Project FALCON

Dynamic Asset Rating Primary Transformers

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FALCON

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Executive Summary

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

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

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

Dynamic asset rating associated with primary transformers appear to offer up to 10% average increase in rating at times of year when there is generally higher load, and as such could offer potential for further development. Such development could be targeted at existing transformers that are approaching thermal/load limits, and would involve: limited installation of temperature & load monitoring; tuning of transformer specific models; and assessment of potential to run at higher than nominal ratings. Such development would include addressing the issue of risk management with respect to transformer life. With this method, there may be a small number of days where the ambient temperatures are materially above seasonal averages, and if these coincide with high loading, accelerated (vs par) life usage may occur on such days. It is recommended that further work should initially focus on a candidate primary transformer to trial actual solution provision (to an asset nearing capacity) and demonstrate actual benefit delivery.

SECTION 1

Project Introduction[1]

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

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

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

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

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

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

This report presents the work undertaken through project FALCON on the dynamic asset rating of Primary Transformers on the 33/11kV network.

SECTION 2

Introduction to Technique Trial

2.1 Presentation of Learning

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

LP #	Brief description of learning.

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

2.2 General Overview of Dynamic Asset Rating Technique

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

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

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

2.3 Overview of Transformer DAR Technique

The practice of using transformer dynamic asset rating is to assess transformer oil and winding temperatures (the prevailing thermal state of the asset) and to estimate the additional load that the transformer could carry and still remain within a stated highest winding temperature (known as the hot-spot), for a given ambient air temperature.

For a given transformer, the temperature of the insulation (limiting factor for operation) is governed by the heating effect of current flowing through the windings, and the cooling of the transformer oil. The temperature of the oil (and cooling effect on the insulation) is governed by the ambient air temperature, the heating from load current, and cooling process due the cooling arrangement of the transformer.

Sustained load and cyclic load ratings are given by manufacturers, sometimes with different cooling mechanisms, to limit operating insulation temperatures (typically to less than 98°C or 110°C for a range of ambient temperatures e.g. 20°C [1, 2] up to 30°C [3]) to guarantee that an acceptable service life of at least 20 years can be achieved.

In reality, primary transformers are typically installed as multiple units, where the loss of one unit from service does not interrupt supply, and many transformers are located outdoors where the ambient temperature rarely reaches 30°C. Therefore, the transformers tend not to be operating close to their temperature limits resulting in a longer service life span. It is possible to take advantage of the conditions to rate the transformer dynamically based on hot spot temperature rather than on a static basis.

It should be noted that the hot-spot temperature exists somewhere around the windings but is difficult to exactly locate. The hot-spot location and temperature is a function of transformer design and cooling functionality, ambient air temperature, oil temperature, and winding losses amongst other parameters. This makes the hot-spot temperature complex to assess with any degree of certainty. Although direct measurement methods do exist, they can only be applied to newly built units, for which the manufacturer can install bespoke technically advanced measuring facilities (for instance sensors with fibre-optic cables). Therefore, for existing in-service applications, the hot-spot temperature may only be computed.

To establish a dynamic asset rating for a transformer, two elements are necessary:

- a thermal model of the transformer is required to assess prevailing transformer oil and winding temperature given previous load and ambient air temperatures; and
- a process is required that will iteratively increase modelled load current and calculate consequential hot-spot temperature (using the thermal model) until the limiting hot-spot temperature is reached. The load current that results in this limiting hot-spot temperature is the dynamic asset rating, or ampacity of the transformer. This can be either sustained or cyclic.

Fundamental to this assessment of ampacity is the thermal model of the asset. According to industry standards (Section **4.1**), the hot-spot temperature is calculated as:

$$\theta_h = \theta_a + \Delta\theta_o + \Delta\theta_h \qquad \text{(Equation 1)}$$

Where:

θ_h is the hot − spot temperature;

θ_a is the ambient air temperature;

$\Delta\theta_o$ is the rise in top − oil temperature above ambient; and

$\Delta\theta_h$ is the rise in hotspot temperature above top − oil temperature.

From Equation 1 it is clear that ambient air temperature is fundamental to hot spot temperature.

An outline of the IEC 60076 calculation of hot-spot temperature is shown in Figure 1. Within this, it can be seen that there are:

- two process inputs - K (the transformer's per unit load current) and Θ_a (the ambient air temperature)[2]; and
- a number of model parameters (e.g. $\Delta\Theta_{or}$, R, x etc.) that are used within the calculation.

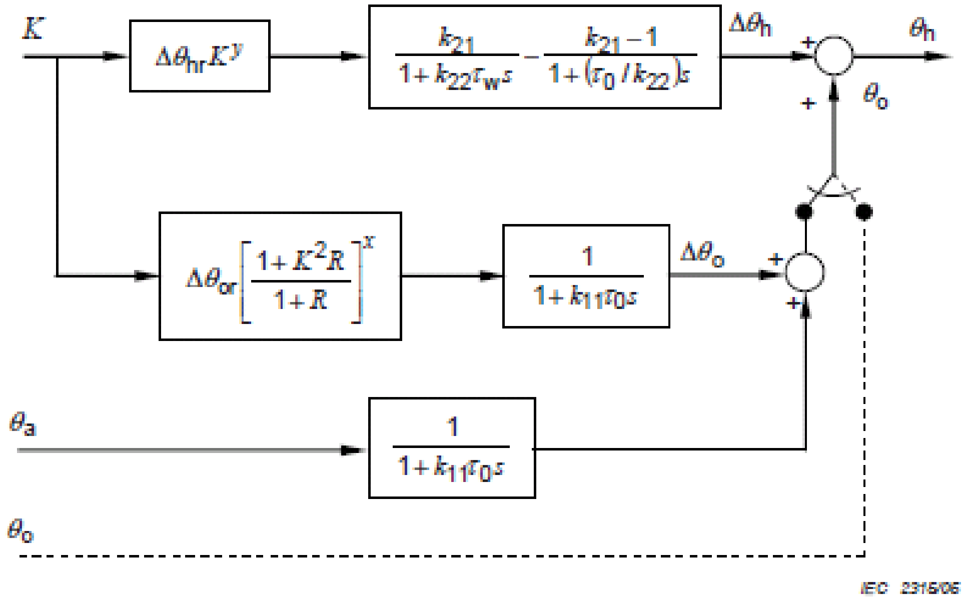

Figure 1: Outline of the IEC 60076 calculation of hot-spot temperature [2]

The potential benefits that may be expected when considering dynamic asset rating of transformers within an electricity distribution network include:

- Deferring network reinforcement by allowing more current to pass through the transformer when the weather conditions are favourable to cooling without adversely affecting life;
- Assisting with ratings when highly fluctuating loads are connected (i.e. average rate of loss-of-life of the transformers are still within specified limits even if temporarily the transformer is overloaded compared to nameplate rating).

[2] Figure 1 also shows an optional input of a direct input of the transformer top oil temperature Θ_o.

However, the accuracy of the dynamic asset rating calculation is very dependent on a number of key points:

- The models use mathematical constants within their calculated analysis such as oil and winding thermal time constants, and full load and no load losses. In order to ensure the accuracy of the analysis these constant values need to be confirmed.
- Good operating data (e.g. ambient air temperature, and accurate loading) is key to estimating the hot-spot temperatures. This has two aspects, one is the availability and accuracy of the data and the second is the time periods with which the data is measured.

Appropriate validation needs to occur between the modelled temperatures and the equivalent measured temperatures, to establish confidence in the modelling fundamental to the technique. As previously discussed, the hot-spot of the transformers within the trial are not directly measurable, therefore confidence in the thermal modelling and estimation of ampacities is dependent on:

- Establishing appropriate modelling parameter values that result in a sufficient coincidence of modelled and measured values of top oil temperature; and
- Robust assumptions about the parameter values used to estimate the rise in hotspot temperature above top-oil temperature.

Minimum basic data requirements to allow a thermal model to be constructed and validated, and for dynamic asset rating values to be estimated are:

- Ambient air temperature (the indoor temperature for housed transformers, external air temperature for outdoor substations)
- Transformer current
- Top oil temperature (for validation)

2.4 Overview of approach to the technique trial

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

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

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

The overall process approach to the technique trial is shown in Figure 2.

