SP ENERGY NETWORKS

Flexible Networks
for a Low Carbon Future

Methodology & Learning Report

Work package 2.1: Dynamic thermal rating of assets – Primary Transformers

May 2015

LCN Fund
Low Carbon Networks

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Contents

Contents [continued]

Contents [continued]

Executive Summary

Background

Through previous projects, SP Energy Networks (SPEN) developed a real-time thermal rating (RTTR) system in their network in North Wales, with the aim of releasing network capacity for additional wind generation and providing visibility of the thermal state of the network:

In the previous project, funded through the LCN Fund Tier 1 mechanism, SPEN partnered with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to implement the North Wales RTTR system to cover over 90 km of 132 kV network.

From a year of monitoring, ending on 23rd September 2013, it was demonstrated that a significant network carrying capacity can be unlocked by deploying RTTR system. RTTRs of the North Wales circuits within the network were calculated and average uplifts of 1.24 to 1.55 times the static summer rating were found.

Under this project, as part of work package 2.1 of "Flexible Networks for a Low Carbon Future", we have investigated solutions to increase network capacity, required to connect and manage increasing levels of demand. One of these solutions trialled in this project was deploying RTTR system for 33kV overhead line networks in Scotland. The site selected for trialling RTTR system was the two Cupar – St Andrews 33kV circuits which will require network upgrade in new future due to load growth in St Andrews area.

This reports presents the work carried out and outcomes of implementation of RTTR system on the Cupar – St Andrews circuits.

Aims and objectives

The key aims and objects of this project were as follows:

- Create headroom of up to 7% in Cupar – St Andrews 33kV circuits that defers further network investment;
- Install weather monitoring to investigate how asset rating can be optimised by considering real-time environmental conditions;
- Develop advanced thermal management system in parallel to the monitoring with consideration of appropriate thermal modelling tools.

RTTR system enhancement

Although the RTTR system has been successfully trialled in SPEN's North Wales 132 kV network during previous projects, the Cupar – St Andrews RTTR system builds on and goes beyond the previous project by featuring the following enhancements:

- Deployment of line sensors to directly measure the temperature of the conductors;
- Development of a conductor temperature estimation algorithm based on meteorological measurements, rather than only estimating thermal capacity;
- Validation of the RTTR model through comparison between calculated and monitored conductor temperatures;
- Enhancement of the accuracy and reliability of RTTR by increasing the number of weather stations;
- Development and implementation of a graceful degradation algorithm in SPEN's Network Management System (NMS), allowing the system to be robust in the face of missing measurement data;

Outcomes

The key outcomes of the work package are as follows:

- Four weather stations were installed along the Cupar – St Andrews 33 kV circuits at different locations. Five overhead line sensors, four of which co-located with weather stations and monitor temperature and current of conductors, were installed.
- The real-time monitored data were transmitted to the RTTR calculation module hosted in a stand-alone PowerOn Fusion server. The RTTR values and all monitored data are available through a dashboard specifically designed for the Cupar – St Andrews circuits within the PowerOn Fusion NMS.
- A graceful degradation methodology was developed and implemented in RTTR system to ensure the estimated RTTRs are within an acceptable degree of accuracy when transmission of real-time monitored weather parameters to the RTTR module is interrupted.
- A methodology for estimating temperature of overhead line conductors was developed and validated against monitored conductor temperatures at four locations along the Cupar – St Andrews circuits
- The calculated RTTR values for a year period starting from 25th April 2014 showed that the average thermal rating uplift by deploying RTTR system is around 11% when compared to the respective seasonal thermal rating.

Learning derived from the methods used

- For a weather-based RTTR system, it is important to identify micro-climate regions along an overhead line as it is more likely that network thermal pinch points are in these regions. This was demonstrated in this report by a comparison study between RTTR calculations using one weather station and multi weather station monitoring micro-climate regions, see section 4.8 for more details.
- The outcomes of this trial show that using a weather-based thermal state estimation technique can provide RTTRs with an acceptable level of accuracy. However, the confidence in the RTTR system would be enhanced by deploying a limited number of line temperature sensors at wind shielded locations. The purpose of using line sensors can be firstly for initial validation of the thermal state estimation algorithm and secondly for operating as an independent check and alarm system in long term operation.
- The effect of solar radiation can be significant on the RTTR values especially during summer period when high solar radiation is experienced. Engineering Recommendation (ER) P27 suggests a solar radiation of 0 W/m2 and ambient temperature of 20°C for thermal rating calculation during summer period. Our data analysis showed that there are occasions when solar radiation and ambient temperature are higher than those in ER P27, and therefore the RTTRs are actually lower than static rating. If these conditions coincide with sustained high load on the overhead lines it could overheat and damage the assets.
- It is recommended to conduct a fresh review on the assumptions made in ER P27 considering the lessons learnt from this project and other LCNF projects. Industry would benefit from an ENA working group to share the knowledge on RTTR and develop and update ERs and technical guidance required for Distribution Network Operators (DNOs) and Transmission Operations (TOs).
- The power supply for the pole-mounted RTU and measurement equipment should be calculated for the worst case scenarios and consider the winter period where the daylight is short. In wooded area or areas surrounded by hills the total solar gain may be not enough to maintain the supply for RTTR equipment by only using solar panels.

Learning derived from the methods used [continued]

- Interference in radio communication between the FMCT-6 line sensors and RTU distorted the monitored conductor temperature data. The interference was the due to electric field of the overhead line. Although these line sensors were tested in a laboratory environment for a high current condition, the test voltage was not as high as 33kV and therefore the radio interface due to magnetic and electric fields created in the laboratory was different from the interference level on site around 33kV conductor. This issue was resolved by updating the digital filter firmware in line sensors. The process was carried out remotely and without the need to dismount the sensors. The lesson learnt from this issue was that testing equipment in a laboratory environment should be similar to the site conditions e.g. voltage level and loading.
- The RTTR system relies heavily on the real-time weather data monitored at different locations of the network. Any interruption in the data transmission process, from monitoring equipment to RTTR calculation engine, affects the reliability of RTTR system. In order to enhance the reliability of RTTR system against data transmission interruption the following measures were implemented: i) the number of weather stations was increased, so that a weather station was installed every 5 km; ii) a graceful degradation algorithm was deployed to conservatively estimate missing data and gracefully degrade RTTR values towards seasonal ratings when increasing amounts of weather data was missing. The details of graceful degradation algorithm are given in section 3.8.
- Based on the results of this trial, we are concerned that surface mounted conductor temperature sensors may not accurately measure the actual conductor temperature due to impact of surrounding weather conditions on the sensor, see section 4.9. We recommend that further studies and laboratory tests need to be carried out to provide guidance and recommendations for appropriate method of attachment and sensor specifications.

Further development

In order to fully adopt any of the above RTTR system applications in business as usual, the following developments have been identified:

RTTR forecasting implementation: RTTR forecasting is an essential feature for full adoption of RTTR systems. A forecasting methodology should be added to the RTTR calculation process to boost the confidence on any planning decisions that are made based on RTTR.

Implementing conductor temperature estimation methodology: Real-time conductor temperature estimation and comparison with the monitored conductor temperature can be an additional feature of an RTTR system to indicate, in real-time, the accuracy of RTTR values.

Updating policy documents: The existing technical manuals and policy documents need to be updated to incorporate the application of RTTR in generation connection offers, network planning and operations codes of practice.

Establish interface between RTTR system and active network management (ANM) system: There are significant potential benefits in deploying an RTTR system within an ANM scheme for controlling outputs of the generators. SPEN have has already trialled an ANM system for controlling generators' outputs, through the "Accelerating Renewable Connections" (ARC) LCN Fund project. SPEN has held a workshop with ARC and RTTR project partners to explore the way forward for integrating RTTR system within ANM system.

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[1] TNEI supporting document 8279-33-01-AVR Location Summary

1 Introduction

SP Energy Networks (SPEN) has trialled the implementation of real-time thermal rating (RTTR) system on the two 33 kV Cupar – St Andrews circuits as part of the "Flexible Networks for a Low Carbon Future" project, which is funded through Tier 2 of the Low Carbon Network (LCN) Fund mechanism. An RTTR system has been successfully trialled in SPEN's North Wales 132 kV network during previous projects; however, the Cupar – St Andrews RTTR system builds on and goes beyond the previous projects by featuring the following enhancements:

- Deployment of line sensors to directly measure the temperature of the conductors
- Development of a conductor temperature estimation algorithm based on meteorological measurements, rather than only estimating thermal capacity
- Validation of the RTTR model through comparison between calculated and monitored conductor temperatures
- Enhancement of the accuracy and reliability of RTTR by increasing the number of weather stations
- Development and implementation of a graceful degradation algorithm in SPEN's Network Management System (NMS), allowing the system to be robust in the face of missing measurement data

This report presents the work carried out for the implementation of the Cupar – St Andrews RTTR system and provides a summary of outcomes and lesson learnt from this project.

2 Background

Through two previous projects, SPEN developed an RTTR system in their network in North Wales, with the aim of releasing network capacity for additional wind generation and providing visibility of the thermal state of the network.

The first project, funded by the Innovation Funding Incentive (IFI) and Technology Strategy Board (TSB), researched, developed and installed an RTTR system on 7 km of 132 kV distribution network. Additionally, an active thermal controller system (combining RTTRs with a distributed generation (DG) output control system) was also developed, prototyped and validated. Data from a field trial of the RTTR system was collected and analysed before the project came to a close in March 2010. SPEN partnered with University of Durham, AREVA T&D, Imass and Parsons Brinckerhoff for the project, and this consortium received the Institution of Engineering and Technology (IET) Innovation Award in the Power / Energy Category in 2010.

For the second project, funded through the LCN Fund Tier 1 mechanism, SPEN partnered with Parsons Brinckerhoff, GE Energy, Nortech Management Ltd and Skye Instruments to build on the IFI/TSB project and extend the implementation of the North Wales RTTR system to cover over 90 km of 132 kV network. The RTTR system comprised a meshed network of 10 weather stations that, together with a detailed geographical model and thermal state estimation algorithm, allowed the thermal ratings of 8 overhead lines to be calculated in real-time. The system was integrated into SPEN's Network Management System (NMS) to give complete thermal visibility of the North Wales 132 kV network from Connah's Quay to Pentir.

From a year of monitoring, ending on 23rd September 2013, the RTTRs of the circuits within the trial network were calculated and average uplifts of 1.24 to 1.55 times the static summer rating were found. This additional capacity translates into a potential increase in average annual energy yield of 10% to 44% for the circuits considered.

Although the North Wales project successfully implemented an area-wide RTTR system, it would have benefited from the installation of conductor temperature monitoring equipment to provide further validation of the RTTR system behaviour. However, due to supply chain issues and outage constraints, this element of the project did not take place. Furthermore, the following lessons learnt were made on the project regarding deploying RTTR systems:

1. The importance of incorporating graceful degradation algorithms within the monitoring and control system to deal with equipment failure, communications interruptions and erroneous data.
2. The balance between centralised and distributed intelligence, and using distributed intelligence to report back information (not just data).
3. The use of multiple vendors for equipment supplies.

Following the North Wales project closing down in the latter half of 2013, the Technology Readiness Level (TRL) of RTTR was assessed to be 7.

3 Details of the work carried out

This section presents details of the work carried out to implement the RTTR system on the Cupar – St Andrews circuits.

3.1 Project location

The project location is between Cupar and St Andrews and includes the two 33 kV overhead line circuits located in this area. Figure 1 shows the geographical location of the two Cupar – St Andrews 33 kV overhead lines.

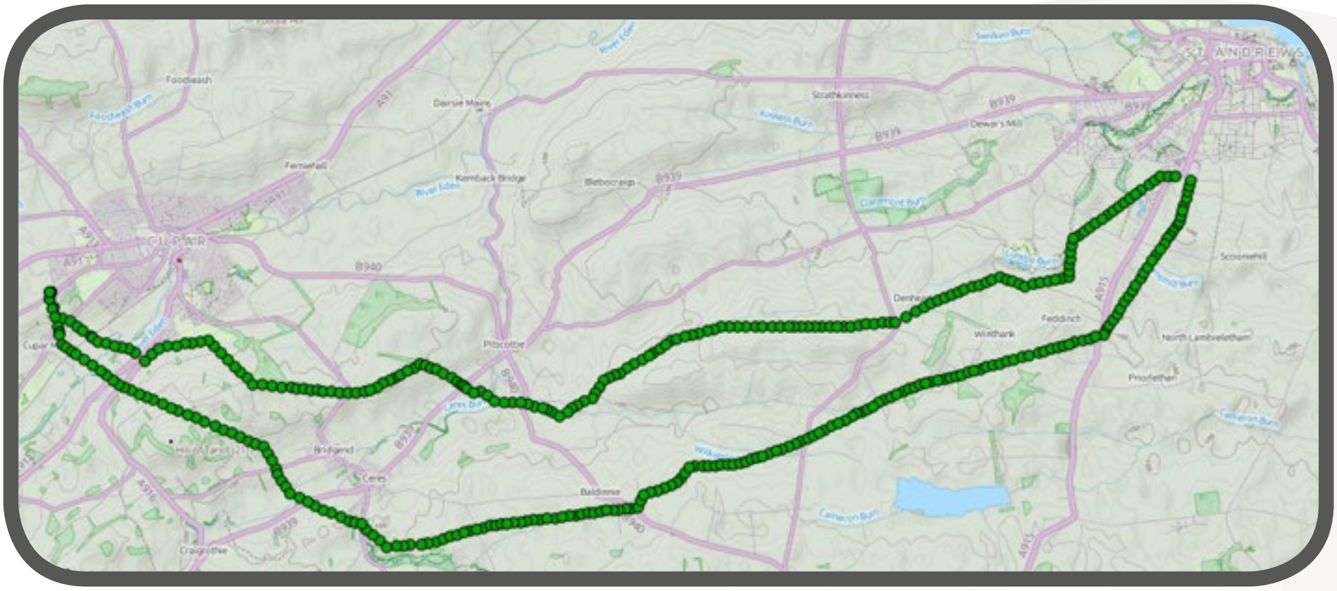

Figure 1: location of the project, Cupar – St Andrews 33 kV circuits

3.1.1 Cupar St Andrews circuits

The St Andrews 33/11 kV substation is supplied solely by two 33 kV circuits from the Cupar 132/33 kV primary substation. Figure 2 illustrates the single line diagram of the 33 kV circuits, which comprise Circuit 1 (SP21313) and Circuit 2 (SP21325). Each circuit is around 15 km in length and is carried by separate 33 kV wooden pole overhead lines.

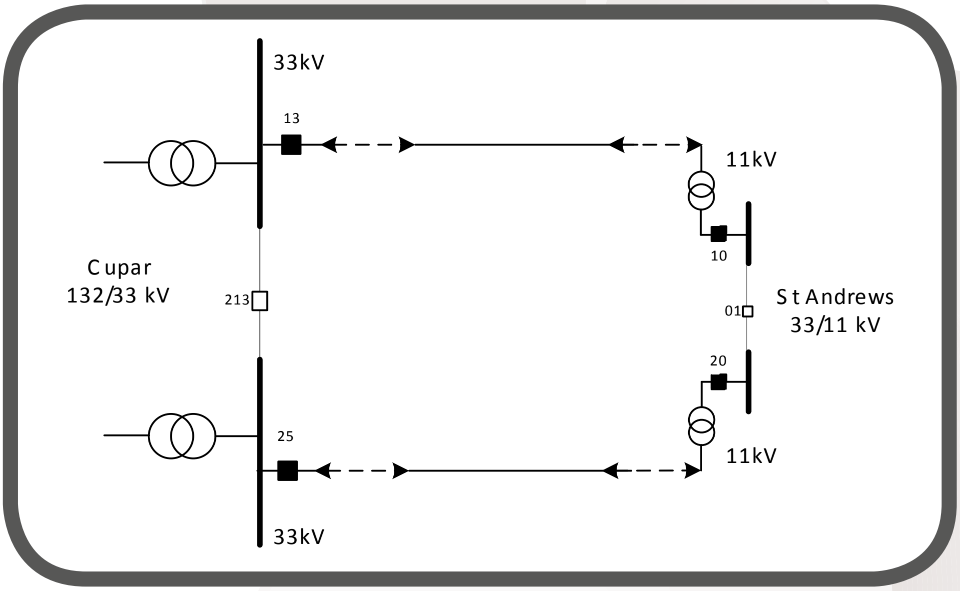

Figure 2: Schematic overview of Cupar – St Andrews 33 kV circuits

3.1.1 Cupar St Andrews circuits [continued]

Figure 3 indicates the conductor types used for each circuit. The majority of each circuit is comprised of 3 x 0.15 Cu and 3 x 0.15 Al ACSR overhead conductor strung between wooden poles. There are also cable sections at the ends of the circuits, between the terminal poles and the 33 kV busbars at the substations.

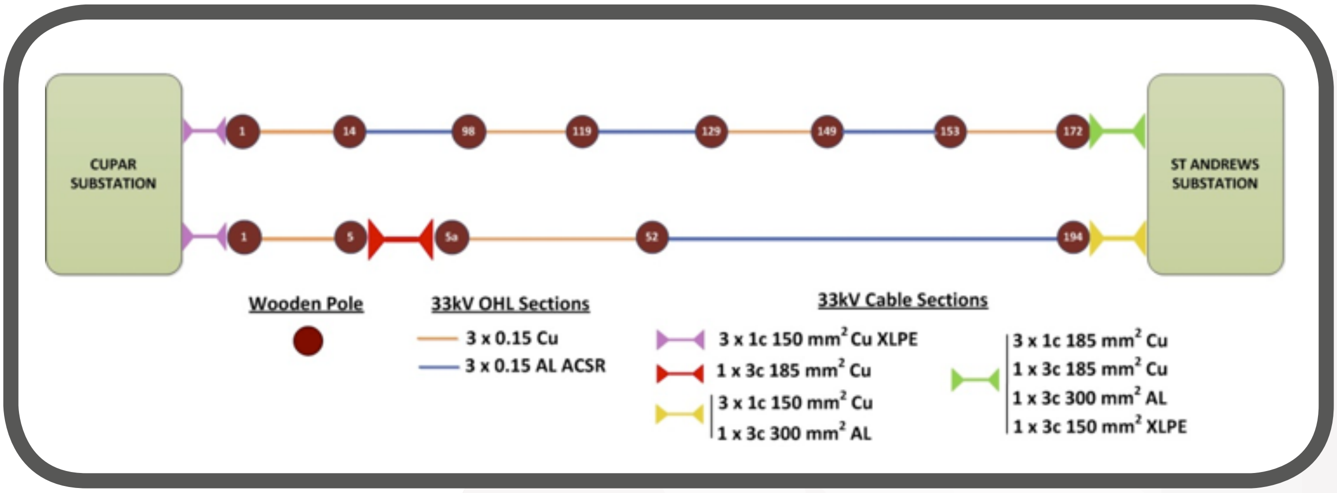

Figure 1: location of the project, Cupar – St Andrews 33 kV circuits

The conventional seasonal ratings of these two circuits are calculated based on a maximum conductor operating temperature of 50°C and the seasonal weather conditions recommended in Engineering Recommendation P27 (November 1986) and CERL Report RD/L/N/129/79. The seasonal ratings of the overhead line conductor sections used in the Cupar – St Andrews 33 kV circuits are given in Table 1.

Table 1: Seasonal rating of overhead line conductor section

33 kV OHL conductor type	Winter rating* (MVA)	Summer rating*(MVA)
3 x 0.15" CU	25.5	20.5
3 x 0.15" ACSR	27.8	22.4

**The winter period is defined as the months between October and April, inclusive; whereas the summer period is defined as the months between May and September, inclusive.*

3.1.2 St Andrews demand

The electrical demand of St Andrews predominantly consists of residential and commercial customers. St Andrews is one of the fast growing load centres in East Fife, which is mainly due to town expansion and general load increase. St Andrews winter peak demand in 2013 was around 20 MVA.

In order to identify the peak hours of the St Andrews demand, a load clustering analysis[1] was carried out on three years (2011, 2012, and 2013) of hourly demand recorded at St Andrews 33/11 kV substation. Clustering techniques were used to estimate the typical seasonal demand profile.

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[1] *K-means clustering methodology was used, for more details about K-means clustering methodology see "K-means clustering via Principle Component Analysis", by Ding, Chris and He, Xiaofeng, 2004.*

3.1.2 St Andrews demand [continued]

Figure 4 shows typical winter and summer daily load profiles for weekdays and weekends for the area supplied by St Andrews 33/11 kV substation. The per unit (p.u.) load values shown in Figure 4 use maximum daily demand as a base. As shown in Figure 4, the winter peak time is more likely to happen between 10:00-13:00 or 14:00-19:00.

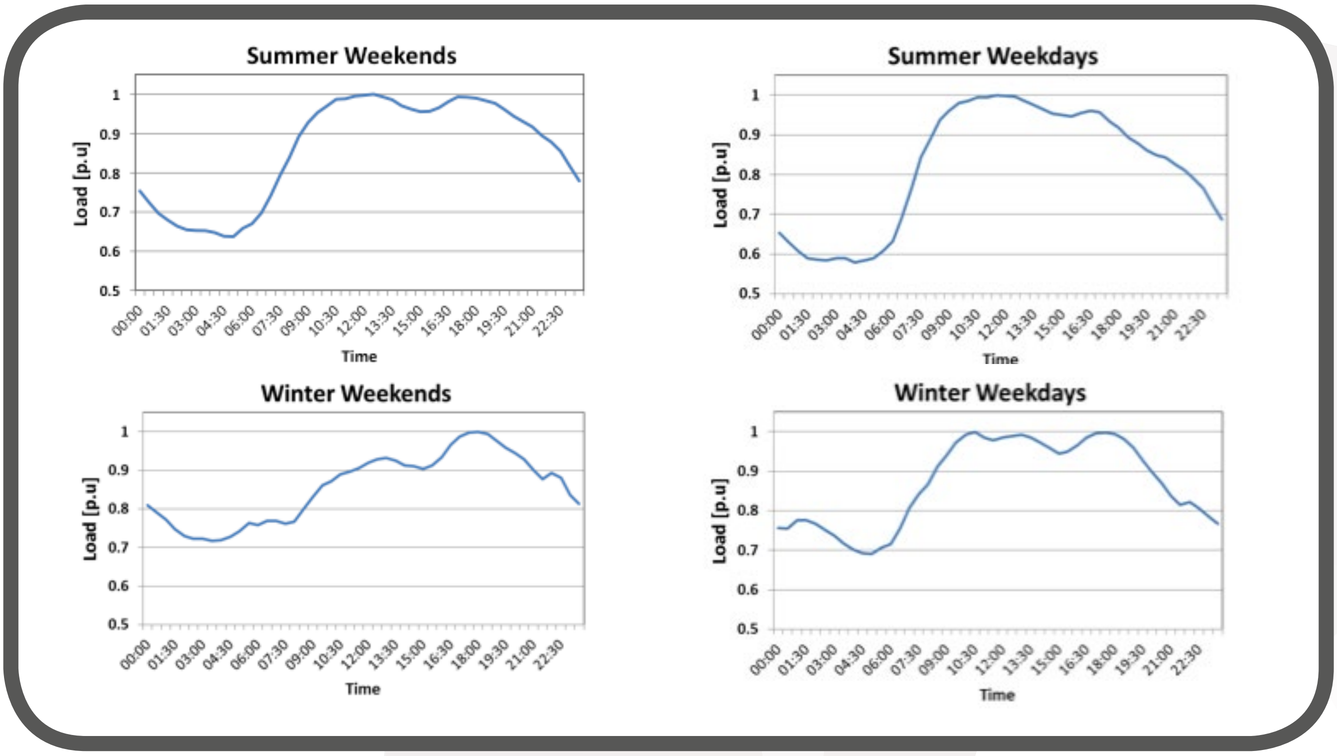

Figure 4: Seasonal typical load profile for St Andrews area

3.2 Methodology for selecting the RTTR system approach

SPEN have previously utilised a thermal state estimation methodology for the 132 kV North Wales network RTTR system as part of Tier 1 LCNF project, “Implementation of Real-Time Thermal Ratings”[1]. The thermal state estimation methodology for the North Wales RTTR system was selected based on an extensive literature survey and outputs of previous R&D projects. As this methodology has been successfully developed and utilised by SPEN, the same principle of thermal state estimation with an integrated sensor approach was adapted for the Cupar – St Andrews RTTR system.

In this methodology, a meshed network of weather stations together with a detailed geographical model of the overhead line is used to estimate the weather conditions at the vicinity of each span in a real-time basis. The RTTRs of each span within the Cupar – St Andrews circuits are then calculated using the estimated weather parameters and conductor thermal rating algorithms given in IEC TR61597[2] and CIGRÉ WG22.12[3] standards. This approach identifies the span within each circuit that has the lowest rating, and this critical span is used to provide the rating for the entire circuit. By modelling the entire system, complete real-time thermal visibility of the overhead line network is provided and the DNO can identify the most frequently limiting spans within the overhead lines.

