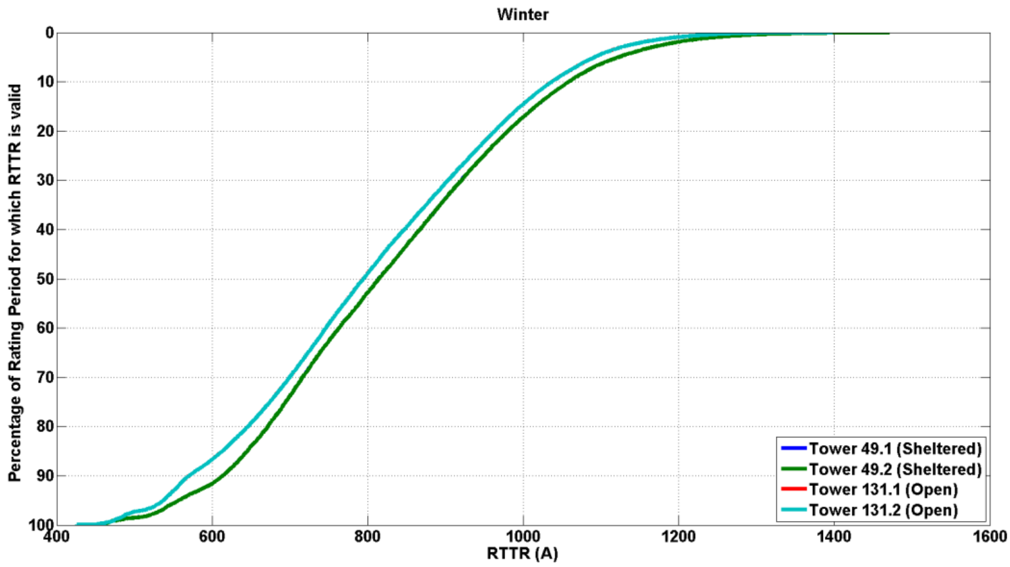


Figure 5-2: Winter RTTR CDF for all EHV sites

	Tower 49.1	***Tower 49.2***	***Tower 131.1***	***Tower 131.2***
Percentage of RTTR > P27 Static Rating	**96.7**	**96.7**	**94.8**	**94.8**
Percentage of RTTR < P27 Static Rating	**3.3**	**3.3**	**5.2**	**5.2**
Percentage of possible RTTRs calculated	**96.7**	**96.7**	**94.8**	**94.8**

Table 5-1 - Winter RTTR Statistics – All EHV Sites

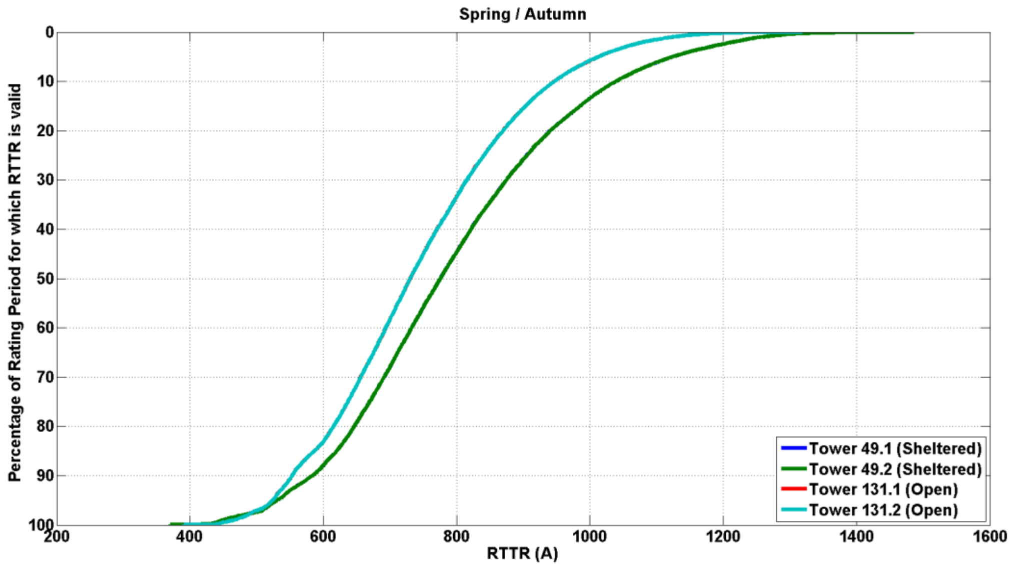


Figure 5-3: Spring/Autumn RTTR CDF for all EHV sites

	Tower 49.1	*Tower 49.2*	*Tower 131.1*	*Tower 131.2*
Percentage of RTTR > P27 Static Rating	97.4	97.4	97.0	97.0
Percentage of RTTR < P27 Static Rating	2.6	2.6	3.0	3.0
Percentage of possible RTTRs calculated	97.4	97.4	97.0	97.0

Table 5-2: Spring / Autumn RTTR Statistics for all EHV sites

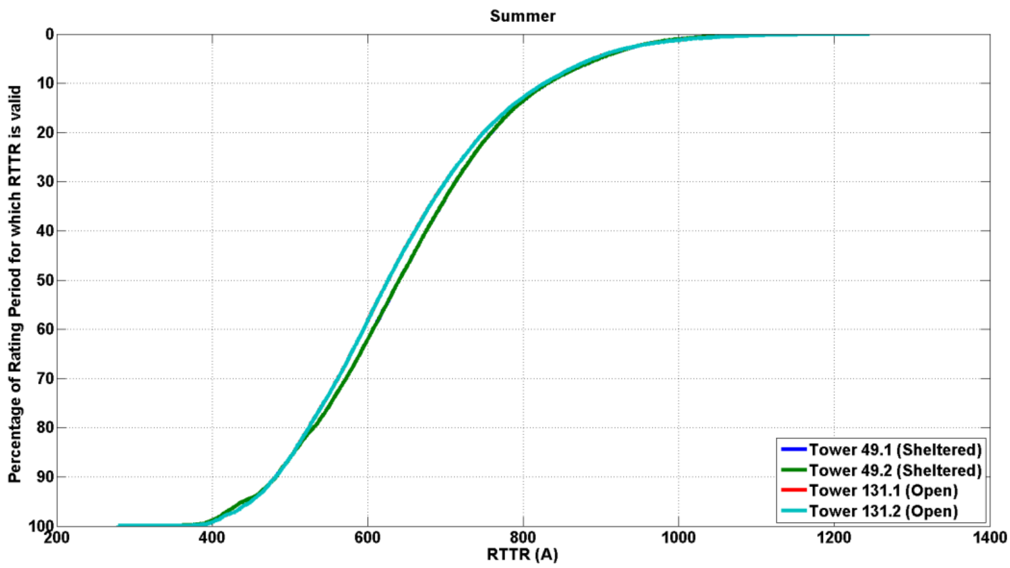


Figure 5-4: Summer RTTR CDF for all EHV sites

	Tower 49.1	Tower 49.2	Tower 131.1	Tower 131.2
Percentage of RTTR > P27 Static Rating	95.7	95.7	96.8	96.8
Percentage of RTTR < P27 Static Rating	4.3	4.3	3.2	3.2
Percentage of possible RTTRs calculated	95.7	95.7	96.8	96.8

Table 5-3: Summer RTTR statistics – All EHV sites

Good agreement has been shown between the developed offline CIGRE models and the calculations on site. In addition to the real-time rating model, a conductor temperature and a dynamic CIGRE model have been developed. This shows the implementations are the same.

Significant increases in thermal capacity have been found at the monitoring points, although the potential for network capacity increases at the heavily sheltered HV sites is somewhat decreased.

The RTTR at some sites is found to be considerably below the presently implemented P27 static rating, particularly in the winter static rating period (Figure 5-5 to Figure 5-7). This is due to the worst case scenario of very low wind speeds combined with relatively high ambient temperatures. However, at the most sheltered site, the RTTR gives an increase in network capacity for over 80% of the period.

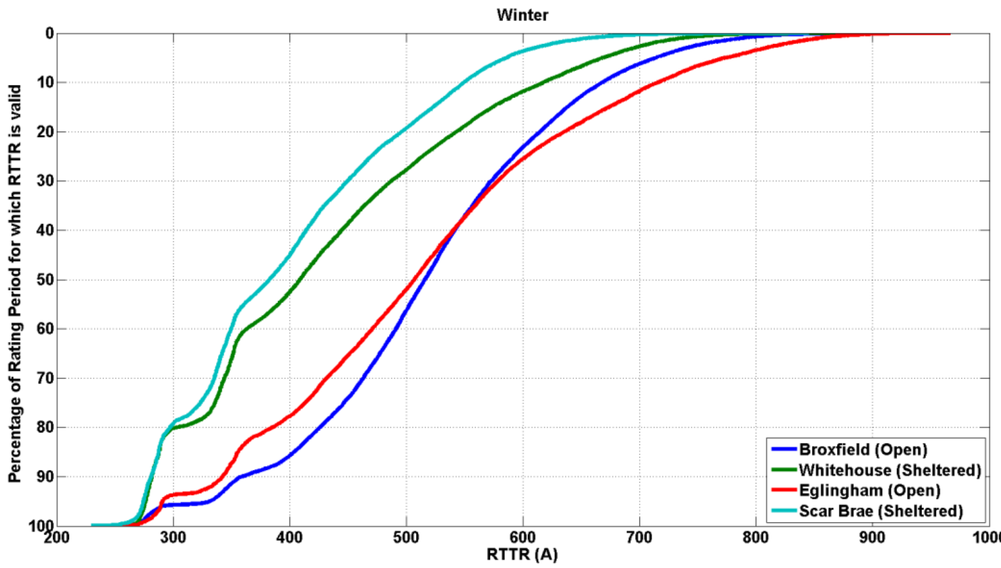


Figure 5-5: Winter RTTR CDF for all HV sites

	Broxfield	*Whitehouse*	*Eglingham*	*Scar Brae*
Percentage of RTTR > P27 Static Rating	**95.8**	**80.9**	**94.0**	**80.4**
Percentage of RTTR < P27 Static Rating	**4.2**	**19.1**	**6.0**	**19.6**
Percentage of possible RTTRs calculated	**76.9**	**86.1**	**86.7**	**86.9**

Table 5-4: Winter RTTR statistics for all HV sites

Winter results are only available for four locations as shown above, because the fifth location (equipment from Eglingham re-located to Earle Mill) was not installed in winter 2012, and did not produce results for winter 2013 due to communications issues.

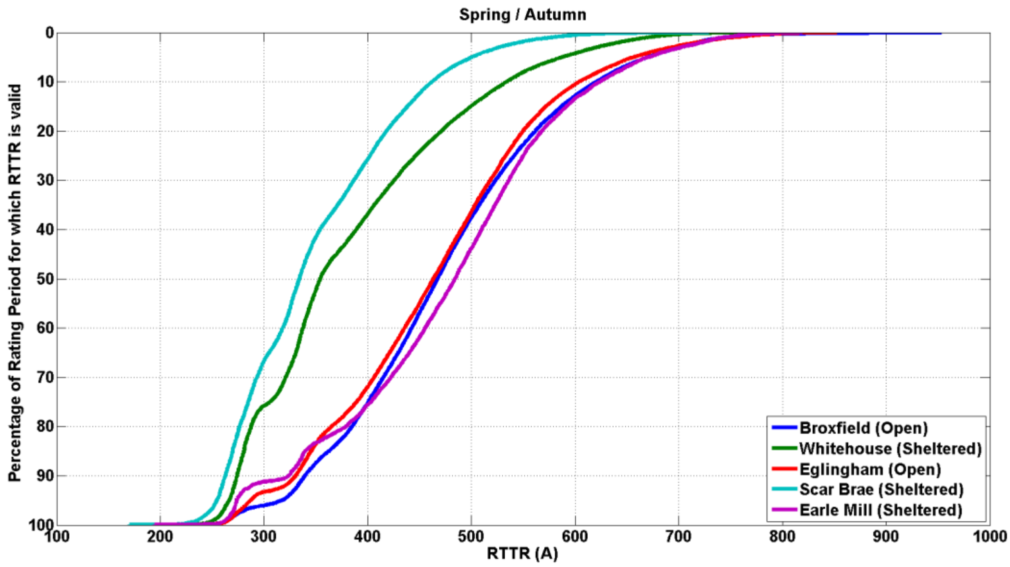


Figure 5-6: Spring/Autumn RTTR CDF for all HV sites

	Broxfield	*Whitehouse*	*Eglingham*	*Scar Brae*	*Earle Mill*
Percentage of RTTR > P27 Static Rating	**97.7**	**89.2**	**97.3**	**81.1**	**94.4**
Percentage of RTTR < P27 Static Rating	**2.3**	**10.8**	**2.7**	**18.9**	**5.6**
Percentage of possible RTTRs calculated	**91.2**	**66.8**	**75.8**	**74.8**	**20.5**

Table 5-5: Spring / Autumn RTTR Statistics for all HV sites

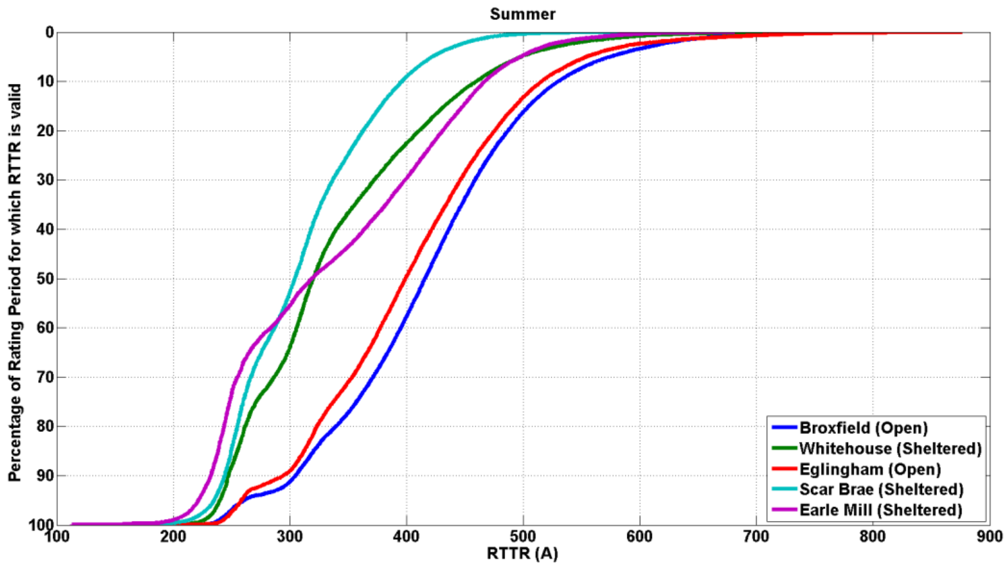


Figure 5-7: Summer RTTR CDF for all HV sites

	Broxfield	*Whitehouse*	*Eglingham*	*Scar Brae*	*Earle Mill*
Percentage of RTTR > P27 Static Rating	**99.3**	**96.4**	**99.7**	**94.0**	**86.3**
Percentage of RTTR < P27 Static Rating	**0.7**	**3.6**	**0.3**	**6.0**	**13.7**
Percentage of possible RTTRs calculated	**99.8**	**76.6**	**91.8**	**82.5**	**60.2**

Table 5-6: Summer RTTR Statistics for all HV sites

Overhead line ratings have a wide distribution with long, low-probability, tails. This is normally expressed in terms of exceedance, the % of the time (over a year or season) when the actual capacity of the line will be lower than the given rating. This has historically been set to a small (but non-zero) percentage, recognising that the costs of achieving zero exceedances are not justified by the safety benefits.

The long tail of the distribution means that in order to choose a single rating which will be exceeded only under exceptional conditions, a great deal of capacity must be wasted under normal conditions, offering little increase (or a reduction!) in network capacity over present ratings.

At some sites, particularly on the HV system, the rating which is available under 99% of weather conditions encountered is lower than the present rating (this does not take load variation into account). To achieve an increase in network capacity therefore some form of active network management will be needed to ensure that network loading can be curtailed at times of low network capacity.

The full CIGRÉ method for determining conductor temperature requires a wide range of input weather data, which is expensive to gather. Analysis was therefore conducted to see whether the ratings process could be simplified (as was done for ER P27) without substantially reducing the RTTR ratings. Three simplifications were proposed:

1. Using a fixed wind angle, rather than calculating yaw angle for each span.
2. Ignoring solar radiation heating of the conductor.
3. Ignoring the cooling effect of rainfall.

Numerical studies of the effects of ignoring wind direction, and assuming a fixed wind direction where carried out. These showed that, whilst the fixed angle gave an unduly pessimistic rating, the effect was only significant at high wind speeds, where large increases in rating were being calculated. If the maximum RTTR rating is constrained by other factors to a small multiple of the ER P27 rating (which is likely to be the case), then the impact is minimal. Thus on distribution networks, there is no need to measure wind direction.

Ignoring solar radiation will obviously result in a lower conductor temperature being calculated than is actually the case. However, the experimental work in ACE104 showed that the highest (limiting) conductor temperatures all occurred overnight when solar radiation is zero. Sensitivity analysis also showed that the impact of solar radiation was limited to 9% change in rating, so this (expensive to measure) parameter can be omitted.

Finally, the cooling effect of rainfall has to be considered. This is a high-maintenance measurement to make, because the only approach known is a rain gauge and tipping bucket system with multiple moving parts. By ignoring the cooling effect of rain (only present some of the time, and not strongly correlated with network load), the conductor temperatures will be lower than predicted, so the result is a safe, conservative rating.

The above results assume that the exceedance value set by ER P27 is still valid. If this exceedance value is reviewed, then the conclusions may be substantially altered. Work to explore this (and understand whether the ER P27 ratings actually deliver the exceedances they claim) is being undertaken in a Network Innovation Allowance (NIA) project “Improved statistical ratings for distribution overhead lines” SN0004.