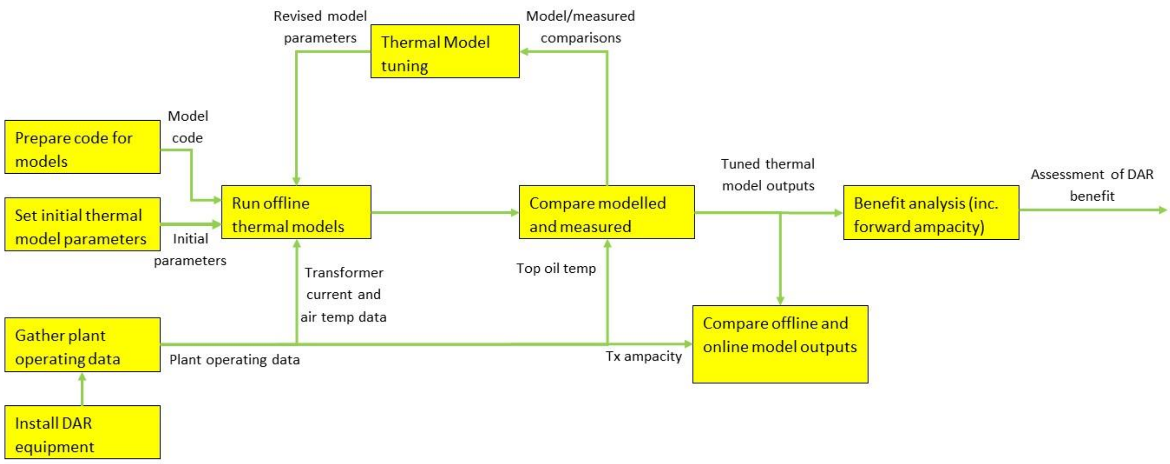

Figure 2: overall process approach to the technique trial

SECTION 3

Design, Construction and Commissioning

This technique trial sought to provide the data outlined in section 2.3 for a pair of primary transformers to allow an offline thermal model to be created and validated, and for transformer dynamic asset rating values to be estimated.

3.1 Overview of selected assets

The asset scope of the primary transformer DAR trial was the pair of transformers located at Marlborough Street Primary substation. One of the transformers is shown in Figure 3.

Figure 3: Transformer at Marlborough Street Primary substation

Ratings of the transformers are 12/19/24MVA (sustained ONAN[3] 98^{o}C / summer cyclic OFAF[4] 120^{o}C / emergency continuous winter OFAF 140^{o}C). The transformers are located in an outdoor area in close proximity to 4 metre high brick substation security walls, which themselves are mostly surrounded by mature trees. There is also a blast wall of the same height between the two transformers within the substation walls. As a consequence, both transformers are partially protected from wind and are shaded from the sun (particularly in winter).

3 ONAN is a cooling mode standing for oil natural, air natural

4 OFAF is a cooling mode standing for oil forced, air forced which means both oil pumps and air fans are operational to aid cooling

3.2 Overview of as-installed equipment

Each primary transformer was monitored for load current and ambient air temperature as inputs to the thermal modelling/DAR assessment. In addition, top of tank oil temperature, top of cooler oil temperature and bottom of cooler oil temperature monitoring was installed to validate the thermal model. Figure 4 provides a schematic overview of the measurement and data collection arrangement.

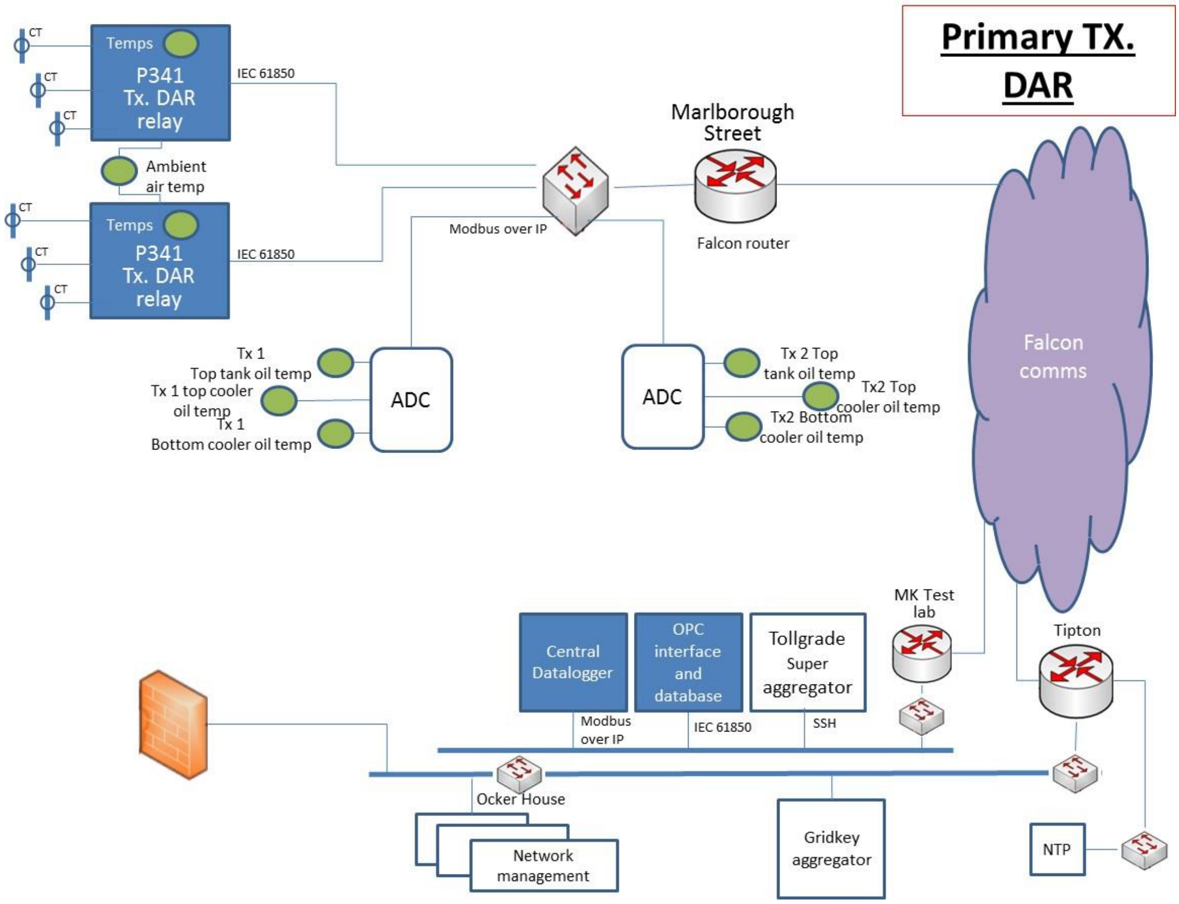

Figure 4 : Schematic of installed Primary transformer DAR scheme

In summary, the installed equipment comprised of:

- One Alstom P341 DAR relay (model P34131BB6M0800J, running software P341____6__800_A) per transformer, headline real-time calculation of bottom oil, top oil and hot spot temperatures (note: not potential ampacity), communicating via IEC 61850 over IP network;
- CTs at transformer 11kV circuit breakers providing current measurement fed directly to the respective P341 relay;
- PT100 resistance thermometer measuring ambient air temperature connected to iSTAT400 transmitter providing 4-20mA output signal fed to P341 relay;
- Three PT100 resistance thermometers per transformer, with direct three-wire connection to an Exemys RME1 acquisition module, providing measured values of: top

of tank oil temperature; top of cooler oil temperature; and bottom of cooler oil temperature via thermometer pockets. The Exemys RME1 (resistance thermometer to Ethernet) acquisition module in turn communicates oil temperatures via Modbus over the FALCON IP network to a dataTaker DT80 data logger.

In-situ views of top of tank and the bottom of cooler temperature sensors are shown in Figure 5.

Figure 5 : Illustration of top of tank and bottom of cooler oil temperature sensor

Placement of the ambient air temperature sensor was further considered following review of initial data, and was repositioned such that it was out of direct sun, away from air vents and a Stevenson Shield was fitted.

3.3 Data and data transfer

The process of data collection for offline modelling is illustrated in Figure 6.