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[1] *Final close-down report for RTTR system implementation in North Wales 132 kV networks is available at https://www.ofgem.gov.uk/publications-and-updates/first-tier-low-carbon-network-fund-project-implementation-real-time-ratings-submitted-scottish-power-spt1001*

[2] *IEC, 1995, Standard TR 61597 Overhead electrical conductors – calculation methods for stranded bare*

[3] *CIGRÉ WG 22.12, 1992, “The thermal behaviour of overhead line conductors”, Electra, vol. 114 (3), 107-125*

3.3 Enhancements compared to previous RTTR project

Although the North Wales RTTR system project successfully implemented RTTR across a wide area of network, it would have benefited from the installation of conductor temperature monitoring equipment to provide further validation of the RTTR system behaviour. However, due to supply chain issues and outage constraints, this element of the project did not take place.

Furthermore, one of the lessons learnt from the previous project was the importance of incorporating a graceful degradation algorithm within the monitoring and control system to deal with equipment failure, communications interruptions and erroneous data.

Although the principle of calculating real-time thermal rating for the Cupar – St Andrews project is similar to the previous RTTR system implemented in North Wales, SPEN have improved the RTTR system in this project by featuring the following enhancements:

1. Utilising line sensors to measure the real-time temperatures and currents of the conductors at different locations within the Cupar – St Andrews 33 kV network (please refer to section 3.5 and section 3.6)
2. Implementing a graceful degradation algorithm, allowing the system to be robust in the face of missing measurement data (please refer to section 3.8)
3. Developing a conductor temperature estimation algorithm based on meteorological measurements (please refer to section 3.9)
4. Comparing the performance of two different wind sensor types – cup anemometer and ultrasonic – and assessing their effect on the RTTR accuracy
5. Using different manufacturers for monitoring and communication equipment
6. Enhancing the RTTR system reliability and accuracy by increasing the number of weather stations (please refer to section 3.5).

3.4 Trialling Methodology

The following methodology was used in this project to develop the RTTR system for the Cupar – St Andrews 33 kV network:

1. Adoption the thermal state estimation approach successfully trialled in the North Wales 132 kV RTTR system
2. Identification of locations where monitoring equipment should be installed across the Cupar – St Andrews 33 kV network
3. Specification and procurement of the equipment for the RTTR system
4. Installation and commissioning of the monitoring equipment, and establishment of the communication systems to transmit the field data to iHost and the RTTR calculation engine in the NMS
5. Development of a conductor temperature estimation methodology followed by validation of the calculated conductor temperatures against monitored values
6. Development and implementation of a graceful degradation algorithm
7. Collection of field data and calculation of RTTR values; data analysis was then performed on the calculated and monitored data to determine the network capacity that could be unlocked by using the RTTR system
8. Capture of lessons learnt in the process of implementing the RTTR system for Cupar – St Andrews network and provision of recommendations to enable the deployment of an RTTR system as business as usual.

3.5 Methodology for selecting the locations of monitoring equipment

The monitoring equipment deployed in Cupar – St Andrews RTTR system includes weather stations and overhead line sensors. Weather stations are used to monitor and estimate the weather conditions along the overhead line. The overhead line sensors provide additional information including actual temperature of the conductor and the loading (current) of the conductor. The combination of this monitoring equipment can enhance the reliability of the RTTR system and provide adequate field data to validate the calculated RTTR values.

3.5.1 Weather stations

There is a trade-off between the investment cost of network instrumentation and the accuracy of the network thermal visibility that such instrumentation provides. Research from Durham University suggested that a maximum distance of 10 km between meteorological stations is required for real-time thermal rating system operation, to ensure that meteorological conditions at line orientation changes and within microclimate regions are captured.

One of the learning points from the North Wales RTTR project was that the weather stations may not always operate flawlessly. The weather sensors may become faulty or the GPRS communication between weather stations and iHost may be interrupted. These issues were experienced in the North Wales RTTR project and can take a long period to be rectified.

In order to enhance the reliability of the RTTR system and reduce the impact of losing weather data on the accuracy of the calculated RTTRs, it was decided that the maximum distance between meteorological stations should be around 5 km. Therefore, in the event of losing meteorological inputs from one of weather stations, the remaining weather stations could provide acceptable visibility of the weather conditions across the network.

It is essential that meteorological stations are located strategically to capture the presence of microclimates along the overhead line. A microclimate is a local atmospheric zone where the meteorological conditions may differ significantly from the surrounding area.

The following steps were taken to specify the locations of the weather stations:

1. Carry out desk-top analysis using SPEN Geographical Information System (GIS) to identify the potential microclimate regions.
2. Survey the terrain and environment of the two 33 kV Cupar – St Andrews overhead lines to confirm the results of desk-top analysis.
3. Identify the poles where equipment should be installed after confirming road access and acceptable GPRS signal strength.

Four regions were recommended as locations for installing weather stations along the two 33 kV circuits. The locations of these pole-mounted weather stations are shown in Figure 5, and more details of these locations can be found in Appendix A.

3.5.1 Weather stations [continued]

As part of the "Flexible Networks for a Low Carbon Future" project, meteorological stations had been installed in a number of substations – namely Cupar, St Andrews, Leuchars – for the purpose of estimating the operating temperature of the 33/11 kV transformers at those substations. These substations are located within 15 km distance of Cupar – St Andrews 33 kV circuits, so their data was used in addition to the pole-mounted weather station data in the weather estimation process for these circuits. The locations of these building-mounted weather stations are shown in Figure 5.

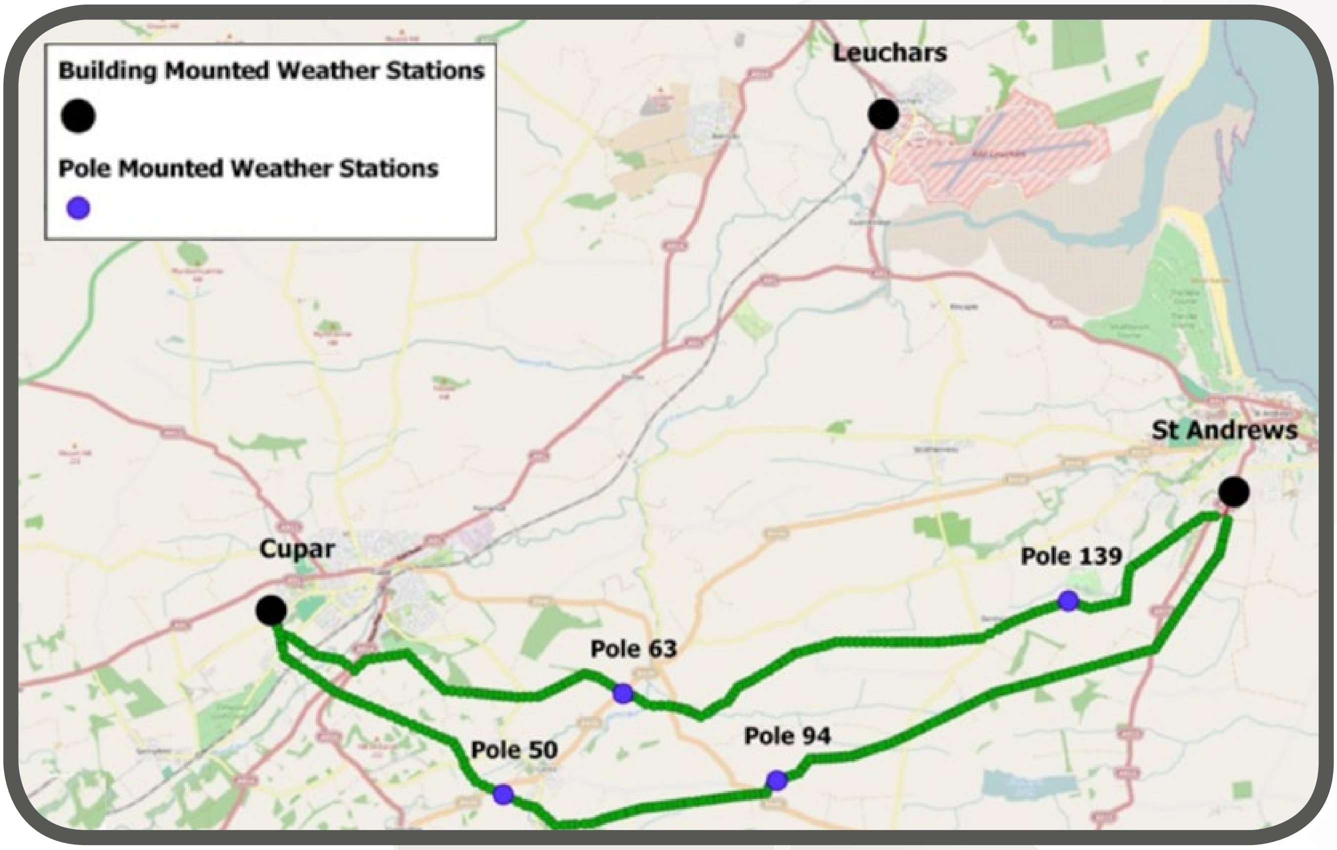

Figure 5: Locations of the pole-mounted and building-mounted equipment for the Cupar – St Andrews RTTR system

3.5.2 Overhead line sensors

GE Energy's intelligent line monitoring system (ILMS) solution includes FMC-T6 overhead line sensors co-located with the pole-mounted weather stations. There are three line sensors (one for each phase) mounted directly on the conductors at each site. GE Energy's ILMS solution also includes a sensor network gateway (SNG) that collects and transmits both weather station data and FMC-T6 data to iHost every 5 minutes.

The FMC-T6 sensors co-located with the weather stations provide adequate monitoring data to validate the thermal model of the overhead line.

3.6 RTTR System architecture

The Cupar – St Andrews RTTR system architecture is shown in Figure 6. A centralised calculation process approach was used, following the same approach taken for the North Wales RTTR projects. Weather parameters measured at the pole-mounted and building-mounted weather stations are transmitted every 5 minutes to the iHost located at the St Asaph substation in North Wales. This data are then transferred to the PowerOn Server hosting the RTTR calculation engine. This calculation engine uses the weather parameters together with fixed parameters for the Cupar – St Andrews RTTR system to calculate the carrying capacity of each span. The results of calculation are available in the control room and through a web interface. The measured and calculated parameters from the RTTR system are also recorded to PI (SPEN's data historian).

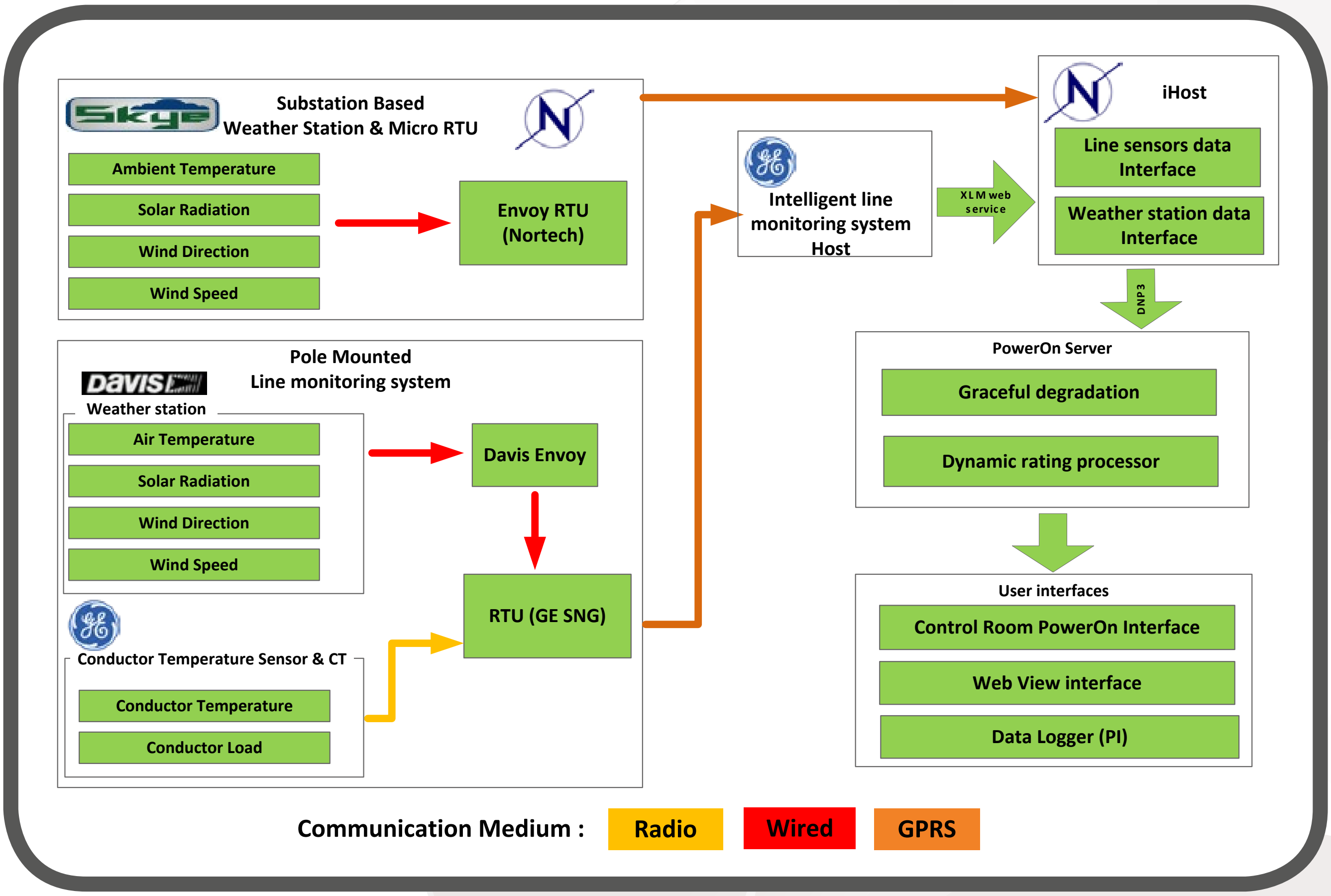

Figure 6: Overview of RTTR system architecture

3.6.1 Communication

For the Cupar – St Andrews installation specifically, the weather station data is provided via a RS232 serial link to a Nortech iHost system using the DNP3 protocol.

The iHost system acts as a data concentrator. It communicates directly with the Nortech Envoy RTUs at the weather stations located at the Anstruther, Cupar, Leuchars and St Andrews substation sites.

The four GE-supplied ILMS weather stations have been installed on poles distributed throughout the Cupar – St Andrews circuits. The GE SNG3 devices within these weather stations were hard wired to the Davis weather station and connected wirelessly to the three transducers measuring current and temperature on each phase in the vicinity of the pole. These current and temperature values do not currently participate in the RTTR calculation.

The weather and conductor data is communicated via GPRS to an ILMS server hosted by GE. The ILMS server makes this data available as an XML web service which the iHost server interrogates.

3.6.2 RTTR calculation engine

Figure 7 illustrates the operation of the RTTR calculation process itself:

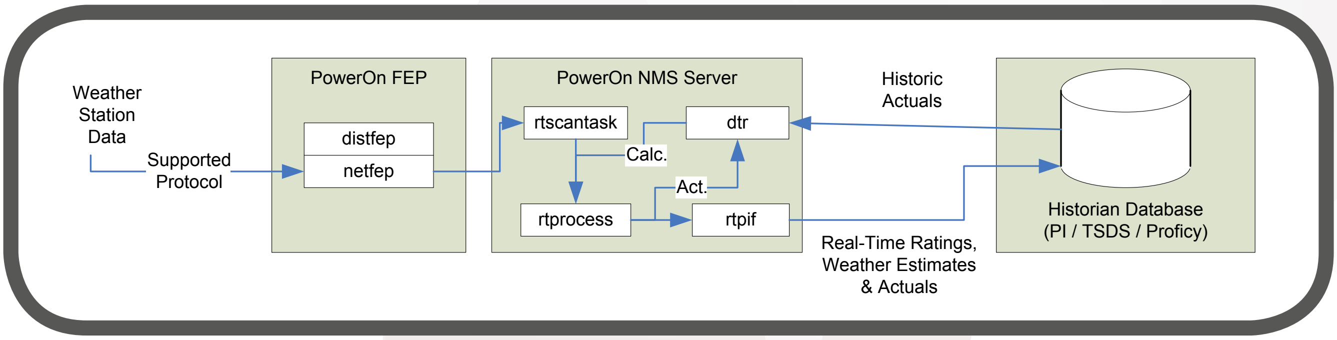

Figure 7: RTTR calculation process

The weather station data is received by the PowerOn Front End Processor (FEP) as 5-minute average values for Wind Speed, Wind Direction, Ambient Temperature and Solar Radiation via any supported protocol.

This data is passed to the *rtscantask* process on the PowerOn NMS server, which in turn passes the data to *rtprocess*, which manages the Real Time (RT) database.

Every 5 minutes, the *dtr* process interrogates *rtprocess* for the most recent RT weather station values. Any weather parameters that have not had a last good value within the last 15 minutes are estimated according to the Graceful Degradation algorithm, which queries recent good quality historic measured values from the historian database.

Once any required weather parameter estimates have been calculated, the *dtr* process simulates the weather conditions at each span along each circuit, calculates the rating of each span and reports the minimum calculated rating and limiting span, as well as any estimated weather station parameters back to *rtprocess*.

The *rtprocess* process passes the measured weather station values, the estimated weather station values, the calculated real time ratings and the limiting span data to the *rtpif* process, which in turn forwards it to the selected historian for future reference.

Finally, the measured, estimated and calculated values may be presented diagrammatically on either the standard PowerOn client, or via the lightweight HV WebView viewer.

3.6.3 Data system

In order to calculate the RTTR of an overhead line which is modelled as series of line spans, a number of fixed (non-time-varying) parameters are required:

- Geographical model of the overhead lines: this includes the geographical parameters such as the coordinates of each 33 kV overhead line pole, the terrain type in the vicinity of each span, and the minimum ground clearance for each span.
- Electrical and thermal parameters of the overhead lines: this includes the detailed electrical parameters of the conductor used for each span in the overhead lines and the maximum conductor operating temperature at each span.
- Weather station installation parameters: this includes geographical parameters such as the coordinates of the weather stations, terrain types around weather stations and the anemometers' installation heights. In addition, the accuracy of each weather sensor is also defined in the RTTR model.
- Physical constant: the physical constants are those used for modelling the heat transfer process through radiation, convection and conduction.
- User-defined parameters.

The functional specification of the RTTR algorithm and data requirements specification for the RTTR system can be obtained from the Tier 1 RTTR system implementation project[1].

The time-varying data, which include weather data, circuit loading and conductor temperature, is transmitted to the iHost using intelligent RTUs. In order to avoid high volume data transmission and streaming data between the RTUs and iHost, the time-varying data are locally sampled every 70ms and only the average values over a 5 minute period are transmitted. At the end of each 5-minute time period, the RTUs are programmed to calculate maximum, minimum and average values for each weather parameter and conductor monitored data. These data sets, transmitted at five-minute intervals, are sufficient to facilitate the calculation of RTTRs.

To facilitate offline system validation, and to assist with the quality assurance process, key system data is time-stamped as transmitted and stored in the SPEN's data historian. The following data is recorded:

- Meteorological data monitored at all weather stations
- Conductor current and temperature monitored by the FMC-T6 line sensors
- Calculated RTTR values for each circuit
- Limiting span within each circuit.

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[1] *Final close-down report for RTTR system implementation in North Wales 132 kV networks is available at https://www.ofgem.gov.uk/publications-and-updates/first-tier-low-carbon-network-fund-project-implementation-real-time-ratings-submitted-scottish-power-spt1001*

3.6.4 Monitoring equipment

The following measurements are taken at each weather station location:

- Ambient temperature (˚C)
- Solar radiation (W/m2)
- Wind speed (m/s)
- Wind direction (degrees)

Different weather stations are used for the building and pole-mounted installations. There are two key differences between these stations: 1) ultrasonic anemometers are used at the building-mounted installations, while a cup-type is used at the pole-mounted installations; and 2) the pole-mounted installations also include co-located line sensors that monitor:

- Line current (A)
- Line temperature (˚C)

Key specifications of the measurement equipment are included in the Appendix C.

3.6.5 Weather stations: building-mounted

There are four building-mounted weather stations participating in the Cupar – St Andrews RTTR system. These weather stations are located at:

- St Andrews 33 / 11 kV substation
- Cupar 132 / 33 kV substation
- Leuchars 33 / 11 kV substation
- Anstruther 33 / 11 kV substation – It should be noted that this weather station has only little impact on RTTR values due to its distance from Cupar-St Andrews circuits.

Building-mounted weather stations comprise Skye Instrument weather sensors and Nortech RTUs. The specification of the weather sensors are given in Appendix B.

3.6.6 Weather stations: pole-mounted

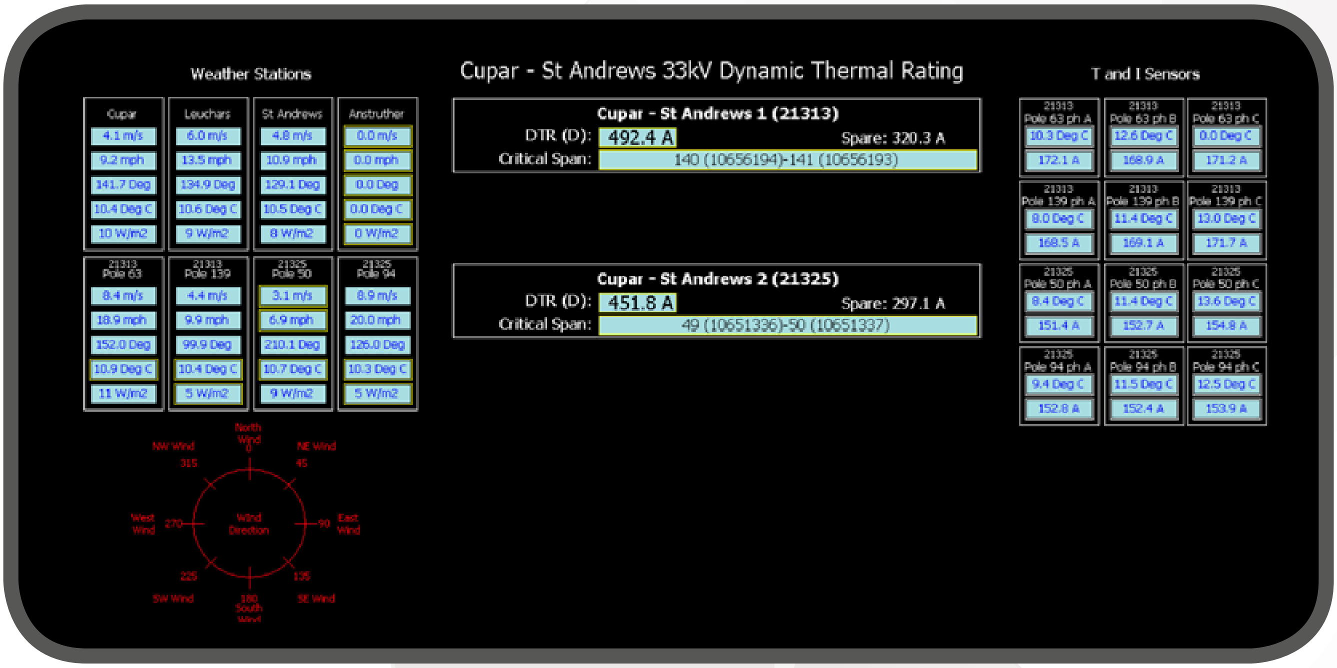
In addition to substation-based building-mounted weather stations, four pole-mounted weather stations were installed in order to monitor weather parameters at remote locations. These weather stations are located at poles 50, 63, 94 and 139 on the two Cupar – St Andrews circuits (as shown in Figure 3). The pole-mounted weather stations were manufactured by Davis Instruments and are part of GE's intelligent line monitoring system. The power supply for this unit is locally provided by a 30 W solar panel together with 2 x 12 V lead acid batteries. The specification of weather sensors are given in Appendix C.

3.6.7 Line sensors

GE FMCT6 line sensors are part of GE's intelligent line monitoring system and are co-located with the pole-mounted weather stations. There are three of these line-powered sensors (one for each phase) mounted directly on the conductors at each site, monitoring phase current and conductor temperature. The rating of the CT of the line sensor is 600 A, higher than the static rating (437 A winter rating) of the Cupar – St Andrews circuits.