Analysis is required to understand how RTTR can be deployed and if active network management is used and the amount of controllable load or generation that is required. The maximum controllable load that is required is the maximum difference between the load/generation and rating that may occur. This may not occur when the ratings is lowest or highest. Generators or new load will want to understand the likelihood of constraint before signing to such a connection agreement.

The risks associated with RTTR falls into three areas:

- The risk that the load/generation and weather conditions are such that the load is greater than the RTTR rating.
- The risk that communications fail
- The risk that load/generation control fails

The DNO needs to understand these risks. A new customer will want to understand the frequency of control actions to understand the financial risk.

The other option to provide active network management is Energy Storage although at present it is challenging to build an effective business case for Energy Storage on distribution networks.

5.6 Summary of lessons learned

This section provides the summary of the key learning gained throughout the project process - from initial design through to operation of an OH Line RTTR system. Detailed information is provided in the following relevant sections of this report.

5.6.1 Overhead Line RTTR Concept Design

RTTR LL 5.1. Overhead line RTTR model based on CIGRE WR 22.12: 1992 was successfully deployed.

RTTR LL 5.2. The thermal dynamic calculation for an Overhead Line has been successfully implemented by utilising P27 assumptions excepting forced convection heat loss which was calculated based on environmental conditions.

RTTR LL 5.3. Key conditions for OH Line RTTR are the magnitude of the wind speed and angle of incidence to the conductor, as they affect the thermal dynamics of the conductor.

RTTR LL 5.4. If single measurement devices are used along an Overhead Line circuit section, they should be installed to the location likely to have the lowest rating i.e. an area heavily sheltered from the wind.

RTTR LL 5.5. The location likely to have the lowest rating will need to be checked regularly (e.g. once a year) as tree growth or new buildings could cause the position to change.

RTTR LL 5.6. The same site dependent static parameters used in P27 are required in RTTR to calculate conductor operational temperature.

RTTR LL 5.7. Line temperature measurements at one point should not be used as a direct means for rating an OHL as the temperature can vary in a span under critical conditions. The average temperature should be used.

RTTR LL 5.8. Thermal-time constant for Overhead Lines is of the order of five to ten minutes and therefore the sampling rate from equipment should be less than or equal to 5 minutes.

RTTR LL 5.9. For distribution OHL RTTR schemes in normal circumstances it is sufficient to use:

RTTR LL 5.10. a fixed wind angle to the conductor of 12 degrees

RTTR LL 5.11. fixed absorptivity and emissivity of 0.9 and 0.8 respectively

RTTR LL 5.12. No consideration of solar heating or evaporative cooling

RTTR LL 5.13. Measured wind speed and ambient temperature values

5.6.2 Overhead Line RTTR Procurement and Installation

RTTR LL 5.14. At present, on line measurement devices which determine line sag and line angle are more costly for procurement and installation, than devices measuring line temperature and current from which sag can be calculated.

RTTR LL 5.15. Due to the small thermal-time constant and the significant impact of small changes in ambient conditions, real-time thermal rating requires data accurate to within 1 or 2 %.

RTTR LL 5.16. Manufactures generally overstate their product's capability, which can influence the direction of the solution design. The communication methods should be specified to ensure the correct functionality is attained.

RTTR LL 5.17. Line mounted measurement devices were too heavy for hot-stick installation. If OHL RTTR becomes BaU, ideally the mass of sensors should be reduced to allow hot-stick installation methods, as it will reduce resource and cost requirements.

RTTR LL 5.18. The line mounted device should be powered by scavenging from the line to which it is connected. This avoids problems with flat batteries in winter which have plagued solar systems in the UK.

RTTR LL 5.19. Auxiliary equipment including the local controller, weather station and communication devices should be powered using small scale photovoltaic generation supplemented by a battery for times of low generation. This avoids the need for a separate mains supply at the installation location.

RTTR LL 5.20. The solar panel should be installed with a South facing aspect to achieve maximum effectiveness. The bracket should be installed so that the panel is at an angle of 50° - 65° to the horizontal.

RTTR LL 5.21. Evaporative cooling (caused by rain) and solar heating are ignored within the thermal model. For distribution systems measurement of these parameters is not necessary but was carried out for experimental analysis within the trials.

RTTR LL 5.22. Given the short time constants of Overhead Lines, a rating every 5 minutes is required.

5.6.3 Data Analysis

RTTR LL 5.23. The trial results showed significant increases in thermal capacity of Overhead Lines compared to static ratings calculated under ER P27, particularly for double circuits.

RTTR LL 5.24. In particularly sheltered areas, combinations of low wind speed and high ambient temperatures resulted in ratings which were lower than their static equivalents for a small proportion of the time.

RTTR LL 5.25. To use RTTR for Overhead Lines, active network management is required to maintain the distribution system within operational and statutory limits.

RTTR LL 5.26. Analysis is required to understand how RTTR can be deployed and, if active network management is used, the amount of controllable load or generation that is required and associated safety and financial risk to the customer.

6 Transformer RTTR

6.1 Implementation of Transformer RTTR in the CLNR project

For Transformers, RTTR systems measured transformer load, ambient and transformer temperatures to assess the real time rating based on the equations set out in IEC 60076. As no off the shelf system was available and therefore the components for Transformer RTTR were installed and the IEC 60076 Part 7 equations coded.

Transformers RTTR was installed at 2 primary substations:

- Denwick 20/25MVA stepping from 66kV to 22kV with fan cooling and ±10.5 taps in 1.5% steps
- Rise Carr 15 MVA stepping from 33kV to 6.4kV with fan cooling and +4 to -15 taps in 1.5% steps
- 21 distribution Transformers were also monitored:

Transformer Site	Voltage(kV)	Rating (kVA)
Alnwick St James	20/0.4	300
Belford West	20/0.4	315
Doddington Village	20/0.4	315
Wooler Ramsey	20/0.4	315
Darlington Melrose	6/0.4	500
Darlington Russell	6/0.4	500
Darlington Valley	6/0.4	500
Akeld	20/0.4	500
Harrowgate Hill	6/0.4	750
High Northgate	6/0.4	750
Marwood Crescent	6/0.4	500
Mortimer Road	11/0.4	800
Redburn	11/0.4	500
Sidgate Lane	11/0.4	315
Wooler Bridge	20/0.4	500
Stooperdale Offices	6/0.4	500
Tickhill	11/0.4	750
Wooler St Mary	20/0.4	500
Beaumont Reservoir	20/0.4	750
Waren Mill	20/0.4	800
Stone Close	20/0.4	1000

Table 6-1 – Monitored Distribution Transformers with Voltage and Power Ratings

Apparent power, ambient temperature and frame temperature were recorded for the distribution transformers as it was not possible to monitor the oil temperature or winding temperature.

The sites were a selection of exposed rural sites and enclosed, indoors sites. There was also a selection of positions used to for the location of the frame temperature sensors.

6.2 Lessons learned from design

6.2.1 Present UK Practice for Transformer Ratings

The normal load rating of a transformer is determined by the equations in IEC 60076 Part 7. The rating is that load that the transformer can sustain such that its hot spot temperature reaches no more than 98 degrees. At this temperature the transformer should not exhibit excessively fast ageing and should be able to sustain this loading for its design life. Engineering Recommendation P15 sets out the increase in ageing that occurs when the load is above the normal rating and the reduction in ageing due operating above 98 degrees and how this can be calculated. P15 also demonstrates that a transformer can be loaded higher with the same resulting hot spot temperature if the ambient temperature is lower. Under outage (N-1) conditions, transformers may run at up to 140% of their rated load for a short period as the additional ageing is negligible over the design life of the transformer.

P15 proposes two options to take into account cyclic loading. The exponential equations process sums the ageing of the transformer under different loading over a cycle. Each period that is summed must be long enough for the transformer to reach steady state. This process assumes step changes in load and the overshoot in hot spot temperature, which occurs before steady state, is not modelled. If the load is varying at a rate that is quicker than the time constant of the transformer, this is not taken into account.

The second option which P15 lists is the full IEC model with differential equations, this approach is used within real time ratings. Note the exponents x and y that govern the temperature overshoot of the hot spot temperature over the top oil temperature may vary with age and design of transformer and the values proposed are typical. Both models have certain assumptions:

- The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.
- As a first approximation, the temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference g_r between the two straight lines (g_r being the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank).
- The hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding because allowance has to be made for the increase in stray losses, for differences in local oil flows and for possible additional paper on the conductor. To take into account these non-linearities, the difference in temperature between the hot-spot and the top-oil in tank is made equal to $H \times g_r$, that is, $\Delta\theta hr = H \times g_r$ where g_r is average winding to average oil (in tank) temperature gradient at rated current, and H is a constant describing the difference between the top oil and hot spot temperature.

With the exception of emergency ratings, P15 recommends using an average ambient temperature and a weighted average that produces the same aging if the temperature varies over a load cycle.

The focus of P15 is on the aging of transformer under different conditions and suitable ratings to prevent premature ageing rather than on real time ratings. Under real time ratings, the transformer should not be put under more adverse conditions than it would be if the assumptions made for static ratings for normal loading conditions were correct. Some of the points P15 highlights are also important to consider when operating under real time ratings:

- The temperatures of windings, cleats, leads, insulation will increase, and may not be cooled as much as the Transformer.
- The leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the leakage flux.
- As the temperature changes, the moisture and gas content in the insulation and the oil will change.
- Bushings, tap-changers, cable-end connections and current Transformers will also be exposed to higher stresses which encroach upon their design and application margins.

Note that if the transformer is operating in conditions that are more benign than those assumed by static ratings, the ‘bonus’ of additional lifetime achieved may be lost if real time ratings are applied. Most primary transformers operate in parallel and therefore their loading in normal conditions is under 50% of their rating. Therefore, even increasing this via real time ratings should not have an adverse impact on lifetime.

Given the value and number of distribution transformers, little in-depth analysis has been carried out on the ratings of distribution transformers. Information on parameters such as mass of windings to oil and losses is hard to obtain except for new transformers; how they may change over time is unknown.

6.2.2 Concept Design Transformer RTTR

By measuring the load, oil temperature or winding hot spot temperature and ambient temperature the thermal behaviour and using the IEC differential equations, the real time rating of a transformer can be determined. In the case of distribution transformers it is not possible to retrofit oil temperature monitoring, the nearest practical proxy is the frame temperature.

The additional but static information that is required is the:

- Mass of the Transformer, windings and oil
- Losses at no load and rated load
- The difference between the average oil temperature and hot spot temperature
- Type of cooling mechanisms (e.g. fans)

Effect of Transformer RTTR on noise levels (an issue known to be of concern to neighbours) was discussed at the Lessons Learned Workshop. Normally transformer noise falls when they are under heavier load, although noisy cooler groups may be run more if RTTR is applied. Recent Strategic Technology Programme work considering use of variable speed drives and starting them preemptively to maximise capacity may be relevant here. UKPN have a LCNF trial to demonstrate the application of this approach.

6.2.3 New load profiles

In some situations with large penetration of low carbon technologies, PV panels may lead to HV back-feed during the day, but large EV charging may increase loads overnight. These are different load cycles to most typical transformer loadings at present. It is a not a situation for which ER P15 offers any guidance, except for noting that its ratings are only valid for the load curves given. It is unclear what the capacity of a transformer is likely to be under back feeding conditions. Furthermore the transformer may not be the limiting factor; tap changers or other ancillaries could be the pinch point.

6.3 Lessons learned from procurement and installation

6.3.1 Market Analysis

No off the shelf system was available for RTTRs for Transformers. There are systems for monitoring the oil or winding temperature of a primary transformer to estimate its rate of ageing, but these do not implement RTTR. One company - Dynamic Ratings - claimed to offer a system but it proved impossible to procure.

Initially it appeared that with some small modifications the monitoring and software of the Trafoguard system could be used to provide a real time rating system rather than an estimate of lifetime for which it was designed. However during the course of the project, it was found that this was not the case. Therefore individual sensors were procured and the IEC equations were implemented in software.

6.3.2 RTTR System Components

Figure 6-1: Example of a Frame Temperature monitor.

For RTTR for distribution transformers the following measurements were made:

- Ambient temperature
- Frame temperature (Figure 6-1)
- Apparent power for each phase

Wind speed and sunshine may also have an impact but these were not measured and are not included in the model.

For primary transformers, oil temperature was measured and tap position is required for an accurate output. Winding or oil temperature should be more easily measured in the case of primary transformers as fibre optic sensors or oil pockets should be present. Therefore, frame temperature is not needed.

6.3.3 Communications Systems

Data transfer from the transformer location to the control system fundamentally relies on a reliable communication system utilised to transfer data. While primary substations are more likely to have good communication infrastructure that can carry a further data stream, this is not a given for distribution sites.

6.3.4 Equipment Installation

There were a number of challenges to install the required monitoring equipment.

Implementing an RTTR system on primary transformers requires an outage. Installation of equipment has to be built into a network operational programme and transformers that are highly loaded have limited outage opportunities to allow the monitoring equipment to be installed.

Tap position was hard to obtain on most existing units as only a glass view window with no remote tap indication was available. Reporting tap setting is mainly a problem for older, primary transformers, as all new transformers have an external digital tap position output. Retro-fitting such an output is not easy and depends on the make and model of tap changer. Older units only have a “tap in progress” light, and a glass window with a dial behind it for the operator/ inspector on site. No electrical output for remote tap indication is available. New tap changers can send this information to a central point but these are only a small part of the population. Inferring tap position from voltage and current measurements did not prove successful as there were too many other variables. An additional benefit of good tap monitoring is that it allows for much better maintenance planning, as it distinguishes between the transformer which taps end to end every day, and the one which only ever uses two of its taps, which will then wear very unevenly.

On the primary transformers, attempts to retrofit an electrical output to the legacy 1960s Winding Temperature Indicator (WTI) dial failed. This approach is also hampered by the multiple different designs of WTI in use. A second temperature sensor was fitted into the transformer oil pocket alongside the existing equipment to solve this problem, but this was only possible because of an outage which allowed the transformer to be drained down to access the oil pocket. Fitting a parallel sensor ensured that the over-temperature switches which run pumps, fans and SCADA alarms are unaffected by the changes and do not require re-commissioning.

Interposed CTs were used to measure load current to avoid disturbing the protection wiring and the time consuming re-commissioning that would entail. This is likely to be required for any retrofit transformer RTTR system, for the same reasons.

Providing all the relevant inputs to the RTTR model will be challenging. Therefore, it is recommended that the potential for a self-learning model which adapts to the transformer in a closed-loop manner is investigated. This would also address concerns about the differences between transformers of the same name-plate capacity from different manufacturers, and the amount of engineering margin allowed.

New transformers are all fitted with fibre optic winding temperature sensors, and could be specified with extra CTs for load current monitoring. However, these will take a long time to trickle through, due to the long life of power transformers.

Information on primary transformers is generally reasonably documented for primary transformers but this normally only extends to the nameplate / IEC parameters, not manufacturer-specific information. It can be unclear whether ratings are Continuous Maximum or Continuous Emergency. The latter is a UK industry “special” standard, exploiting fact that primary transformers are in pairs (or more) for redundancy. Because this results in normal operation at less than 50% load (so that load can be maintained with one out of service), Continuous Emergency Rated transformers are smaller and cheaper, but can only be run to their nameplate rating for 5% of their design life, because at the nameplate rating they get much hotter than normal (Continuous Maximum Rated) transformers. This was expected to be a rare event (less than 5% of the time) because it would only happen with one transformer out of service. This may have implications for RTTR on these transformers if the type of rating is not clear.

6.3.5 Distribution transformers

Distribution transformers can only be manually tapped, therefore tap position is not needed. Frame temperature was measured however it is unclear whether this provides a more useful input that just ambient temperature.

Installation on distribution transformers could be carried out without an outage.

6.4 Lessons learned from testing and commissioning

Additional surveying is required to understand the limitations in a particular substation:

- The transformer condition (actual remaining life) before proceeding – for example Dissolved Gas Analysis.
- Other design limits on the transformer and associated equipment, for example:

- Tap changer reverse flow rating (if applicable)
- Voltage limits / tap ranges at proposed loading
- Transformer connection cable rating limits

As with the OHL RTTR, there are other constraints on the transformer loading apart from its thermal rating. In particular, some on-load tap changers are known to have reverse power flow ratings as low as half their forward rating, which may make Transformer RTTR moot for some in-feed applications (or a replacement tap-changer would be required). It will also be necessary to carry out the design work to make sure that if the extra load is put through the transformer, there is sufficient tap range to keep the system voltage within limits.

Temperature sensor calibration has been limited – sensors were checked by the supplier prior to installation (so the reading reflects the probe temperature), but no on-site testing was done. Therefore, the question of how the sensor temperature relates to the oil or tank temperature is open. Paint etc. on tank, ambient temperature and weather may also affect sensor calibration. On-site calibration of sensors should be carried out after installation.

Primary transformers will have much more protection equipment than secondary, but in both cases the over-current protection will be set up to protect against faults, not overload. Therefore, it is unlikely that Transformer RTTR will require protection settings to be adjusted. If the Transformer RTTR is working correctly, it should not cause higher than rated operating temperatures, so the existing thermal protection (typically 2-stage alarm and cut-out based on oil temperature) will not be affected. The CT Burden Time-Limit fuse may need checking to ensure that the protection fuse does not blow if the transformer is operated above the CT rating for substantial periods (this should already be higher than the continuous rating of the main transformer).

6.5 Lessons learned from data gathering

The Trafoguard relays purchased originally (for primary transformers) proved to be unsuitable for RTTR. The Trafoguard relays are a monitoring device which measures transformer ageing, but not available capacity. Many attempts were made to convert the Trafoguard system to calculate capacity, but no useful results could be obtained, which is why the Transformer RTTR was ultimately implemented in the Remote Distribution Controller (RDC) as part of the Active Network Management System. As a result, fewer primary transformers were implemented than hoped, and none that is loaded at normal rated capacity.