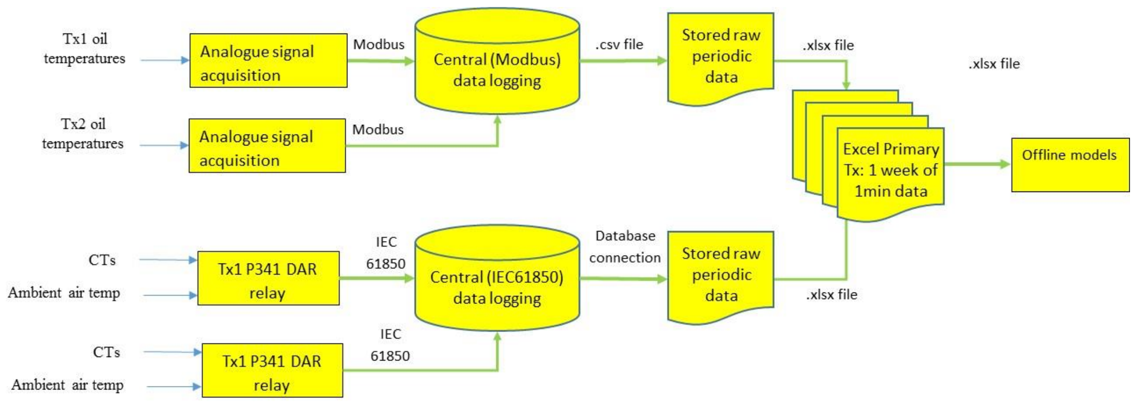

Figure 6: Data collection for offline modelling, offline/online model comparison and benefit assessment

Transformer oil temperature measurement acquisition

The Exemys RME1 analogue signal acquisition modules installed at each site are web-enabled Ethernet I/O modules featuring:

- built-in web server that allows remote configuration, I/O monitoring and I/O control via a standard browser; and
- support for Modbus/TCP protocol, providing integration with installed data logging equipment

By hardware design, the modules directly connect to three-wire resistance thermometers. The modules are configured with a signal name for each sensor input, and given an IP address according to the project schedule of IP addresses.

Configuration of DT80 data logger to poll the Exemys RME1 modules required:

- reading the RME1 input register (Modbus function code 4);
- setting of data type to 16 bit signed integer (DT80 default is 16 bit signed integer); and
- no requirement to provide a Modbus "unit id" field setting.

A typical data retrieval command for the DT80 data logger was “4modbus (ad"172.29.***.***",r4:1,0.1,=1..3cv), retrieving the three temperature values from one of the Primary transformers.

Load current, air temperature and P341 outputs acquisition

The Alstom P341, with DAR functionality is an example of a substation intelligent electronic device (IED). Input measurements and calculated values associated with the P341 DAR relays are made available via the device’s integral IEC61850 data model. Within FALCON, connection to the IED’s data model was achieved via software (MatrikonOPC Server for IEC 61850). This software acts as both a client (connecting to multiple IEDs), and a server, providing the data to further clients (for example a historian, or an Excel plug-in).

Within FALCON, the Matrikon Server for IEC61850, OPC Desktop Historian and OPC Excel reporter were deployed to allow source data access, storage and retrieval of the P341 DAR data.

Collation of data

The dataTaker data is downloaded from the device as a csv file and the OPC Desktop Historian data is extracted into Microsoft Excel using OPC Excel Reporter. These two sets of data were combined via a series of Excel files to output a weekly report of minutely data:

- An OPC data file is updated by inputting the required dates, which in turn updates arrays created with OPC Excel Reporter with data from OPC Desktop Historian;
- A second processing file is updated which links to the raw data in the OPC data file and standardises record time. This processing file is also where dataTaker data is inserted;
- A third file uses pivot tables to sort the data and average multiple values per measurement period. It outputs datasheets in which every minute for a week has a quality measure: “1” meaning the value given was provided by the measurement device, and “0” meaning the value is extrapolated from the one before to give a continuous set of data, but was not provided by a measurement device;
- A final “values only” Excel file is then prepared for transmission to the offline modelling and assessment stage.

3.4 Key Learning from Implementation

3.4.1 Technique-Specific Learning

LP 1.	Air temperature sensors should be positioned such that they are out of direct sun, away from air vents and with Stevenson Shields fitted.

LP 2.	Supplied P341 relays did not include calculation of a dynamic rating for transformers. However, the relays do calculate a model-based hot spot temperature.

LP 3.	No continuous data collection occurred around winding temperature indicators (WTI). A limited number of spot readings were taken. From these it was apparent that significant differences between the two transformers existed, with very similar levels of load. It was not reasonably practicable to resolve these instrument output differences within the scope of the project. Appropriate notifications were made within the business.

LP 4.	No explicit ongoing data collection occurred on transformer cooling mode. When required, manual records were taken. As load current was typically less than 50% of the sustained rating it can be reasonably assumed that transformer operational mode was ONAN unless stated otherwise.

LP 5.	It was not possible to monitor transformer tap position as part of the data logging – therefore this was assumed to remain on nominal tap position. It was judged that this marginal difference in windings resistance does not substantially alter the findings.

LP 6.	Manufacturer software status needs to be known in advance so expectations on functionality can be managed:

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

3.4.2 Generalised and Cross-Technique Learning

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

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

- The relays, although issued with a FAT test certificate were inconsistently configured for operation. For Primary transformers this involved the communications parameter (for connection to the FALCON IP network) and detailed asset parameters.

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

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

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

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

SECTION 4

Thermal Models

All DAR assessment is predicted on a thermal model, and confidence in that model. These models include parameter values that are specific to each asset. This section describes the work undertaken within the project to prepare thermal models for Primary Transformers that gave acceptable coincidence to measured oil temperature values, and the learning that resulted.

4.1 Overview of thermal models

There are three main mathematical models from three common standards that apply to mathematical modelling of transformers, see Table 1.

Standard	Load	Model	Time constant	Cooling mode	Used in	Year
IEEE C57.91 [3]	Step	Exponential	Variable	√		2011
IEC 60354 [1]	Step	Exponential	Fixed	√	Alstom relay	1991
IEC 60076-7 [2]	Step/ Dynamic	Multi-exponential function or differential	Fixed	√	Recommended for SIM	2005

Table 1: Summary of the transformer thermal models under review.

Note: IEC 60354 is an earlier standard than IEC 60076-7, and has largely been superseded by it. As the Alstom relay used IEC60354 this was also considered within the modelling. All three models were coded to enable comparison between them and against measured results.

Whilst the three standards use different algorithms/calculation models, they are each dependent on parameters that are very similar. Table 2 shows a breakdown of some of those key parameters within each model, and a description of the models and associated parameters is given in Appendix C.

Standard	Standard defined constants	Input variables	Transformer specific model parameters
IEEE C57.91	*n,2m*	K,T_a	$R, \Delta T_{tor}, \Delta T_{hsr}, \tau_o, \tau_{hs}$
IEC 60354	*x,y*	K,θ_a	$R, \Delta\theta_{tor}, \Delta\theta_{hsr}, \tau_o, \tau_{hs}$
IEC 60076-7	*x,y,* k_{11}, k_{21}, k_{22}	K,θ_a	$R, \Delta\theta_{or}, \Delta\theta_{hr}, \tau_o, \tau_{hs}$

Table 2 : Parameters in Transformer Thermal models

It is important to note a key modelling complication associated with Primary transformers compared to Distribution transformers:

- The input variable K (rating of measured current to rated current) and transformer specific variables ($R, \Delta T_{tor}, \Delta T_{hsr}, \Delta\theta_{tor}, \Delta\theta_{hsr}, \Delta\theta_{or}, \Delta\theta_{hr}$) are all dependent on the rating of the transformer;

- Under different operating regimes (e.g. cooling modes, or hot-spot temperature limit) the transformer has different rated current; and
- The transformer rated current is not explicitly identified under all the operating regimes required to fully model operation (e.g. ONAF[5] and OFAN[6]); though
- the two limit cases are defined, and parameter value calculation methods are available from standards:
  - ONAN with 98^{o}C hotspot (12MVA); and
  - OFAF with 140^{o}C hotspot (24MVA).

Work to identify appropriate parameter values, and resulting coincidence to measured values under ONAN cooling is described in Section 4.2. It should be noted that the transformers ordinarily operated in this cooling mode throughout the trial period, as would be expected. The only time that other cooling modes were in operation was under FALCON initiated test conditions.

A limited amount of work investigating additional model parameter values that appropriately describe the transformers behaviour under ONAF, OFAN and OFAF conditions was undertaken and is described in Section 4.5.

[5] ONAF – oil natural air forced

[6] OFAN – oil forced air natural.

4.2 Model validation

Mathematical details of the above models (including IEC60076 differential, IEC60076 multi-exponential, IEC60354 exponential, and IEEE C57.91 exponential) were implemented in MATLAB. Where known, transformer-specific model parameter values were used. Where not known, example values from the standards were used as a starting point for model tuning.

Initial model testing was carried out through the use of an arbitrary load current step function. This work was aimed at confirming valid model implementation, and basic coincidence between models.