3.6.8 User interface

A web view application was designed to provide a real-time thermal rating data of Cupar-St Andrews RTTR system for desktop users. The user interface of this application is shown in Figure 7. All the monitored parameters at the pole-mounted and building-mounted equipment are presented in a real-time basis in this application. The calculated real-time thermal rating of each circuit is also shown along with the critical span and the spare capacities.



Cupar - St Andrews 33kV Dynamic Thermal Rating

Weather Stations

Cupar	Leuchars	St Andrews	Anstruther
4.1 m/s	6.0 m/s	4.8 m/s	0.0 m/s
9.2 mph	13.5 mph	10.9 mph	0.0 mph
141.7 Deg	134.9 Deg	129.1 Deg	0.0 Deg
10.4 Deg C	10.6 Deg C	10.5 Deg C	0.0 Deg C
10 W/m2	9 W/m2	8 W/m2	0 W/m2

21313 Pole 63	21313 Pole 139	21325 Pole 50	21325 Pole 94
8.4 m/s	4.4 m/s	3.1 m/s	8.9 m/s
18.9 mph	9.9 mph	6.9 mph	20.0 mph
152.0 Deg	99.9 Deg	210.1 Deg	126.0 Deg
10.9 Deg C	10.4 Deg C	10.7 Deg C	10.3 Deg C
11 W/m2	5 W/m2	9 W/m2	5 W/m2

Cupar - St Andrews 1 (21313)
DTR (D): 492.4 A Spare: 320.3 A
Critical Span: 140 (10656194)-141 (10656193)

Cupar - St Andrews 2 (21325)
DTR (D): 451.8 A Spare: 297.1 A
Critical Span: 49 (10651336)-50 (10651337)

T and I Sensors

21313 Pole 63 ph A	21313 Pole 63 ph B	21313 Pole 63 ph C
10.3 Deg C	12.6 Deg C	0.0 Deg C
172.1 A	168.9 A	171.2 A
21313 Pole 139 ph A	**21313 Pole 139 ph B**	**21313 Pole 139 ph C**
8.0 Deg C	11.4 Deg C	13.0 Deg C
168.5 A	169.1 A	171.7 A
21325 Pole 50 ph A	**21325 Pole 50 ph B**	**21325 Pole 50 ph C**
8.4 Deg C	11.4 Deg C	13.6 Deg C
151.4 A	152.7 A	154.8 A
21325 Pole 94 ph A	**21325 Pole 94 ph B**	**21325 Pole 94 ph C**
9.4 Deg C	11.5 Deg C	12.5 Deg C
152.8 A	152.4 A	153.9 A

Figure 8: Cupar-St Andrews RTTR dashboard

3.7 Methodology for installation of equipment

3.7.1 Installation of substation-based weather stations

A method statement was developed to outline the procedure for installing a weather station in a substation compound, mounted on the side of a substation building. This method statement is included for reference in Appendix B. An example of a substation-based weather monitoring installation is given in Figure 9.

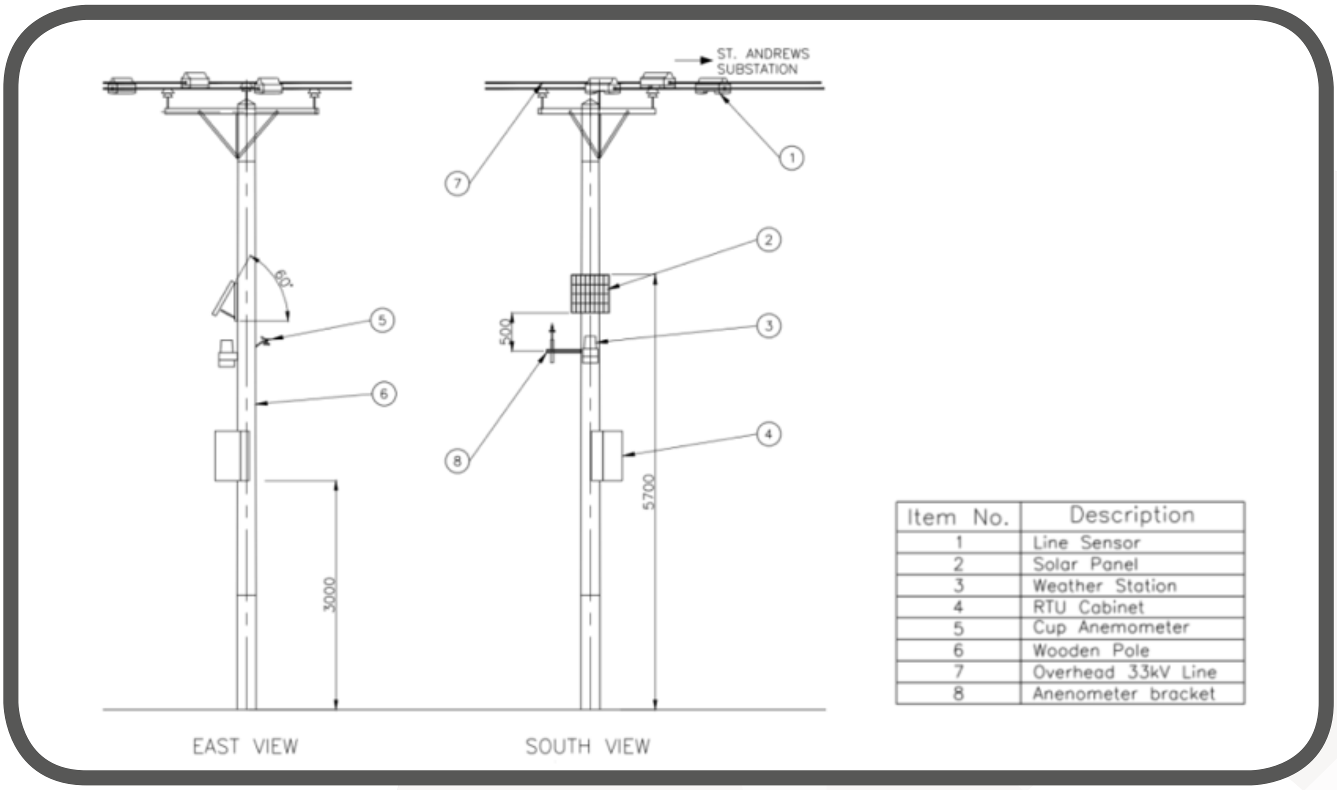
3.7.2 Installation of pole-mounted weather stations

A method statement was developed to outline the procedure for installing GE ILMS equipment on 33kV pole overhead lines. This method statement was based on recommendations and instructions provided by GE Energy as well as SPEN's health and safety policies. In order to avoid wind shielding having an impact on the cup anemometer, an extension mounting bracket was also designed.

Figure 10 shows a general plan illustrating the position of each component on the 33 kV pole. As the orientation of the overhead line and conditions at each pole is different, specific site plans were prepared for all four sites. The installation method statement and the specific site plans are given in Appendix B.

Figure 9: Building-mounted RTTR monitoring equipment installed at a substation

3.7.2 Installation of pole-mounted weather stations



Item No.	Description
1	Line Sensor
2	Solar Panel
3	Weather Station
4	RTU Cabinet
5	Cup Anemometer
6	Wooden Pole
7	Overhead 33kV Line
8	Anenometer bracket

Figure 10: Position of the weather and line monitoring system equipment on a 33 kV pole

Figure 11 is a photo of one of the pole-mounted monitoring equipment installations.

Figure 11 RTTR monitoring equipment installed on a 33 kV pole

3.8 Methodology for developing graceful degradation

Calculation of an overhead line RTTR using thermal state estimation is based on the variations in weather conditions along the overhead line. Due to communication system failures or sensor malfunctions, the correct values of all real-time weather parameters may not be received as an input to the RTTR system. Therefore, a process is required to sanitize the affected weather parameters to ensure the estimated RTTR is within an acceptable degree of accuracy.

One of the learning points from the RTTR system implementation project for the 132 kV network in North Wales was the need for a methodology that degrades RTTR values gracefully towards static seasonal ratings when some weather parameters are unavailable, whereby increasingly conservative estimates are made of the RTTR of the circuits as an increasing number of weather station parameters become unavailable.

Based on learning from the previous project, a graceful degradation methodology was developed to keep the RTTR system operation within acceptable accuracy when one or more weather parameters measured by weather stations are not available and are identified as "unhealthy". Data from remaining "healthy" sensors within a zone of influence is then used to estimate the "unhealthy" parameters, which are then used for calculating RTTRs. Figure 12 provides an overview of the graceful degradation methodology.

3.8.1 Graceful degradation functionalities

The graceful degradation methodology uses the healthy weather sensors to provide a conservative estimated value for a weather sensor that has been identified as unhealthy. As the behaviours of weather parameters are different, the methodology for estimating each weather parameter is different.

The following functionalities have been developed within the graceful degradation algorithm:

- Identification of "unhealthy" sensors
- Provision of conservative estimated values for the sensors that have been identified as unhealthy
- Use of different methodologies for estimating different weather parameters
- Flexible input parameters are used, so that the algorithm can be adapted to different overhead lines and different quantities/locations of monitoring equipment
- Switches to the seasonal rating values when the number of available healthy sensors falls below an acceptable number
- Records estimated values and health status of the sensors in SPEN's data historian.

The graceful degradation algorithm functional specification is given in Appendix D.

3.8.1 Graceful degradation functionalities [continued]

The graceful degradation methodology was developed and implemented in PowerOn Fusion NMS using the following steps:

1. Data analysis was carried out to determine the correlation between weather parameters at different weather stations
2. The data analysis results were used to develop the graceful degradation algorithm
3. The graceful degradation algorithm was tested and validated against different scenarios, which were created based on field data
4. An algorithm specification document was produced, so that GE Energy could implement the graceful degradation methodology in the RTTR module within the PowerOn Fusion NMS
5. User acceptance tests were carried out to approve the implementation within NMS.

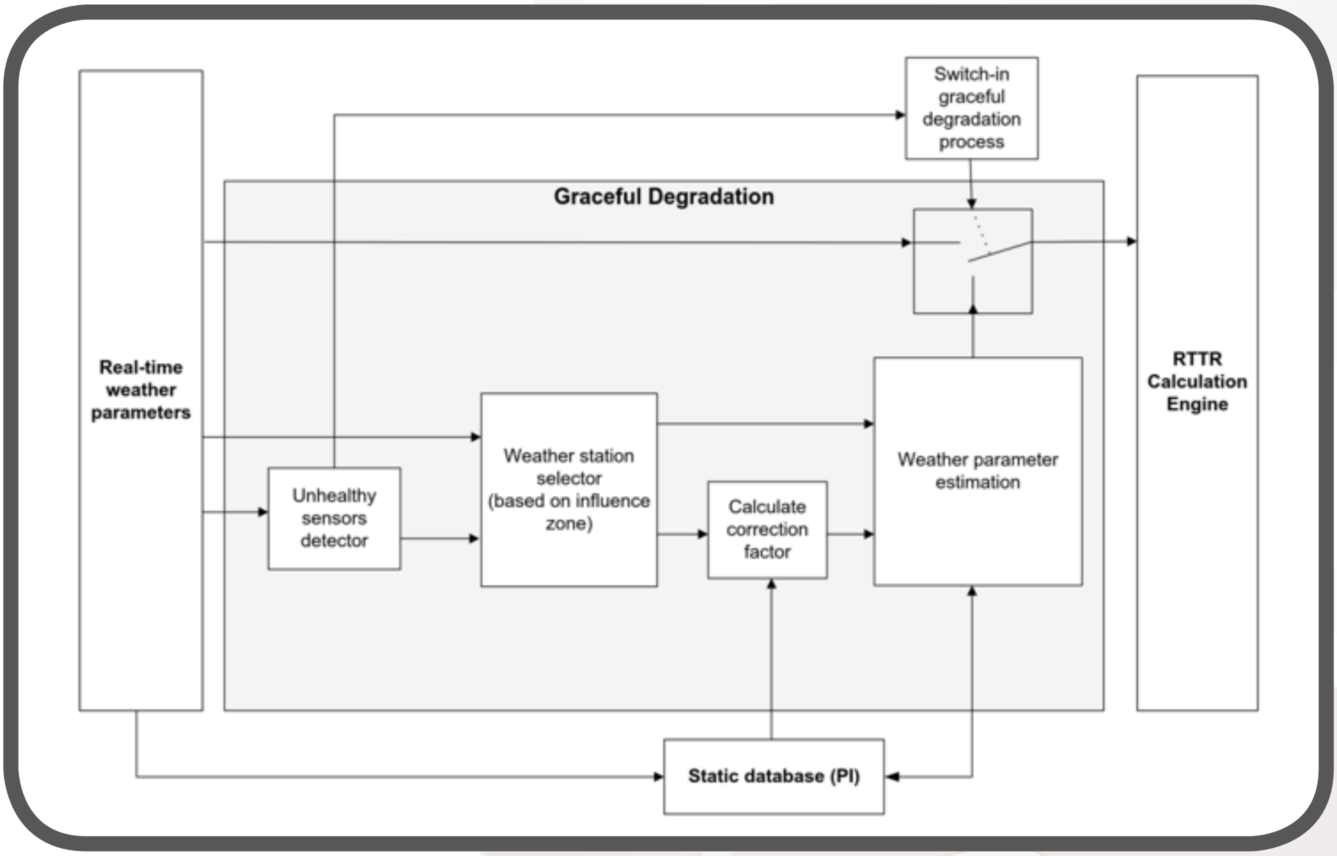


Figure 12: Overview of the graceful degradation methodology

3.8.2 Graceful degradation user acceptance test

Each test performed consisted of a number of steps:

1. Setting the testing environment variable to dictate the date and time to use instead of the current time for the historian queries.
2. Running a script to set the weather station parameters in the real-time database to those matching the specified date and time, and marking any "bad" parameters as required by the test.
3. Running the dtr process in debug mode, redirecting the output to a file.
4. Running a script on the debug output file, in order to extract the weather station values used in the calculation, both measured and estimated, as well as extracting the calculated Dynamic Thermal Ratings and Limiting Spans for the two Cupar – St Andrews circuits. This allowed comparison of the calculated results using graceful degradation against the expected results.
5. If necessary, the debug output file could be examined to gain further information about the weather conditions calculated for any given span.

A total of 14 test scenarios were created:

1. Loss of Wind Speed weather sensor at a single site
2. Loss of Wind Direction weather sensor at a single site
3. Loss of Solar Radiation weather sensor at a single site
4. Loss of Ambient Temperature weather sensor at a single site
5. Loss of Wind Speed weather sensors at three sites
6. Loss of Wind Direction weather sensors at three sites
7. Loss of Solar Radiation weather sensor sensors at three sites
8. Loss of Ambient Temperature weather sensors at three sites
9. Loss of Wind Speed weather sensors at five sites
10. Loss of Wind Direction weather sensors at five sites
11. Loss of Solar Radiation weather sensor sensors at five sites
12. Loss of Ambient Temperature weather sensors at five sites
13. Loss of all four weather sensors at two sites
14. Loss of all four weather sensors at six sites

These scenarios exercised the operation of the algorithm both to use the last good value within the first 15 minutes of a sensor failure, and the use of the historian to estimate values where the no good data has been received from the sensor for a period in excess of 15 minutes. The test environment also allowed sufficient flexibility for additional test scenarios to be explored on an ad-hoc basis.

3.9 Methodology for developing conductor temperature algorithm and RTTR model validation

An RTTR system equipped with direct conductor temperature monitoring equipment assists control room engineers in gaining further confidence in the system. In the North Wales RTTR system, installation of the conductor monitoring equipment did not take place due to supply chain issues and outage constraints. SPEN have now implemented this element within the Cupar – St Andrews RTTR system by deploying GE Energy's FMC-T6 conductor monitoring equipment.

In addition to direct monitoring of the conductor temperature at some locations along the overhead line, the RTTR system can be benefitted from a conductor temperature estimation module. This is a complementary module to RTTR system that estimates the real-time temperature of the conductor at each span of overhead line.

An algorithm specification document that provides guidance for calculating thermal transient behaviour of overhead line conductors based on IEC 61597 and CIGRÉ W22.12 has been produced, and is included as Appendix E. This algorithm was tested and validated against monitored conductor temperatures at four locations along the Cupar – St Andrews circuits.

3.10 Methodology for trial of different method of attachment for conductor temperature sensor

The original recommendation from the manufacturer for connecting the conductor temperature sensor included covering the temperature sensor with Denso tape in order to protect against water ingress. However, using Denso tape may affect the accuracy of the monitored conductor temperature as the conductor and temperature sensor may not be exposed to the same environmental conditions.

In order to investigate the effect of the method of attachment, two sets (2 x 3) of FMC-T6 sensors were installed at both sides of pole 50 in the Cupar – St Andrews Circuit 2 (South Circuit), as shown in Figure 13. Three different methods of attachment were trialled for FMC-T6's temperature probe as shown in Figure 14 and described below:

- **Method A:** Attaching the temperature probe on top of the conductor with Denso tape, and securing the temperature probe with cable ties and thermal paste
- **Method B:** Attaching the temperature probe on top of the conductor without Denso tape, and securing the temperature probe with cable ties and thermal paste
- **Method C:** Attaching the temperature probe below the conductor (away from direct sunlight) without Denso tape, and securing the temperature probe with cable ties and thermal paste

The methods used for attaching the temperature probe at Node 1 and Node 2 are given in Table 2:

Table 2: Method of attachment for FMC-T6 temperature probe at Node 1 and Node 2

	Phase R	Phase S	Phase T
Node 1	Method A	Method A	Method A
Node 2	Method A	Method B	Method C

3.10 Methodology for trial of different method of attachment for conductor temperature sensor [continued]

In order to investigate the effect of method attachment following methodology was trialled:

1. Trial of the three methods of attachment for temperature probe at pole 50 as explained in Table 2
2. Data gathering from all of the sensors at pole 50 for every 5 minute interval
3. Data analysis of the recorded data to compare the temperature variation between phases and temperature of same phases on both sides of pole 50
4. Estimation of the conductor temperature for each phase using the methodology described in section 3.9 and comparison of the estimated temperature with monitored values
5. Develop recommendations and conclusions based on the results of the trial

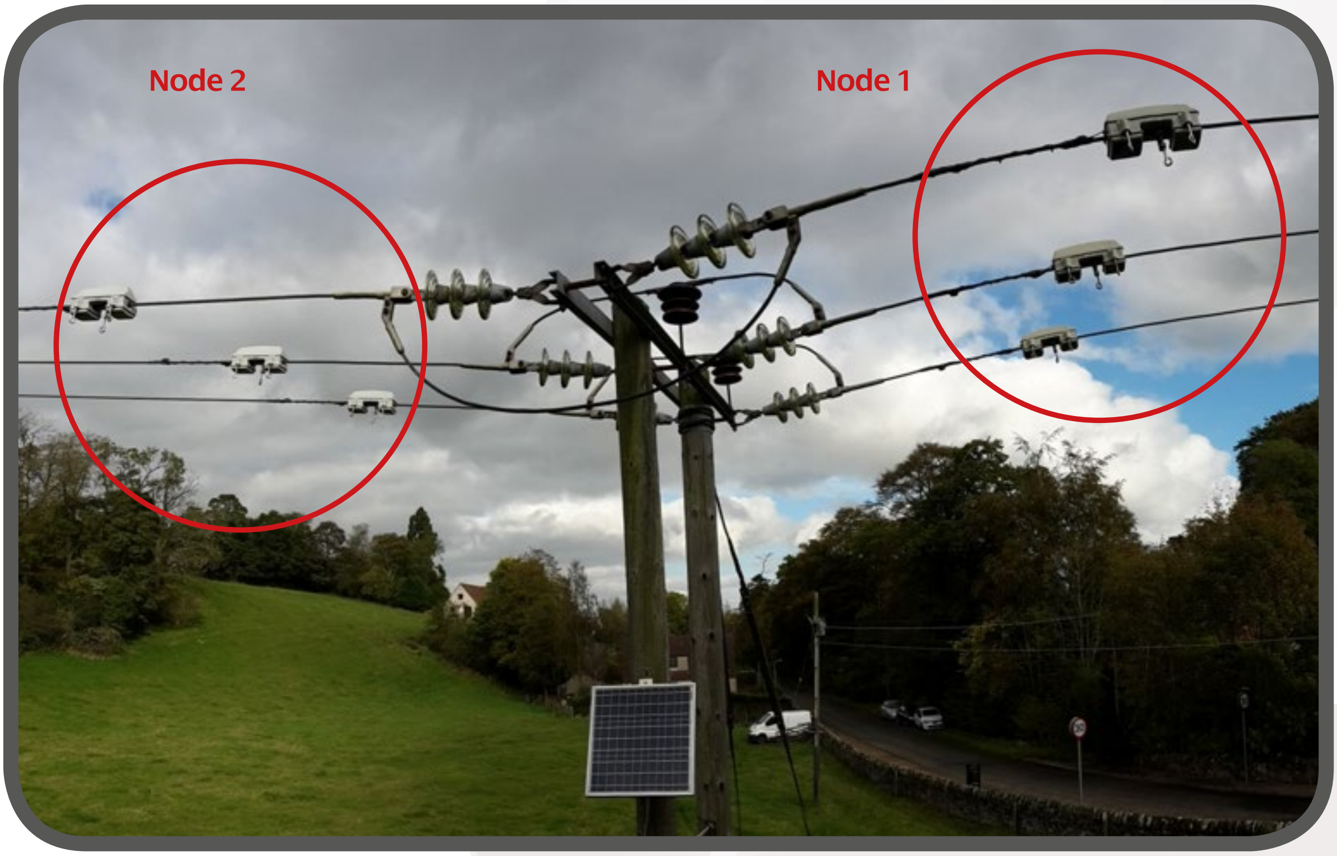


Figure 13: Installations at pole 50 and position of line sensors at Node 1 and Node 2

3.10 Methodology for trial of different method of attachment for conductor temperature sensor [continued]

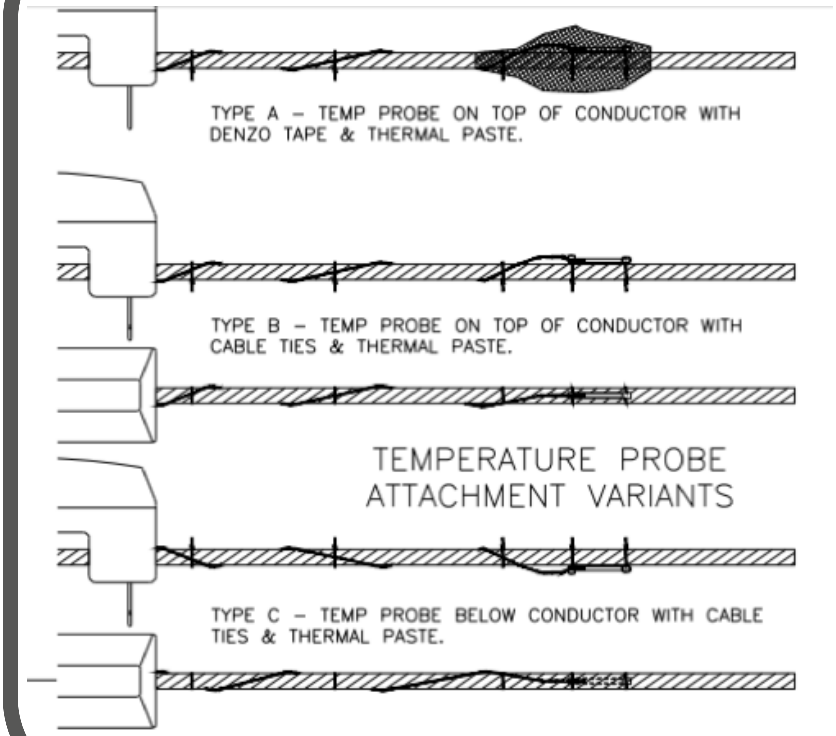


Figure 14: Methods of attachment trialled at pole 50

4 The outcomes of the work

The key outcomes of the work are outlined as follows:

- Four weather stations were installed along the Cupar – St Andrews 33 kV circuits at different locations. Five overhead line sensors, four of which co-located with weather stations and monitor temperature and current of conductors, were installed.
- The real-time monitored data were transmitted to the RTTR calculation module hosted in a stand-alone PowerOn Fusion server. The RTTR values and all monitored data are available through a dashboard specifically designed for the Cupar – St Andrews circuits within the PowerOn Fusion NMS.
- A graceful degradation methodology was developed and implemented in the RTTR system to ensure the estimated RTTRs are within an acceptable degree of accuracy when transmission of real-time monitored weather parameters to the RTTR module is interrupted.
- A methodology for estimating temperature of overhead line conductors was developed and validated against monitored conductor temperatures at four locations along the Cupar – St Andrews circuits
- The calculated RTTR values for a year period starting from 25th April 2014 showed that the average thermal rating uplift by deploying RTTR system is around 11% of the static thermal rating
- Data analysis was carried out on a 12-month period of data of weather parameters, conductor temperatures and RTTR values.