The RDC model does not use the actual transformer top oil temperature, as it was deliberately operated with parameters for a much smaller transformer in order to produce RTTR constraints for the Active Network Management System. Otherwise this could have been used to improve or measure the output accuracy. One of the limitations of the RDC implementation is that there is no local ampacity output, the ampacity figure has to be sent via communications links as it is calculated by the central PowerCC system. Therefore, implementing generation constraint schemes without relying on communications links was not possible; this would have to be provided for future systems.

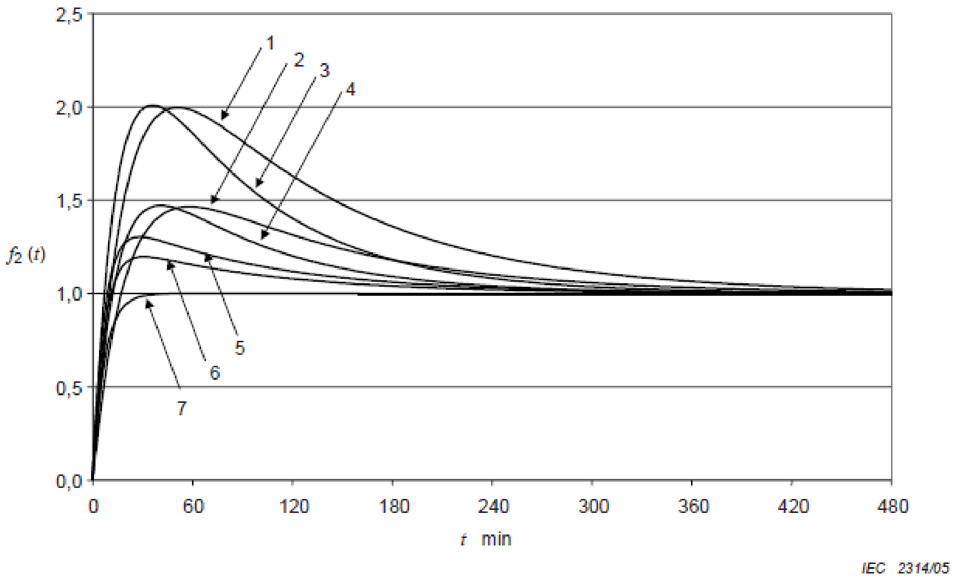
The settings within the Active Network Management System steered the RTTR to calculated ratings for the next 30 minutes. As the thermal time constants of transformers are longer than this, 30 minutes is too short a timescale. Figure 6-2 from the IEC standard shows the function of relative increase in the hot spot and top oil temperature gradients. This demonstrates that within a 30 minute time period, the transformer may still be in a transient state such that if the load persists the temperature of the winding may increase above that predicted within 30 minutes.

During the transient state, the behaviour of the oil and winding in transmitting heat may change and the linear assumptions of the model may no longer hold. Whether the shape of the transient curve is as described is uncertain, particularly given that the constants may not be correct or may change with time. This is particularly true where fans are operating as the parameters change with different cooling. The thermal behaviour is not modelled with enough accuracy such that changes operation can be taken into account during the transient stage.

In addition the exponentials governing are also dependent on the winding and oil time constants. These are calculated from the mass of the coils, their losses and specific heat capacity of the materials. Experience gained from the project shows that these values are often unknown.

Furthermore, the parameters are obtained from a heat run test from the transformer starting in ambient conditions. Once a transformer is loaded this may not be the case and therefore the shape of the curve should be treated with caution.

In future calculations over a longer time period (e.g. 180 minutes) should be made used to ensure the transformer model is based on steady state conditions.



Key

1 ONAN – restricted oil flow
2 ONAN
3 ONAF – restricted oil flow
4 ONAF
5 OF – restricted oil flow
6 OF
7 OD and distribution transformers

Figure 6-2: Relationship between gradients of the top oil and hot spot graphed in the IEC standard for different types of transformer

6.5.1 Potential applications

Whilst there is uncertainty within the calculations, the data from the RDC showed that there is potential for additional capacity depending on the location of the transformer and the shape of the load curve. A significant margin of error can be built into the calculations to compensate for unknown values. RTTR for Transformers can be used in a number of ways:

- Where a transformer may be close to being over loaded according to its static rating, a desktop study using SCADA load data and the closest available weather data can provide a more accurate assessment of the spare capacity available. NPg carry out a bespoke desktop study that takes into account the load cycle and condition of the transformer but this could be enhanced with RTTR.
- Similarly, current and ambient temperature data could be used to study whether there is sufficient capacity for a new connection using RTTR. This could be particularly relevant for seasonal loads, loads used at particular times of day or wind or solar generation.
- As a means to understand the impact of shading or new build around a transformer.
- Where there is controllable generation or load, real time measurements and ratings can be used with Active Network Management. The amount of load or generation that would need to be managed and how long for will need to be assessed.

- In the case of secondary transformers, full scale monitoring may not be appropriate but current and ambient temperature could provide sufficient data to provide a warning system for a transformer becoming significantly overloaded. This could be used to target upgrades to where they are needed.

For desktop studies, this capability should be built into NPADDS so that planning decisions can be made, on whether to use RTTR.

6.6 Lessons Learned from the Modelling

6.6.1 Overview

Within the time available it was difficult to draw useful learning from the data available. Whilst initial modelling demonstrated that there is significant capacity available (over 100% increase), this was modelling with a hot spot temperature limit of 130° degrees so it could not be compared with static ratings that limit the temperature to 98° degrees. At 130° degrees over a prolonged period, the water content of the oil will boil and its heat transfer properties will change. It is also likely that the tap changer would not be able to operate.

The equations and assumptions of linearity have not been tested at such high loads so it is not clear whether they hold.

Furthermore as the transformer were not heavily loaded, these may not be good examples as the oil is significantly below its temperature limit at the start of the calculation. Heavily loaded transformers will reduce the additional headroom as it will heat the windings.

There was insufficient time for EA Technology to model the primary transformers taking into account tap changes. The conclusions below draw mostly on the models of the distribution transformers.

6.6.2 Distribution Transformers

Information on the distribution transformers' static parameters for the range of sites was found to be mostly incomplete or inaccurate. The date and types of transformers were uncertain and therefore it was not possible to find information on the mass, losses and hot spot temperature.

Analysis of the available data showed little correlation between the parameters that were known and the rating of the transformers. There was no scaling factor that could be consistently applied.

Therefore, running the RTTR equations would have been inconclusive as the impact of these factors is unknown. Furthermore it would be difficult to compare the additional capacity between transformers when the load curves are very different in shape. Therefore, it was decided to study the sensitivity to variations in losses, physical design and hot spot temperature rise using the model and the temperature and loading data. The analysis followed the project in studying 30 minutes limiting the temperature to 98° degrees. The analysis showed the considerable difference in RTTR using a timescale of 30 minutes and a longer period. Whether the 30 minute ratings are safe to use is also uncertain as described in sections 6.5 and 6.6.1. However, to give a preliminary assessment of the impact, a longer period was run for Wooler St Mary's with a time period of 180 minutes. Four transformers where the parameters were more certain and data reasonably complete were chosen for analysis (Table 6-2):

Name	Voltages (kV)	Rating (KVA)
Akeld	20/0.4	500
Sidgate Lane	11/0.4	315
Stooperdale Offices	6/0.4	500
Wooler St Mary	20/0.4	500

Table 6-2 - Secondary transformers used for data analysis.

Note: Akeld is an indoor transformer but a de-rating factor was not applied. The addition capacity at all four was calculated for June to August and December to February (i.e. in summer and winter). For Sidgate Lane and Wooler St Mary the mass of the winding and core was increased and decreased by 10% and the losses at full load increased and decreased by 10%.

Typical phase current curves for weekdays (Wednesday was used as a sample) and Saturdays in summer and winters are shown in Figure 6-3.

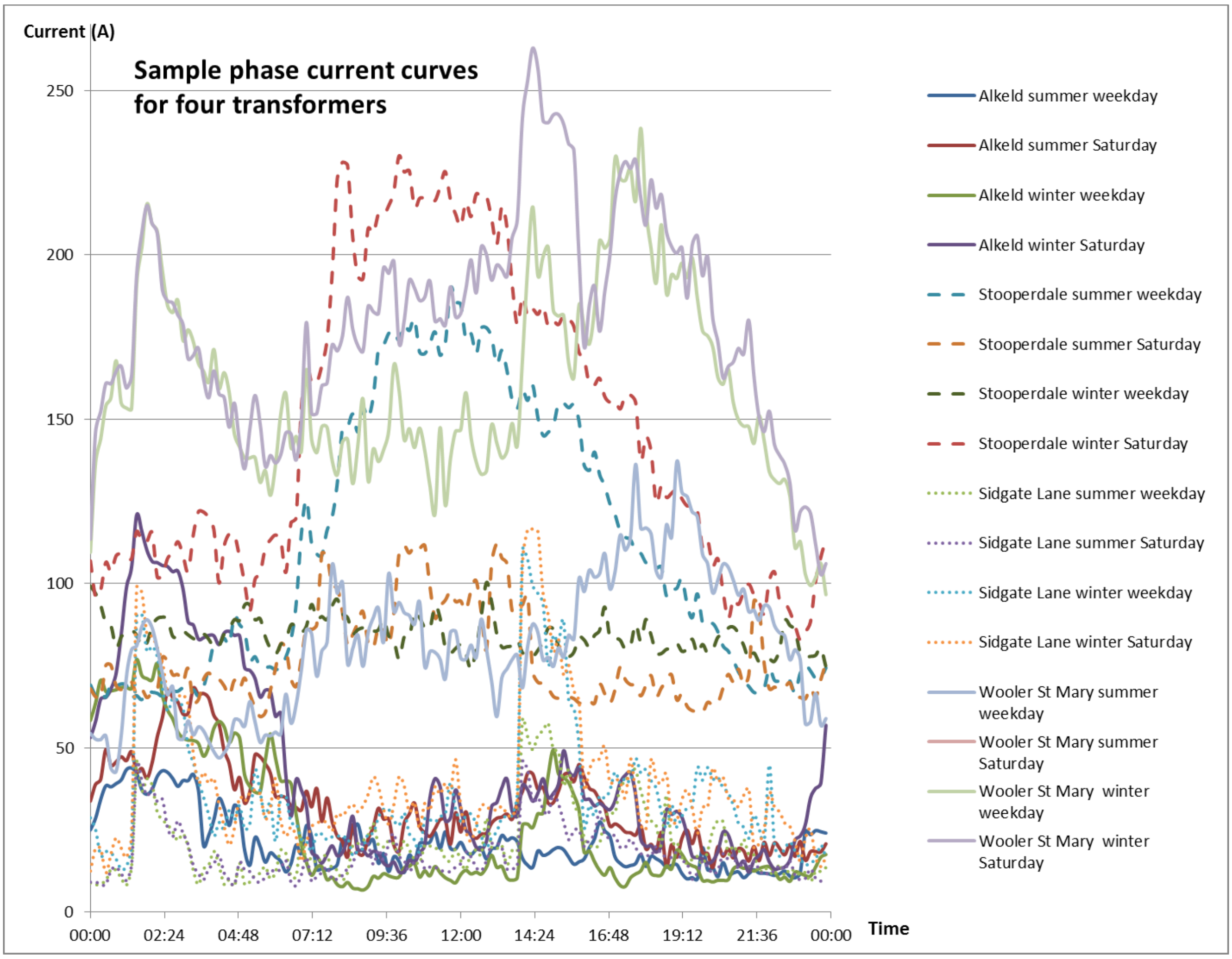


Figure 6-3: Typical phase current for the four transformers studies in summer and winter on a weekday and Saturday.

The only transformer that is particularly heavily loaded is Wooler St Mary in winter and therefore its RTTR rating may be lower than the other sites. This transformer follows a domestic curve and there is a considerable drop in load during the summer when ambient conditions are most onerous.

Stooperdale Offices does not follow the domestic profile, rather it has a flat curve or a peak during the day indicating offices and machinery are drawing power. It is interesting to note that its second highest demand is in summer during a weekday, presumably due to air conditioning. This could be a cause for concern as ambient temperatures are highest at these times. Whilst the rating of the transformer is not exceeded, the RTTR will be lowest at these times, as shown in Figure 6-4 and Figure 6-5. These graphs demonstrate that reducing temperature or current increases capacity. Note the variation in current is much greater than that in temperature. As a result the sudden drop in capacity at about 5am is likely to mostly be due to a drop in current (at the same time as the temperature is decreasing). It is interesting to note that this transformer will have periods to cool when the load is flat and low.

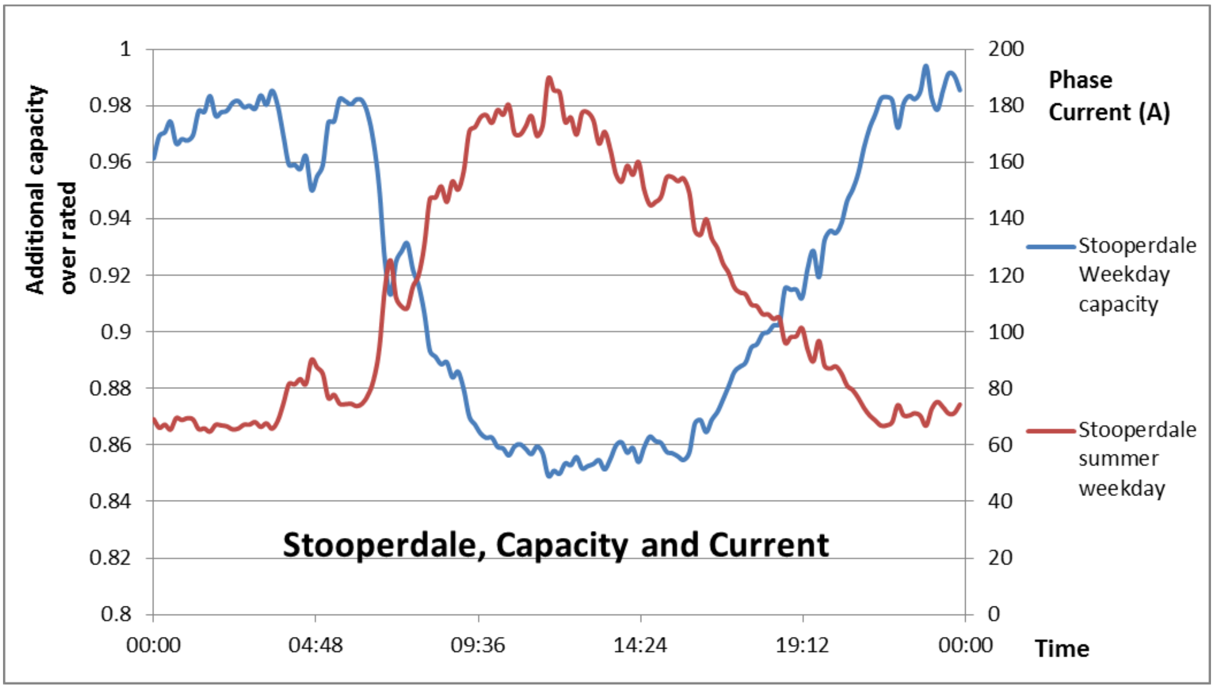


Figure 6-4: Stooperdale capacity and current, example weekday in summer

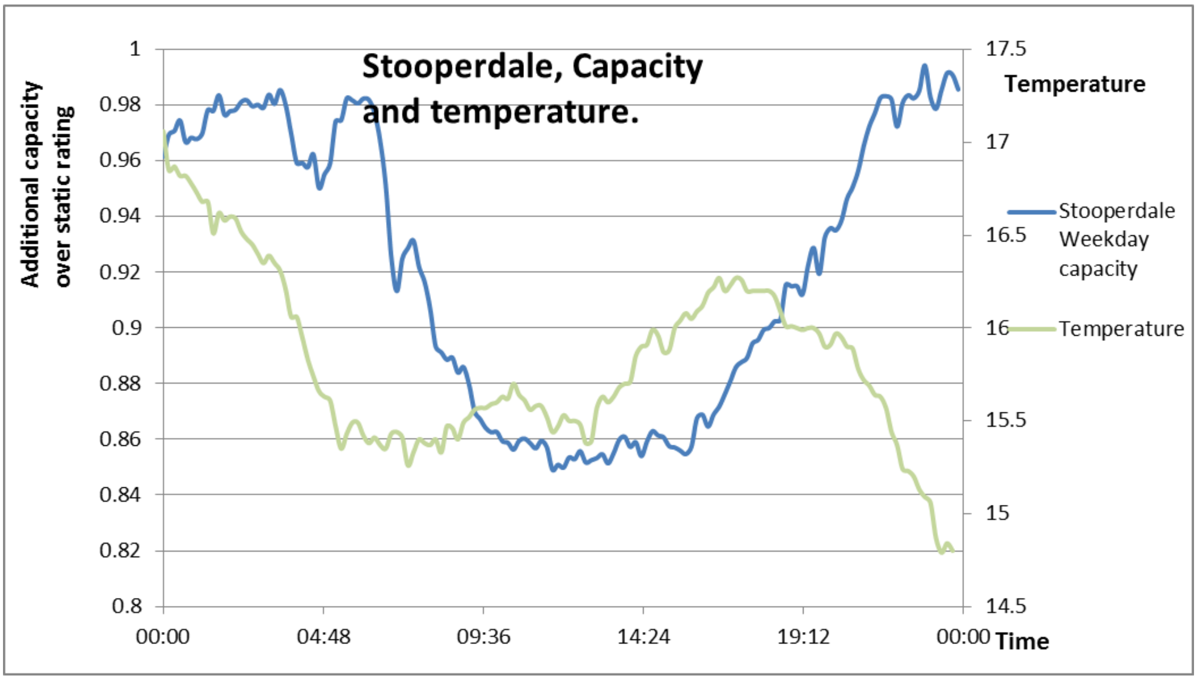


Figure 6-5: Stooperdale Capacity and temperature, example summer weekday

Akeld is lightly load but has a peak during the early hours of the morning especially in winter indicating off peaking space and water heating may be present. As the temperature at night is lower, these loads could be more easily managed. Whilst it is difficult to distinguish the impact of the two factors, Figure 6-6 and Figure 6-7 show how the rise in current or temperature reduces the additional capacity available from RTTR. The impact of temperature is probably less marked at Akeld as it is indoors. For some loads, temperature and load are inversely proportional (e.g. direct electric heating) whilst others, they are proportional (e.g. air conditioning). This demonstrates the importance of understanding the load profile and its disaggregation.