Subsequently, trial data was then used to generate thermal model outputs, and these were compared to trial measured values. Tuning of model parameters was undertaken such that acceptable correlation to measured values was achieved.

Finally, comparisons were made between:

- The offline IEC60354 model and the online relay outputs; and also
- Between the three offline models outputs.

This validation process is illustrated in Figure 7.

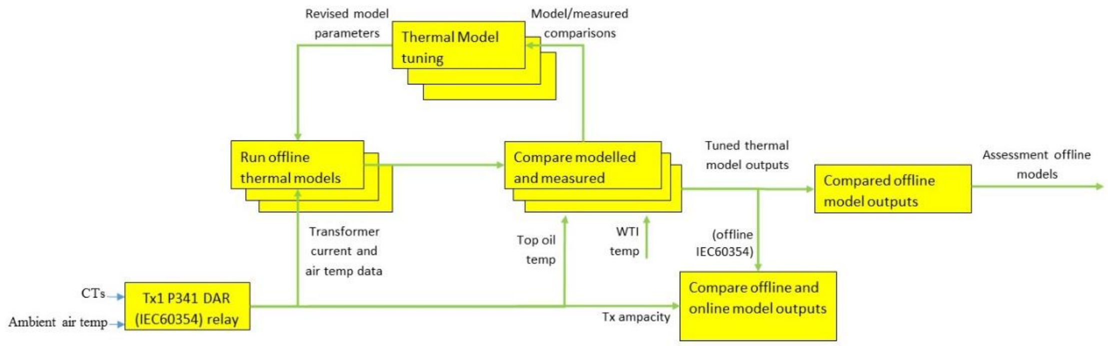

Figure 7: Thermal model validation process

4.2.1 Step function comparison

A large load step was simulated to understand the transient behaviour of the models with time following this event.

Results and discussion of the top-oil temperature and hot-spot temperature responses are contained in Appendix C.5. As a result of this work it was concluded that:

LP 11.	Necessary knowledge and understanding to correctly implement Standards-based transformer thermal models had been established.

In addition, it was also established to the satisfaction of the project that:

LP 12.	Under theoretical load step test conditions the DAR transformer models all produce similar results.

4.3 Top oil-related parameter tuning

The accuracy of the models (both offline and as implemented in the Alstom P341 relay) is dependent on the selection of parameters used within the models. By preference, and where available these were taken from the transformer test certificates as asset specific indications. In the remaining instances values were taken from example values in respective standards.

Following initial parameter validation the test data was used to tune some of the parameter values. The tuning of transformer models for DAR is advertised within industry [9] but the proprietary knowledge on their processes is not available. Further notes on thermal model parameter value estimation are contained in Appendix C.6.

FALCON project work on Distribution transformers identified:

- Two key parameters are responsible for the mismatch between model and experimental values of top oil temperature:
  - $\Delta\theta_{or}$ - Top oil rise over ambient temperature at rated load (°C); and
  - τ_o - Thermal time constant of oil temperature rise (s); and
- A new process of tuning transformer model parameters, where:
  - The two parameters are adjusted for a week of trial data until a "best fit" curve is obtained. The process of finding a "best-fit" is based on using weighting functions to look at key indicators such as root means square error and peak (difference) values and then choosing the combination with the lowest values;
  - The revised parameter values (for each week's data) are then recorded and compared to values generated over other weeks;
  - Once sufficient data has been analysed, a set of permanent parameter values is established.

An example of modelled output with different model parameter values is shown in Figure 8, demonstrating the worth of model selection and tuning within the thermal model.

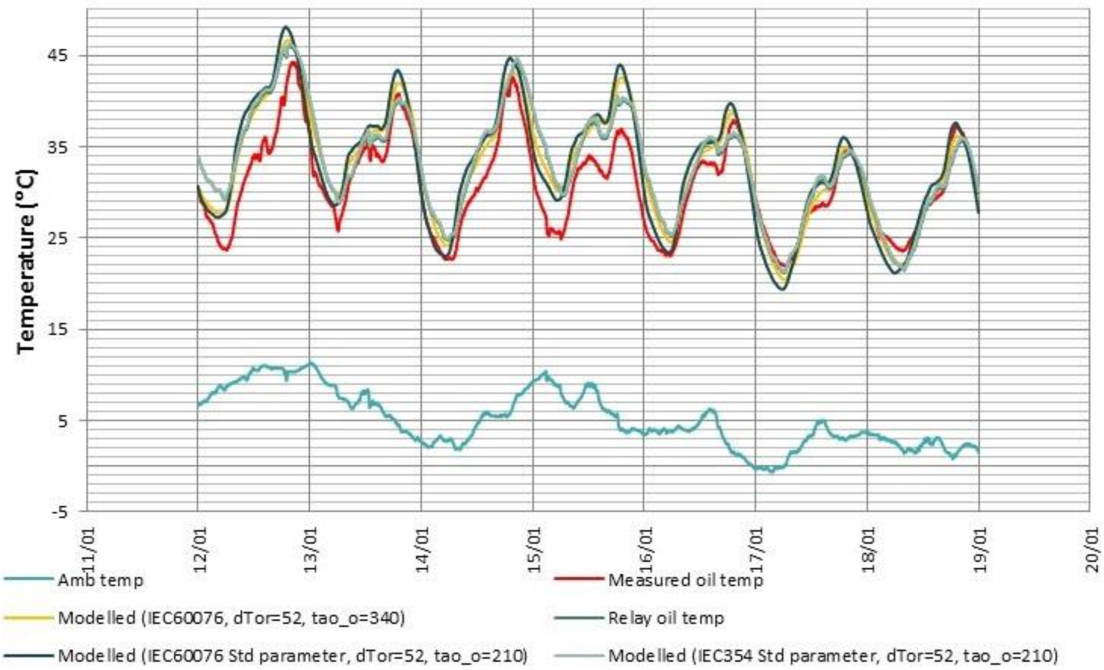

Figure 8: Modelling results with different models and model parameter values (T1, w/c 12/01/2015)

Optimised parameter values for the FALCON trial Primary transformers were calculated for both $\Delta\theta_{or}$ and τ_o using weekly data. The weekly optimum values are shown in Figure 9 and Figure 10.

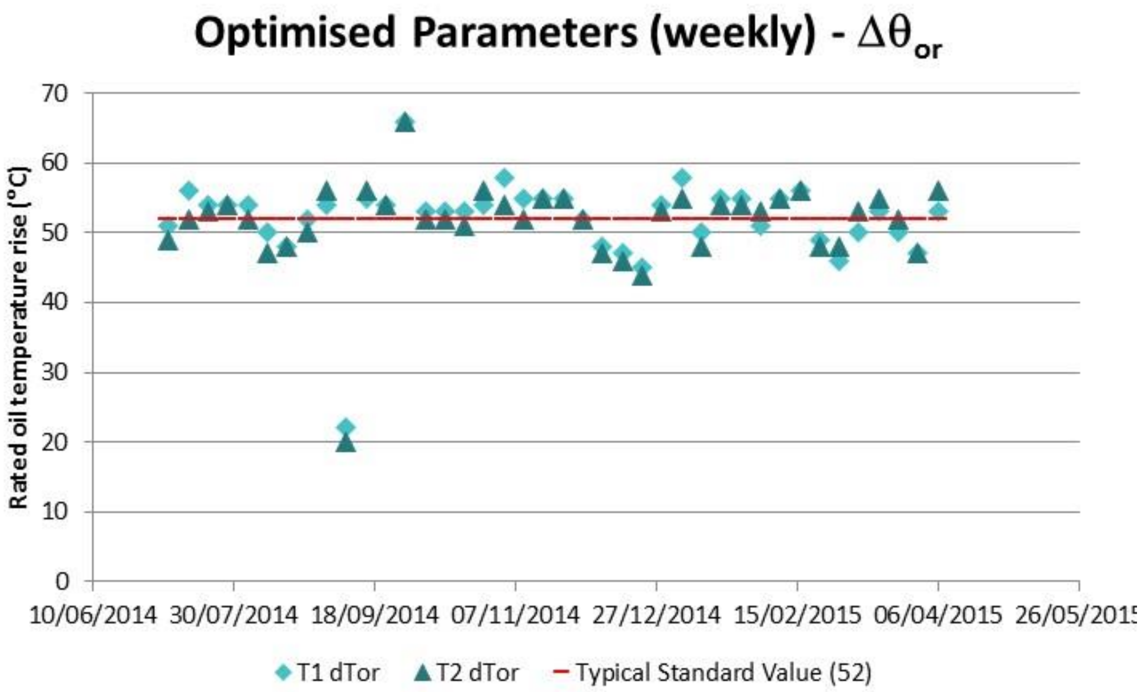

Figure 9: Optimise parameter $\Delta\theta_{or}$ using weekly data (T1 and T2).