This section presents the recorded data and results of data analysis from the trial of the RTTR system for the Cupar – St Andrews 33 kV network.

Weather parameters, currents and temperatures of the overhead line conductors are recorded at five minute intervals. The thermal rating for each span of the two Cupar – St Andrews 33 kV circuits were calculated using the real-time weather parameters estimated at different points on the network and the physical parameters of each span.

The calculated RTTRs have been compared with summer and winter static thermal ratings. The winter period is the months between October and April, whereas the summer period is the months between May and September.

4.1 Summary of weather data

Weather parameters were recorded at the four weather stations installed along the Cupar – St Andrews circuits: at poles 63 and 139 in Circuit 1 (SP21313), at poles 50 and 94 in Circuit 2 (SP21325), and at the three building-mounted stations in the St Andrews, Cupar, and Leuchars substations. The average of each weather parameter is transmitted at five minute intervals to an iHost server located in St Asaph. This is the same iHost server that was used for collecting the field data for the North Wales RTTR system.

4.1.1 Wind speed

Wind speed is very volatile weather parameter that varies from weather station to weather station and from time to time. Wind speed at a given location is affected by different factors such as altitude and terrain type. Figure 15 shows the wind speed variations against time for the seven weather stations. A summary of the recorded wind speeds is given in Table 3.

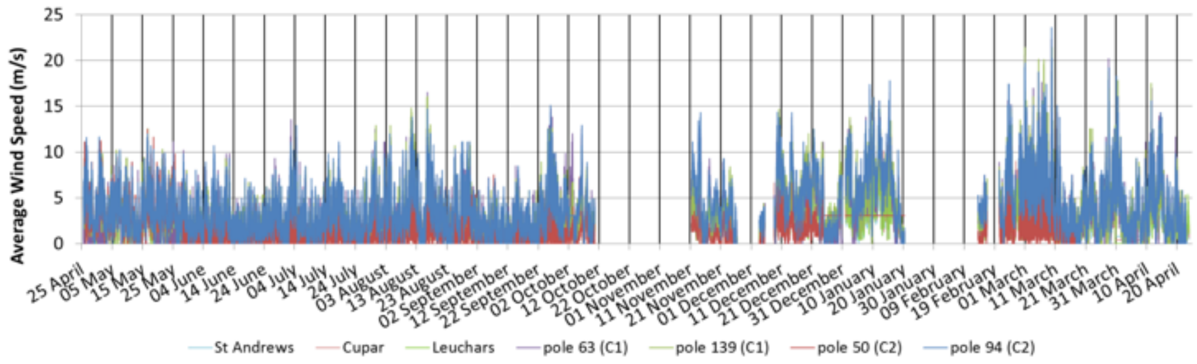


Figure 15: Wind speed variation against time at four locations

As shown in Table 3, the highest wind speed of 23.6 m/s was recorded in pole 94 during winter period, which has a winter average of 4.80 m/s. The maximum wind speed during summer is 16.5 m/s which was recorded at pole 63. The summer average wind speed at this location was 2.4 m/s. Pole 50 has the lowest average wind speed for the studied period, 1.35 m/s. This is to be expected, as Pole 50 is located in an area shielded by hills.

Table 3: Summary of wind speed at each weather station

Wind Speed (m/s)	Pole 63	Pole 139	Pole 50	Pole 94	St Andrews	Cupar	Leuchars
Summer season							
Maximum	16.50	16.00	12.50	15.10	6.24	8.07	6.36
Average	2.40	2.45	1.35	3.13	1.38	1.93	1.77
Winter season							
Maximum	22.30	21.40	13.80	23.60	9.84	14.95	13.36
Average	4.15	4.20	1.56	4.80	2.19	3.23	2.78

4.1.1 Wind speed [continued]

Figure 16 shows the daily average wind speed (for each 24 hour period) at each location. It can be seen in Figure 16 that wind speed at pole 50 is usually lower than other locations. Due to communication issues at different periods such as from 10th October to 11th November 2014, and from 21st January to 11th February 2015, Cupar and St Andrews weather stations reported constant wind speed, shown as data gaps in Figure 16. Leuchars wind sensor had a wiring issue that was rectified on 10th September, so the wind speed data at this location is not shown before this period.

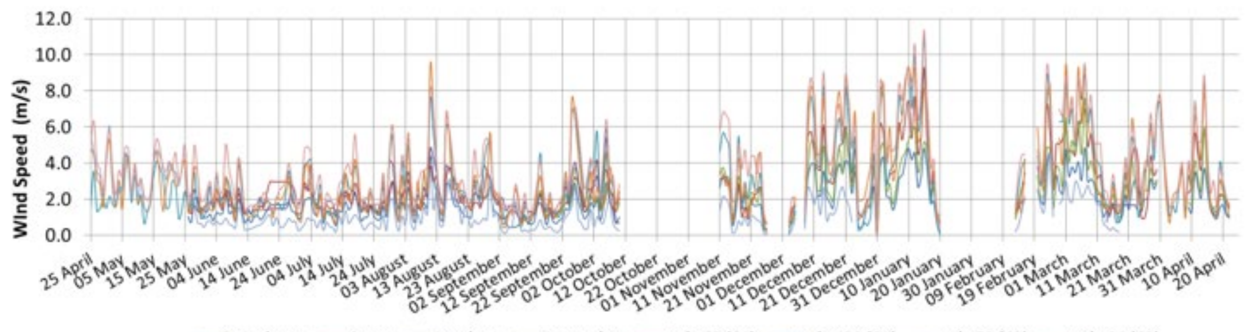


Figure 16: Daily wind speed averages for weather stations

4.1.2 Wind direction

Figure 17 shows the prevailing wind direction at each weather station. All substations and both circuits experience predominantly south-westerly and north-easterly winds. Pole 50 also experiences southerly wind that may be due to geo-topological characteristics around pole 50 – which includes hilly and wooded areas –that would affect the wind direction.

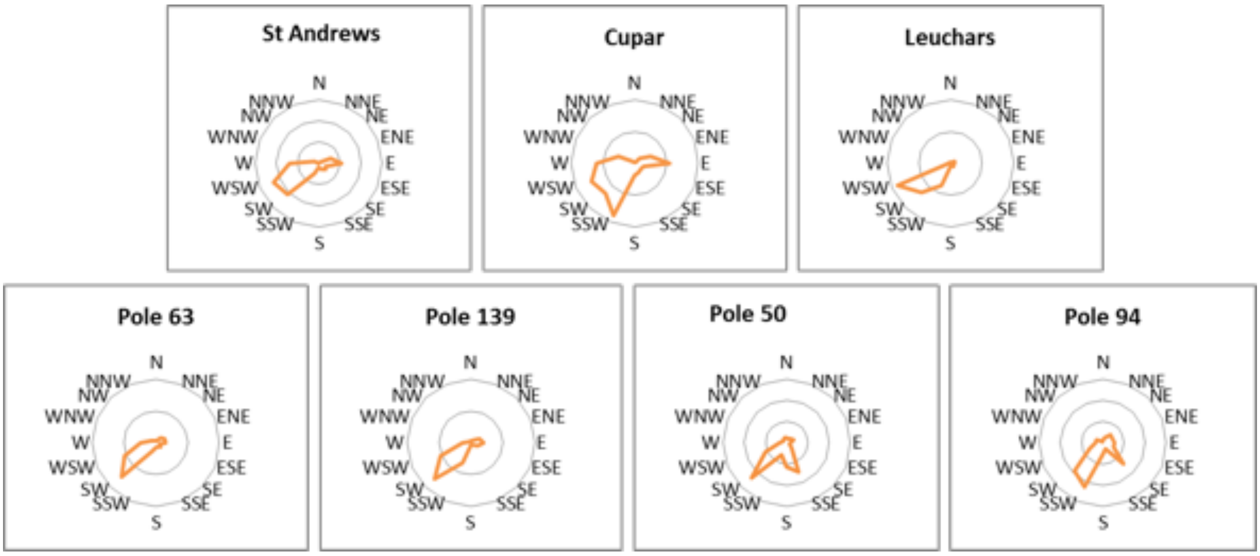


Figure 17: Wind direction at the St Andrews, Cupar and Leuchars weather stations and the four pole-mounted weather stations

4.1.2 Wind direction [continued]

Figure 18 and Figure 19 show the wind direction during the day (from 08:00 to 20:00) and during the night (20:00 to 08:00), respectively. There is no major difference between the prevailing wind directions during day and night.

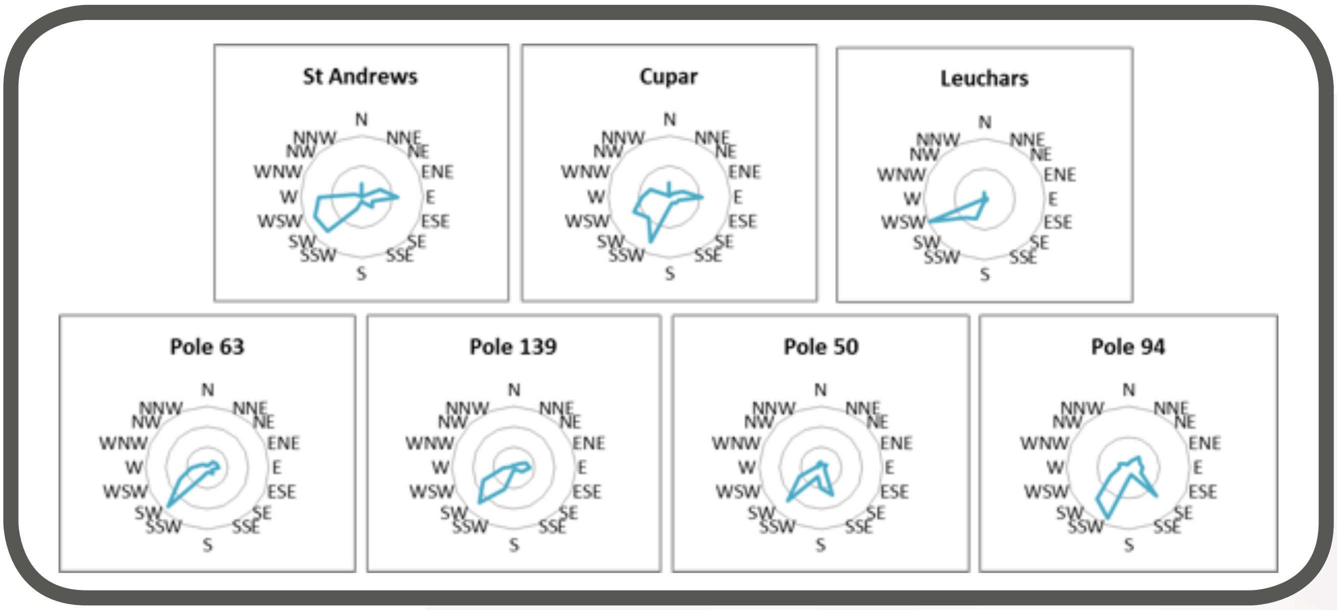


Figure 18: Wind direction during the day at weather stations

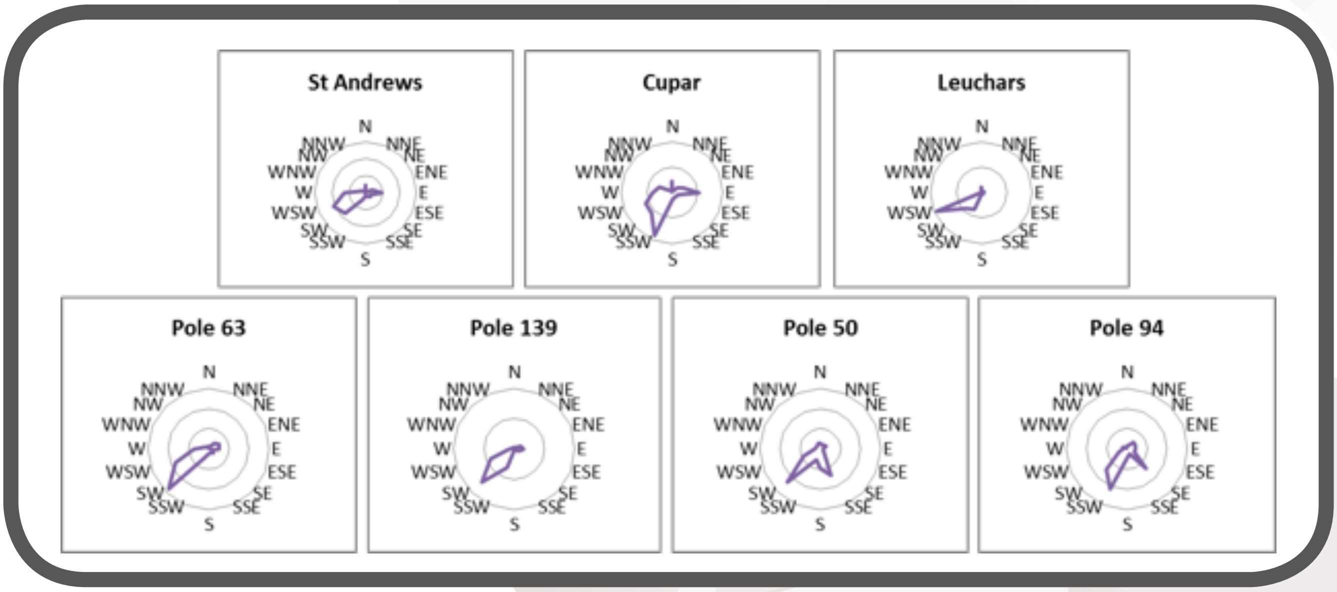


Figure 19: Wind direction during the night at weather stations

4.1.3 Ambient temperature

The ambient temperature and its variation were very similar at all weather stations. Figure 20 shows the ambient temperature variations during the studied period.

A summary of the recorded ambient temperatures is given in Table 4. The maximum ambient temperature recorded was 26.9°C, on 26th July at 13:35 at Cupar substation. The minimum temperature was -5.6°C, on 29th December at 8:35 at pole 63.

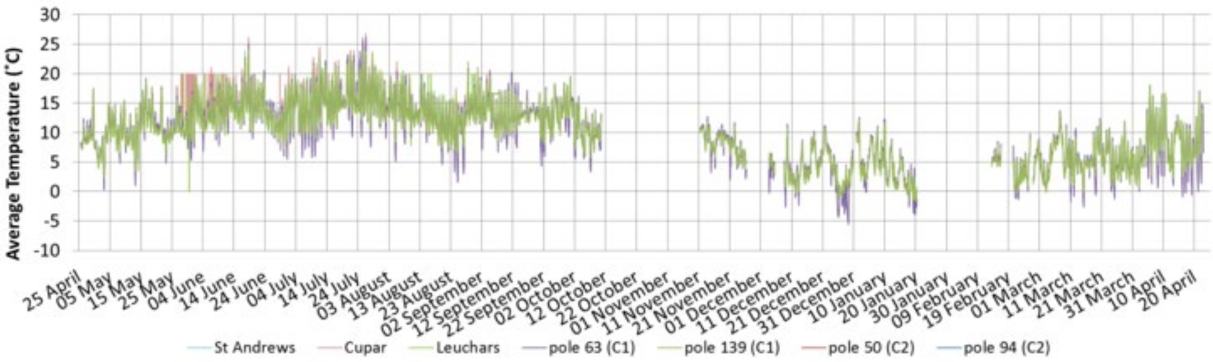


Figure 20: Ambient temperature at weather stations

Table 4: Summary of ambient temperature at each weather station

Ambient Temp (°C)	Pole 63	Pole 139	Pole 50	Pole 94	St Andrews	Cupar	Leuchars
Summer season							
Maximum	26.1	24.1	26.0	24.7	24.4	26.9	24.9
Minimum	0.3	2.2	1.4	3.2	4.6	4.3	2.8
Average	13.1	12.9	13.1	12.8	14.5	14.2	14.2
Winter season							
Maximum	18.0	18.1	15.8	16.8	18.3	18.6	17.9
Minimum	-5.6	-1.8	-3.3	-1.9	-2.5	-3.4	-3.6
Average	6.0	6.0	6.2	5.7	6.5	6.0	5.8

4.1.4 Solar radiation

The solar radiation usually follows a bell-shaped curve during a 24 hour period, as is illustrated in Figure 21, which shows solar radiation variations for a sample day. The solar radiation differences between locations are predominantly due to cloud cover or shading effect in hilly areas.

The measured solar radiation for the entire period of study is shown in Figure 22. The average solar radiation of all weather stations during daylight hours for the studied period was 254.8 W/m2.

The average daily solar radiation (during daylight hours) recorded at different locations is shown in Figure 23. Daily solar radiation at pole 50 is lower than the other weather stations as pole 50 is in a hilly area, which affects the received solar radiation at the pole 50 location, especially when sun is close to horizon during sunrise and sunset.

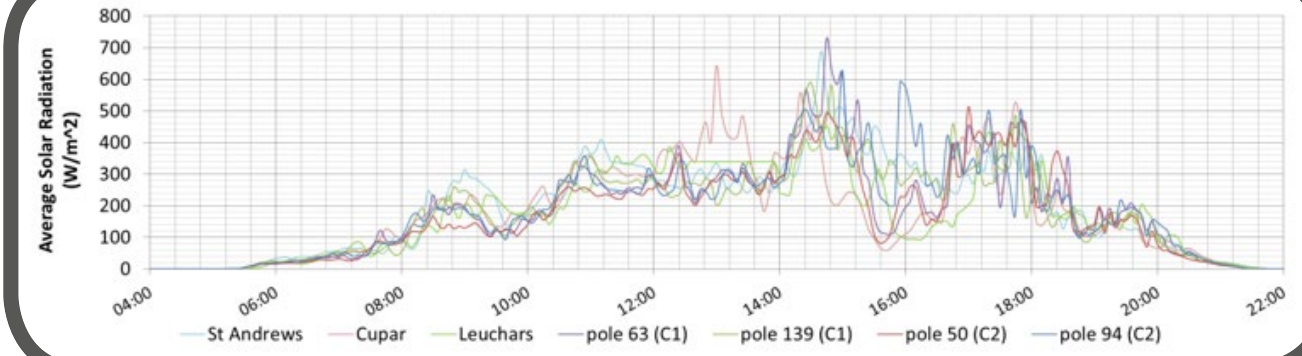


Figure 21: Solar radiation variations recorded during 1st August 2014

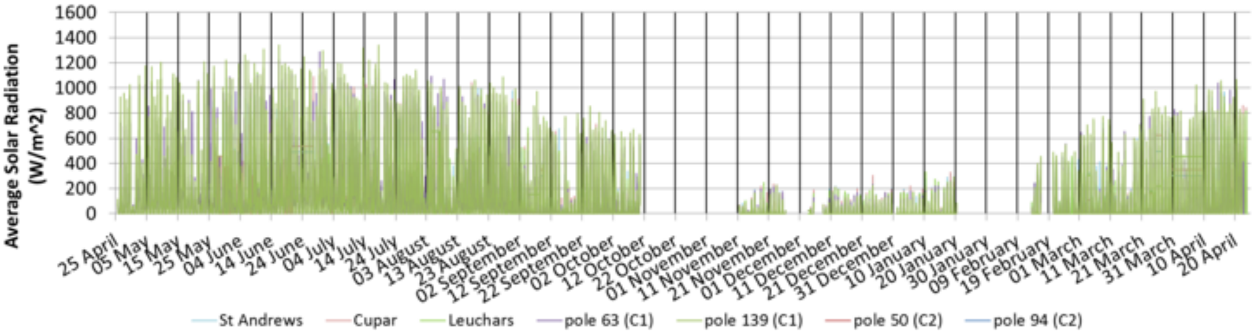


Figure 22: Solar radiation at the weather stations

4.1.4 Solar radiation [continued]

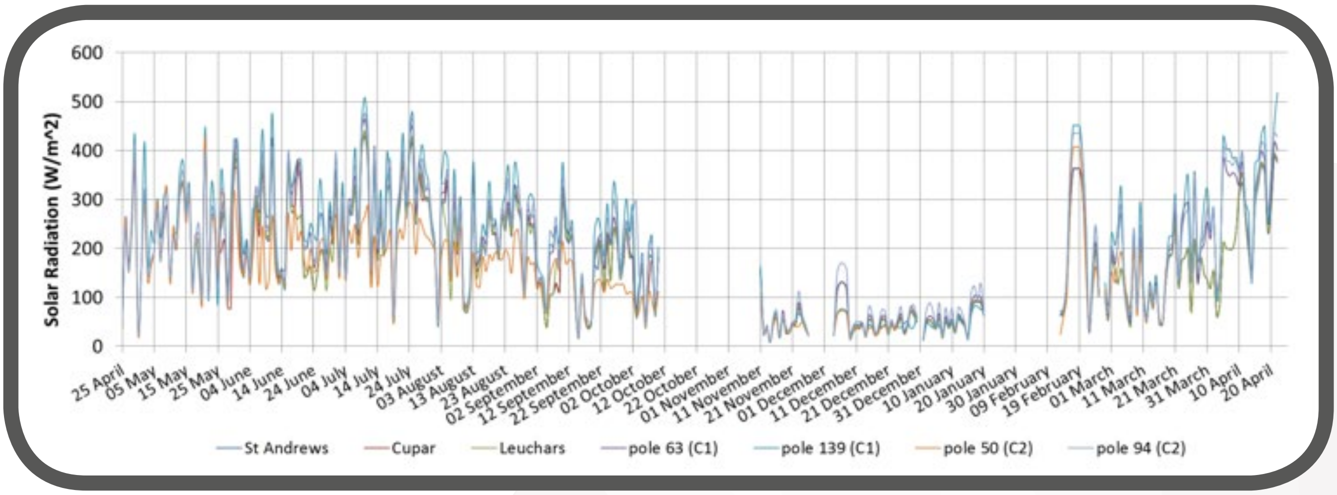


Figure 23: The daily average solar radiation recorded at the weather stations

Table 5 shows the maximum and average levels of solar radiation for each of the monitoring locations. The highest solar radiation was recorded at pole 139 on 16th June at 12:40 with a value of 1341 W/m2. During winter period, the maximum solar radiation was 1067 W/m2 recorded at the same location.

Table 5: Summary of solar radiation recorded at each weather station in W/m2

	Summer Season		Winter Season	
	Maximum	Average	Maximum	Average
Pole 63 (C1)	1266	244.1	1027	152.9
Pole 139 (C1)	1341	264.5	1067	164.8
Pole 50 (C2)	1160	189.0	687	115.5
Pole 94 (C2)	1202	247.5	1011	152.2
St Andrews	1097	307.6	645.8	177.9
Cupar	1119	323.8	593.2	162.4
Leuchars	1125	338.7	598.7	222.1

4.2 Weather station correlation analysis

The weather stations are located within an approximately 15 km area between Cupar and St Andrews. Within this area, the variations of weather parameters recorded at each weather station may follow a similar pattern to the parameters measured at other weather stations. In other words, weather parameters can be correlated across multiple locations. In this section, the results of correlation analysis on the different weather parameters are presented.

The results of correlation analysis can feed into graceful degradation methodology for estimating a missing weather parameter in case of sensor failure or malfunctioning of the communication system.

Figure 24 shows the general interpretation of the correlation coefficients that indicate the linear strength between two variables. The sign of the correlation coefficient shows the direction of the relationship between two variables. A positive sign means that when one variable increases, the other variable will also increase, whereas a negative sign indicates that as one variable increases the other variable will decrease, and vice versa.

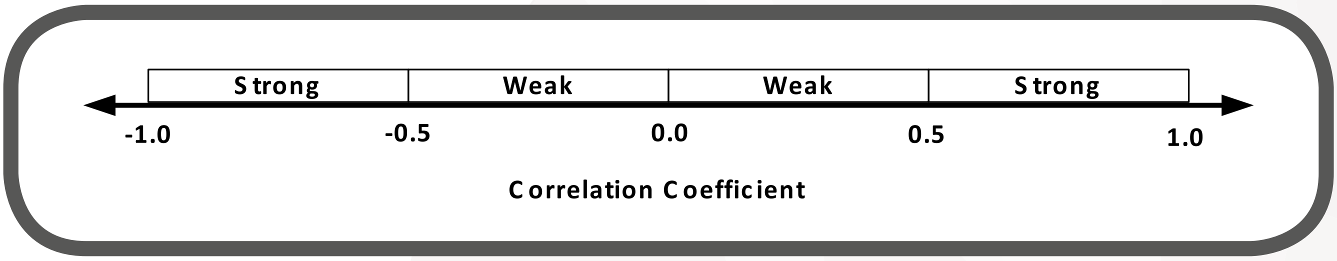


Figure 24: Correlation coefficient definition

In the following section the results of correlation analysis for the different weather parameters recorded at the weather stations are discussed.