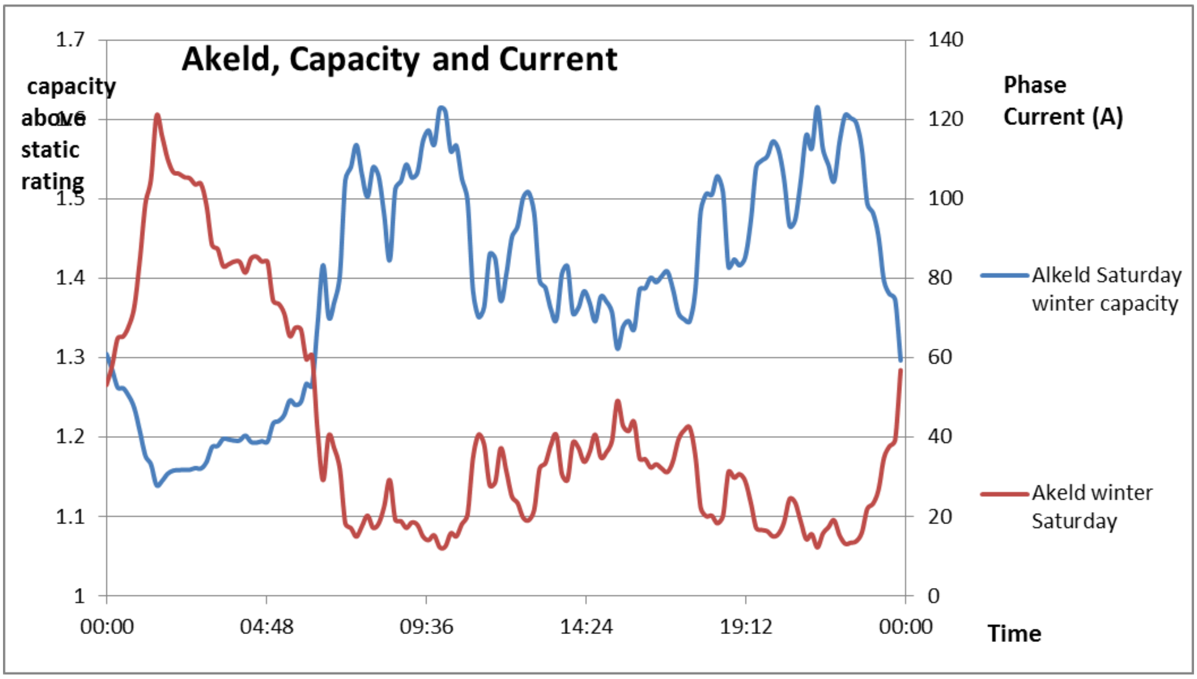


Figure 6-6: Akeld capacity and current, example Saturday in winter

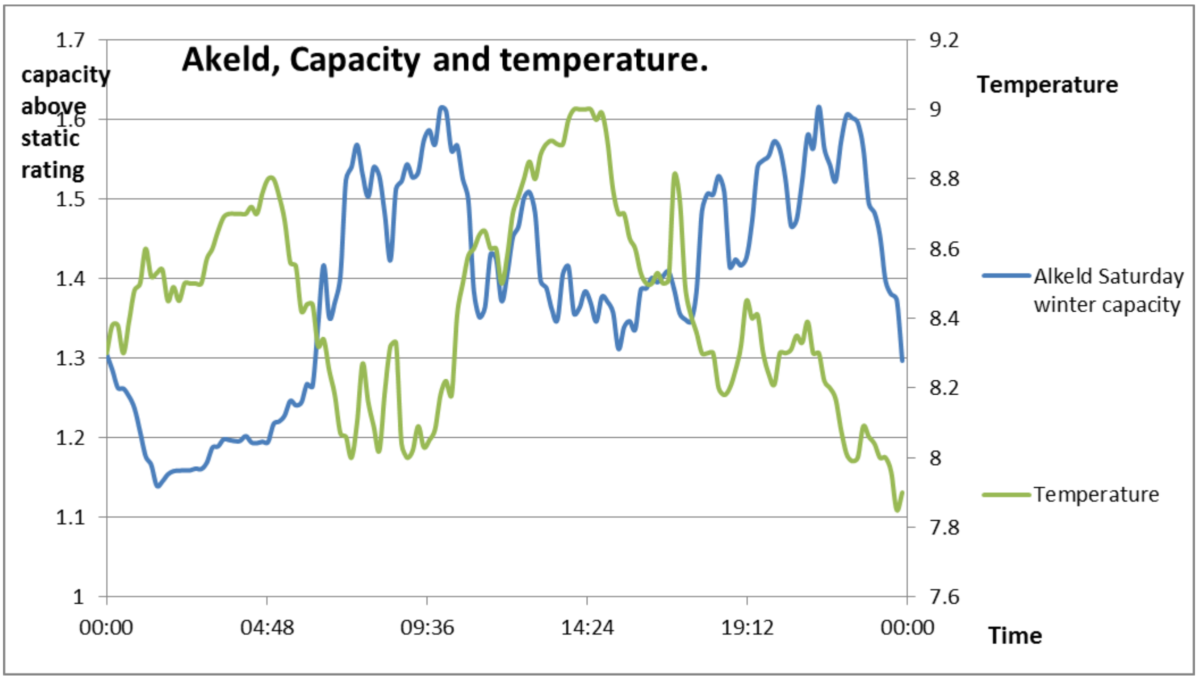


Figure 6-7: Akeld capacity and temperature, example Saturday in winter

6.6.3 Additional Capacity 30 or 180 minutes

For Akeld, Stooperdale Offices, Sidgate Lane and Wooler St Mary the RTTR values were calculated for June to August and December to February with a 30 minute time period. The probability of different values of additional capacity were calculated for each case. In each case the additional capacity was unrealistically large (over 100%). For Wooler St Mary's the model was rerun with a time period of 180 minutes (Table 6-3). This gave typical additional capacity of between 10% and 40% of static ratings which is in line with previous studies by EA Technology and claims by the company Dynamic Ratings.

As described previously, this emphasises the need to calculate ratings for a 180 minute period or more.

Comparing the additional capacity for summer and winter. The range of additional capacity for the four transformers is about 10% higher in winter than in summer. However, the total load in winter is higher than the total load in summer. It is likely that the lower ambient temperatures are compensating for the higher load in winter.

Additional Capacity	Winter 180 minutes	Summer 180 minutes	Winter 30 minutes	Summer 30 minutes
0 - 0.1	0%	1%	0%	0%
0.1 - 0.2	0%	37%	0%	0%
0.2 - 0.3	46%	62%	0%	0%
0.3 - 0.4	54%	0%	0%	0%
0.4 - 0.5	0%	0%	0%	0%
0.5 - 0.6	0%	0%	0%	0%
0.6 - 0.7	0%	0%	0%	0%
0.7 - 0.8	0%	0%	0%	0%
0.8 - 0.9	0%	0%	0%	2%
0.9 - 1.0	0%	0%	20%	17%
1.1 - 1.2	0%	0%	65%	38%
1.2 - 1.3	0%	0%	15%	32%
1.3 - 1.4	0%	0%	0%	11%

Table 6-3 Comparison of additional capacity with a 30 and 180 minutes window for Wooler St Mary's

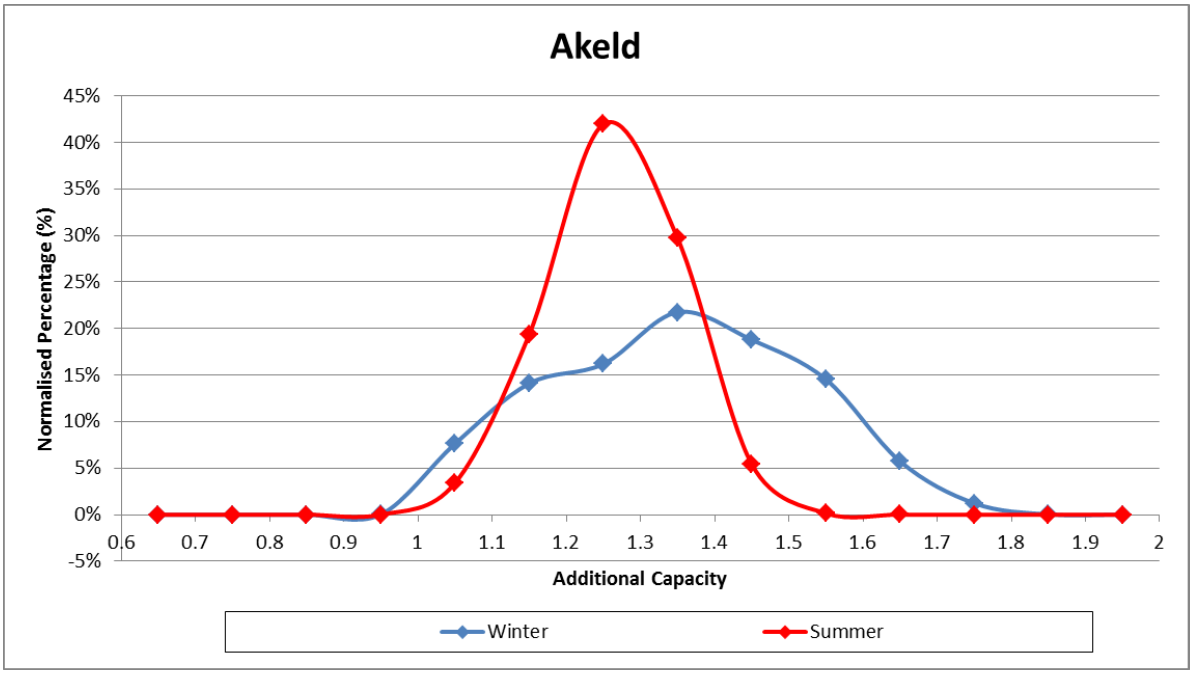


Figure 6-8: Comparison of the probability distribution in summer and winter at Akeld.

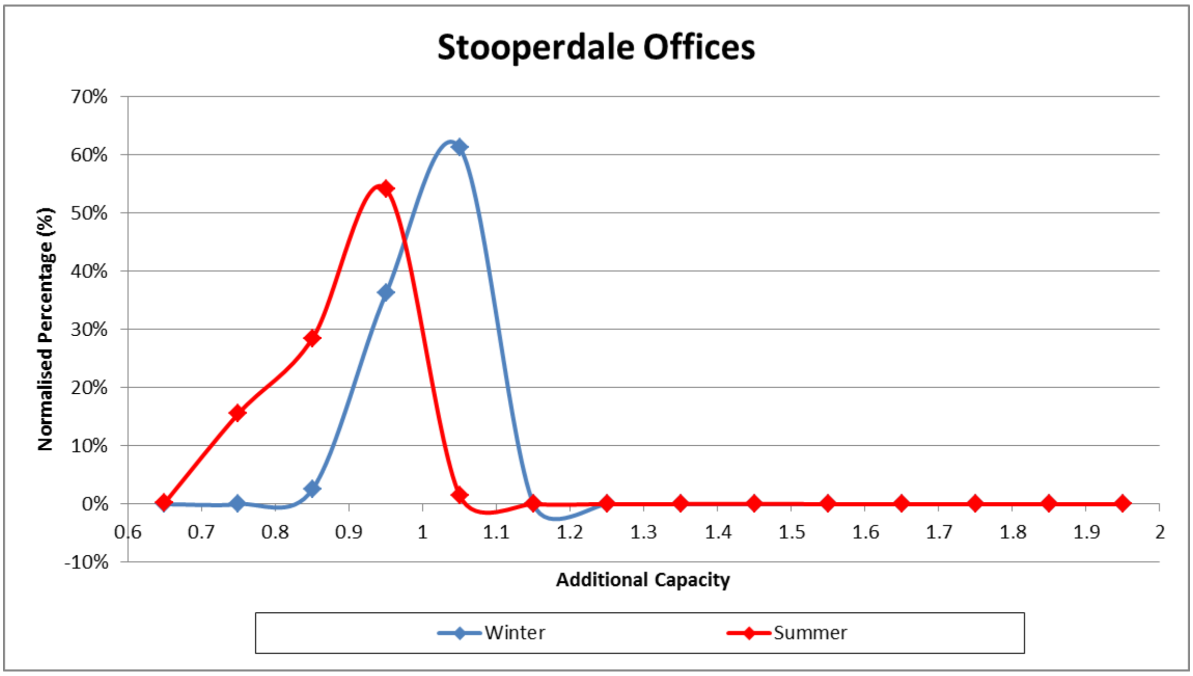


Figure 6-9: Comparison of the probability distribution in summer and winter at Stooperdale Offices

Studying the shape of the probability functions, there tends to be a marked difference in shape between summer and winter. For example, Sidgate Lane shows right skew in the range of additional capacity in summer, whereas there is a left skew in the range of additional capacity in winter (Figure 6-10 and Figure 6-11). Stooperdale is skewed right in summer and winter (Figure 6-9). Akeld has a much wider range in summer to winter (Figure 6-8). Given that the granularity of the binning for the probability distribution is not high, this could be less marked in reality. The diurnal and seasonal variation in temperatures are likely to be similar across the North-East. Therefore, the main causes of the difference in distribution of additional capacity is likely to be due to:

- Difference in load curves from transformer to transformer and from summer to winter
- Difference in designs of transformer

Implications

The work done under the CLNR project for Transformer RTTRs has shown that the calculation of Transformer RTTR should be over a time period of 180 minutes or more.

This emphasises the need to understand the shapes of load curves and how they will affect the capacity of a transformer. In the examples above, the transformer is not overloaded. However, where a transformer is loaded close to its static rating, the shape of the load curve could determine whether it is actually loaded to above its RTTR. Further work is required in this area.

6.6.4 Sensitivity Analysis to Mass of Windings and Full load losses

Sidgate Lane and Wooler St Mary were used to investigate the sensitivity to mass of the windings and full load loss values. In the each case RTTR was calculated where:

- The mass of the windings was increased and decreased by 10%
- The loss at full load was increased and decreased by 10%

In the case of Wooler St Mary these studies were carried out for a time period of 30 and 180 minutes.

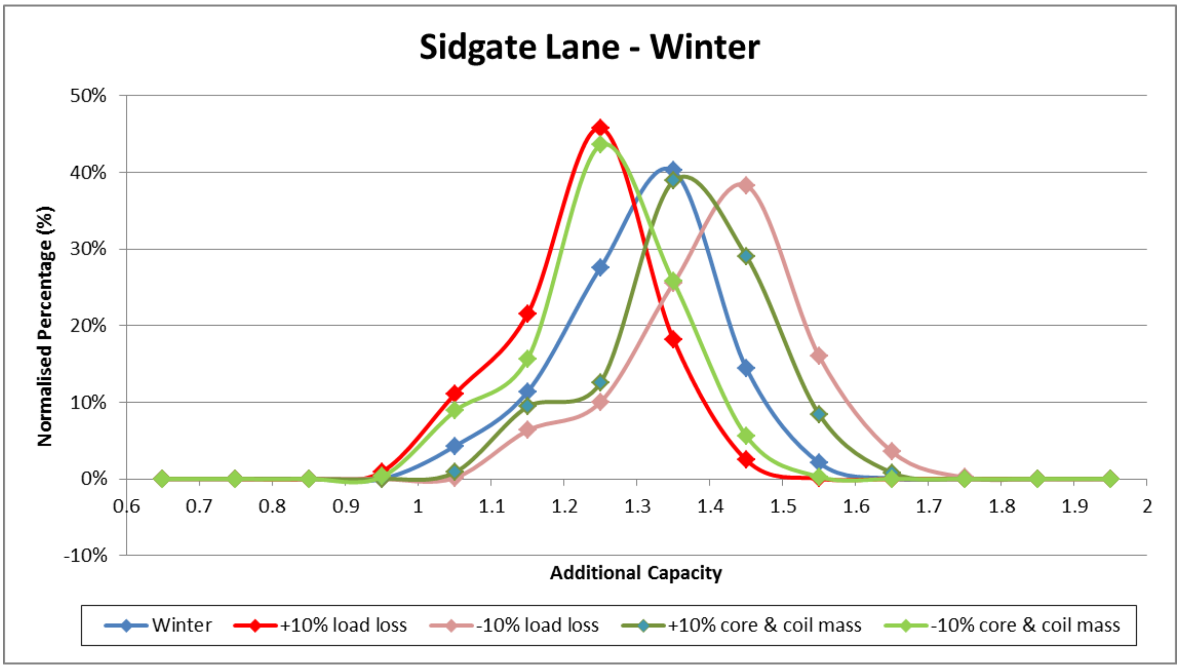


Figure 6-10: Comparison of the Probability Functions of Additional Capacity in Winter for Sidgate Lane