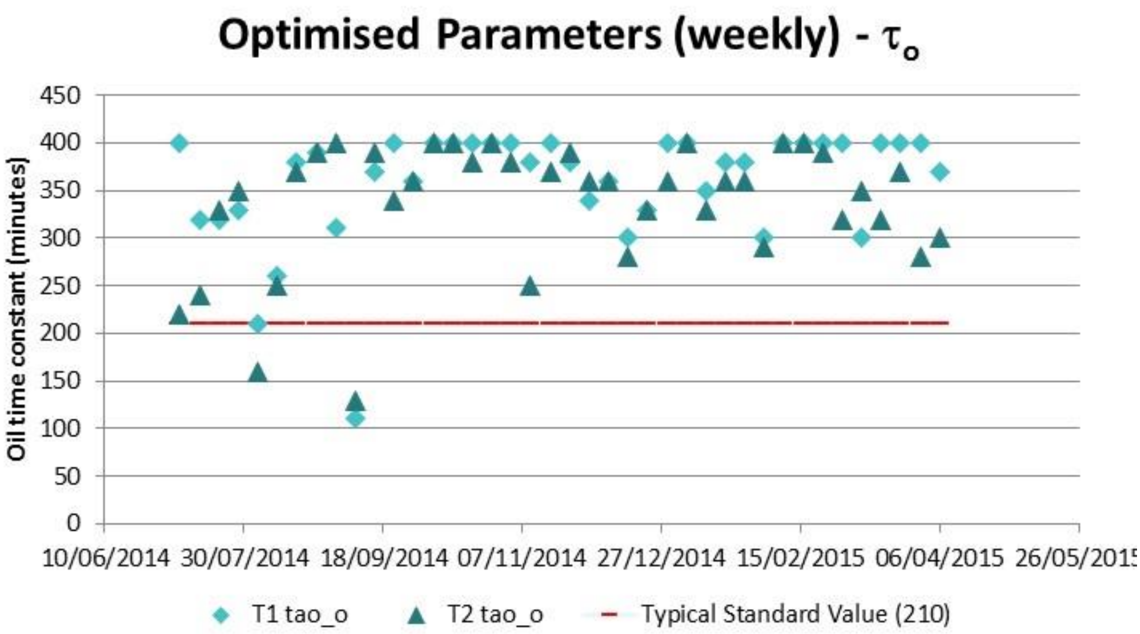

Figure 10: Optimise parameter τ_o using weekly data (T1 and T2)

Table 3 gives the average values (data from mid-April 2014 to mid-January 2015) of the optimised parameters for T1 and T2 respectively (removing anomalous data). It can be seen that values of $\Delta\theta_{or}$ for both transformers are very similar and also close to the IEC60076-7 standard value (52°C). However, whilst values for the average tuned top oil time constant for the two transformers are in close agreement, they are higher than the example value from the standard (210 min for ONAN).

	T1		T2	
	$\Delta\theta_{or}$ (°C)	τ_o.(min)	$\Delta\theta_{or}$(°C)	τ_o.(min)
Mean	52	337	49	341

Table 3: Summary of the average optimised parameters

The result of this tuning exercise was that:

- the selected modelling value for $\Delta\theta_{or}$ is 52°C, unchanged from standard example value; and
- the selected modelling value for τ_o is 340 minutes, higher than the standard example value of 210minutes.

The importance of time constant selection on accuracy of modelled output can be seen with reference to Figure 11.

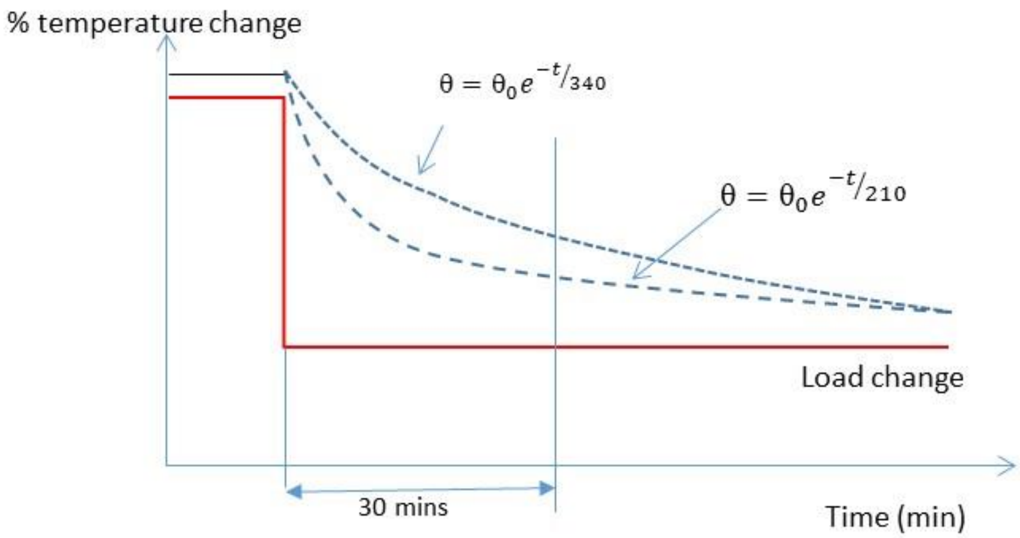

Figure 11: Effect of time constant on accuracy of temperature calculation

After a 30-minute period, $e^{-t/340} = 0.916$ and $e^{-t/210} = 0.867$, therefore the "typical" value for oil time constant results in around 5% more cooling than the longer parameter determined time constant. The oil time constant is heavily dependent on the mass of oil in the transformer – not something that can be accurately taken into account by the use of a generic value due to variation in different transformer manufacturer's designs over different MVA ratings.

In addition, whilst all the models showed good agreement, IEC60076 was chosen as the preferred offline model within which tuning was completed. This was mainly to maintain consistency with the Distribution transformer modelling under FALCON.

4.4 ONAN comparisons between modelled and measured data

Having selected appropriate parameter values (described in Section 4.3 above), these were then applied to the thermal model, and output values were calculated for the full set of input data (transformer load current and ambient air temperature) covering one year. These outputs were then compared to measured values.

Figure 12 shows an example of the comparison between the measured and modelled top oil temperature. The results show a good level of correlation between measured top oil temperature and calculated top oil temperature.

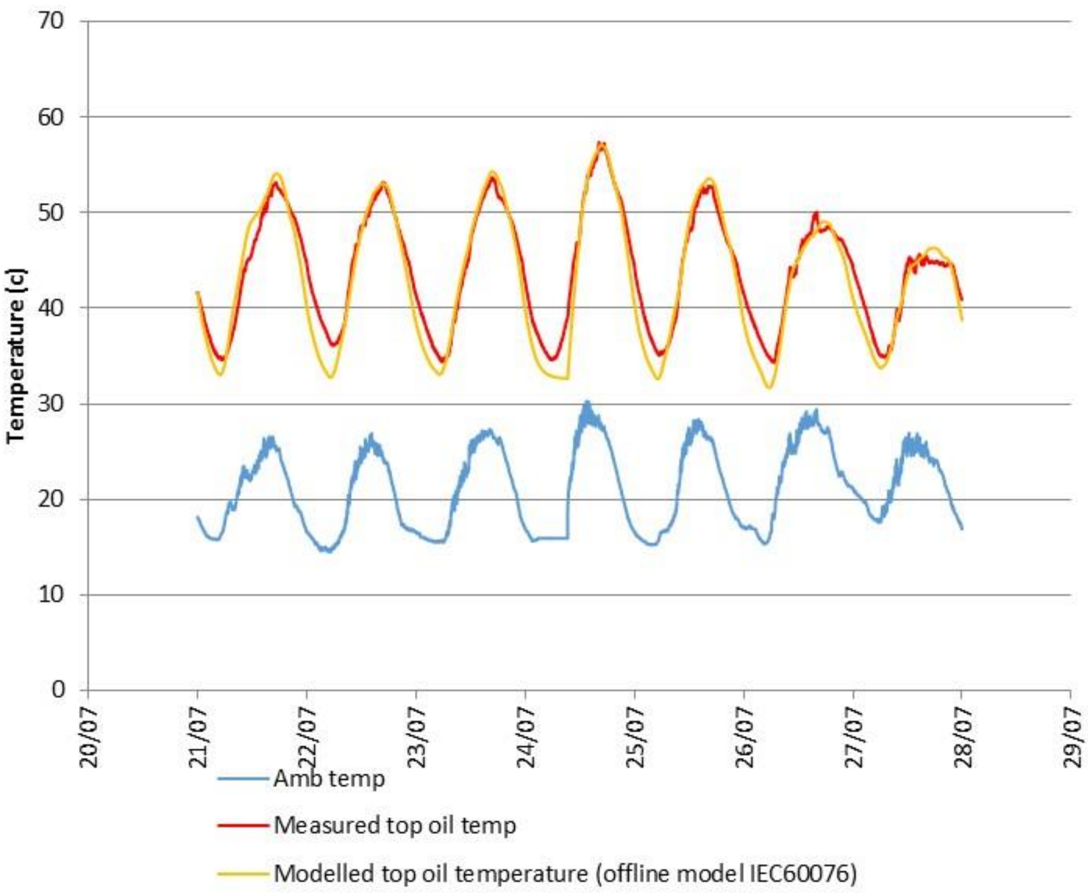

Figure 12: Top-oil temperature modelling results for Marlborough St T1 - w/c 21/07/2014