4.2.1 Ambient temperature

Table 6 shows the correlation coefficients between the ambient temperatures recorded at the different weather stations. It can be seen there is a very strong correlation between ambient temperatures at different weather stations. This level of correlation suggests that ambient temperature at a weather station can be estimated with a high level of accuracy by using the ambient temperature data recorded at other weather stations.

Table 6: Correlation between ambient temperatures recorded at different locations

	St Andrews	Cupar	Leuchars	Pole 63	Pole 139	Pole 50	Pole 94
St Andrews	1.00	0.95	0.93	0.93	0.98	0.93	0.94
Cupar	0.95	1.00	0.91	0.95	0.96	0.96	0.95
Leuchars	0.93	0.91	1.00	0.90	0.92	0.89	0.90
Pole 63	0.93	0.95	0.90	1.00	0.95	0.99	0.94
Pole 139	0.98	0.96	0.92	0.95	1.00	0.95	0.97
Pole 50	0.93	0.96	0.89	0.99	0.95	1.00	0.94
Pole 94	0.94	0.95	0.90	0.94	0.97	0.94	1.00

4.2.2 Solar radiation

Table 7 shows the correlation coefficients between the solar radiation values recorded at the different weather stations. There are strong correlations for solar radiation between different locations. Pole 50 is the least correlated to other weather stations, which is due to the geo-topological characteristics of pole 50. Pole 50 is surrounded by a hilly area where solar radiation can be affected when sun close to horizon around sunrise and sunset. As the solar radiation values recorded at different weather stations are strongly correlated, the solar radiation at one weather station can be accurately estimated using solar radiation data at other weather stations.

Table 7: Correlation between solar radiation values recorded at different locations

	St Andrews	Cupar	Leuchars	Pole 63	Pole 139	Pole 50	Pole 94
St Andrews	1.00	0.72	0.77	0.74	0.80	0.55	0.74
Cupar	0.72	1.00	0.70	0.72	0.71	0.53	0.69
Leuchars	0.77	0.70	1.00	0.71	0.75	0.54	0.71
Pole 63	0.74	0.72	0.71	1.00	0.77	0.64	0.80
Pole 139	0.80	0.71	0.75	0.77	1.00	0.56	0.76
Pole 50	0.55	0.53	0.54	0.64	0.56	1.00	0.62
Pole 94	0.74	0.69	0.71	0.80	0.76	0.62	1.00

4.2.3 Wind speed

Table 8 shows the correlation coefficients between the wind speeds recorded at the different locations. Leuchars is not shown because the wind sensor at this weather station was faulty for the majority of the studied period. The results show the wind speed correlations between different weather stations are strong except for pole 50, which is the least correlated with other weather stations owing to pole 50 being located in a hilly area where it is shielded from the wind.

Table 8: The correlation between wind speeds recorded at different locations

	St Andrews	Cupar	Pole 63	Pole 139	Pole 50	Pole 94
St Andrews	1.00	0.66	0.79	0.82	0.65	0.80
Cupar	0.66	1.00	0.76	0.57	0.57	0.69
Pole 63	0.79	0.76	1.00	0.80	0.68	0.85
Pole 139	0.82	0.57	0.80	1.00	0.66	0.79
Pole 50	0.65	0.57	0.68	0.66	1.00	0.59
Pole 94	0.80	0.69	0.85	0.79	0.59	1.00

4.2.4 Wind direction

Table 9 shows the correlation coefficients between the wind directions recorded at the different locations. Leuchars is not shown because the wind sensor at this weather station was faulty for the majority of the studied period. Wind direction at pole 50 has a very weak correlation with other locations whereas there is strong correlation between wind directions recorded at the other weather stations.

Table 9: The correlation between wind speeds recorded at different locations

	St Andrews	Cupar	Pole 63	Pole 139	Pole 50	Pole 94
St Andrews	1.00	0.65	0.65	0.74	0.31	0.66
Cupar	0.65	1.00	0.68	0.61	0.33	0.67
Pole 63	0.65	0.68	1.00	0.62	0.34	0.66
Pole 139	0.74	0.61	0.62	1.00	0.33	0.64
Pole 50	0.31	0.33	0.34	0.33	1.00	0.31
Pole 94	0.66	0.67	0.66	0.64	0.31	1.00

4.3 Summary of St Andrews load profile

The pole-mounted installations also included co-located line sensors to monitor the line current (A) and conductor temperature (°C) for each phase (R, S and T) of the overhead line. The data from these sensors was available from 9th June 2014 when the installation was completed.

Figure 25 and Figure 26 show the current loading of the Cupar – St Andrews Circuit 1 and Circuit 2. The maximum loadings for the circuits are shown in Table 10.

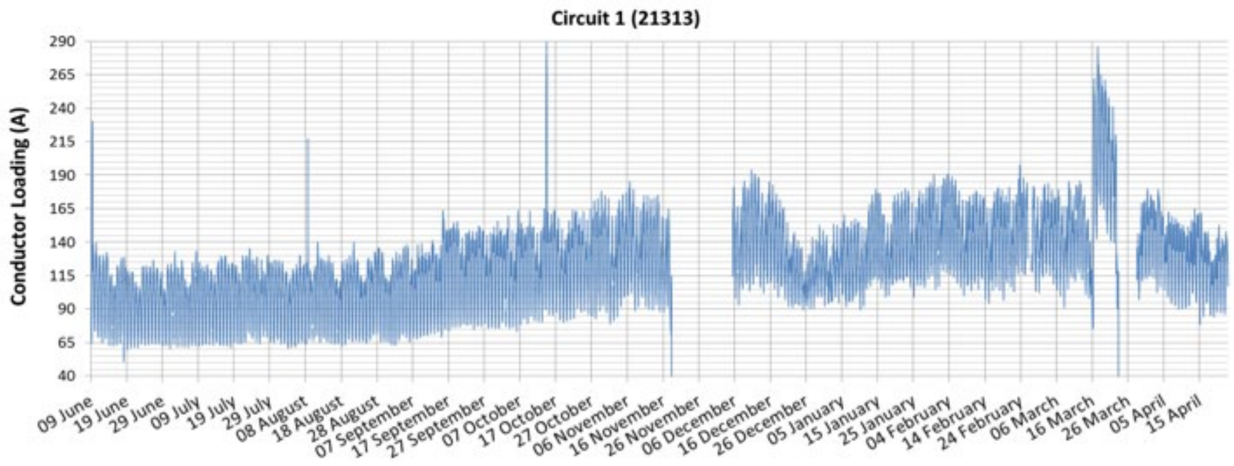


Figure 25: Loading of Circuit 1

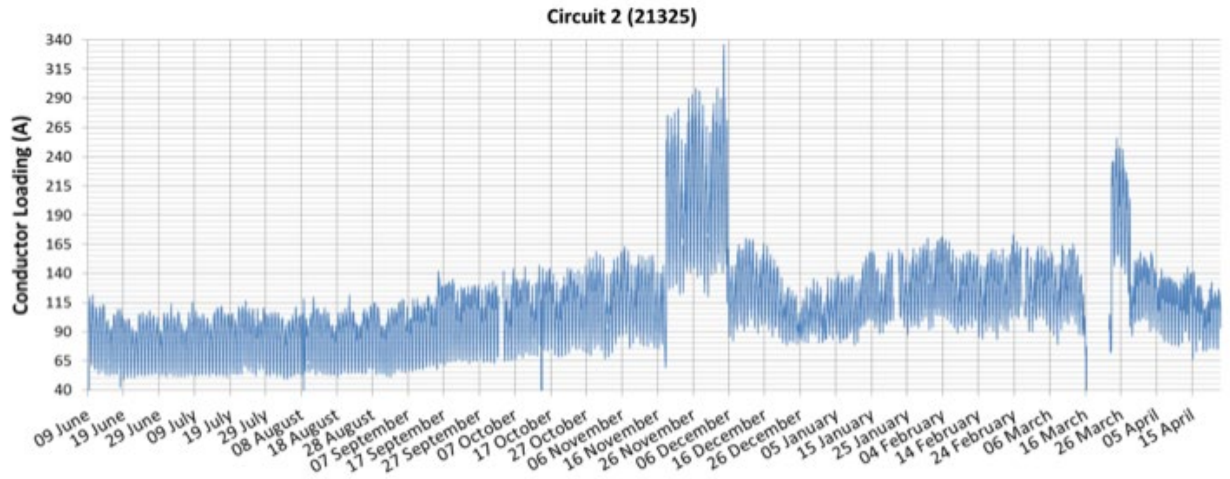


Figure 26: Loading of Circuit 2

4.3 Summary of St Andrews load profile [continued]

The loadings of the three phases on each circuit are usually not completely balanced. The maximum loading unbalance recorded for Circuit 1 was 7.4 A, and for Circuit 2, 4.8 A. The average loading unbalance for Circuit 1 and Circuit 2 was 1.49 A and 1.05 A, respectively. It should be noted that the load discrepancy between phases can be partly accounted for by the accuracy of the sensors, which is ±1%.

Table 10: Maximum conductor loading for the Cupar – St Andrews circuits

	Summer Season		Winter Season	
	Circuit 1	Circuit 2	Circuit 1	Circuit 2
Max (A)[1]	230.4	143.9	290.8	340.0

[1]Maximum occurs when the other circuit is switched off.

4.4 Summary of conductor temperatures

Conductor temperature depends on the loading of the conductor and the weather conditions at any given instant. The conductor temperatures monitored at four locations are shown in Figure 27 and Figure 28 for Circuit 1 and Circuit 2, respectively. A summary of the recorded conductor temperatures is given in Table 11. Additional line sensors were installed at pole 2 of Circuit 2 on 14th October 2014. Pole 2 is selected as the direction of the spans at this pole is likely to create a small angle with prevailing wind. The highest temperature value of the three phases for each instant is used when calculating the maximum, minimum and average conductor temperatures over the studied period.

The designed operating temperature for the Cupar – St Andrews 33 kV overhead lines is 50°C. The results show that the conductor temperatures at the monitored locations have been within the permissible limit (below 50°C).

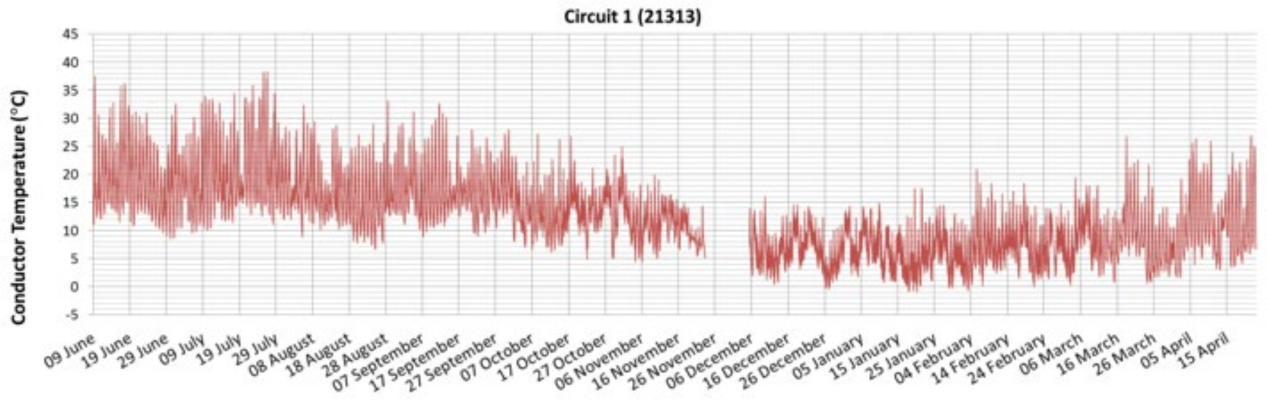


Figure 27: Conductor temperature of Circuit 1 (maximum measured temperature at Pole 63 and Pole 139)

4 The outcomes of the work [continued]

4.4 Summary of conductor temperatures [continued]

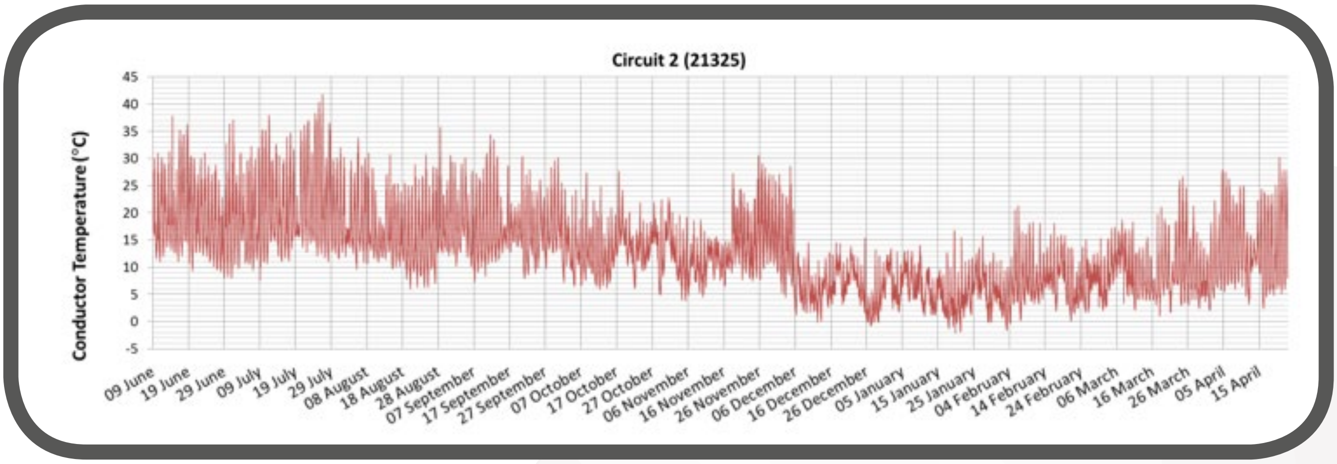


Figure 28: Conductor temperature of Circuit 2 (maximum measured between at Poles 2, 50 and 94)

Table 11: Summary of conductor temperature recorded in Cupar – St Andrews

	pole 63	pole 139	pole 50	pole 94	pole 2[1]
Summer Season					
Maximum	38.3	36.2	41.8	38.1	—
Minimum	1.3	6.6	1.5	5.8	—
Average	16.9	17.4	17.7	17.0	—
Winter Season					
Maximum	26.5	27.2	30.5	25.8	30.2
Minimum	-4.8	-1.2	-5.3	-2.9	-2.4
Average	7.4	8.8	9.6	8.7	7.4

[1] *pole 2 was installed on 14th October 2014*

The maximum conductor temperature of 41.8 °C was recorded at pole 50, which occurred during high solar insolation (722 W/m2), low wind speed (0.8 m/s) and a small angle of attack for the wind (around 20°). The loading of Circuit 2, where pole 50 is located, was around 85 A at this time. The maximum temperature in winter was 30.5 °C also recorded at pole 50.

In general, as pole 50 is located in an area surrounded by hills and shielded from wind, conductor cooling through convection may be lower than other locations; hence, pole 50 is more likely to be the thermal pinch point of Circuit 2. The lowest conductor temperature was recorded at pole 63.

4.5 Summary of RTTR values

The RTTR calculation engine uses the weather parameters recorded at the weather stations to calculate the RTTR of the Cupar – St Andrews circuits.

Figure 29 and Figure 30 show the RTTRs of Cupar – St Andrews Circuit 1 and Circuit 2 from 25th April 2014 to 23rd April 2015. The Figures also show the summer and winter static thermal ratings at 350A and 437A, to allow comparison to the RTTRs. The results show that the real-time thermal ratings are usually greater than the static rating, which would allow a higher carrying capacity for Cupar – St Andrews 33 kV circuits.

The weather station, which is currently mounted at Pole 50, was initially installed at Pole 54. However, this weather station was moved to Pole 50 on 9th June 2014 due to wayleave issue. Pole 50 is a more shielded location compared to Pole 54. This explains a sudden reduction in RTTR values for Circuit 2 after 9th June 2014, see Figure 30.

The average thermal rating uplift offered by RTTR system is around 12.0% for Circuit 1 and 10.0% for Circuit 2 compared to the seasonal thermal ratings. The uplift has been calculated comparing the uplifts for each season against the respective static ratings, which are 14.0% and 10.0% for summer and winter, respectively, for Circuit 1; and 14.0% and 7.0% for Circuit 2.

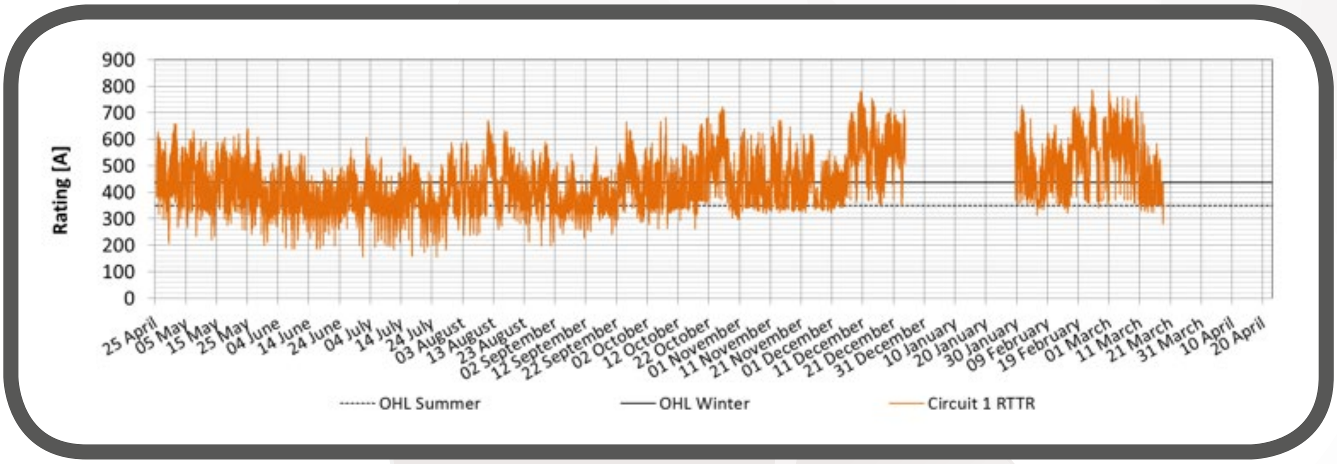


Figure 29: Real-time thermal rating of Circuit 1 (SP21313)

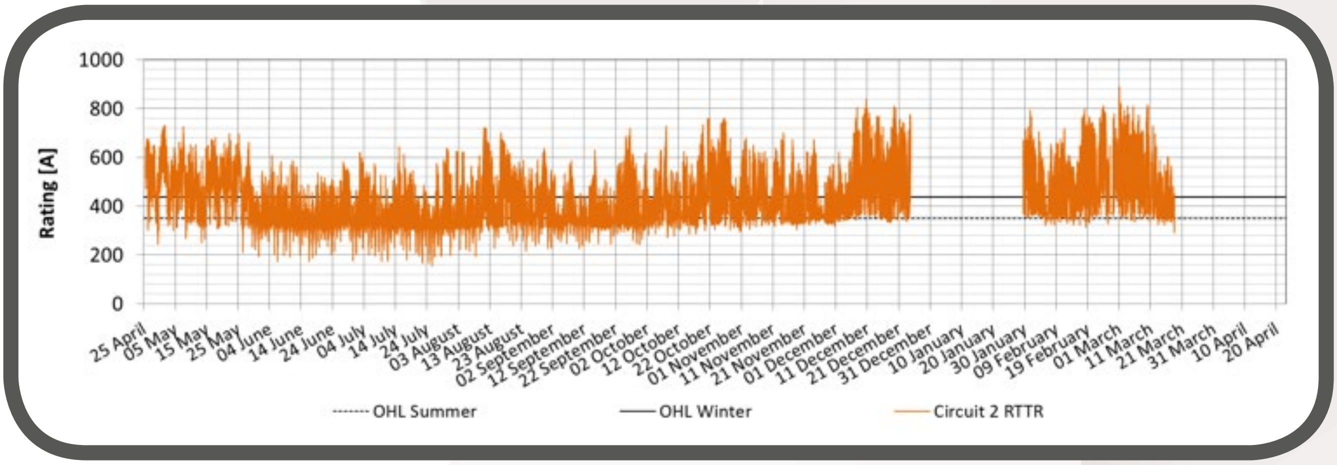


Figure 30: Real-time thermal rating of Circuit 2 (SP21325)

4.5 Summary of RTTR values [continued]

The reason that the average Circuit 2's RTTR is lower than Circuit 1's RTTR is that wind speed at pole 50 on Circuit 2 is often lower than the other sites. The low wind speed can have a significant effect on cooling of the conductors and creates a thermal pinch point that affects the ratings of the overhead line.

Figure 31 and Figure 32 illustrate the circuit loading and RTTR for Circuit 1 and Circuit 2 respectively, while Figure 33 and Figure 34 show the circuit loadings as a proportion of the RTTRs. These Figures show the circuit loading is much lower than RTTR. The maximum load to RTTR ratio for Circuit 1 is around 87.9%, which occurs on the 18th March 2015 at 13:30. For Circuit 2 the maximum load to RTTR ratio is around 95.4%, which occurs at 4th December 2014 15:00.