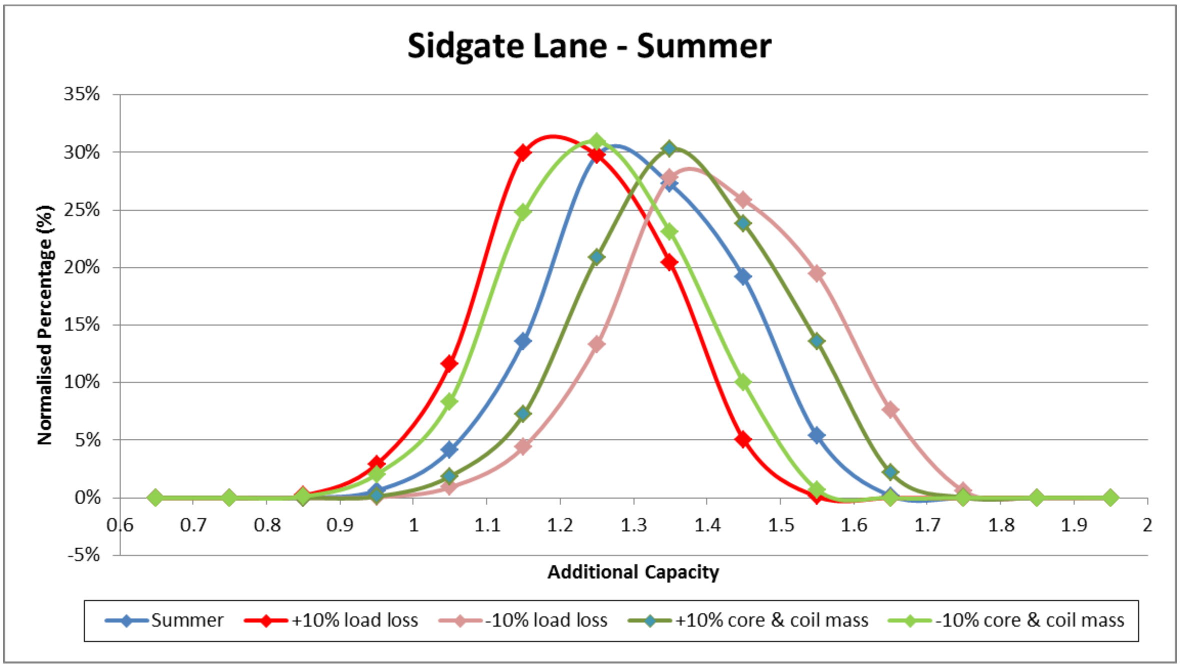


Figure 6-11: Comparison of the Probability Functions of Additional Capacity in summer for Sidgate Lane

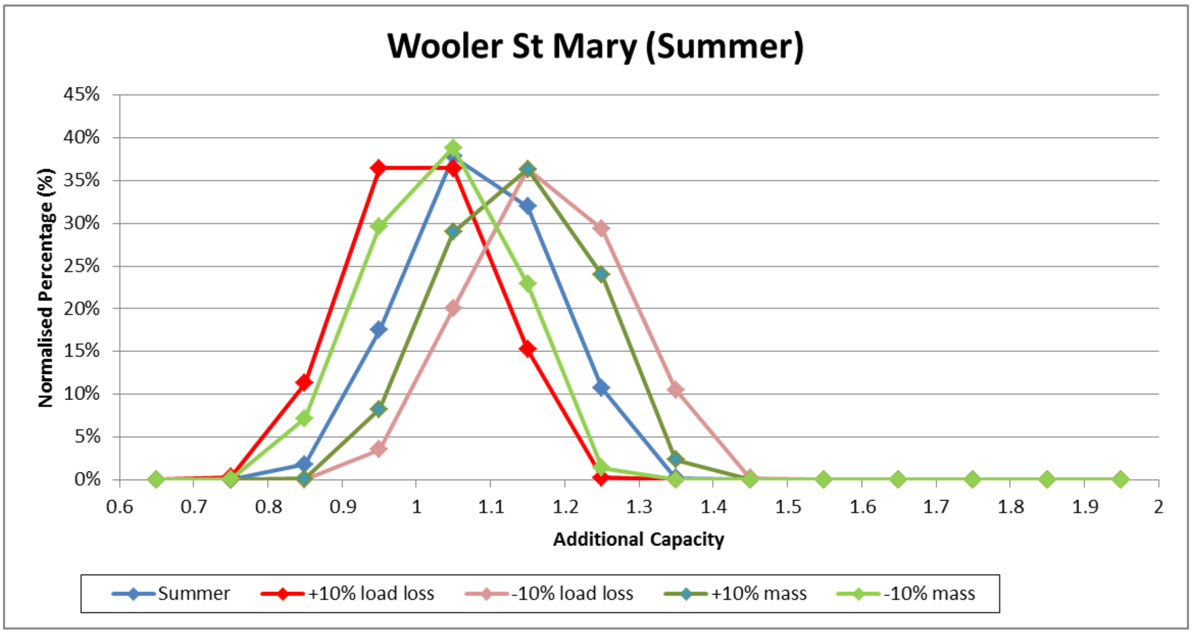


Figure 6-12: Comparison of the Probability Functions of Additional Capacity in winter for Wooler St Mary

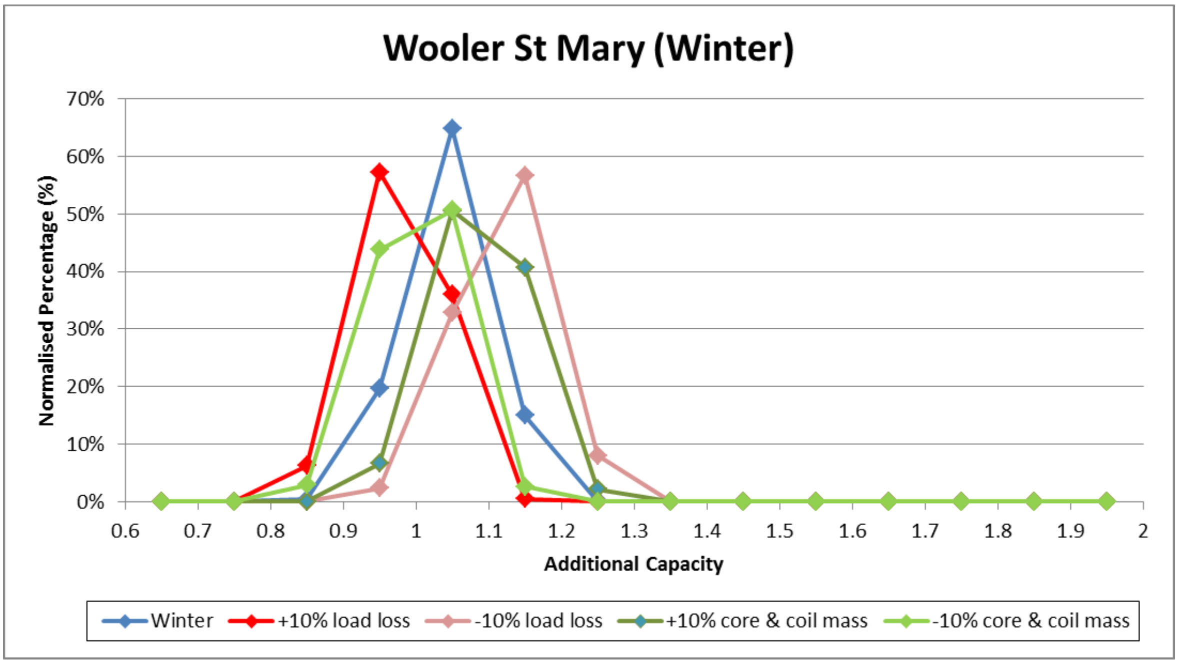


Figure 6-13: Comparison of the Probability Functions of Additional Capacity in summer for Wooler St Mary.

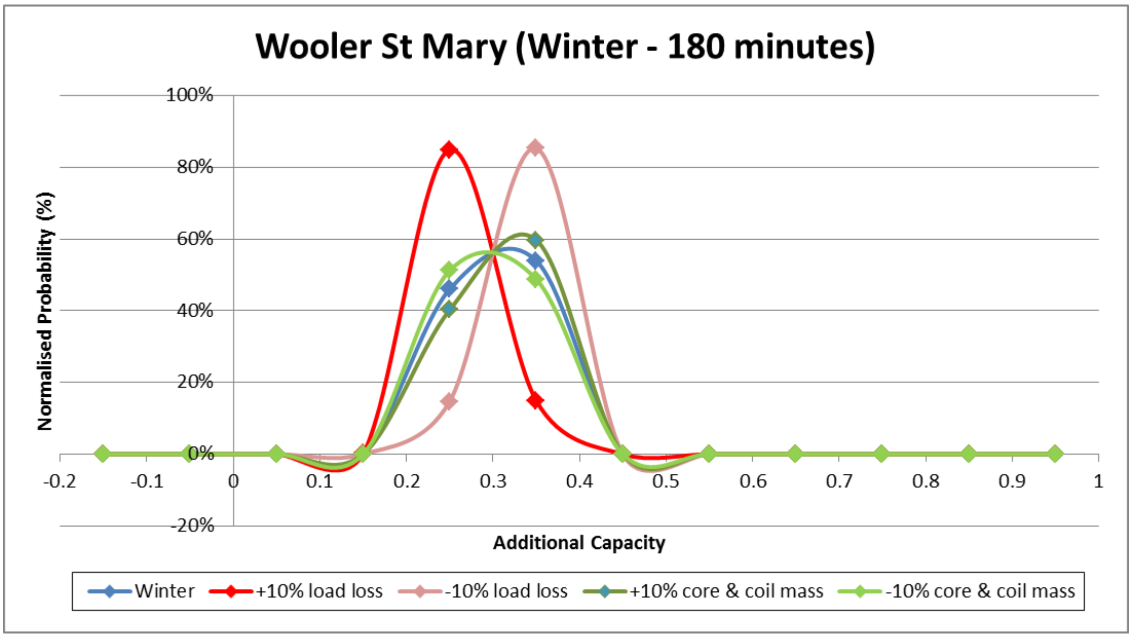


Figure 6-14: Comparison of the Probability Functions of Additional Capacity in winter for Wooler St Mary over 180 minutes.

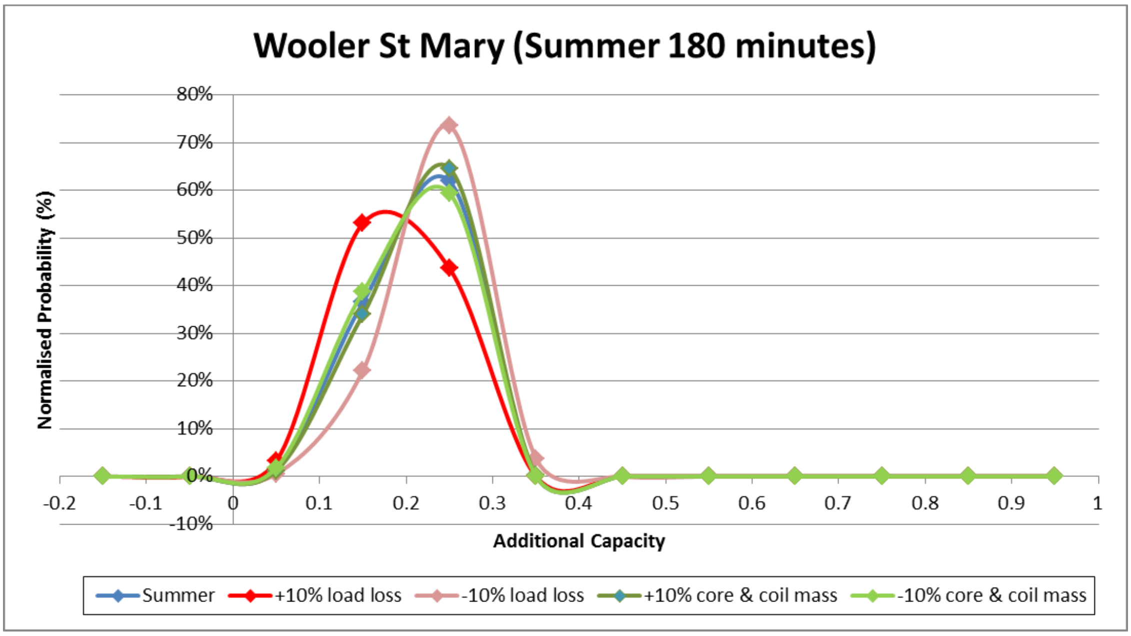


Figure 6-15: Comparison of the Probability Functions of Additional Capacity in summer for Wooler St Mary over 180 minutes.

Mass of the Windings

The mass of the windings appears to have little impact on the range of the additional capacity in either summer or winter. The impact of reducing the mass appears to have more impact than increasing it. The exponential terms in the thermal equations are dependent on the value of the mass of the windings; therefore there is a non-linear relationship with the capacity. This is the case whether the calculations are completed over 30 minutes or 180 minutes (Figure 6-10 to Figure 6-15). However, it is most marked for the summer case at Wooler St Mary when calculations are over 180 minutes (Figure 6-15).

Full Load Losses

In all cases the full load losses had a significant impact on the median additional capacity, increasing the median by ±10-15%. The shape of the probability function also changes. This could be because a greater full load loss value is likely to have more of an impact where the transformer is running at a load over a sustained period (Figure 6-10 to Figure 6-15).

Note that the impact is sufficient that under the highest loading in winter the increases in losses was sufficient that this would cause the loading to be higher than the rating for a few half hour periods in the year.

Implications

Understanding the behaviour of losses of a transformer is likely to have a greater impact on the accuracy of RTTR than mass of the coil and windings. The impact is likely to be different under different loading.

6.6.5 Frame Temperature

Given there were a number of uncertainties within the model and the hot spot temperature could not be verified, there was no reliable means to determine whether using frame temperature rather than ambient temperature was a better input to the model. It was concluded that this could only be ascertained via laboratory tests.

6.6.6 Uses for the Outputs

The outputs of an RTTR model can be used in a number of different ways.

- Warning system for when secondary transformers are actually overloaded
- Desktop planning to understand the actual capacity for existing and/or new loads
- Means to target upgrades to where they are actually needed
- Means to assess the impact of shading (e.g. from new buildings)
- Real time measurements and calculations for RTTR potentially linked to active network management, use of Energy Storage or precooling via fans.

To facilitate the desktop studies described above, RTTR models for distribution transformers should be included in NPADDS.

6.7 Summary of lessons learned

This section provides the summary of the key learning gained throughout the project process - from initial design through to operation of a Transformer RTTR system. It includes lessons learned from EA Technology through the project implementation, feedback from Northern Powergrid in the workshops, and outcomes of data analysis from Newcastle University. Detailed information is provided in the relevant sections of this report.

6.7.1 Transformer RTTR Concept Design

RTTR LL 6.1. By measuring the load, oil or winding hot spot temperature and ambient temperature, the real time thermal rating of a transformer can be determined using the IEC differential equations.

RTTR LL 6.2. Additional, static, information is required in addition to the real-time data. These include mass of the winding, core and oil mass; losses at no load and rated load; difference between average oil temperature and hot spot temperature; and type of cooling mechanisms.

RTTR LL 6.3. RTTR for transformers is of particular use to understand the impact of new loads and generation or where the transformer load curve is an unusual shape.

6.7.2 Procurement and Installation

RTTR LL 6.4. No off the shelf system was available for transformer RTTR.

RTTR LL 6.5. While primary substations are more likely to have good communication infrastructure that can carry a further data stream, this cannot be assumed for distribution sites.

RTTR LL 6.6. Providing all the relevant inputs to the model will be challenging. Therefore, it is recommended that the potential for a self-learning model which adapts to the transformer in a closed-loop manner in investigated. This would also address concerns about the differences between transformers of the same name-plate capacity from different manufacturers.

6.7.3 Testing and Commissioning

RTTR LL 6.7. Additional surveying is required to understand the limitations in a particular substation, specifically: The transformer condition (actual remaining life); other design limits on the transformer and associated equipment; on-load tap changer's reverse power flow ratings; and that sufficient tap range is available to keep the system voltage within limits.

RTTR LL 6.8. Temperature sensor calibration should be checked.

RTTR LL 6.9. The CT Burden Time-Limit fuse may need checking to ensure that the protection fuse does not blow if the transformer is operated above the CT rating for substantial periods.

RTTR LL 6.10. The winding and oil will not be taken beyond their design temperatures using the CLNR RTTR systems. However, it is important to ensure design limits of other components are not exceeded.

6.7.4 Data Gathering and Modelling Analysis

RTTR LL 6.11. Future systems should have a local ampacity output that can be used for local control or constraint management, without communications.

RTTR LL 6.12. RTTR systems need to calculate ampacity headroom. Inference from other measurements designed for other purposes (e.g. ageing as calculated by the Traffoguard system) does not work.

RTTR LL 6.13. The data from the monitoring undertaken shows that there is potential for additional capacity depending on the location of the transformer and the shape of the load curve. There are uncertainties but even with a margin of error there is still additional capacity available.

RTTR LL 6.14. The window over which RTTR is calculated should be at least 180 minutes to ensure that the transformer would reach steady state with a constant load.

RTTR LL 6.15. It is important to understand the shapes of load curves and how they will affect the capacity of a transformer.

RTTR LL 6.16. The full load losses of a transformer are likely to have a greater impact on the accuracy of RTTR than mass of the coil and windings. The impact is likely to be different under different load curves.

6.7.5 Uses for the Outputs

RTTR LL 6.17. CLNR has shown that RTTR for transformers could be used as a warning system for overload on secondary transformers.

RTTR LL 6.18. CLNR has shown that RTTR for transformers could be used to inform desktop planning to understand existing capacity, the impact of changing generation and demand, and the impact of shading.

RTTR LL 6.19. CLNR has shown that RTTR for transformers could be used with real time measurements and active network management or precooling via fans to utilise additional available capacity.

RTTR LL 6.20. CLNR has observed that the majority of RTTRs for transformers show capacity beyond the static ratings. However, further work is needed to establish the relationship between temperature, load and time.

7 Conclusions

The Customer-Led Network Revolution has successfully implemented Real Time Thermal Rating (RTTR) systems on Underground Cables, Overhead Lines and Transformers at voltages ranging from 400v at LV to 66 kV. The Real Time Thermal Ratings are calculated at resolutions of up to 5 minutes and accessed by the CLNR Active Network Management System. The calculated Real Time Thermal Ratings have been used by the Active Network Management System to coordinate the operation of the other CLNR Smart Grid technologies (energy storage and demand response) in dispatching real power to demonstrate how they could be used to avoid overloading the distribution system.

For Underground Cables, Overhead Lines and Transformers the Real Time Thermal Rating trials have demonstrated that under certain conditions they can be operated above their present - static - ratings without exceeding the design parameters of the assets.