Whilst comparison data was generated for the whole of the trial period, five weeks were chosen to illustrate findings, one week for each season (Table 4).

Season	w/c
Spring	21/04/2014
Summer	23/06/2014
High Summer	21/07/2014, 15/09/2014
Autumn	13/10/2014
Winter	19/01/2015

Table 4 : Typical weeks over the course of the year

High level indicators and key points of learning are presented in subsequent report sections for:

- Top oil temperature (Section 4.4.1);
- Bottom oil temperature (Section 4.4.2); and
- Hot-spot temperature (Section 4.4.3).

In addition, charts showing modelled and measured data are shown in Appendix D (for top oil temperature), Appendix E (for bottom oil temperature) and Appendix F (for hotspot temperature).

4.4.1 Top oil temperature comparison

Table 5 shows a summary of the absolute difference between the measured top oil temperature and that calculated by using the models described above for Transformer 1.

Model	Top-oil difference indications (measured values vs modelled values) °C					
	Indicator	w/c 21/04/2014	w/c 23/06/2014	w/c 15/09/2014	w/c 13/10/2014	w/c 19/01/2015
Relay (IEC60354)	Max	4.8	5.6	5.0	5.6	6.1
	Min	0.0	0.0	0.0	0.0	0.0
	Mean	1.9	2.1	1.5	1.8	1.8
Offline IEC60354	Max	4.6	5.9	5.0	5.8	6.3
	Min	0.0	0.0	0.0	0.0	0.0
	Mean	1.8	2.1	1.4	1.7	1.8
Offline IEC60076	Max	5.3	6.2	4.9	6.1	6.0
	Min	0.0	0.0	0.0	0.0	0.0
	Mean	2.0	2.2	1.6	2.2	2.1
Offline IEC60076 (parameter tuning)	Max	6.9	5.6	3.7	5.1	6.6
	Min	0.0	0.0	0.0	0.0	0.0
	Mean	2.4	1.3	0.9	1.2	1.7
Offline IEEE C57.91	Max	4.6	5.9	5.0	6.0	6.3
	Min	0.0	0.0	0.0	0.0	0.0
	Mean	1.8	2.1	1.4	1.7	1.8

Table 5: Summary of the maximum and minimum errors on top-oil temperatures.

LP 13.	All the models give results which are comparable with the measured values. The majority of top oil calculated results are within approximately 6°C of the measured value regardless of the parameter set or model chosen.

LP 14.	The calculated results for the relay top oil temperature and the IEC60354 model are very close indicating that the coding in the relay is sufficiently understood allowing it to be replicated using off-line models.

LP 15.	The models tend to marginally overestimate the top oil temperature (by design). This is important and beneficial as it leads to conservative (marginally lower) estimated ampacity, preventing potential operation of the transformers at hotspots greater than limit values.

4.4.2 Bottom-oil temperature comparison

An advantage of the IEC60354 model is that it also calculates the bottom oil temperature, not done by the other models. This is an additional point of comparison to validate the thermal modelling. Figure 13 shows an example of the comparison between measured and calculated bottom oil temperature. The relay reported value and offline model are so close in value that they can’t be differentiated on the graph. A comparison of the remaining seasons is shown in Appendix E. Table 6 shows a summary of the difference between measured and modelled bottom oil temperature.

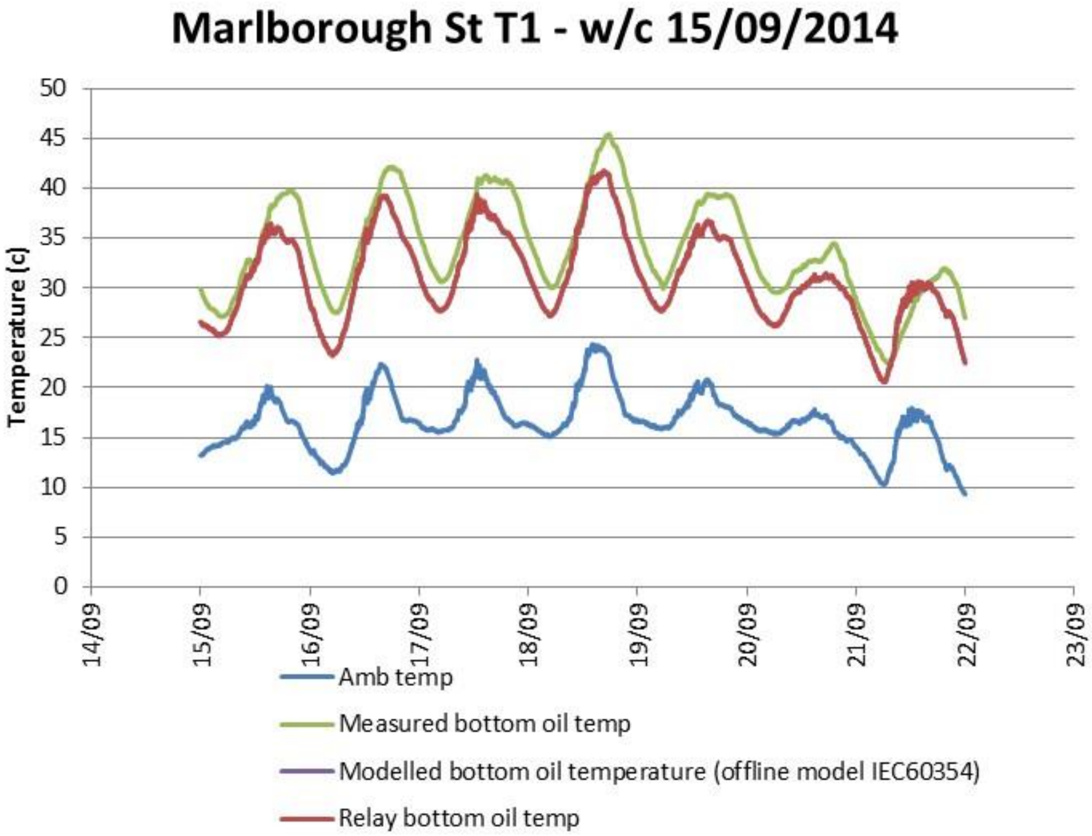

Figure 13: Bottom-oil temperature modelling results compared to measured and relay values (T1, w/c 15/09/2015)

Model	Bottom-oil difference indications (measured values vs modelled values) °C					
	Indicator	w/c 21/04/2014	w/c 23/06/2014	w/c 15/09/2014	w/c 13/10/2014	w/c 19/01/2015
Relay (IEC60354)	Max	7.9	7.5	6.0	5.5	7.0
	Min	0	0	0	0	0
	Mean	2.2	2.2	2.9	2.3	2.4
Offline IEC60354	Max	7.8	7.3	6.1	5.6	7.2
	Min	0	0	0	0	0
	Mean	2.2	2.2	3.0	2.4	2.4

Table 6: Summary of the maximum and minimum errors on bottom-oil temperatures.

LP 16.	The level of accuracy of the bottom oil temperature calculation is of a similar value to the top oil temperature calculation and offers a useful cross check of model accuracy.

4.4.3 Hot-spot temperature comparison

The hot-spot location and temperature is a function of transformer design and cooling functionality, ambient air temperature, oil temperature, and winding losses amongst other parameters and cannot be measured directly as part of the trial.