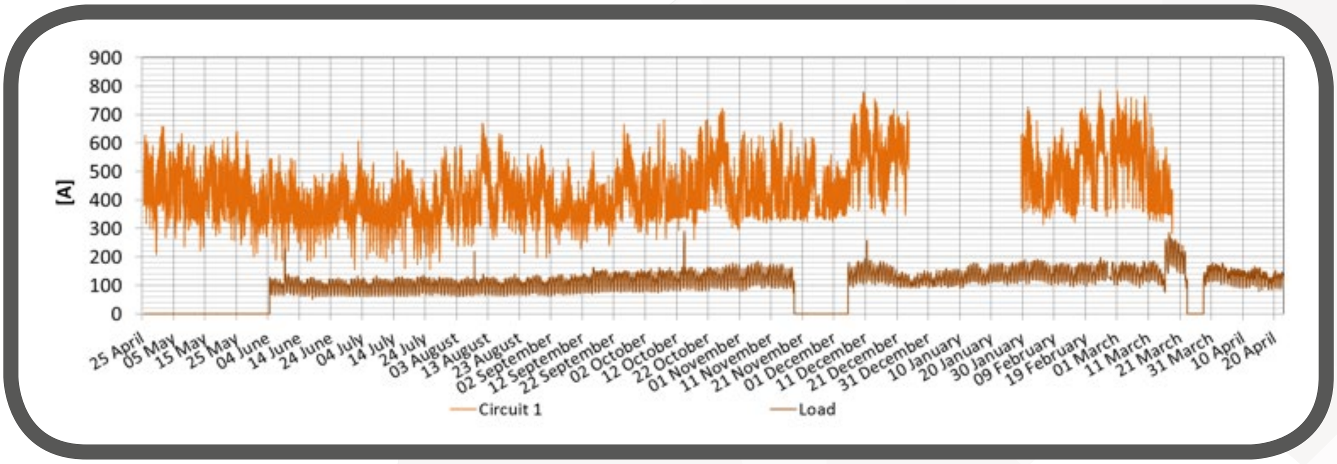


Figure 31: RTTR and loading for Circuit 1 (SP21313)

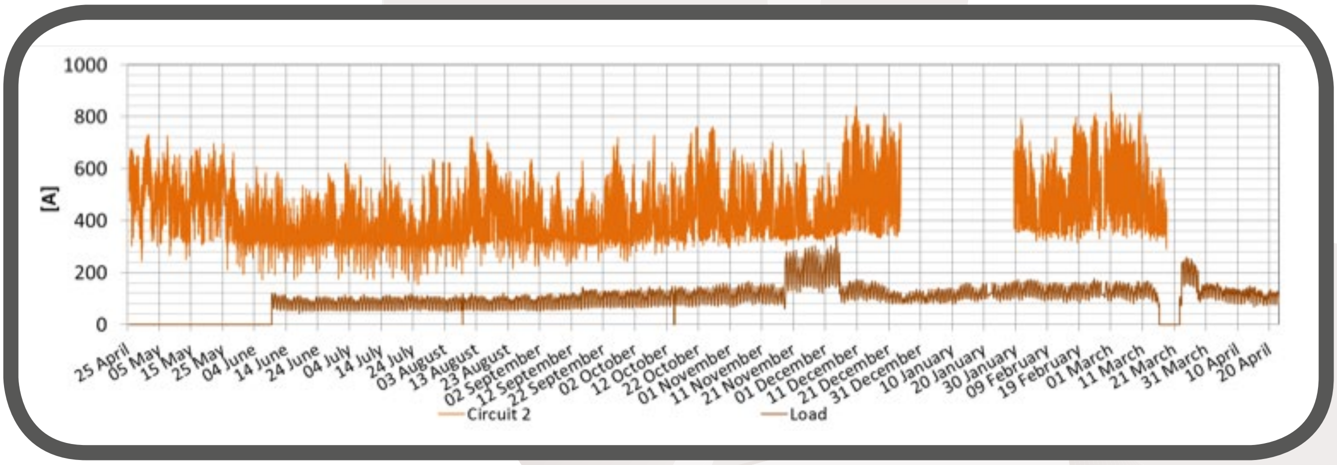


Figure 32: RTTR and loading for Circuit 2 (SP21325)

4.5 Summary of RTTR values [continued]

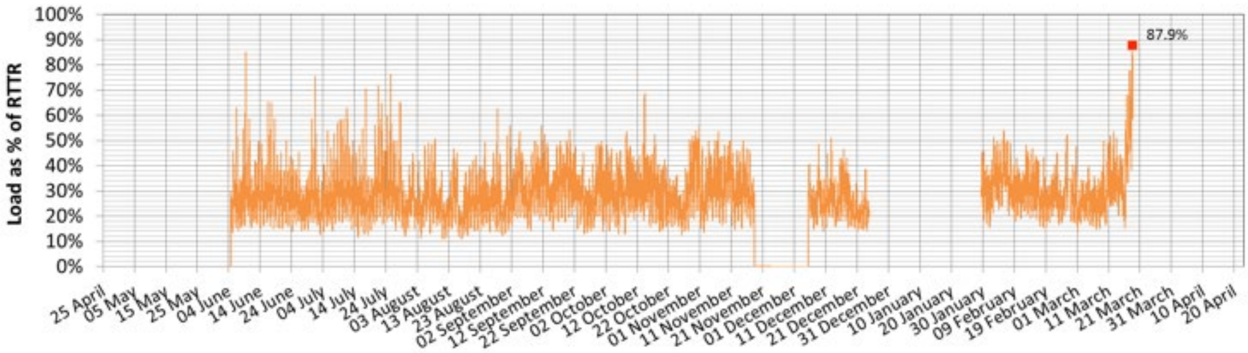


Figure 33: Load to RTTR ratio for Circuit 1 (SP21313)

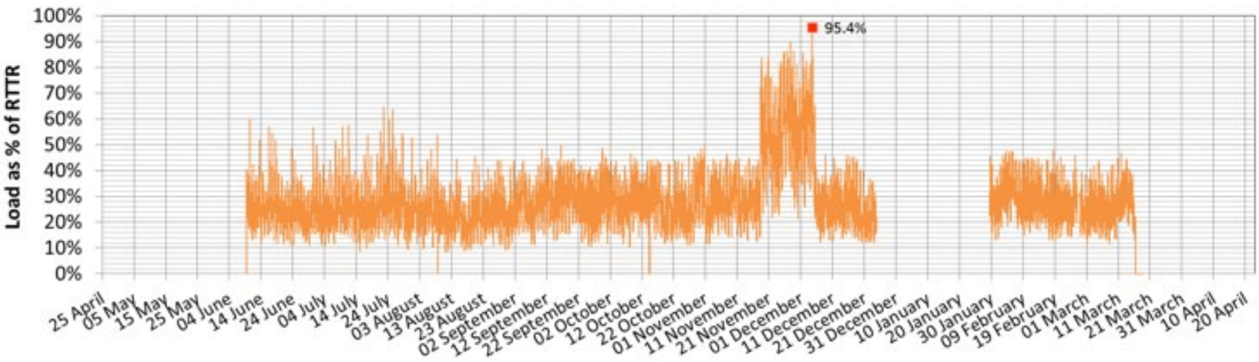


Figure 34: Load to RTTR ratio for Circuit 2 (SP21325)

4.5 Summary of RTTR values [continued]

Figure 35 and Figure 36 show the frequency of each span that was identified as the limiting span (or critical span). For Circuit 1, the span between pole 1 and pole 2 is reported as the most frequent critical span, closely followed by the span between pole 171 and pole 172. Spans between poles 9 and 9a, and between poles 154 and 155 have also been identified as some of the most frequent critical spans.

For Circuit 2, as shown in Figure 36, the critical span is the span between pole 50 and pole 51.

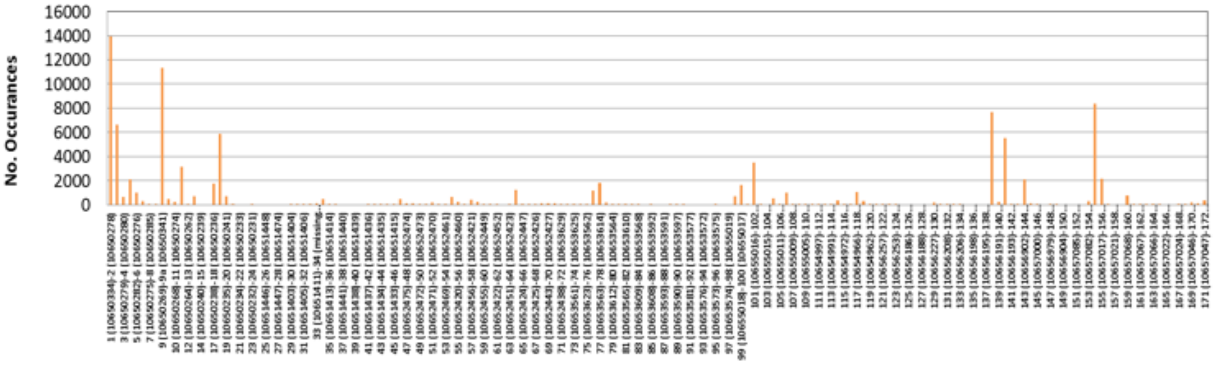


Figure 35: Frequency of critical spans in Circuit 1

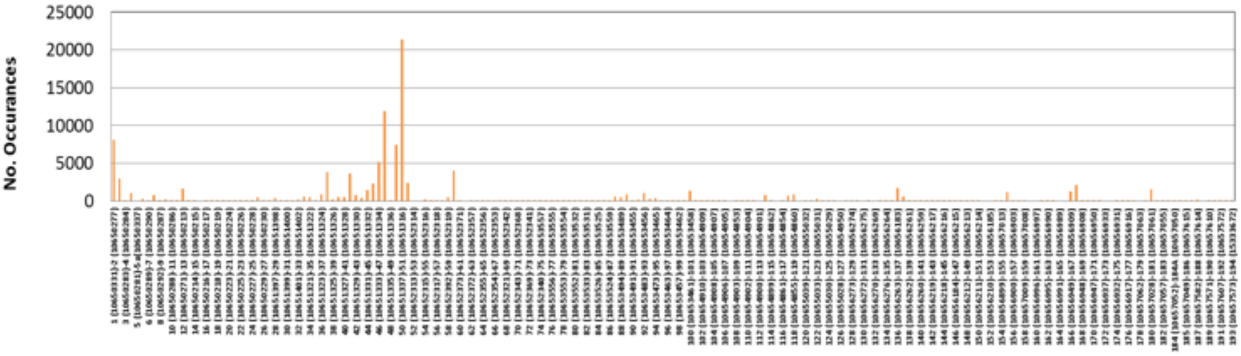


Figure 36: Frequency of critical spans in Circuit 2

4.5 Summary of RTTR values [continued]

Figure 37 and Figure 38 show the additional energy which can be transferred through the Cupar – St Andrews circuits for different levels of uplift if compared to the summer rating. As an example, with 20% uplift on the summer rating, an additional 17 GWh can be transferred through circuit 1. This energy is around 50% of the ultimate energy yield when no constraint is applied on the uplift.

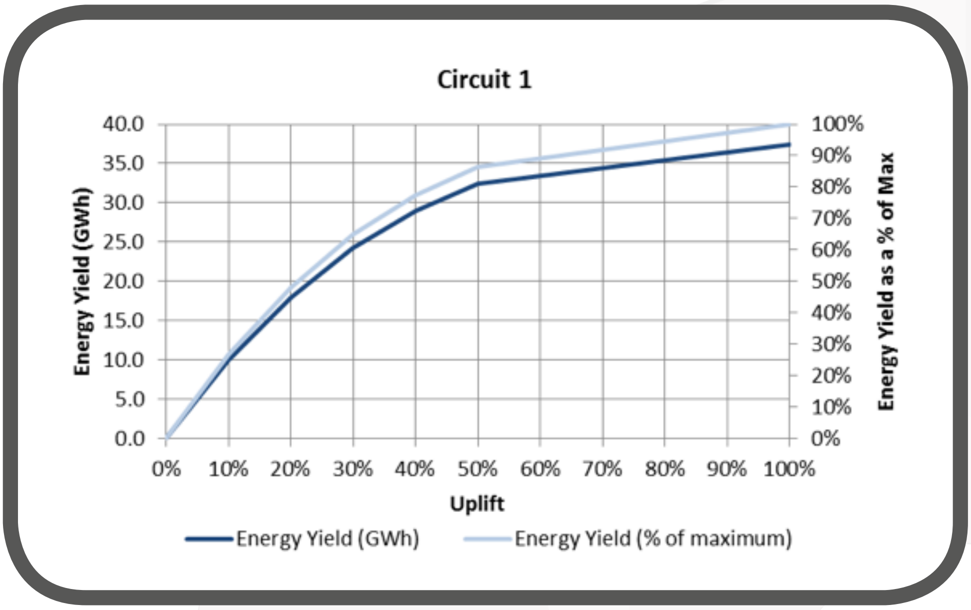


Figure 37: The additional energy yield for different uplift levels of circuit 1

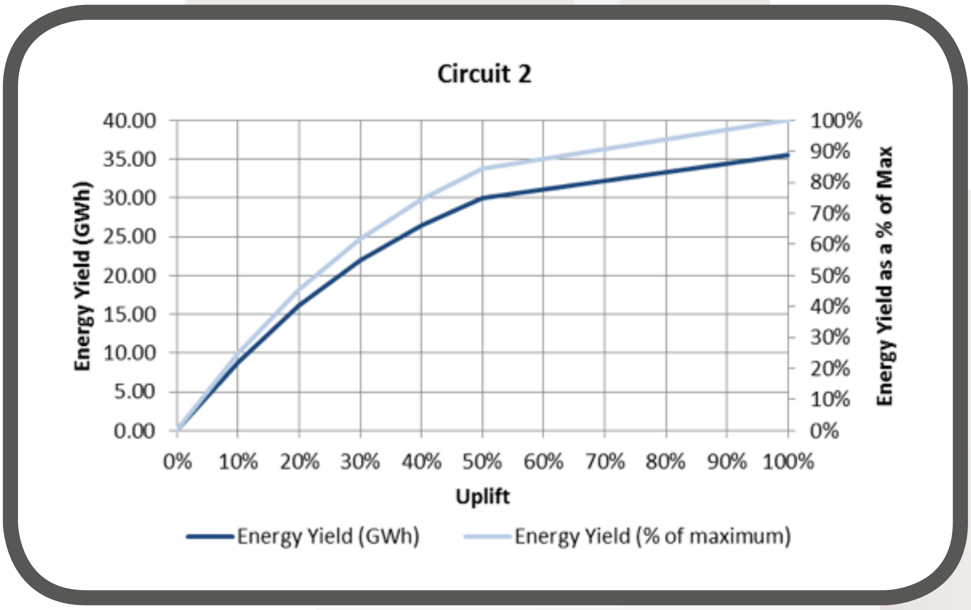


Figure 38: The additional energy yield for different uplift levels for circuit 2

4.5 Summary of RTTR values [continued]

The key results of RTTR for the studied period are summarised in Table 12.

Table 12: The key RTTR results highlighted for the Cupar –St Andrews 33 kV circuit

	Circuit 1	Circuit 2
	Summer Season	
Maximum RTTR	669.2 A (11/08/14 5:05)	729.8 A (1/05/14 19:10)
Average RTTR	398.5 A	399.3 A
Minimum RTTR	155.3 A (25/07/14 14:00)	153.8 A (25/07/14 15:25)
Additional Energy Yield[1]	12.6 GWh	13.6 GWh
Curtailed Energy[2]	2.1 GWh	2.8 GWh
% time RTTR above static rating	68.4 %	59.3 %
Maximum Load/RTTR ratio	83 %	64 %
Most frequent critical span	pole 1 – pole 2	pole 50 – pole 51
	Winter Season	
Maximum RTTR	786.86 (23/02/15 14:15)	879.11 (1/03/15 3:30)
Average RTTR	484.92	468.73
Minimum RTTR	261.24 (17/10/14 14:05)	271.40 (8/10/14 11:40)
Additional Energy Yield[1]	12.6 GWh	11.1 GWh
Curtailed Energy[2]	3.9 GWh	5.3 GWh
% time RTTR above static rating	63.4 %	56.1 %
Maximum Load/RTTR ratio	87.9 %	95.4 %
Most frequent critical span	pole 1 – pole 2	pole 50 – pole 51

[1] *Net additional energy that can be transferred through the circuit (increased energy minus curtailed energy)*

[2] *Energy below the seasonal (summer) rating*

For the research purposes a dataset including weather parameters, conductor temperatures and RTTR values for a month period in winter and summer is given in Appendix F.

4.6 Conductor temperature estimation & model validation

As explained in 3.9, a methodology for estimating the temperature of the conductor based on the meteorological data and the conductor loading was developed. In order to validate the RTTR model and the methodology for conductor temperature estimation, calculated conductor temperatures were compared with the measured values at the four locations (pole 50, pole 63, pole 94 and pole 139) where GE Energy's intelligent line monitoring system equipment is installed. This comparison was performed for a two day period from 11 June 2014 00:00 to 13 June 2014 00:00, which was selected at random.

4.6.1 Assumptions

The following assumptions were made for the conductor temperature calculations, model validation and for the comparisons between the calculated values and the monitored data:

- Weather parameters and the conductor current were updated every 5 minutes. During this 5 minute period, it was assumed that all parameters remain unchanged.
- The electrical and physical parameters of the spans considered were same as those used in the Cupar – St Andrews RTTR system.
- The weather parameters at each span were assumed to be the weather parameters recorded at an adjacent weather station plus (or minus) the accuracy of the sensors. The accuracy tolerance of the sensors was added to or deducted from the actual measured values to represent a conservative estimation. For example, wind sensor tolerance was deducted from the measured wind speed whereas the solar radiation sensor tolerance was added to the measured solar radiation.
- The recorded values for the loadings of the three phases of OHL were usually different. This was due to the fact that the loadings of three phases are not always balanced, and also because the accuracy of line sensors was +/-1%. For validation purposes, the largest recorded value of the three phases was assumed as the loading of the conductor for each time instant.
- The recorded values of conductor temperatures of the three phases of OHL are usually different. This was due the fact that the loading of the three phases are not balanced, and also because the accuracy of the line sensors was +/- 2˚C. For validation purposes, the largest recorded value of the three phases was assumed as the temperature of the conductor for each time instant.
- It was assumed the AC resistance of the conductors remain unchanged with respect to variations in conductor temperature.
- For modelling the transient thermal behaviour of the conductor, it was assumed that the thermal behaviour of the conductor had linear behaviour for every 10 seconds. For more details about modelling the transient behaviour of the conductor see Appendix E.

4.6.2 Validation results

Figure 39 shows a comparison between the calculated and monitored conductor temperature values at Pole 63. The results show the calculated and measured conductor temperatures follow similar variations and the difference between them is usually within the equipment accuracy range. The average absolute differences between calculated and measured temperature in this case is around 0.9°C.

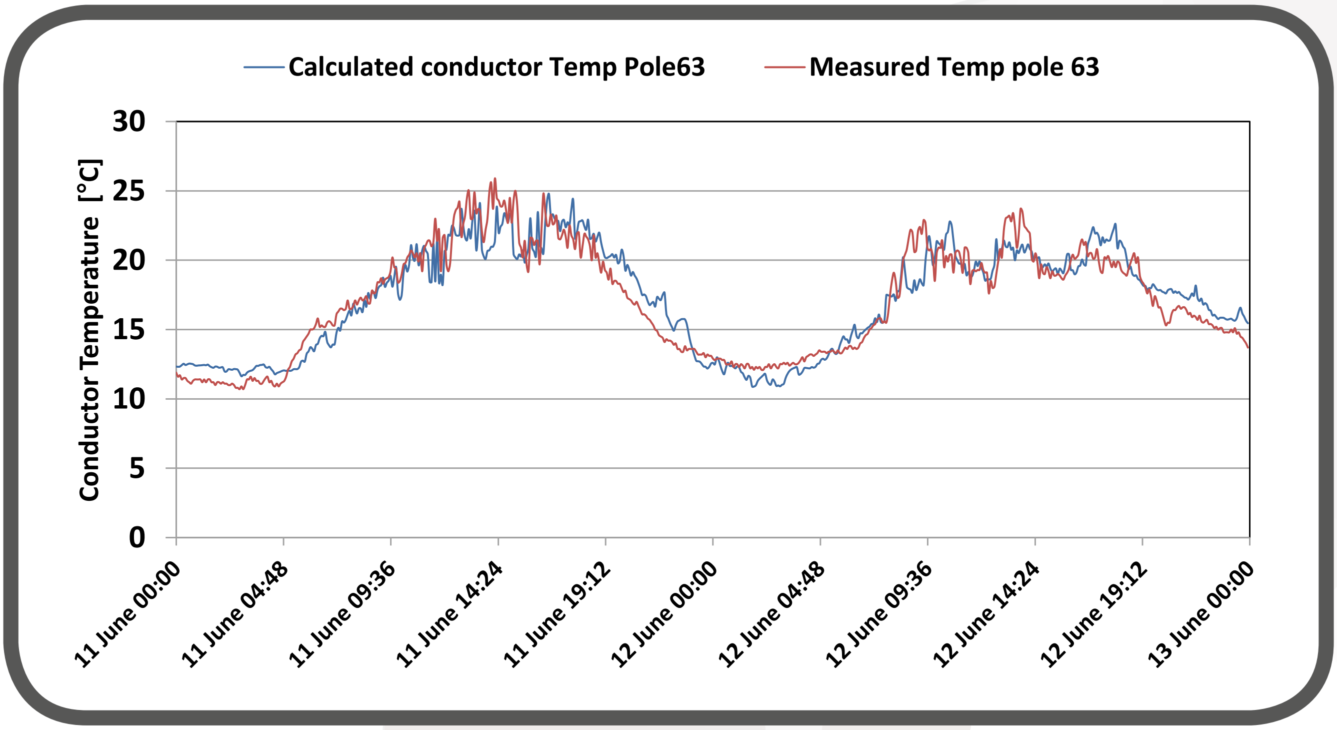


Figure 39: Calculated and measured conductor temperature at pole 63

The following factors may cause the discrepancies between the calculated and measured conductor temperature values:

- *Granularity of the monitored parameters:* The average values of the weather parameters over 5 minute periods were used for conductor temperature calculation. In reality the weather parameters, especially wind speed, are very volatile and any change in them can affect the transient thermal behaviour of the conductor.
- *Accuracy of the equipment:* The measured parameters are not 100% accurate and each monitored value is associated with a degree of accuracy. Any deviation from the actual value due to the accuracy of the sensor can contribute to the discrepancies between calculated and monitored conductor temperature values.
- *Accuracy of the overhead line model:* The parameters of the overhead line model are associated with degree of accuracy. For example the resistance of the conductor or the emissivity and absorption coefficients may change due to conductor aging.

4.6.3 Overhead line temperature heat map

In order to demonstrate the conductor temperature variations along the overhead line, the conductor temperature of each span within the Cupar – St Andrews circuits has been calculated for different meteorological conditions. For these calculations, the interpolation technique, which is also used in RTTR calculation, is used together with the data monitored at weather stations to estimate the weather parameters at each span.

For the purpose of demonstrating overhead line temperature profiles, four snapshots of weather conditions representing day and night weather parameters in summer and autumn are presented, as listed in Table 13. The loadings of the Cupar – St Andrews circuits at these times are given in Table 14.

Table 13: Representative weather conditions considered for different seasons in 2014

	Night	Day
Summer	26th July at 03:00	26th July at 14:45
Autumn	30th September at 03:00	30th September at 14:00

Table 14: Loading of Cupar – St Andrews 33 kV circuits

	Load (A)	
	Circuit 1	Circuit 2
26-Jul-14 03:00	68.6	57.2
26-Jul-14 14:45	103.7	87.9
30-Sep-14 03:00	79.5	66.7
30-Sep-14 14:00	137.0	117.6

4.6.3 Overhead line temperature heat map [continued]

The Cupar – St Andrews overhead line temperature profiles are calculated and the results are presented in Figure 40 to Figure 43.

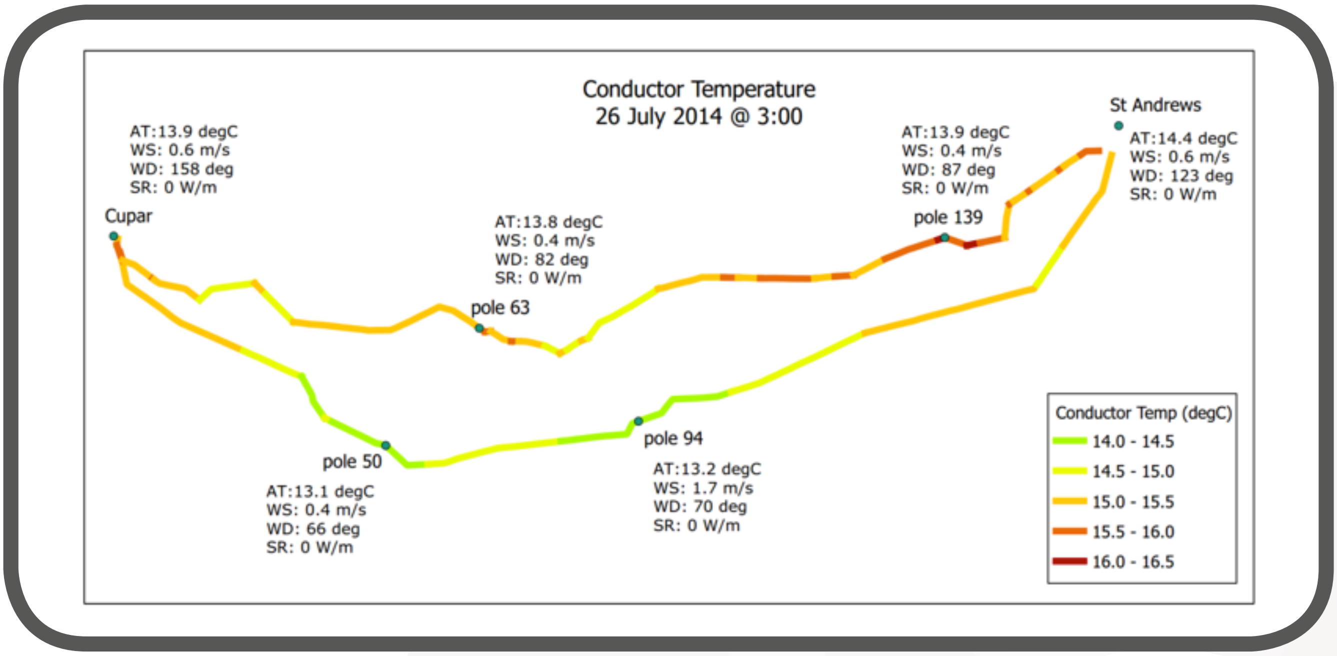


Figure 40: Conductor temperature across the Cupar – St Andrews circuits on 26 July 2014 at 03:00. The metereological measurements at each weather station are indicated

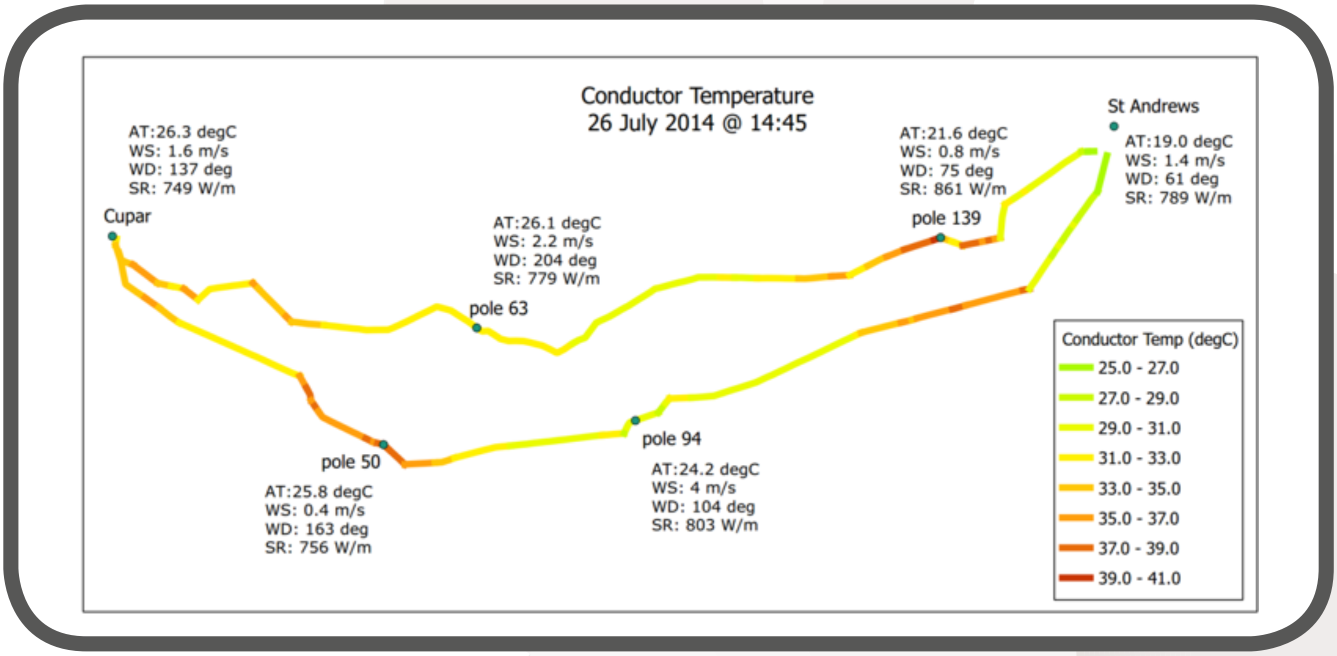


Figure 41: Conductor temperature across the Cupar – St Andrews circuits on 26 July 2014 at 14:45. The metereological measurements at each weather station are indicated.