This report presents lessons learned, both where the project has been successful and where, with the benefit of hindsight, a different approach could be adopted for future projects. The key outputs of this report are the lessons learned which are presented in the relevant sections, for each of:

- Underground Cables
- Overhead Lines
- Ground mounted primary and secondary distribution transformers

The lessons learned fall within the following topics:

- RTTR System Design
- Procurement and Installation
- Testing and Commissioning
- Analysis of the Recorded Data

A number of themes run throughout the various lessons learned:

7.1 Use of Real Time Thermal Ratings

Firstly, CLNR has shown a clear strategy for application of RTTR to all asset types. At each stage, if the problem is solved then there is no need to progress further, significant cost savings are possible:

1. Data collection and analysis to determine if the asset is operating close to its present rating
2. Open-loop rating calculation based on measured values to determine if the asset is overloaded, or whether, given the specific circumstances, the static rating of the asset can be adjusted.
3. Closed-loop operation, where Real Time Thermal Ratings are used (automatically or by control room staff) to manipulate network load to remain within the changing ratings.

4. Finally, the data collected from RTTR systems will help inform planning for network reinforcement work when the capacity of the RTTR system is exhausted and conventional reinforcement is required.

Within each of these stages there are detail variations, depending on the voltage at which the RTTR system is applied, but the principal remains the same. In the third case, the network may always operate in a managed state under RTTR control, or RTTR may only be invoked under post-fault conditions to reduce the customer impact of asset failures, keeping customers on supply when static ratings would require them to remain disconnected.

7.2 Condition of existing assets

Secondly, RTTR projects will always depend on a detailed knowledge of the installed assets. This may pose significant challenges for older assets where there are not good records of installation (but which are the more likely candidates for RTTR deployment). It will be necessary to rely substantially on 'typical' or 'normal practice' values to fill in the gaps. Further work is required to understand what impact this has on the accuracy of the RTTR, and so what safety margin it is necessary to apply to the ratings produced. For distribution transformers, an initial analysis has been set out in this report, but significantly more (mostly desktop studies and collection of rating plate data) can be done, and the approach applied to other asset classes.

It will also be important to have a detailed knowledge of the condition of any asset considered for RTTR. It will not normally be cost effective to install RTTR on an asset which is rapidly approaching replacement, because a replacement asset will be required, and the marginal cost of increased capacity is usually small.

All assets will have non-thermal limits to their rating, which may become the limiting factor after RTTR is applied. For safe operation, these must be understood and complied with, even if the RTTR calculated is higher.

7.3 Additional considerations for distributed assets

Thirdly, distributed assets (overhead lines and underground cables) do not have a single rating. Instead their rating varies along their length as both asset (line construction or cable type) and environment change. The rating of the complete circuit is determined by the lowest individual rating, which may not be constant but rather move under different conditions. The determination of these 'hot spots' or bottlenecks is usually achieved at the second stage of desktop analysis. This process will also suggest where the most targeted interventions can be made to increase the permanent capacity of the asset (e.g. overlaying of specific cable sections or raising critical spans of an overhead line).

7.4 Choice of rating

Fourthly, the choice of what rating to calculate in real time requires careful consideration. The correct decision will depend upon the purpose to which the rating is to be put as well as the nature of the loading the asset is subject to. Pertinent questions will include:

1. What reserve capacity must be preserved in the RTTR calculation? This will depend on the possible operating scenarios (i.e. what is the value of N in N-1 operation), and available responses to demand exceeding the RTTR.
2. What time limit is appropriate for limited ratings? This will depend both on the asset thermal time constant and the available responses to demand exceeding the RTTR.
3. Should ratings be calculated for continuous operating temperature limits, or the higher emergency limits designed for infrequent use (which lead to shortened asset life), or both?
4. What allowances for measurement and modelling uncertainty need to be made to ensure that the combined system remains safe?

7.5 Overview

CLNR has demonstrated the technical feasibility and operational uses for Real Time Thermal Ratings on distribution systems. The decision to use these systems, for which assets, and to what extent, will be determined by network requirement and the learning gained during the CLNR project.

The trialled systems are expected to provide information allowing Distribution Network Operators to minimise cost by showing where unused network capacity can be released and by using RTTRs to show locations where the distribution network may be unexpectedly constrained due to operational or environmental conditions.

Appendix A: Underground Cable RTTR Procurement Procedure Development Working Notes

The following summarises initial comments through procurement process for UG Cable RTTR:

Equipment	Comments
Soil temperature probe	A PRT100 probe was used in order to achieve the specified accuracy. The choice was restricted by the need for a long enough stainless steel sheath to bring the connections to the ground surface and prevent water ingress. A weatherproof head was specified for outdoor use.
Cable sheath temperature probe	The need for a sufficient length of probe made using a flat plate sensor impractical. The temperature measured is not well defined because we are on the boundary between two materials (cable sheath and backfill).
Soil Thermal Resistivity system	Soil thermal resistivity cannot be measured directly. Practically it has to be measured by the non-steady-state method, applying a known heating power and measuring the rate of temperature rise. This needs a measurement control system which can take the readings and perform the required calculations. For this application it also had to be possible to read the result out of the system automatically. Most of the available field test instruments were hand-held and only provided an on-screen display (no digital output) and so were not suitable for this project. The commercial system used was the only one on the market which could provide both the specified accuracy and the facility to operate autonomously without human intervention. Although primarily designed for lab use it was available as a portable system to be taken out into the field and record measurements before bringing the instrument back and downloading the data. This made it possible to construct a continuous measurement system as required for the project.
Phase Current	Measurements of the phase current had to be made without interrupting the protection CT wiring so as to avoid the requirement for outages and protection re-commissioning. This required use of low-current transducers clipped around the CT secondary windings in situ. The accuracy is impossible to determine without knowing the specification of the protection CTs, which has not been made available to us. It proved impractical to obtain clip-on CTs for 1A protection systems so 5A clip-on CTs had to be used with a resulting loss of precision.
Voltage and Phase Current	A standard 3-phase power meter with Modbus interface (intended for the sub-metering market) was used to make both voltage and current measurements. Using a power meter also allows power factor (and hence direction of current flow) to be determined if required.
Sheath Current	Measured directly using a split-core CT fed into another Modbus power meter.

Equipment	Comments
Ambient Temperature	An outdoor-rated air temperature shield, designed to give suitably accurate measurements without solar loading effects etc., was procured from a metrological instrument specialist. The transducer was a PRT100 sensor to be consistent with other sensors and the specified accuracy (thermocouples and thermistors are not accurate enough).
Solar Irradiance	Solar pyranometer with Modbus interface, intended for assessment of solar PV panel performance. The unit used does not meet the original specified accuracy figures but is the best performing sensor available at a reasonable cost. Low-cost sensors from the amateur weather market are both less accurate absolutely, and strongly directional so that the reading varies substantially with the Sun's position in the sky for a constant level of irradiance.

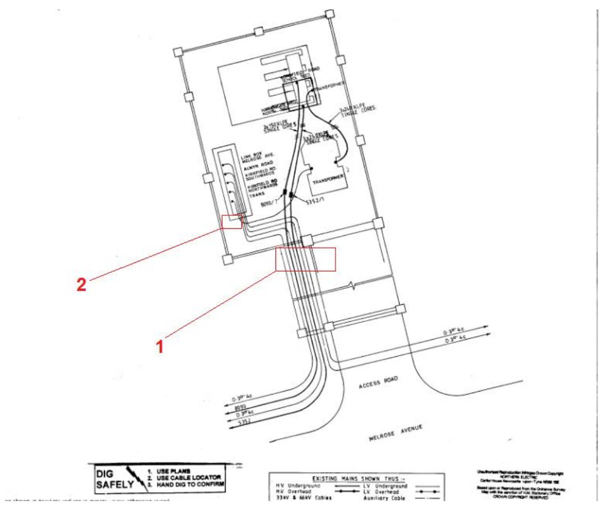
Appendix B: Underground Cable RTTR Monitoring System Installation

Use Case 1: Darlington Melrose LV UG cable RTTR

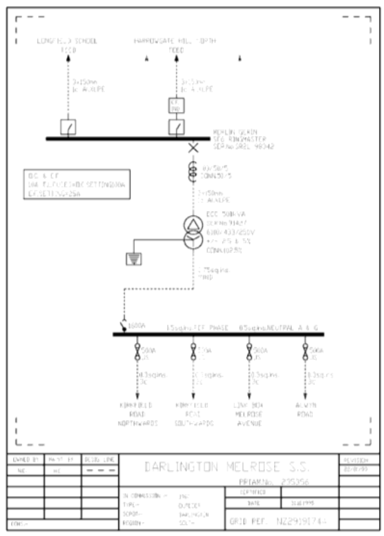
Darlington Melrose secondary substation is an outdoor pad-mount substation with an LV Board housed within a large steel pillar, and comprises a 500 kVA transformer with 4 exit feeders and an LV fuse cabinet.

The Melrose LV feeder was selected for this trial as it has an Electrical Energy Storage device connection downstream and an EAVC upstream. Therefore, measuring RTTR at this location meant that comparisons between various solutions could be made in different situations.

The following pictures are the working notes through the RTTR equipment installation processing.



Melrose substation site-layout



Melrose substation SLD

LV board and previous work had been carried out to provide LV feeder monitoring with equipment contained within a grey cabinet, shown in following pictures.

Nortech LV monitoring equipment (already installed) including Envoy for communications.

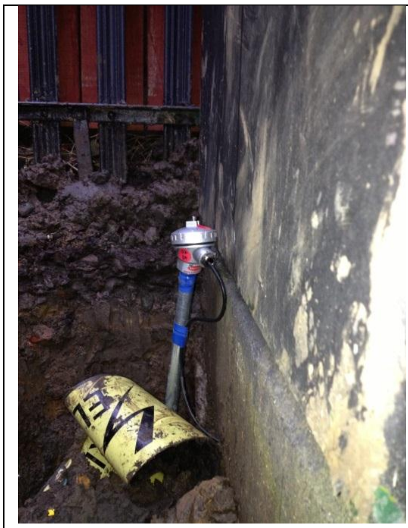
The existing pillar contained an LV board shown in pictures below. Alongside the LV board there was an empty section of LV board pillar which provided space for additional equipment.

 **LV board in the existing steel pillar**	 **Existing steel pillar with empty section used to house equipment**

The following pictures show the installation of an ADSL line and equipment required for safe communications i.e. firewall and VPN router.

 **ADSL installation box.**	 **VPN router inside.**

Following the installation of communications equipment, a temperature probe was buried alongside the existing LV pillar at the same depth to that of the outgoing feeder ways for which RTTRs were to be obtained shown in pictures below. The terminal end of the probe was left protruding from the ground to allow future access.

 **Ground temperature probe being buried and back-filled next to the LV pillar**	 **Finished back-fill next to the LV pillar**

All four substation cables were exposed in the excavated trench, an educated guess had to be made about the best positioning for the PT100 Resistance Thermometer (Soil Temperature Sensor, Close Proximity). Originally this was intended to be installed at an equidistance between the monitored cable and its closest neighbour. However, it was actually installed away from all other cables on the opposite side of the monitored cable. If these temperature measurements are crucial in determining UGC RTTR, it is suggested that installation instructions are produced, clearly defining installation locations including distances.

A temperature sensor was then fixed to the cable sheath using cable ties. The connections from the sensor were fed through black plastic conduit and into the spare chamber within the existing LV pillar. The pictures below show the site work process.

	
Installation of LV cable sheath sensor – conduit to protect sensor, sensor tip fixed to cable with cable tie.	**Excavation back-filled with sand.**

Cable engineers present during the installations were concerned about the potential for damage to the cable sheath when connecting temperature sensors and therefore cable ties were used as opposed to binding wire.

To protect the temperature sensor and provide a method of accessing the terminal end for future maintenance it was fed through solid electrical conduit, shown in the figure above left.

The hockey stick ducting was difficult to manoeuvre because of its rigidity. Plastic flexible ducting would provide a better solution. It was suggested that if there was a force on the external terminals, this could be transmitted along the buried length of the hockey stick ducting and could potentially cause damage to the cable. Once temperature sensors were in place the trench was backfilled using sand, shown in the figure above right.

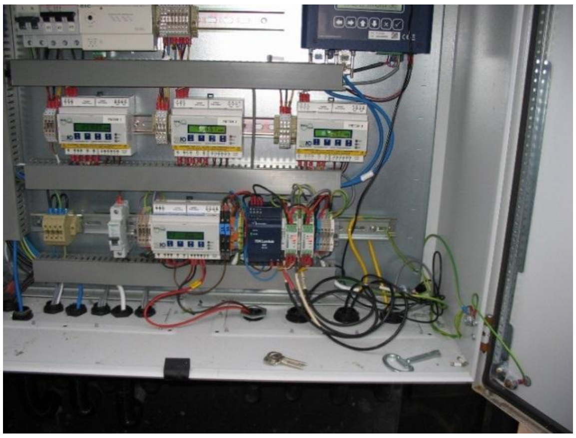
The soil thermal conductivity test set was then installed in an empty part of the LV Board pillar with an LV supply taken from an existing socket set, shown in figure below.

Soil Thermal Conductivity Test Set installed in empty part of LV Board pillar.

LV supply to Soil Thermal Test Set from socket in the LV Board Pillar.

The resistivity sensor was buried in a similar manner to the temperature probes, and connected to the test set.

The pictures below show additional meters required, and the air temperature and solar irradiance sensors were mounted to a bracket located above the monitoring equipment and on-top of the existing LV board pillar. Connections were fed directly into the cabinet housing the monitoring equipment.



Additional meters, PSU and ADCs installed in Nortech monitoring box.

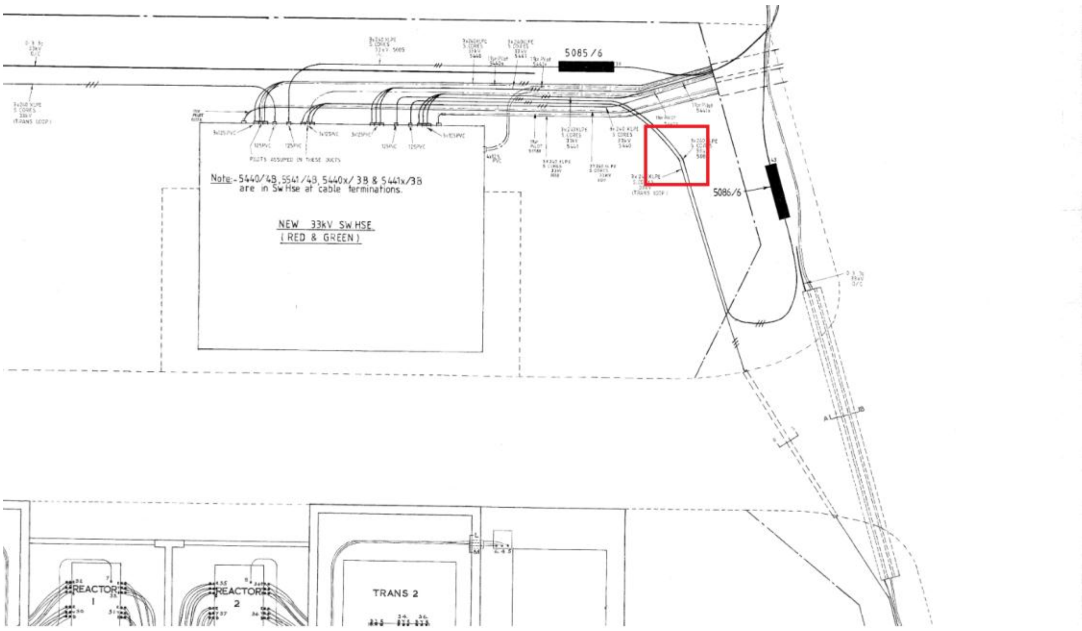
Air Temperature and Solar Irradiance sensors mounted on bracket on LV Board Pillar above the monitoring equipment box.

The work previously carried out by Nortech at the substation, discussed earlier, included the connection of Rogowski coils to individual phase currents (for LV substation monitoring). Using the three-phase currents, Nortech were able to infer a value for the neutral current which is available on iHost; however, additional split-core CTs were connected to the neutral cores of the outgoing feeder ways so that a direct measurement could be made and input into the RTTR model. Direct measurements were made to provide an increased accuracy; using inferred values may be inaccurate due to circulating currents. The measured neutral current could then be input into the RTTR model. The use of either split-core CTs or Rogowski coils is acceptable for current measurements as both devices meet the requirements reported within the specification document.

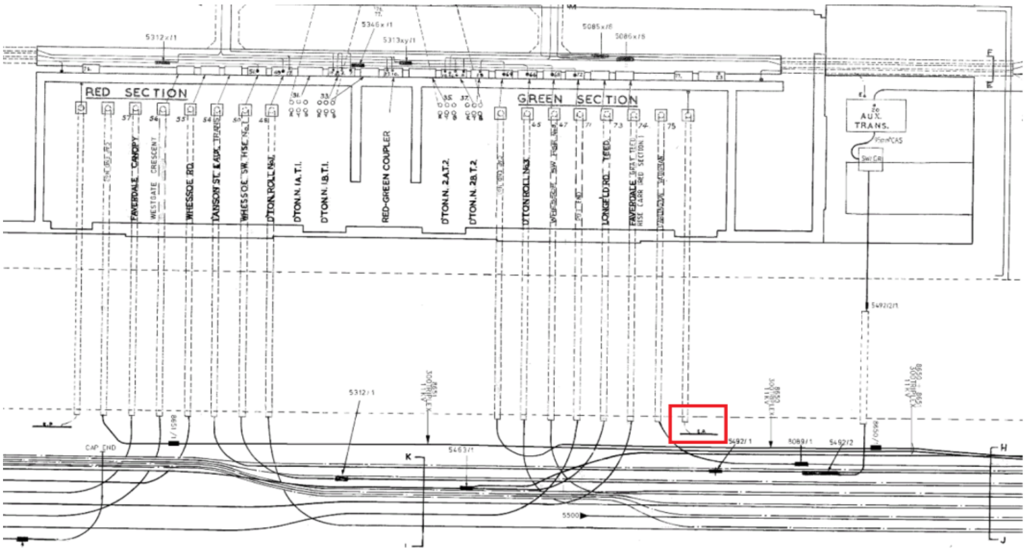
Use Case 2: Darlington Rise Carr, EHV & HV UGC RTTR

Darlington Rise Carr substation site consists of two buildings in a private compound with an access road. A 33 kV supply is brought into the smaller of the two buildings, seven 6 kV feeders being taken from the larger of the two buildings. One of the feeders from this bus bar is the HV "I" Anson Street Teed Auxiliary Transformer feeder, which takes a 6kV cable to a ring main of distribution substations as well as the Auxiliary Transformer, further stepping the voltage down from 6kV to a 230V LV mains supply. This HV feeder was selected as it was the heaviest loaded and therefore most stressed. There were three incoming 33kV cables. The cable being monitored was the EHV cable which was primarily used for supply at this substation.