However, the trial transformers do have winding temperature indicators fitted, that estimate the temperature of the hotspot. A number of values from the winding temperature indicators were recorded throughout the trial as noted in LP 3 (page 24). These values are shown in Table 7, and graphically in Figure 14.

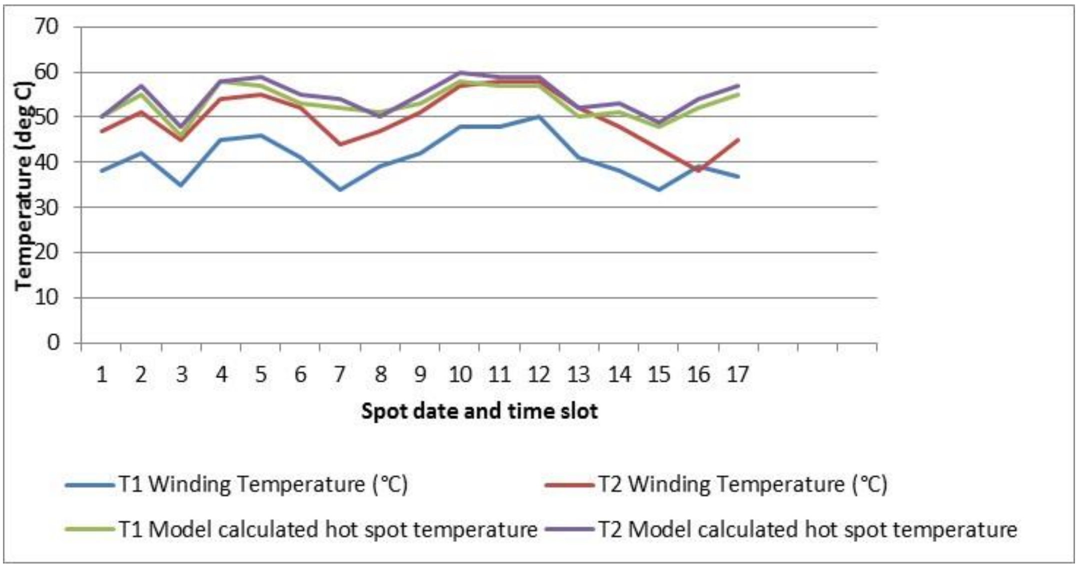

Figure 14: Hot spot temperature modelling results compared to measured WTI values

Date	Time	T1 WTI (°C)	T1 Tap Changer Position	T2 WTI (°C)	T2 Tap Changer Position	T1 Model calculated hot spot temperature	T2 Model calculated hot spot temperature
24/09/2014	08:20	38	7	47	7	50	50
24/09/2014	13:00	42	6	51	7	55	57
25/09/2014	08:15	35	6	45	7	46	48
25/09/2014	14:40	45	7	54	7	58	58
26/09/2014	14:55	46	6	55	7	57	59
07/10/2014	14:45	41	6	52	7	53	55
13/10/2014	09:55	34	7	44	8	52	54
20/10/2014	12:05	39	7	47	7	51	50
24/10/2014	09:25	42	6	51	7	53	55
27/10/2014	15:10	48	7	57	8	58	60
28/10/2014	15:05	48	6	58	7	57	59
30/10/2014	14:45	50	6	58	7	57	59
18/11/2014	10:10	41	7	52	8	50	52
24/11/2014	10:30	38	7	48	8	51	53
02/12/2014	13:40	34	7	43	8	48	49
08/12/2014	11:55	39	7	38	8	52	54
12/01/2015	09:30	37	7	45	8	55	57

Table 7: Summary of the spot reported WTI comparison dates and times.

As previously discussed (LP 3) it was not reasonably practical to resolve the differences between the two WTI indications. Load current and top oil measured values strongly indicate that the two transformers were performing in a very similar manner (as would be expect for identical design transformers operating in parallel), and so should have had similar hotspot indications.

Having described causes for placing limited reliance on comparisons to the WTI values, it is interesting to note that:

- WTI for transformer 1 are generally in very good agreement to the modelled values; and
- WTI for transformer 2 is less than for transformer 1, suggesting that if this was a more accurate indication, then the modelled hotspot temperatures would be over-estimates, and therefore conservative (preventing over estimation of transformer ampacity)

4.4.4 Comparison anomalies

The vast majority of calculated top oil temperatures are within 6^{o}C of the measured top oil temperature over the course of a year. However, there are a small number of days where larger differences occur. Generally these were where the measured value was lower than the modelled value, implying cooling occurred that was not modelled. An example is shown for Transformer 1, w/c 19th January 2015, as shown in Figure 15.

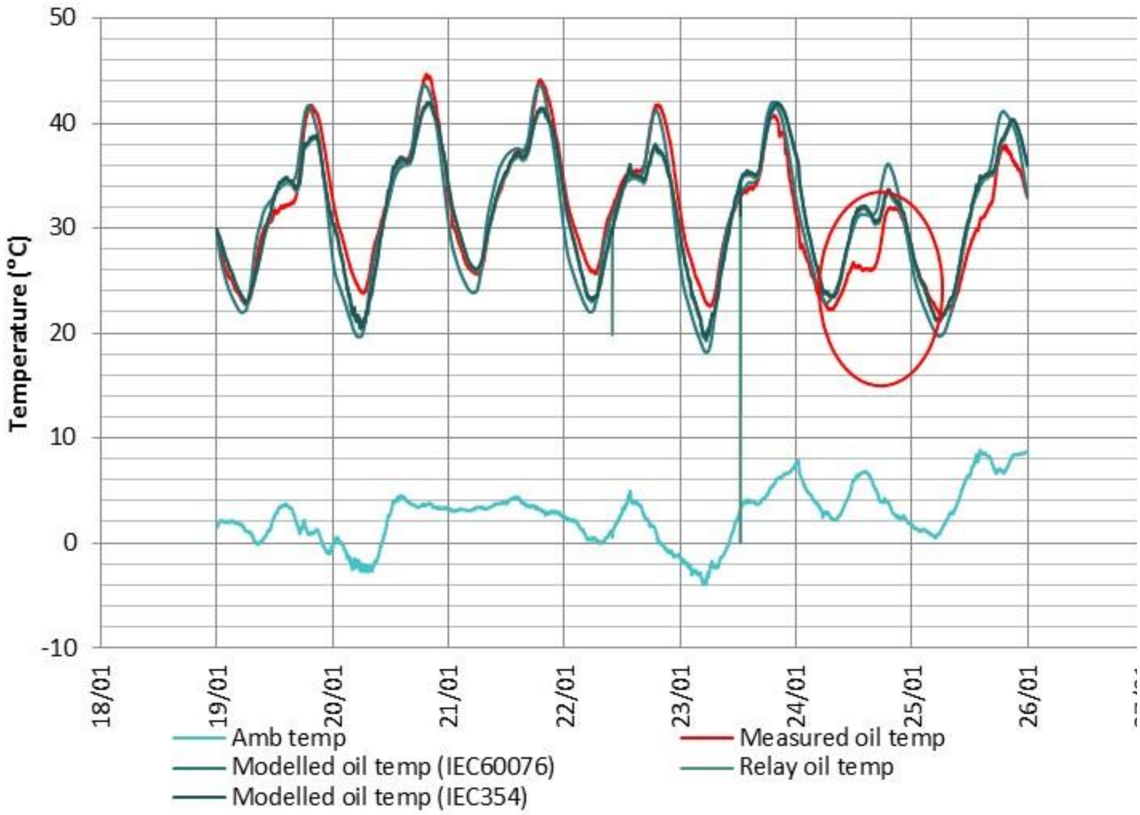

Figure 15: Modelling results with different models compared to measured values (T1, w/c 19/01/2015)

These anomalies and potential causes were investigated, and correlations to rainfall and wind speed (potential causes of cooling not included in the model) were sought. This investigation work is described in Appendix G.

Whilst it seems possible that these cooling events are related to weather conditions that are not accounted for in the modelling, analysis did not suggest strong correlations to available data. It should be noted that this data was of limited validity.

It is concluded that there may be other weather related influences on the modelling of transformers, but these are likely to further cool the transformer, and their influence is inherently conservative on subsequent ampacity estimates.

4.5 Cooling mode effects

Typically the transformer operates under ONAN cooling mode of operation because the transformer is carrying only 50% of the total Primary substation load current. However if the load increases and the winding temperature indication increases, (the hotspot temperature proxy) the indication assembly rotates and mercury tilt switches operate to turn on the oil pump and air fans. The pump comes on first, followed by the fans. As the WTI reduces, the assembly rotates back, and the tilt switches switch off, fans off first, and then pump. As would be expected, a degree of hysteresis exists in this mechanical switching assembly.