4.6.3 Overhead line temperature heat map [continued]

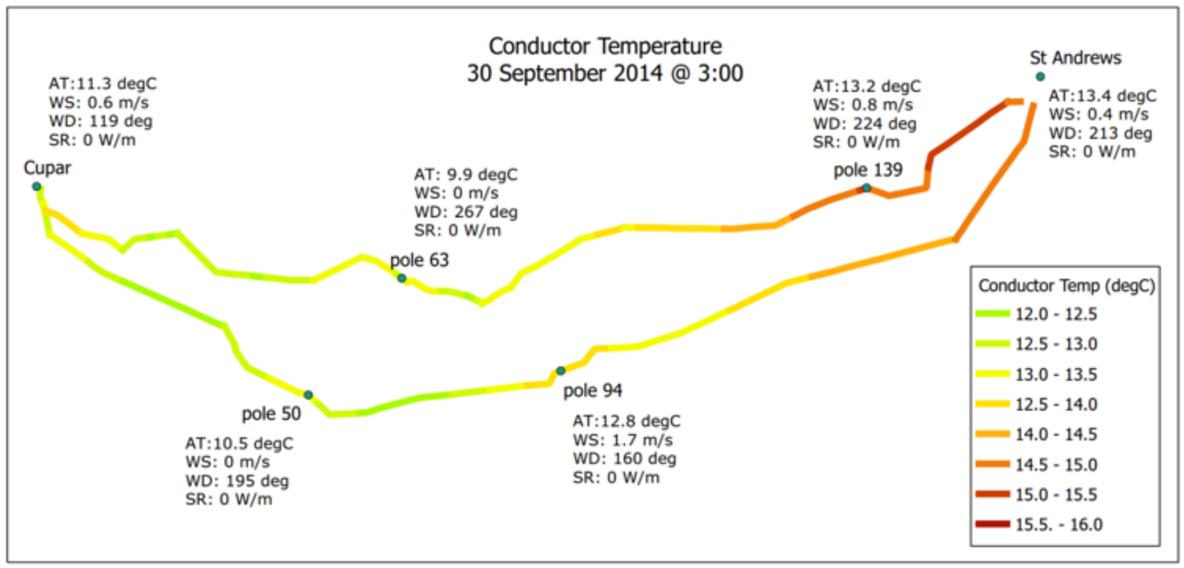


Figure 42: Conductor temperature across the Cupar – St Andrews circuits on 30 September 2014 at 03:00. The metereological measurements at each weather station are indicated.

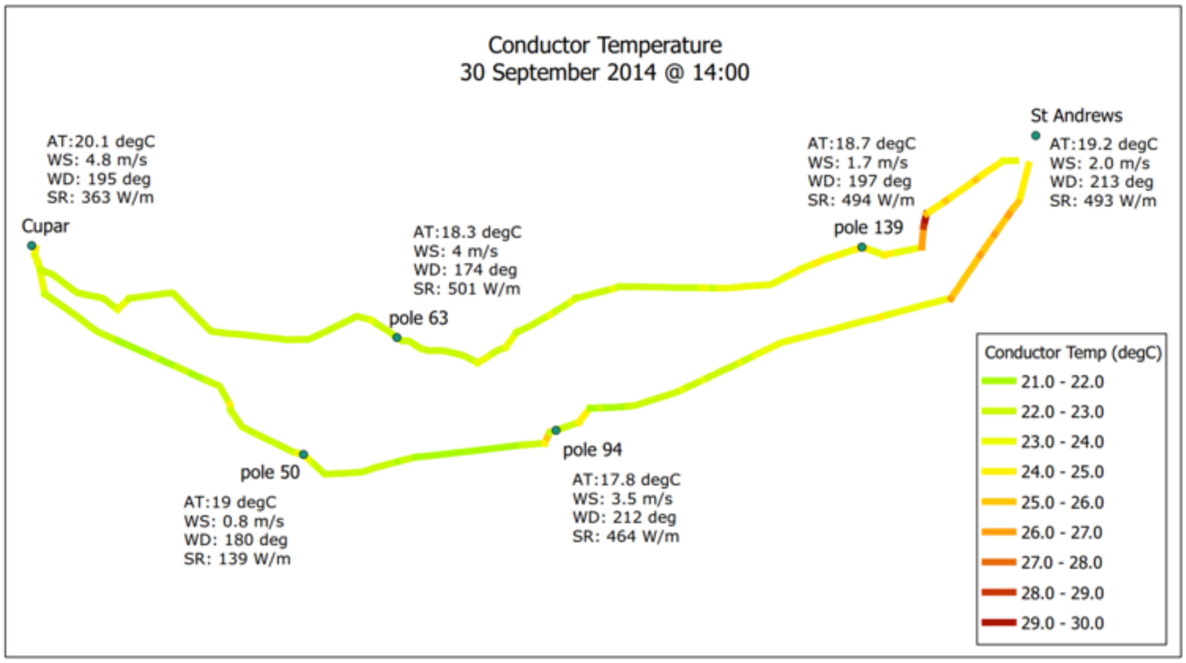


Figure 43: Conductor temperature across the Cupar – St Andrews circuits on 30 September 2014 at 14:45. The metereological measurements at each weather station are indicated

4.6.3 Overhead line temperature heat map [continued]

Figure 40 and Figure 41 show the values for 26th July at 03:00 and 14:45, respectively. The night condition eliminates the solar radiation variable, helping to isolate the effect of the other meteorological parameters.

Figure 40, which is an example of a summer night condition, shows that spans around pole 139 in Circuit 1 experience a higher temperature compared to the rest of the spans. This is due to low wind speed and a westerly wind direction recorded at pole 139. For this example, the maximum differences in conductor temperatures between spans are around 2.0°C for Circuit 1 and 1.0°C for Circuit 2.

In the example for summer day conditions (Figure 41) the spans around pole 139 in both circuits and spans around pole 50 experience higher conductor temperatures than the rest of spans. The conductor temperature at these locations reaches around 40°C. This is mainly due to low wind speed experienced at pole 139 and pole 50. The solar radiation recorded at pole 139 is higher than other locations, and this also contributes to the raised conductor temperature. The maximum differences in conductor temperatures between spans are around 14.0°C for Circuit 1 and 11.0°C for Circuit 2.

In the example of autumn night conditions (Figure 42) the eastern spans of both circuits near St Andrews experience a higher temperature than the western spans of the circuits. This is due to higher ambient temperatures and lower wind speeds recorded at pole 139 and St Andrews compared to the rest of weather stations. In addition, the south-westerly wind direction in eastern parts of the circuits has a small angle of attack relative to the spans in that area and consequently the wind cooling effect would be low. The maximum difference in conductor temperatures between spans is around 2.0°C for both circuits.

In the example of autumn day conditions (Figure 43) the critical span of Circuit 1 is between poles 154 and 155 with a temperature of 29.1 °C. The weather stations at pole 139 and the St Andrews substation recorded a southerly wind direction, which results in a very small angle of attack for the wind (around 10°) at the 154-155 span. The maximum differences in conductor temperatures between spans are around 5.0°C for Circuit 1 and 3.0°C for Circuit 2.

4.7 Correlation between load and RTTR

In the previous RTTR trial which SPEN conducted in North Wales, it was demonstrated that there is a high correlation between the wind farm power outputs and RTTRs as both of these variables highly depends on wind speed. In this project, however, there is not any wind farm connection to the Cupar-St Andrews circuits, and these circuits mainly supply residential and commercial demands in St Andrews area. As shown in Figure 44 the maximum daily loading of the St Andrews – Cupar versus the ambient temperature at the time of daily peak demand for a year period. The St Andrews maximum daily demand is inversely correlated with the ambient temperature i.e. demand increases while the ambient temperature decreases.

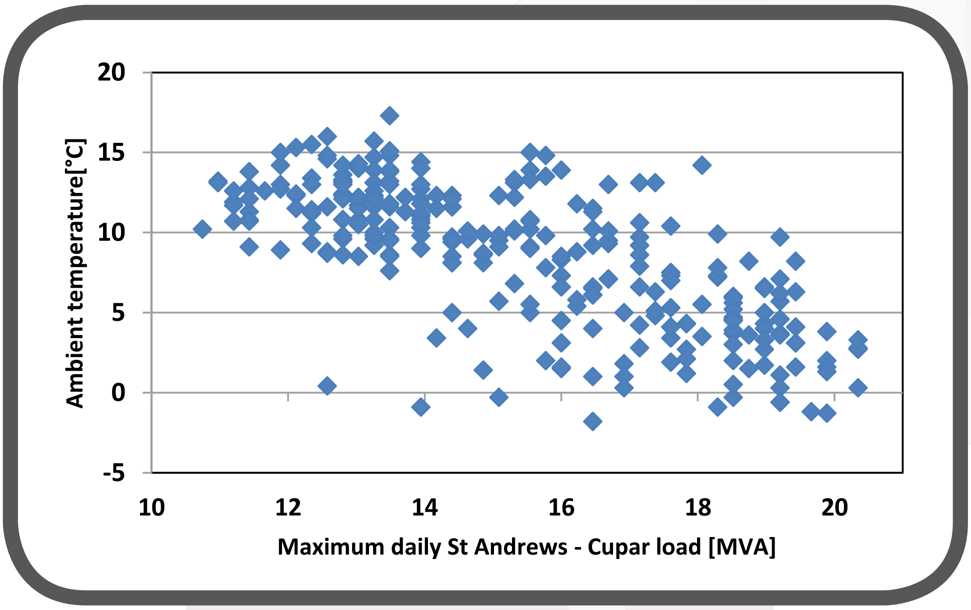


Figure 44: Correlation between demand and ambient temperature in St Andrews area

4.7 Correlation between load and RTTR [continued]

In colder conditions, when ambient temperature is low, overhead line may dissipate a larger heat. RTTR of an overhead line, however, can be highly affected by wind speed which does not have as much impact as ambient temperature on demand. Therefore, it is unlikely to see a strong correlation between RTTR values and the loading of the overhead line. This conclusion is demonstrated in Figure 45 and Figure 46 showing the RTTR values at the maximum loading of the Cupar-St Andrews circuits.

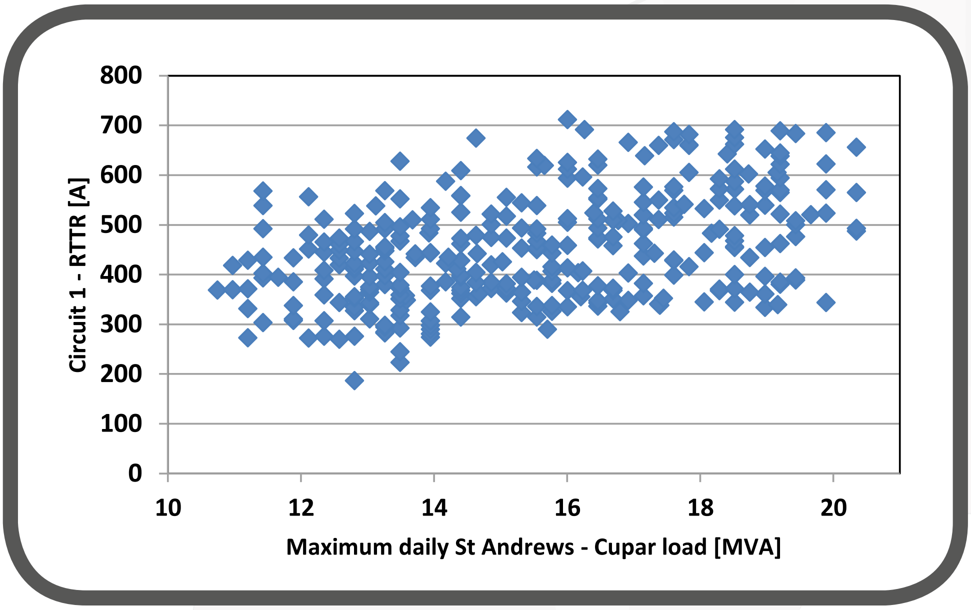


Figure 45: Correlation between Circuit 1 RTTR and demand

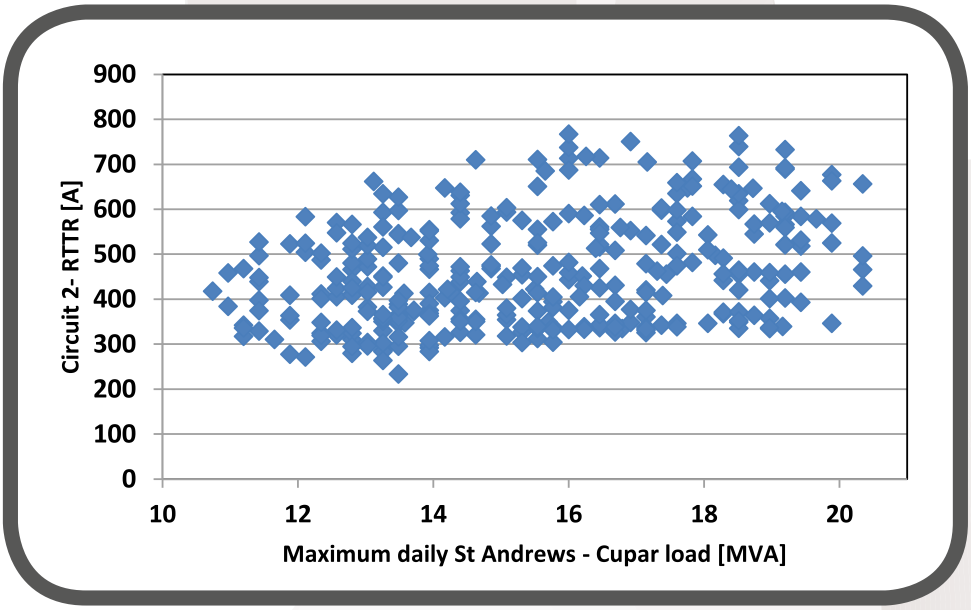


Figure 46: Correlation between Circuit 2 RTTR and demand

4.8 Effect of number of weather stations on RTTR values

As discussed in section 4.2, the weather conditions, in particular wind speed, vary at different locations along the overhead line. In order to reduce the risk of overestimation of the RTTRs and for a reliable RTTR system, it is important to monitor the weather conditions at the micro-climate regions located along the overhead lines. Micro-climate regions e.g. wind sheltered areas can be identified by carrying out a complete survey along the overhead line route. In order to demonstrate the importance of monitoring weather conditions at micro- climate locations, a comparison study was carried out between two following cases:

> **Case 1:** RTTR calculation for Cupar-St Andrews Circuit 2 considering only weather station at Cupar substation which is located at the beginning of this circuit;
>
> **Case 2:** RTTR calculation for Cupar-St Andrews Circuit 2 considering all the seven weather stations.

The calculated RTTRs for the aforementioned study cases for a randomly selected 24-hour period are shown in Figure 47.

As shown in Figure 47, it is very likely that RTTR is overestimated if only one weather station is considered for the RTTR calculation because the effect of wind sheltered areas may be neglected. Therefore, RTTR system which uses a single point weather condition monitoring could be risky and unreliable for a real-time network operation application.

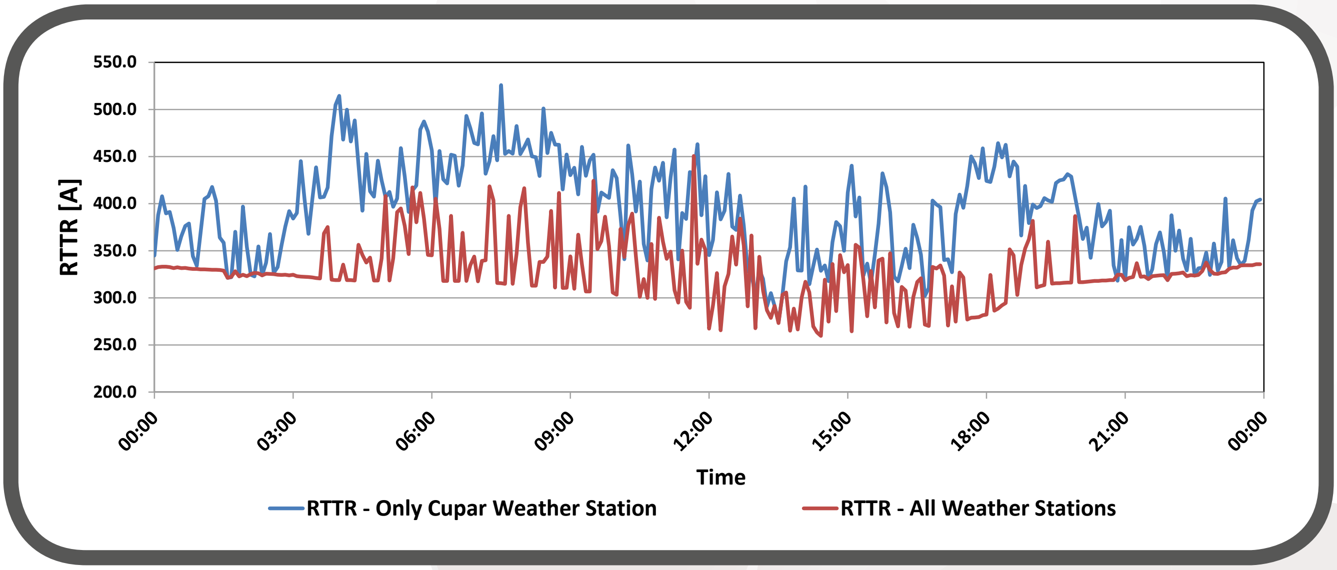


Figure 47: One weather station vs multi weather stations calculated RTTRs

4.9 Results of different methods of attachments

GE solution FMC-T6 line sensors use a temperature probe which is attached directly to the overhead line conductor. As explained in section 3.10, different methods of attachments were trialled for the temperature probe of the FMC-T6 line sensors: Method A, Method B, Method C, see Table 2. The purpose of this trial was to investigate the effect of surrounding weather conditions on the accuracy of measured conductor temperature.

Figure 48 shows the conductor temperature of each phase at Pole 50 for a randomly selected period. The estimated conductor temperature for the same period is also shown in Figure 48. The following observations can be made from the measured data and the comparison with estimated conductor temperature:

> **Observation 1:** The estimated temperature is usually higher than measured temperature. The difference between estimated and measured is larger when the ambient temperature is very low. Figure 49 shows the ambient temperature variation;
>
> **Observation 2:** Temperature of phase R is higher than other phases. The temperature difference between phase R and other phases is larger at the times when a higher solar radiation is recorded at Pole 50 location. Figure 49 shows the solar radiation variation.

The two aforementioned observations may be explained by considering the fact that temperature probe and the conductor experience different thermodynamic conditions. Temperature of a conductor is the result of balance between heat gain (joule energy + solar radiation) and heat loss (convection and radiation). Temperature probe, however, gains heat from conductor and solar radiation and loss heat through (convection and radiation). Therefore, because temperature probe losses heat with the surrounding it is likely that temperature probe reports a temperature lower than actual conductor temperature, this explains the Observation 1.

Temperature probe at Phase R is covered by a dark Denso tape. Therefore, compared to other phases, Phase R is less exposed to wind and also would gain a larger heat from solar radiation (darker surface absorbs higher solar heat). This can explain the Observation 2 mentioned previously.

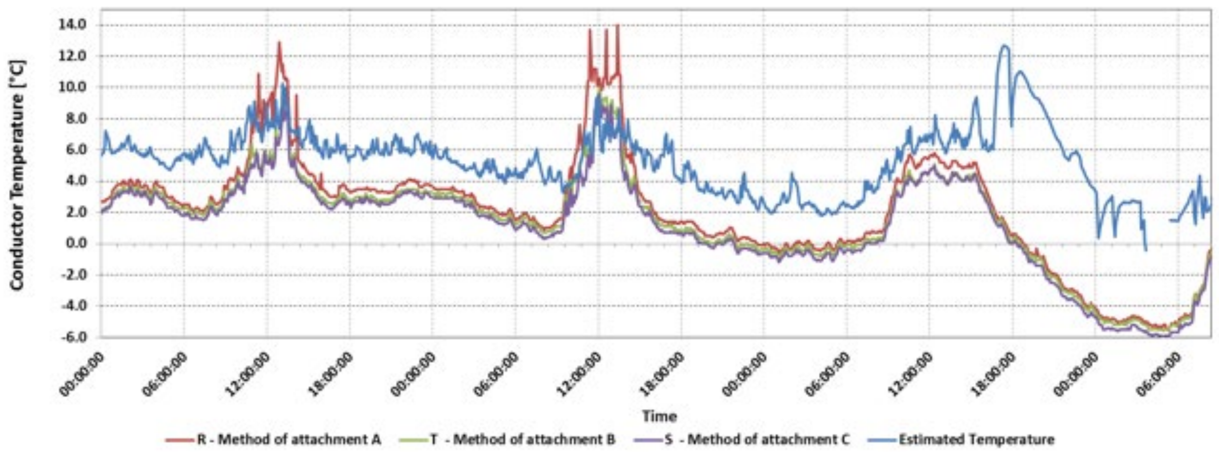


Figure 48: The conductor temperature measured with three different methods of attachment vs the estimated conductor temperature

4.9 Results of different methods of attachments [continued]

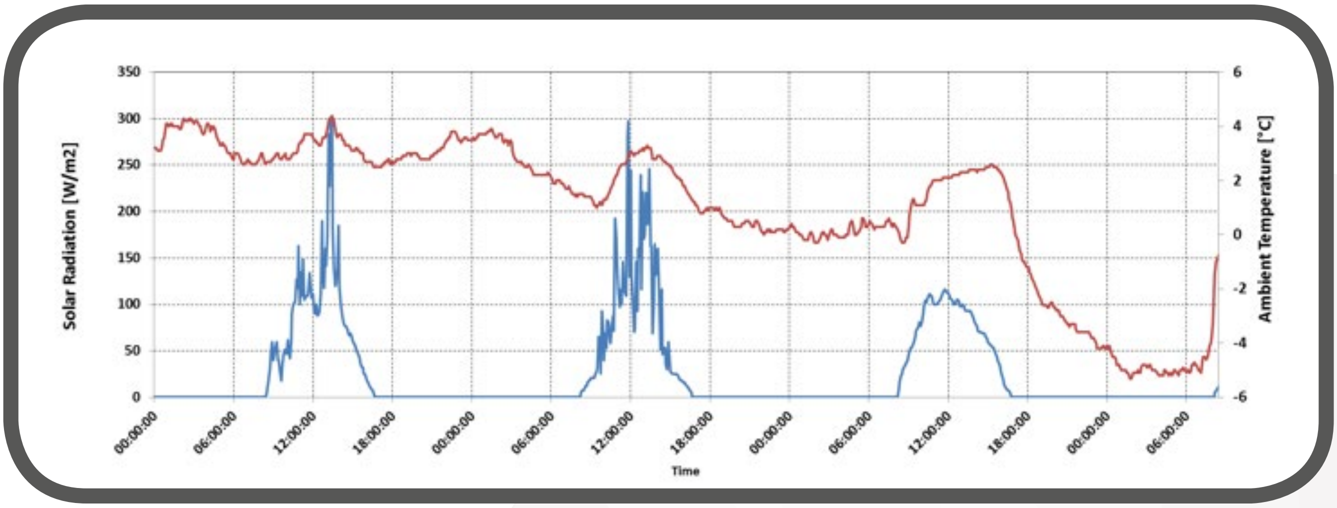


Figure 49: The ambient temperature and solar radiation recorded at Pole 50

4.10 Comparison between Ultrasonic and cup anemometers

GE ILMS equipment uses a Sensor Network Gateway (SNG-3), which is only compatible with cup anemometer technology. The main issue with cup anemometers is their low accuracy in low wind speeds (<0.5m/s) i.e. cup anemometer reports 0m/s for the wind speeds below 0.5m/s. Nonetheless, based on the specifications provided by manufacturers, ultrasonic wind sensors are more accurate in low wind speed conditions.