The red boxes in the following pictures show the locations of excavation for the EHV cable and HV cable.



EHV excavation location at Darlington Rise Carr



HV excavation location at Darlington Rise Carr

EHV Cable

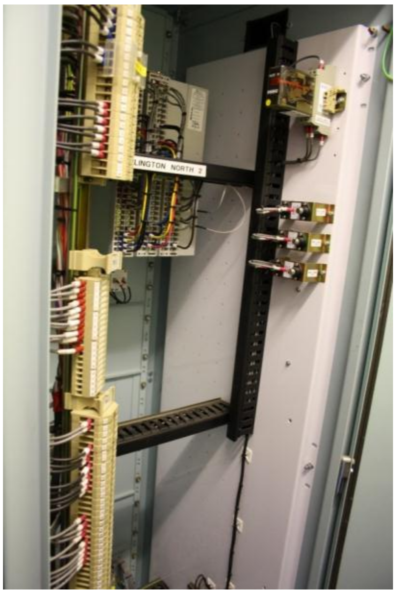
At the Rise Carr primary substation there was a modern brick-built indoor 33 kV substation. An RTTR system was installed to the “Darlington North 2” feeder, shown figure above. The local communications were run under the roadway to the Darlington Rise Carr HV substation, where an Envoy was installed and was used to provide the backhaul for the measured data to the calculation engine server.

	
Brick-built indoor 33 kV substation	**Switchgear showing Darlington North 2 feeder way**

The cable sheath of the EHV cables was found to be inaccessible, shown in Figure below. Cable sheath current measurements were therefore unattainable.

Cables location – sheaths are not accessible here

Current measurements were taken using clip-on CTs fitted around the protection CT wiring within the control cubicle with an EHV Line Meter located at the top of the control cubicle, shown in the figures below.

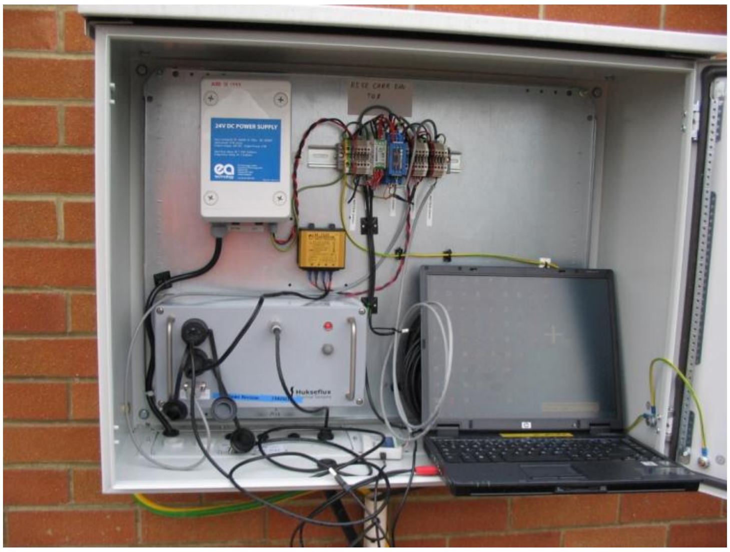


Inside control cubicle

Inside control cubicle

Due to the lack of room within the existing EHV substation, a cabinet was wall mounted on the external wall of the substation. Cables were run to the cable temperature sensors and the Soil Thermal Conductivity Probe. The power supply and connections to local communications were made via a hole made within the wall of the substation building, shown in figures below.

	
EHV Main Panel installed on outside wall of substation.	**Cables run down to cable temperature sensors and Soil Thermal Conductivity Probe, and through wall for power and communications.**



Within the EHV Main Panel were a PSU, ADCs and Soil Thermal Conductivity Test Set. The laptop was used for commissioning.

Once the EHV main panel had been installed connections between the panel and temperature sensors (connected to the EHV cable) were made via a trench, shown in figure below.

Trench and duct from the EHV Main Panel to where the cable is.

Sensors were fed through flexible plastic conduit, making the installation easier when compared with that for LV.

Sensors installed on cable and in backfill to measure surrounding temperature.

In order to avoid the risk subsequent cable faults in the HV and EHV cables being subjected to RTTR, off-line Partial Discharge testing of the cable sections being monitored was carried out via a Very Low Frequency test system to detect any pre-existing problems with the cables (especially joints and terminations) whilst the cable was accessible. It is recommended that for BaU, cable PD testing (on-line or off-line) is carried out to determine the condition of the cable.

 **Earth Rod box houses the temperature sensor heads.**	 **The terminal ends of the temperature sensors were installed within earth rod boxes level with the ground surface, allowing the temperature sensor heads to be accessed in future and ensuring heads were out of the way for on-going ground works and site maintenance.**

Soil Thermal conductivity probe installed below EHV Main Panel in trench. The probe for the soil conductivity sensor was short and therefore had to be installed into the ground directly beneath the EHV Main Panel.

HV Cable

At HV there is a brick-built indoor substation with two sections of bus bar each in a separate room with a coupler between and oil-filled switchgear. The neutral sheath of the cable is exposed and connected to the substation earthing system. This allows measurements of the cable sheath current to be directly measured, unlike at EHV, where the sheath was inaccessible.

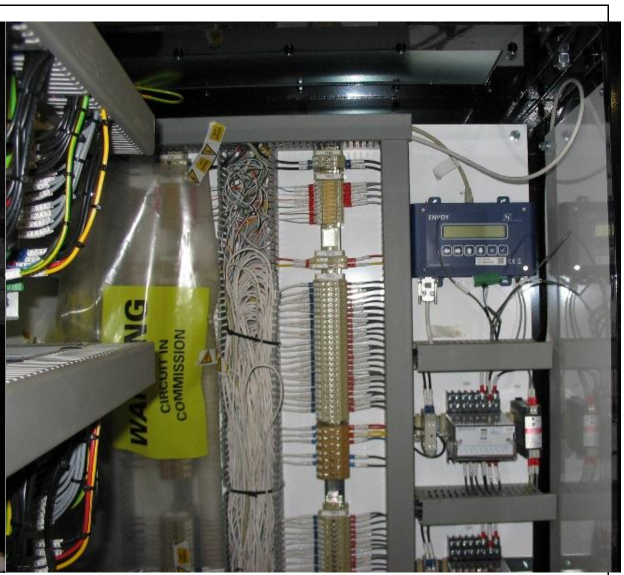
Protection Relays (in room behind HV switchgear), through ducts.

Oil-filled switchgear.

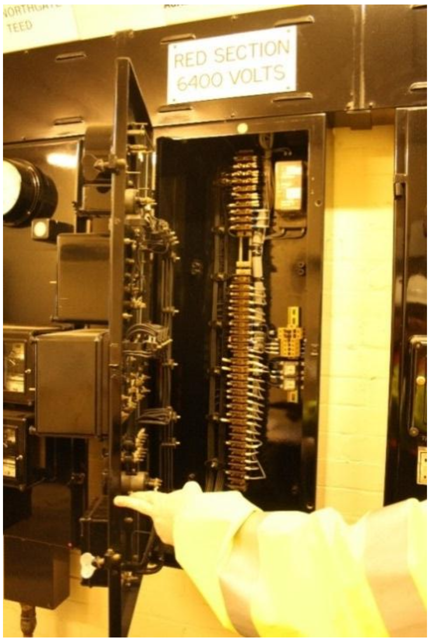
Concrete roadway

Cable-end from HV switchgear showing exposed armour connected to substation earth system.

At Rise Carr additional solutions were under trial, including an Enhanced Automatic Voltage Control (EAVC) system. A modern relay was installed as part of the EAVC trial and housed within a new EAVC panel shown in figure below left. This incorporated a Remote Terminal Unit (RTU), the Envoy unit referred to previously, shown in figure below right, where data would be collected for onward transmission to central systems.

	
EAVC panel	**Inside of EAVC panel showing blue Envoy unit (RTU)**

	
Old workshop with space for "HV Main Panel"	**Space on wall under control panel for additional monitoring equipment**

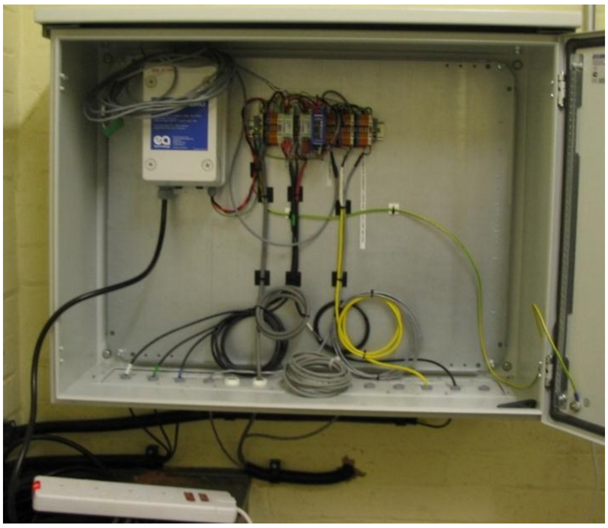


l'Anson Street control panel opened, showing protection CT wiring

Line metering and cable sheath metering, located under l'Anson control panel

The loss of mains protection panel, shown in figure below left, was used to provide a VT signal to the "HV Line Meter" so that the system voltage could be measured.

Loss of Mains protection panel



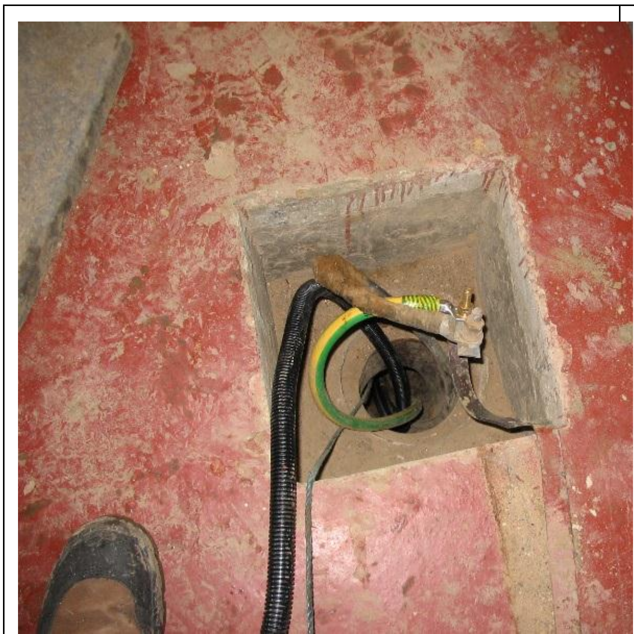
HV Main Panel

The "HV Main Panel" was wall-mounted within the old workshop. The panel, or cabinet, was used to house the PSU, ADCs etc., shown in the figure above right.

The weather station i.e. pyranometer and ambient temperature sensor, were mounted to the roof of the compound outside of the building and connections were made through an existing ventilation panel.

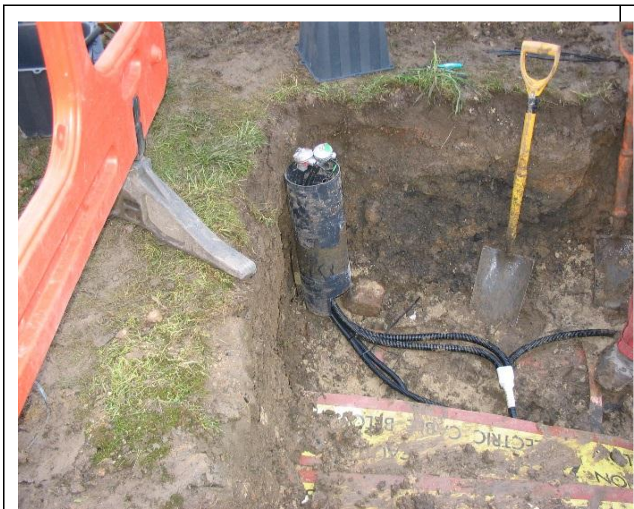
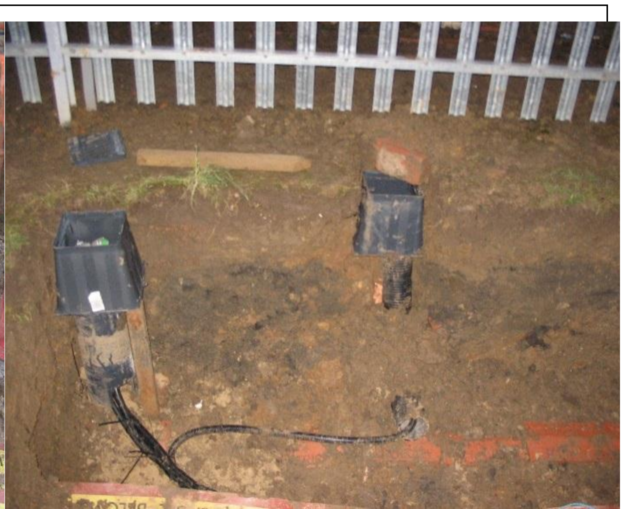
	
Weather station shown on roof of compound with connection made to HV Main Panel through existing ventilation panel	**Weather station**

The cable temperature sensors were run through existing cable ducting, shown in the figure below left, which had been used to run the substation earth line through. The ducting protruded from the roadway on the side farthest from the substation, enabling the sensors to reach the cable reserve, shown in the figure below right.

	
Existing ducting containing Earth line	**Cable reserve**

	
Tone tracer used to identify correct cable	**Cable ties used to attach temperature sensors to cable**

Once the cable had been confirmed, temperature sensors were attached to cables using cable ties shown in the figure above right. Additional sensors were inserted into the medium surrounding the cable and the sensor heads were brought out of the pit until level with ground. Earth box rods were used to house sensor heads prior to running the cable into the substation through plastic flexible conduit and through the existing ducting; this was said to be advantageous as if metal hockey stick ducting was used as in the LV installation, vehicular access (as in the previous figures of this section) may damage the cable sheath or hockey stick ducting.

	
Sensor heads housed in earth rod boxes, level with ground.	**The pit was then backfilled using the excavated material, shown in figure below left.**

Vehicle driven over backfilled trench prior to commissioning of equipment

Appendix C: Overhead Lines RTTR Procurement and Specification Development Notes

The design specification outlined a number of components required for use in an OHL RTTR system. Northern Powergrid selected a prototype system produced by the manufacturers FMC-Tech, a company who, at a later stage in the project were acquired by General Electric (GE).

The constituent components outlined in Table below were procured for each trial location within the project (or nodes).

Equipment	Manufacturers	Model	Comments
On-line measurement device	FMC-Tech	X-NET Node	Line mounted Current and Conductor temperature measuring Sensor (3 or 6)
Local Controller	FMC-Tech	SNG (Sensor Network Gateway) 1	
Power Source	FMC-Tech		30W Solar panel and regulator
Weather Measurement Device	FMC-Tech	Davis Vantage Pro II Weather Station	Third party commercial weather station, integrated by FMC-Tech
Calculation Engine Software	FMC-Tech	X-NET Software Application 1	
Calculation Engine Software (For Faults)	FMC-Tech	T-NET Software Application	

Equipment Procured

The original equipment procurement specification document has been updated into a BaU equipment specification, using the experience gained throughout the procurement stage and installations stages. The following are the key changes to the original equipment procurement specification:

RECOMMENDATION TO PURCHASE Recommendation to purchase , Section 3.1

> **Text extract 1**
> *"All external equipment shall be environmentally tested to IP55 and all internal equipment to IP52 in accordance with BSEN 60529"*

The specification indicates that all external equipment shall be environmentally protected to IP55. To obtain an Ingress Protection rating of 55, devices must be protected against harmful deposits of dust (the first digit) and from low-pressure jets of water from all directions (the second digit). This will allow the devices to be protected outdoors whilst subject to the range of weather conditions experienced in the UK. Internal equipment must be protected to IP52. This is suitable for deployment in a typical substation environment, where the building offers protection from rainfall, but conditions are likely to be dusty, especially if work is being carried out in the building.

RECOMMENDATION TO PURCHASE , Section 3.1, General, On-line Measurement Device

Text extract 2

"The device shall have a backup battery, rechargeable from the line, and capable of providing no less than 48 hours backup power".

The device is a power scavenger, powered from the line to which it is attached. For this reason, the device requires an Uninterruptible Power Supply to provide ride-through if there is a power outage or period of low load through the cable. A requirement for a minimum of 48 hours has been specified to coincide with the present performance of the prototype device that has been installed as part of the project.

In practice this scheme, has worked well despite line loadings well below the rated capacity, and no problems have been encountered with lack of power to On-Line Measurement Devices. Other systems previously trialled, using (line-mounted) solar power, have failed during short, dark, winter days when the input power was insufficient to keep the batteries charged up. This is not expected to be a problem for line-scavenged designs, provided that there is sufficient load current to provide power. This is likely to be the case for circuits being considered for RTTR!

Text extract 3

"The device shall have sufficient on-board non-volatile storage for at least 40 minutes of readings at the maximum operating rate."