GE Energy's new SNG technology (SNG-2) is also compatible with ultrasonic wind sensors. In order to investigate the impact of wind sensor accuracy on RTTR values in low wind speed conditions, GE provided a new SNG (SNG-2) and an ultrasonic wind sensor with no additional cost to be tested at one of the sites (pole 50) where a prevailing low wind speed was experienced. The ultrasonic wind sensor was installed close to the cup anemometer to ensure they are exposed to a same weather conditions, see Figure 50.

The results of comparison between two sensors unexpectedly showed the ultrasonic sensor reports a lower average wind speed compared to the wind speed reported by cup anemometer. This may be due to a shield effect on the ultrasonic sensor by the overhead line pole. At this stage we have not been able to assess the accuracy of ultrasonic sensor compared to cup anemometer and the impact of this accuracy on the calculated RTTR values.

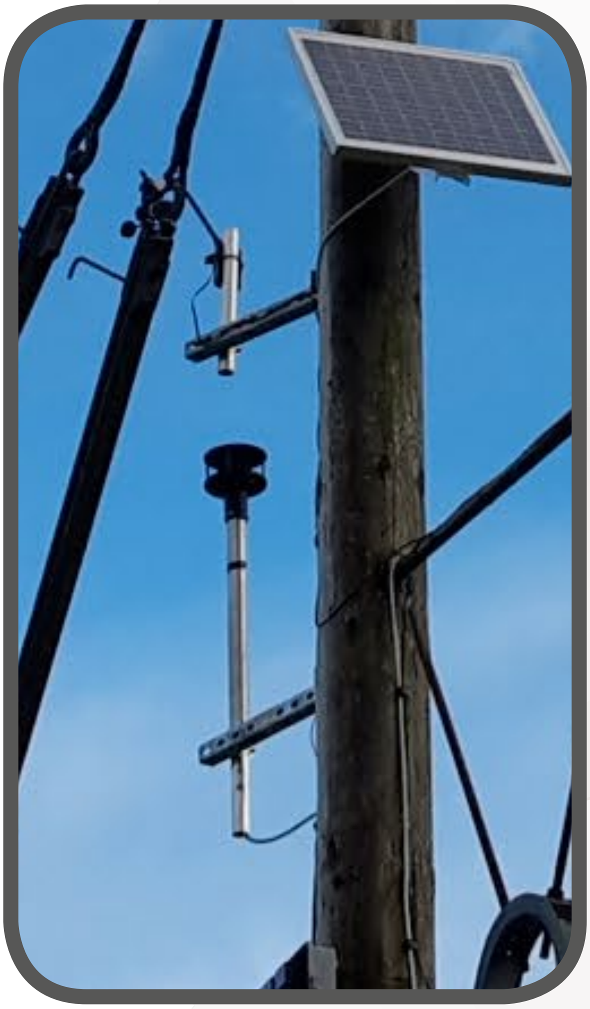


Figure 50: Ultrasonic and cup anemometers installed at Pole 50

5 Performance compared to the original aims and objectives

The target for this work package is to create headroom of up to 7% in Cupar – St Andrews 33 kV circuits that will defer will defer further investment

This project demonstrated that an additional network carrying capacity of around 11% (average of both circuits) can be unlocked by deploying the RTTR system. The potential headroom that can be created was quantified and compared with static seasonal ratings. It was demonstrated that with the additional network headroom provided through RTTR, reinforcement in the Cupar – St Andrews 33 kV network could be deferred.

Weather monitoring will also be installed to investigate how asset rating can be optimised by considering real-time environmental conditions

Weather stations were installed at four different locations along the Cupar – St Andrews 33 kV circuits. This is in addition to other three weather stations which were installed at the 33/11 kV substations located in the Cupar and St Andrews areas. The weather parameters are monitored on a real-time basis and all the monitored data are provided as inputs to an RTTR calculation engine to estimate the maximum possible network carrying capacity in real-time.

An advanced thermal management system will be developed in parallel to the monitoring with consideration of appropriate thermal modelling tools

An RTTR system was implemented for the Cupar – St Andrews 33 kV network. This system reports the real-time thermal rating of circuits to SPEN's NMS as well as providing this information to control engineers through a dashboard specifically designed for Cupar – St Andrews circuits (see Figure 7). In addition to calculated RTTR values, the temperatures of the conductors are also directly monitored at four strategically selected locations along the Cupar – St Andrews circuits. The monitored conductor temperatures are also available through the RTTR dashboard in a real-time basis.

6 Required modifications to the planned approach during the course of the Project

6.1 Increased number of weather stations

The original plan was to install pole-mounted monitoring equipment for around every 10 km along each of the two St Andrews – Cupar 33 kV circuits. In the final plan, however, the pole-mounted monitoring equipment was installed at around 5 km intervals in order to enhance the reliability of the RTTR system against equipment failure, outages for maintenance or telecoms interruptions.

6.2 Use of ILMS server to collect monitored data at pole-mounted installations

The initial plan was to transmit the monitored data at all installations directly to an iHost server located at St Asaph primary substation. The GE ILMS technology used at the pole-mounted installations, however, was designed to transmit data to GE ILMS server. Therefore it was required to establish a communication interface between the GE ILMS server and iHost where all field data are gathered before input in to RTTR calculation engine.

This modification was trialled without any issue, however, as a long-term solution, SPEN is planning to transmit all the monitored data directly to iHost.

It should be noted that there was an advantage of using ILMS server as it provided redundancy against outages of iHost so that data from the pole-mounted installations would be still available through ILMS server.

6.3 Used an extension arm for mounting wind sensor

The original installation methodology for the cup anemometers was to install the wind sensor directly on the overhead line pole. In this methodology, only small gap is left between the overhead line pole and the cup anemometer and therefore overhead line pole may shield the wind. In order to alleviate the wind shielding effect on wind sensor, an extension arm was designed to mount the wind sensor approximately 500 mm from the overhead line pole.

6.4 Trial of different method of attachment for conductor temperature sensors

The manufacturer's recommended method of attaching the temperature probe of the FMC-T6 line sensors included covering the temperature probe with Denso tape. One of the questions raised in the course of project was whether covering the temperature probe with Denso tape may affect the accuracy of the temperature probe and also if the surrounding weather conditions may affect the accuracy of the measured conductor temperature. In order to investigate the effect of the attachment method on accuracy of temperature probe, three different attachment methods were trialled. The methodology and the outcomes of the trial are given in sections 3.10 and 4.9, respectively.

6.5 Trial of different wind sensor technologies (ultrasonic and cup anemometers)

GE ILMS equipment uses a Sensor Network Gateway (SNG-3), which is only compatible with cup anemometer technology. The main issue with cup anemometers is their low accuracy and measurement range in low wind speeds. Nonetheless, the ultrasonic wind sensors are more accurate in low wind speed conditions.

GE Energy's new SNG technology (SNG-2) is also compatible with ultrasonic wind sensors. In order to investigate the impact of wind sensor accuracy on RTTR values in low wind speed conditions, GE provided a new SNG (SNG-2) and an ultrasonic wind sensor with no additional cost to be tested at one of the sites (pole 50) where a prevailing low wind speed was experienced. Ultrasonic wind sensors were positioned near the cup anemometer in order to expose both sensors to a same wind conditions.

6.6 Graceful degradation

In the initial plan for the implementation of the graceful degradation methodology within PowerOn Fusion, the adaptability of the graceful degradation methodology to different RTTR systems e.g. North Wales or Cupar – St Andrews was not considered. In the course of project, however, it was decided to add flexible features to the graceful degradation methodology, which could be altered based on the number of monitored locations or the size of network. This means that, although the core calculation methodology for graceful degradation is the same for all RTTR systems, the input parameters can be adjusted to tailor the methodology for specific RTTR systems.

7 Lesson learnt and recommendations

This section provides an overview on key lessons learnt

- For a weather-based RTTR system, it is important to identify micro-climate regions along an overhead line as it is more likely that network thermal pinch points are in these regions. This was demonstrated in this report by a comparison study between RTTR calculations using one weather station and multi weather station monitoring micro-climate regions, see section 4.8 for more details.
- The outcomes of this trial show that using a weather-based thermal state estimation technique can provide RTTRs with an acceptable level of accuracy. However, the confidence in the RTTR system would be enhanced by deploying a limited number of line temperature sensors at wind shielded locations. The purpose of using line sensors can be firstly for initial validation of the thermal state estimation algorithm and secondly for operating as an independent check and alarm system in long term operation.
- The effect of solar radiation can be significant on the RTTR values especially during summer period when high solar radiation is experienced. Engineering Recommendation P27 suggests a solar radiation of 0 W/m2 and ambient temperature of 20°C for thermal rating calculation during summer period. Our data analysis showed that there are occasions when solar radiation and ambient temperature are higher than those in ER P27, and therefore the RTTRs are actually lower than static rating. If these conditions coincide with sustained high load on the overhead lines it could overheat leading to excessive sag and in extreme cases even damage the assets.
- It is recommended to conduct a fresh review on the assumptions made in Engineering Recommendation P27 considering the lesson learnt from this project and other LCNF projects. Industry would benefit from an ENA working group to share the knowledge on RTTR and develop and updates ERs and technical guidance required for DNOs and TOs.
- The power supply for the pole-mounted RTU and measurement equipment should be calculated for the worst case scenarios and consider the winter period where the daylight is short. In wooded area or areas surrounded by hills the total solar gain may be not enough to maintain the supply for RTTR equipment by only using solar panels.
- Interference in radio communication between the FMCT-6 line sensors and RTU distorted the monitored conductor temperature data. The interference was the due to magnetic field of the overhead line. Although these line sensors were tested in a laboratory environment for a high current condition, the test voltage was not as high as 33kV and therefore the magnetic field created in the laboratory was different from magnetic field on site around 33kV conductor. This issue was resolved by updating the digital filter firmware in line sensors. The process was carried out remotely and without the need to dismount the sensors. The lesson learnt from this issue was that testing equipment in a laboratory environment should be similar to the site conditions e.g. voltage level and loading.

- The RTTR system relies heavily on the real-time weather data monitored at different locations of the network. Any interruption in the data transmission process, from monitoring equipment to RTTR calculation engine, affects the reliability of RTTR system. In order to enhance the reliability of RTTR system against data transmission interruption the following measures were implemented: i) the number of weather stations was increased, so that a weather station was installed every 5 km; ii) a graceful degradation algorithm was deployed to conservatively estimate missing data and gracefully degrade RTTR values towards seasonal ratings when increasing amounts of weather data was missing. The details of graceful degradation algorithm are given in section 3.8.
- Based on the results of this trial, we are concerned that surface mounted conductor temperature sensors may not accurately measure the actual conductor temperature due to impact of surrounding weather conditions on the sensor, see section 4.9. We recommend that further studies and laboratory tests need to be carried out to provide guidance and recommendations for appropriate method of attachment and sensor specifications.

8 Project replication

8.1 Knowledge required to replicate the RTTR system

The knowledge required to replicate this project is outlined as follows:

8.1.1 Standards & engineering recommendations

IEC TR61597 and CIGRÉ WG22.12 are widely used standards for calculating the thermal behaviour of the overhead line conductors. The full details of these publications are as follows:

- IEC, 1995, Standard TR 61597 Overhead electrical conductors – calculation methods for stranded bare;
- CIGRÉ WG 22.12, Technical-Brochure 2002, "The thermal behaviour of overhead line conductors";
- CIGRÉ WG 22.12, 1992, "The thermal behaviour of overhead line conductors" Electra, vol. 114 (3), 107-125.

The information about assumptions and methodology for calculating the static seasonal ratings of overhead lines and cables is discussed in Engineering Recommendation (ER) P27. This ER is widely adapted by UK DNOs as a business as usual approach to calculate the seasonal ratings of overhead line and underground networks.

8.1.2 Previous SPEN's experience in RTTR

SPEN has previously implemented an RTTR system for a 132 kV network in North Wales under LCN Fund Tier 1 mechanism. All documentation from this project, including close-down report, is available on Ofgem's Tier 1 LCN Fund website at:

https://www.ofgem.gov.uk/publications-and-updates/first-tier-low-carbon-network-fund-project-implementation-real-time-ratings-submitted-scottish-power-spt1001

8.1.3 Conference publications

- A Khajeh Kazerooni, W Peat, G Murphy and SCE Jupe: "Real-time thermal rating reliability enhancement using a graceful degradation methodology", submitted to CIRED 2015.
- SCE Jupe, G Murphy and A Khajeh Kazerooni: "De-risking the implementation of Real-time Thermal Ratings", in Proc. 22nd International Conference on Electricity Distribution", Paper 1106, Stockholm, June 2013.
- SCE Jupe, D Kadar, G Murphy, MG Bartlett and KT Jackson: "Application of a Real-time Thermal Rating System for a 132 kV Distribution Network", in Proc. 2nd IEEE PES European Conference and Exhibition on Innovative Smart Grid Technologies, Manchester, December 2011.
- SCE Jupe, MG Bartlett and KT Jackson: "Dynamic Thermal Ratings: The State of the Art", in Proc. 21st International Conference on Electricity Distribution, Paper 0918, Frankfurt, June 2011.
- SCE Jupe, M Bartlett, K Jackson and PC Taylor: "Facilitating the Connection of Wind-Based Generation through Real-Time Thermal Ratings", in Proc. 9th International Workshop on Large-scale Wind Integration, Quebec, October 2010.

8.2 Intellectual property

Table 15 lists the foreground intellectual property (IP) created by this work package, including a summary of how other GB DNOs can access the IP.

Table 15 Intellectual property created by Cupar – St Andrews RTTR project

Intellectual property	Availability
Graceful degradation	Graceful degradation specification document, SPEN
Weather condition data	Via SPEN
Overhead line conductor temperature data	Via SPEN

8.3 Data required to replicate the RTTR system

- Electrical and geographic data to model each line segment, provided in Microsoft Excel file format by the DNO
- Weather data (wind speed, wind direction, ambient temperature and solar radiation) is to be provided as 5-minute average values at synchronised interval via a protocol supported by the PowerOn FEP

8.4 Products required to replicate the RTTR system

8.4.1 Monitoring equipment

Following monitoring equipment is required:

- Weather stations measuring:
    - Ambient temperature
    - Solar radiation
    - Wind speed
    - Wind direction
- Overhead line conductor sensors measuring:
    - Conductor current
    - Conductor temperature

8.4.2 Communications Equipment

- Pole-mounted RTU Envoy and RTU cabinet
- Solar Panel
- SIM Card

8.4.3 Information technology

- iHost for single point-to-point communication with RTUs to gather field data
- System running GE PowerOn v5.2.2 Service Pack 4 or greater, with suitable licence agreement for DTR module for each circuit being modelled
- Suitable PowerOn FEP to interface to systems or RTUs providing weather data. This may be a dedicated FEP or an existing PowerOn FEP
- Configuration of SCADA links for each weather station symbol, this can be implemented by the DNO or with services provided by GE Energy
- A suitable historian (OSI PI, GE TSDS or GE Proficy) to store the historic weather station data used by the graceful degradation algorithm and for post-hoc analysis of the RTTR system performance

8.5 Services required to replicate the RTTR system

- Suitable PowerOn symbology for weather stations and DTR summary pages, these can be developed by the DNO's own team or with services provided by GE Energy
- Site acceptance testing with DNO, supplier of weather station hardware and GE Energy

9 Planned implementation

9.1 Developments compared to North Wales RTTR system

SPEN has trialled the implementation of RTTR systems in 132 kV and 33 kV networks. These projects have demonstrated that there is a potential for unlocking significant network capacity through deploying RTTR systems. SPEN initially trialled an RTTR system in North Wales 132 kV network, and, based on the lesson learnt and challenges encountered during that project, the following requirements for further development of RTTR systems were identified[1]:

- Graceful degradation
- Integration of sensors
- Forecasting

SPEN has now made progress on developing these requirements. In the following a summary of these developments are given.

9.1.1 Developments of graceful degradation methodology

One of the learning points from the RTTR system implementation project for the 132 kV network in North Wales was the need for a methodology that degrades RTTR values gracefully towards static seasonal ratings whereby increasingly conservative estimates are made of the RTTR of the circuits as an increasing number of weather station parameters become unavailable.

As part of the RTTR system implementation in the Cupar – St Andrews 33 kV network, a graceful degradation algorithm was developed. The algorithm was designed in a way that can be deployed and adjusted for different circuits and different number of weather stations. This algorithm has now been implemented in SPEN's PowerOn Fusion NMS. For more details about the methodology of implementation of graceful degradation see section 3.8.

9.1.2 Integration of line sensors

The thermal state estimation approach used in North Wales RTTR project required validation through distributed sensors on the network prior to the system being adopted. However, due to supply chain issues and outage constraints, this element of the project did not take place.

In the Cupar – St Andrews RTTR system, line sensors were deployed to directly measure the current and temperature of the overhead line conductors. A methodology for estimating the temperature of the conductor was developed based on CIGRÉ WG22.12, which was used to estimate the temperature of the conductor at different locations within the Cupar – St Andrews network.

The comparison between estimated conductor temperatures and the measured values demonstrated that the thermal state estimation approach can model the thermal behaviour of the network within an acceptable accuracy. For more details of methodology used for conductor temperature estimation and model validation see section 4.6.

9.1.3 RTTR Forecasting

Forecasting is one of the key requirements for full adaption of RTTR system. SPEN is now conducting "Enhanced Weather Modelling for Dynamic Line Rating" project under the Network Innovation Allowance (NIA) funding mechanism, with the University of Strathclyde as a partner. This project aims to improve the weather estimation methodology and add a forecasting element to RTTR system.

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[1] *See close-down report of implementation of RTTR system in North Wales project at http://www.spenergynetworks.com/pages/dynamic_thermal_rating.asp.*

9.2 Further developments required to modify distribution systems based on learning from RTTR

SPEN have now implemented RTTR systems for 132 kV and 33 kV networks, and these projects have built confidence that significant capacity headroom can be unlocked in overhead lines by deploying RTTR systems. Some of the RTTR applications that can enhance distribution system are as follows:

- Deploying RTTR systems to inform active network management systems for controlling output of generators
- Deploying RTTR systems for network reconfiguration and planned outages
- Deploying RTTR systems to defer or cancel network reinforcement

In order to fully adopt any of the above RTTR system applications in business as usual, the following developments and actions have been identified to be taken by DNOs and non-DNOs:

RTTR forecasting implementation: RTTR forecasting is an essential feature for full adoption of RTTR systems. A forecasting methodology should be added to the RTTR calculation process to boost the confidence on any planning decisions that are made based on RTTR. To do so, the following actions are envisaged:

Actions by DNOs:

- Budget and manage projects for development and implementation of RTTR forecasting algorithm

Actions by non-DNOs (e.g. universities or consulting firms):

- Develop algorithm specifications
- Validate the algorithm using field data
- Provide technical support for developing the forecasting methodology

Actions by non-DNOs (e.g. GE Energy):

- Implement the forecasting algorithm in SPEN's RTTR system

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[1] See close-down report of implementation of RTTR system in North Wales project at http://www.spenergynetworks.com/pages/dynamic_thermal_rating.asp.

9.2 Further developments required to modify distribution systems based on learning from RTTR [continued]

Implementing conductor temperature estimation methodology: Real-time conductor temperature estimation and comparison with the monitored conductor temperature can be an additional feature of an RTTR system to indicate, in real-time, the accuracy of RTTR values. A conductor temperature estimation methodology was developed and tested in the Cupar – St Andrews RTTR project. For further development, conductor temperature estimation methodology can be implemented in SPEN's RTTR system. For this development, the following actions are envisaged:

Actions by DNO:

- Budget and manage a project for implementation of conductor temperature estimation methodology
- Provide requirements and specifications documents for conductor temperature estimation methodology

Actions by non-DNOs (e.g GE Energy):

- Implement conductor temperature estimation methodology in SPEN's RTTR system

Updating policy documents: The existing technical manuals and policy documents need to be updated to incorporate the application of RTTR in generation connection offers, network planning and operations codes of practice.

Establish interface between RTTR system and active network management (ANM) system: There are significant potential benefits in deploying an RTTR system within an ANM scheme for controlling outputs of the generators. SPEN have has already trialled an ANM system for controlling generators' outputs, through the "Accelerating Renewable Connections" (ARC) LCN Fund project. SPEN has held a workshop with ARC and RTTR project partners to explore the way forward for integrating RTTR system within ANM system.

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[1] See close-down report of implementation of RTTR system in North Wales project at http://www.spenergynetworks.com/pages/dynamic_thermal_rating.asp.

10 Business Case

The Flexible Networks project has implemented a number of techniques in combination to achieve the required increase in headroom within each trial area. The business case for the use of the techniques in combination is included in the Case Study report for each of the trial areas. This business case considers situations where RTTR can be used independent of the other techniques.

The case for using RTTR to defer conventional reinforcement for connection of both distributed generation and load are considered:

10.1 Distributed Generation

Our results have shown that there is a strong correlation between wind energy and RTTR. Our results also show that an additional 17GWh of energy yield can be achieved with the RTTR uplift capped at 20%, see section Figure 37and Figure 38.

Where reinforcement is required to accommodate wind generation the lowest cost traditional method would be the rebuild of a 33kV line to achieve additional capacity. We estimate the cost of rebuilding 17km of 33kV overhead line and associated circuit breakers to be £1,270k.

Referring to our Cost Benefit Analysis (Appendix G) the approximate cost of implementing RTTR based on our learning from the trial areas is estimated at £90k. In addition an automatic network management (ANM) scheme is required to control the output of the wind farm in real time to ensure the RTTR of the line is not exceeded. The cost of adding an ANM scheme is estimated at £50k giving a total cost of £140k.

The RTTR option would need to be evaluated by the wind farm developer taking into account the details of their specific project, however we believe that there are circumstances where it is likely to be the preferred option.

10.2 Load

RTTR can be used to provide additional headroom for load, however as the rating varies in real time and cannot be assured it would also be necessary to have the facility to reduce demand when required which may be through a demand side response (DSR) scheme or through the deployment of storage.

The lowest cost traditional method would be the rebuild of a 33kV line to achieve additional capacity. We estimate the cost of rebuilding 17km of 33kV overhead line and associated circuit breakers to be £1,270k.

In appropriate circumstances, a RTTR scheme can defer the requirement for conventional reinforcement. The duration of the deferral period will be dependent on the rate of load growth and we consider the technique to be applicable where a deferral period of at least 8 years can reasonably be expected based on a range of load growth scenarios.

From our cost benefit analysis we estimate that the cost of implementing a RTTR scheme is £90k. It is assumed that the scheme will provide 10% uplift, approximately equal to 2MVA. As stated above it is also necessary to have 2MVA of DSR available as a contingency for times when the increased line rating is unavailable. In other LCNF project[1] the cost of DSR has been estimated at £17.5k per MVA per year, a total of £280k over 8 years. The overall cost of implementing the technique, RTTR plus DSR, is therefore £370k.

Therefore under this scenario an expenditure of £1,270k is expected to be deferred for a minimum period of 8 years by investing in RTTR and DSR for an amount of £370k. Our financial analysis show that the net present value (NPV) benefit of this scenario would be around £153k. In addition, deferring network investment can provide an opportunity to evaluate the load growth more accurately and also explore other smart solutions e.g. demand side response, peak load shifting etc. which can be alternatives to conventional network reinforcement.

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[1] *Second Tier LCNF, Northern Power Grid, Customer-Led Network Revolution*

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Appendix A – Meteorological stations allocation methodology

Appendix B – Installation method statement

B-1 Installation of building-mounted monitoring equipment

B-2 Installation of pole-mounted monitoring equipment

Appendix B – Installation method statement

B-1 Installation of building-mounted monitoring equipment

B-2 Installation of pole-mounted monitoring equipment

Appendix C – Key specifications of equipment

Appendix D – Graceful degradation methodology

D-1 Graceful degradation algorithm specification

D-2 Graceful degradation parameters refinement

Appendix E – Conductor temperature estimation methodology

Appendix F – Datasets

Appendix G – Cost Benefit Analysis