In case of communications failure between the on-line measurement and local controller the device requires non-volatile memory so that data is not lost. A requirement for a minimum of 40 minutes worth of readings has been specified to coincide with the present performance of the prototype device that has been installed as part of the project.

RECOMMENDATION TO PURCHASE , Section 3.1, General, Weather Measurement Device

Text extract 4

"The preferred distance from the pole shall be 10 pole diameters."

RECOMMENDATION TO PURCHASE , Section 3.1, General, Local Controller

"The local controller shall have a backup battery, rechargeable from local renewable sources, and capable of providing no less than 48 hours of backup power."

The Local Controller is powered from local renewable sources (a solar panel in the prototype system) to avoid the costs of installing a transformer or other supply connection to the distribution network. By their nature, these renewable sources are intermittent and do not provide continuous power.

For this reason, the local controller requires a battery backup to provide continuous operation when the renewable power source is not available. A requirement for a minimum of 48 hours has been specified to coincide with the specification of the prototype device that has been installed as part of the project.

If the field trials indicate that 48 hours battery capacity is not adequate to ensure continuous operation of the Local Controller then it may be necessary to increase this specification.

> **Text extract 5**
> *"The time to fully charge the battery shall be no more than 8 hours."*

In operational terms, the time taken for the local renewable sources to charge the battery is as important as the time the battery can sustain the system, as if it is excessive then the battery will never reach full charge and the specified backup time will not be achieved. The value of 8 hours is chosen with solar power in mind to ensure that the battery will be fully charged by one day's worth of daylight.

RECOMMENDATION TO PURCHASE , Section 3.3, Table 1: Device technical specifications

Weather-Measurement device

It is reported in CIGRE Brochure 299 (5), "the maintenance of weather measurement devices should be carried out periodically according to the maintenance intervals and methods recommended by manufacturers." "More sensitive equipment is desirable, but may lead to more frequent and expensive maintenance." The choice of anemometer technology will have a substantial effect upon the maintenance required, which normally determines the maintenance requirements of the Weather-Measurement device.

The OHL RTTR systems installed on the CLNR project utilised Cup anemometers and moving vane direction indicators. The alternative to these mechanical instruments is to employ an ultrasonic anemometer, which uses changes in the velocity of sound to determine the (vector) velocity of the wind flow.

Cup type instruments have the longest history, and remain the lowest cost means of measuring wind speed. However, because of the multiple moving parts, periodic maintenance will be required, once per year. Cup anemometers also have a specified cut-in speed, i.e. wind speed below which they will not start to revolve and so no data will be returned. This is typically around 1 ms^{-1}, which is important to the lowest wind conditions when conductor temperatures are highest. EA Technology's experience is that under icing conditions, cup anemometers easily become frozen up and cease to revolve, although this is unlikely to affect RTTR schemes due to the low temperatures required for ice to accrete!

Ultrasonic anemometers are more expensive initially, but, because they do not require any moving parts, are maintenance free. They have a cut-in speed of essentially zero, and respond much more rapidly to changing air flow because there is no moving part inertia to slow the response down. They are largely (although not completely) immune to icing problems in cold conditions.

Both cup and ultrasonic anemometers have successfully been used for Overhead Line rating studies in the past, so the choice will depend on the required precision, and the trade-off between initial costs and on-going maintenance requirements.

The maintenance schedule of on-line measurement devices and local controllers is specified to be no less than 3 years. Originally, this period was chosen to coincide with the duration of the CLNR project however, with a Business-as-Usual (BaU) a similar period is required. The reason for this is that both devices contain back-up batteries so as to ensure continual operation, especially at periods of minimal lighting for the local controller which relies upon solar power. These batteries will require replacing due to degradation as they are charged and discharged; for this reason 3 years was deemed as a sensible minimum maintenance interval. Attempting to extend this would be likely to run into problems with intermittent operation as batteries progressively age and hold less charge.

Lifetime of equipment

The lifetime of devices is specified to be no less than 10 years. This is a compromise between the expected lifetime of modern electronic equipment and the operational requirement for robust, reliable equipment. Whilst a longer lifetime for the equipment could be specified, to do so would considerably increase the capital cost, and it is unclear whether there is a sound business case for this.

The cost increase of a long lifetime system will only be justified if the equipment is to remain in service for substantially more than 10 years. Because of the ongoing load growth on the network, it is questionable whether an OHL RTTR system will permit enough capacity uplift to accommodate more than 10 years' worth of load growth on a circuit. Once reinforcement of the RTTR circuit is undertaken, then the RTTR system is no longer required. This does not mean that RTTR is not worth doing – by deferring the reinforcement by (say) 10 years, a considerable Net Present Value gain can be made, which is offset against the cost of the RTTR scheme.

Weight of equipment

The maximum weight for both weather measurement devices and local controllers should be 25kg. This coincides with the maximum weight allowance for safe, manual-handling of devices. Upon reviewing the typical weight of similar devices, this specified weight should be easily attainable.

The maximum weight specified for an on-line measurement device is 8kg to minimize the increase in tension on conductors. Again, when reviewing the weight of similar devices, this specified weight should be easily attainable.

Sampling rate

The sampling rate of devices should be less than the smallest time constant within the thermal models used to calculate the RTTR. Within the models, the thermal time constant is the time-dependent step change of the heat of Overhead Lines and is around 10 minutes for the Overhead Line conductors on the distribution network. For this reason, a sampling period of 5 minutes is considered suitable as it is less than the likely thermal time constant of distribution line and practically achievable in terms of power requirements and typically available bandwidth in remote locations.

Impact resistance

A 2 joule impact resistance (or IK07) is specified for equipment to ensure a high level of robustness as stated in European standard EN 62262. This is the ability of a material to absorb energy and plastically deform without fracturing.

Operating temperature

The maximum operating temperature for an on-line measurement device is specified as 80°C, to ensure operation even under extraordinary (fault) conditions. Distribution lines will have design temperatures of 50, 65 or 75 degrees Celsius – even if real time ratings are used to permit excursions to these temperatures where ground clearance would not be compromised, temperatures approaching 80 degrees would represent the absolute extreme as beyond these irreversible annealing of aluminium conductors would occur. To contain the risk of damage, it is unlikely that DNOs would allow temperatures any higher than 80 degrees. Furthermore, the value coincides with the maximum operating temperature of the installed prototype.

RECOMMENDATION TO PURCHASE , Section 3.3, Table 3: Device technical specifications

Minimum operating line current

For equipment operated by scavenging power from the load on the Overhead Line (in this case the on-line measurement devices) it is important that sufficient power is scavenged to keep the equipment operating reliably. What level of current is available will depend on the size and loading of the Overhead Line – a large-section tower line will have much more current available than a thin-section wood pole circuit. Hence a specification relative to the full scale measurement current of the device is sensible so that the minimum operating current reflects the varying sizes of lines on which it may be deployed. The specified performance of 5% is based upon the advertised capabilities of the installed prototype.

Full Scale Current

The full scale current specification of the sensor will also need to be chosen to suit the current carrying ability of the Overhead Line to which the system is being fitted. The rating required must be not just large enough to measure the existing (probabilistic) rated current of the line, but also the increased ampacity made possible by the RTTR system. The exact requirement thus depends on the capacity uplift achieved and is not well defined. Specifying a sensor with too small a full scale current will artificially constrain the operational ampacity gain (the ampacity cannot exceed the measureable current), whilst too large a value degrades the accuracy of measurements at normal currents. The specified scale of 50% above the P27 rating of the line is a compromise based on reported ratings improvements from other RTTR projects.

This is an area where there is still active research going on, and it may be necessary to review this conclusion in the light of the findings of the project to revise ER P27 (SN0004 "Improved statistical ratings for distribution overhead lines").

Absorptivity and emissivity of conductor

The absorptivity is only relevant to cases where solar or other radiant heat affects the conductor. Having shown (above) that solar radiation is not a significant factor in limiting conductor ratings, we do not need to be concerned with absorptivity. The emissivity of the conductors is important to the determination of radiative cooling, but this is a small part of the total cooling under normal conditions, so the error introduced by using a fixed emissivity value is not large.

It is not generally practical to make field measurements of conductor absorptivity or emissivity, and so fixed values must be used. The choice is then between using a one-off measurement at installation time, and using pre-determined default value. Although the absorptivity and emissivity of a conductor are affected by the conductor's age (new Aluminium conductors have absorptivity of the order of 0.2 to 0.3, after a few years' service this approaches 0.9 (CIGRE)), this does not seem to vary greatly between sites.

Given these considerations it is considered reasonable to use default fixed values for emissivity and absorptivity in OHL RTTR applications.

RECOMMENDATION TO PURCHASE , Section 3.4, Table 4: Site Dependent Parameters

To determine the OHL RTTR also requires some site dependent static parameters to be determined upon installation. The parameters in Table 4 are required as parameters within thermal model(s) to calculate RTTR:-

The above site variable parameters are required to calculate conductor temperature, and thence the sag and the minimum clearance (smallest distance between conductor and ground). The first two parameters are used as a method of calibrating the model to the specific span and its installed conductor tension, and should be measured at the same time (or within a couple of minutes of one another). For efficiency, this pair of values should be measured during the installation of devices.

RECOMMENDATION TO PURCHASE , Section 3.4.1, RTTR Model Outputs

With BaU, DNOs primary focus will be on the ampacity (spare capacity) and the minimum electrical clearance of the conductor. Conductor Temperature can be used for model failure mitigation. Health indicators are required for knowledge that the RTTR is operating correctly so that the control system does not take inappropriate actions based on incorrect information.

All outputs require a time stamp so that they can be appropriately interpreted and stored. All these time stamps are to be in Universal Co-ordinated Time (UTC). UTC is the international standard time reference of the Internet, with no changes for local time variations (e.g. British Summer Time). This is strongly preferred for the internal operation of systems because it is unambiguous (unlike local time, where there will be 'duplicate' and 'missing' hours at each time change) and easy for computer systems to manipulate reliably. An unambiguous conversion to local time can be made via standard operating system routines for user interaction if required.

Appendix D: Overhead Lines RTTR Installation

Within the CLNR project, installations were to be made to EHV (e.g. 66kV or 33kV) and HV (e.g. 20kV, 11kV or 6kV) Overhead Lines. OHL RTTR systems were installed in “White house”, “Broxfield”, “Broomhouse”, “Scar Brae” and “Grange Wood”. All of these sites are in Denwick in the North East of England in the project’s rural network test cell.

Installations across varying locations were similar with the main differences being between pole mounted and tower mounted systems. For this reason, the next sections discuss installations that are either pole or tower mounted as opposed to at each individual site.

To see a video of the installation use the QR code or select the link underneath.

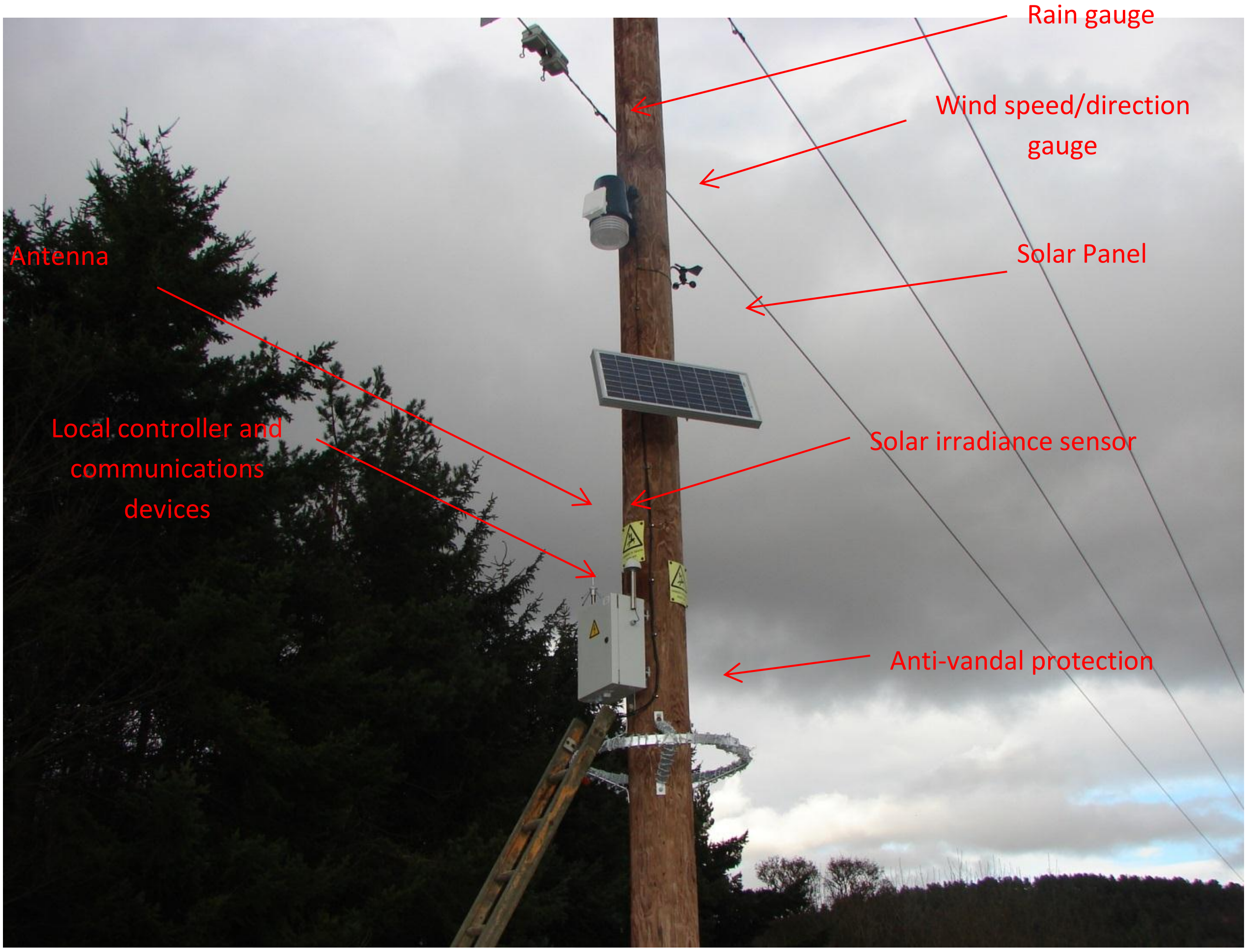
Installation Video http://www.youtube.com/watch?v=6oJUvlamwcw

Use Case 1: Pole Mounted Overhead Line Real-time Thermal Rating systems

The OHL RTTR system consists of:

- A padlocked cabinet (10mm diameter hasp), housing the local controller equipment and communications devices with an external antenna to boost the signal.
- A solar panel (and backup battery) powering the equipment within the cabinet.
- A weather station; wind-speed and direction sensor, rain gauge and a solar radiation sensor.

Inspections were carried out on the poles to ensure that they were structurally sound before attaching any new equipment to them. A barb wire anti-vandal device was attached to ensure equipment could not be tampered with in the future. The solar panel, weather sensors and local controller cabinet were then mounted to the pole using brackets, shown in figure below.



Constituent components

The local controller cabinet was installed at the lowest point, to allow access to the local controller for calibration and future maintenance. An insulated bucket (cherry picker) was used to install the equipment, shown in figure below.

Cherry-picker with insulated bucket

Once equipment was mounted to brackets attached to the poles, the online sensors were connected to each of the conductors. To do this all the conductors were shrouded to provide insulation and ensure accidental phase-to-phase contact could not be made when installing sensors, shown in figure below.

Shrouding two of the conductors whilst working on furthest to ensure no phase-phase contact

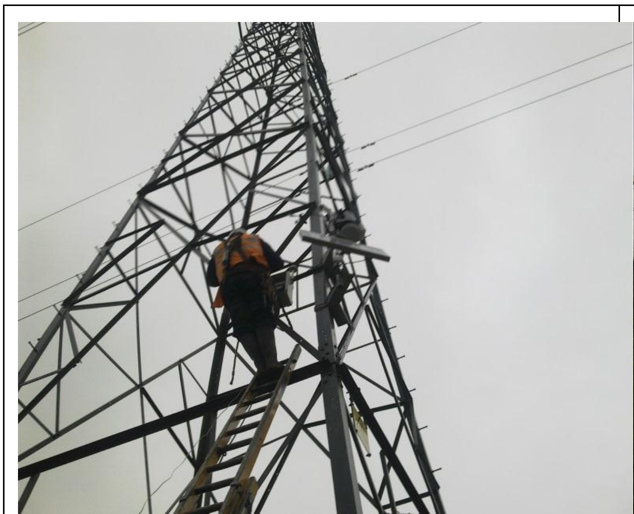
Installation on lines at up to 20kV was carried out by live line working ('Hot Glove') engineers. Connecting sensors was simple, requiring the sensor to be positioned on the conductor before tightening bolts were screwed into place. See pictures below.

Connection of an online sensor, (b) an online sensor

It is suggested that if OHL RTTR becomes BaU, procurement preference is given to sensors which can be attached to conductors using "hot-stick" methods; removing the need for cherry pickers, and requiring less manpower, reducing costs.

Use Case 2: Tower Mounted Overhead Line Real-time Thermal Rating system

The same equipment was installed to EHV Overhead Lines supported by tower structures however, different procedures were adopted. For these installations, an outage of the line was required. For tower structures cherry pickers were not used. Installation engineers used ladders to get to a position above ground where vandalism would be less likely, and, using safety harnesses for protection, installed the local controller, weather station and solar panel brackets and devices (figure below left).

	
Installing local controller, weather station and photovoltaic panel	**Winching equipment to installation engineers on the tower**

To install sensors to the OHLs, two installation engineers climbed the tower until they were above the conductors. A ladder was then connected to ropes and winched to the installation engineers, shown in figure above right. The ladder was connected to a beam on the tower, allowing one of the engineers to climb down and get closer to the conductor, whilst the other ensured his safety.

Installing on-line sensors using ladders from the cross-arm

For enquires about the project

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