LP 17.	If proved beneficial changes to allow more control over pumps and fans for DAR purposes would require control system changes to the transformer cooling system.

As the primary transformers have different cooling modes available, this requires changes to the model to reflect this. In particular, within the model there are different constants associated with the different cooling modes (as discussed in Section 4.1).

An example of the effect of the cooling mode on top oil temperature is shown in Figure 16. This shows a step increase in load and the automatic changes in cooling mode that occur as a consequence of changes in transformer temperature.

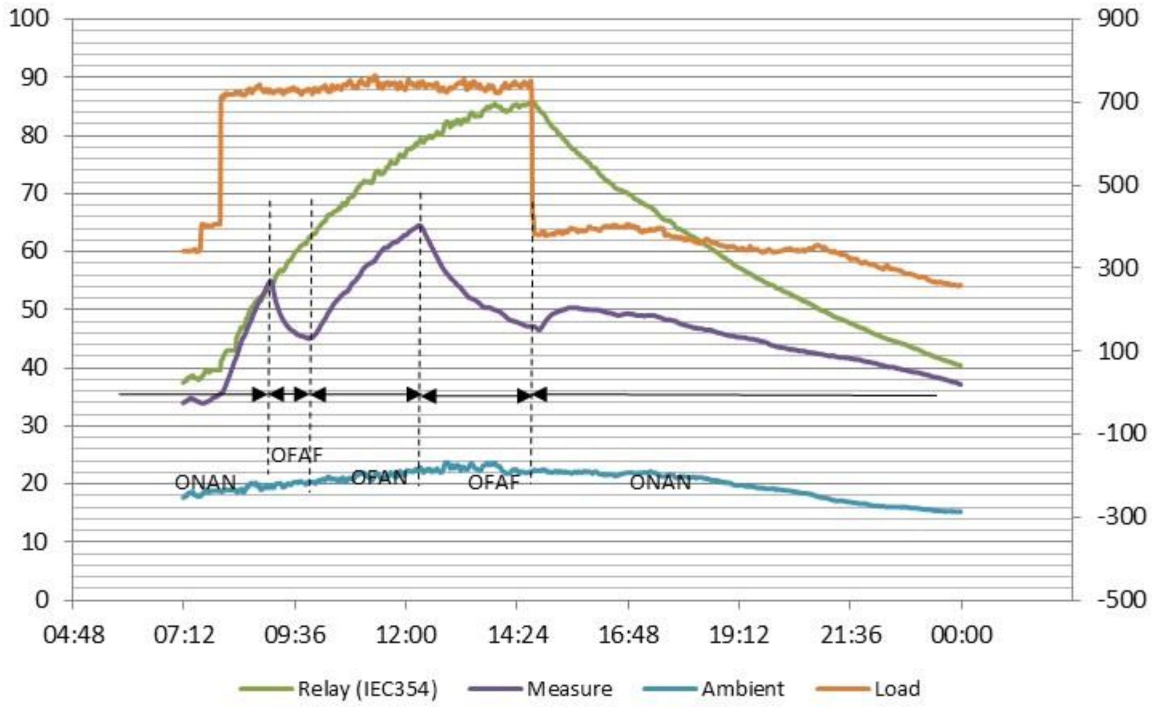

Figure 16: Top-oil temperature comparison, T1, ONAN, 9th Jul 2014

The measured top oil temperature can clearly be seen to respond to the initial change in load current, and subsequently change in response to changes in operating cooling mode. However, the relay modelled top oil temperature does not match the actual measured value during this period. This is because the relay has no input identifying which cooling mode is operating, and does not have the multiple sets of model parameter values that would be required to accurately model response under different cooling modes.

LP 18.	The cooling mechanism is not an input to the relay and therefore different cooling techniques are not recognised by the relay, and more importantly

	the modelled temperatures are not accurate during different cooling modes.

Whilst the relay is limited in in what can be modelled, it is possible to alter the offline thermal models such that different cooling modes, and the associated model parameter values, are used. Tests were undertaken throughout June 2015 to further investigate model parameter values associated with the different cooling modes. A description of this work is contained in Appendix C.7.

As a result of this work, altered model parameter values were identified and used to significantly improve the modelling of a transformer with ONAN, OFAN, ONAF and OFAF models of operation (as experienced with the trial transformers). Figure 17 illustrates how revised parameter values can effectively be used to model the response of the transformer to different cooling modes.

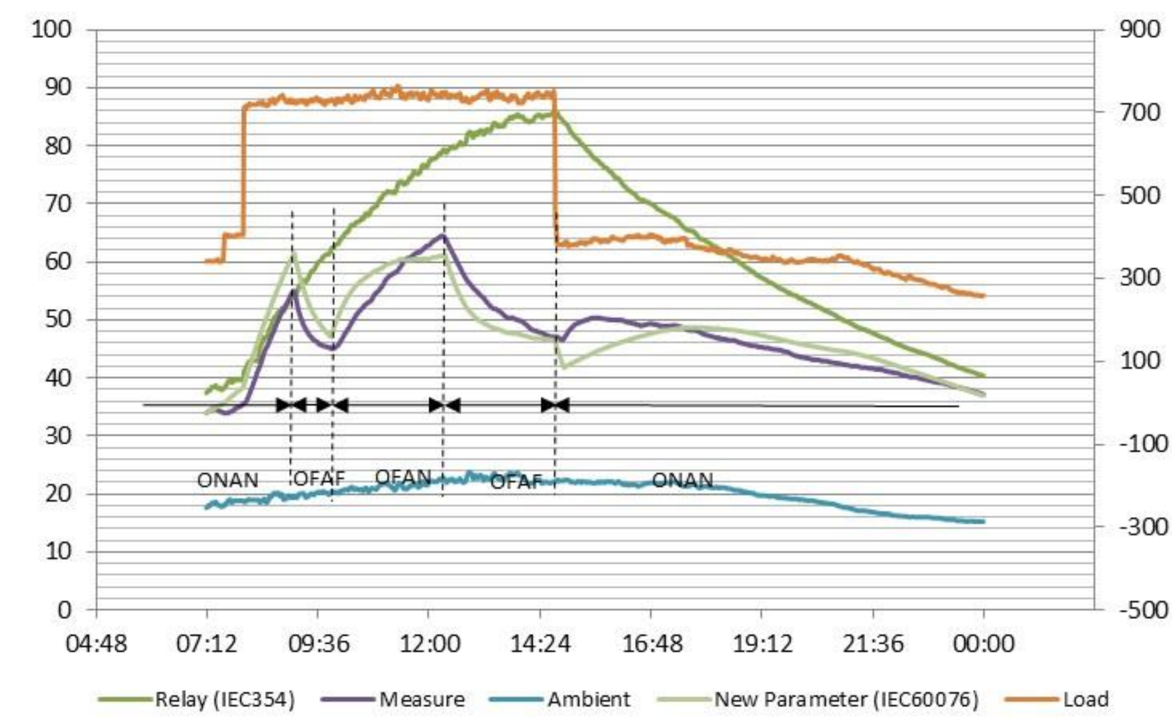

Figure 17: Top-oil temperature comparison, T1, ONAN, 9th Jul 2014 with revised parameter value modelling included

The following learning results from this:

LP 19.	Modelling of transformers under different cooling modes is important to being able to accurately model thermal response over a full range of operation.

LP 20.	Modelling of different cooling modes requires a revised set of parameter values for each cooling mode.

LP 21.	Tests and modelling work carried out under FALCON have demonstrated that such sets of parameter values can be identified, and these show good correlation to measured values.

LP 22.	The capability to model the transformer under different cooling modes is a precursor to consideration of pre-emptive cooling.

SECTION 5

Dynamic Asset Rating

This section describes the work undertaken within the project to use the developed Primary Transformer thermal model to derive dynamic asset ratings, and compare these to the sustained static ratings associated with the transformers.

5.1 Boundaries of operation

Sustained, cyclic and emergency ratings are given by manufacturers, sometimes with different cooling mechanisms, to limit operating insulation temperatures.

Typically, transformers are designed and rated by the manufacturer to operate with a winding hot spot temperature of less than 98°C for a range of ambient temperatures with an average of 20°C under sustained operation[7], to guarantee an acceptable service life of at least 20 years. In practice, operating temperatures are significantly less than this for the vast majority of service life, with actual service lifetime potentially being multiples of 20 years.

5.2 Approach to calculation of Dynamic Asset Rating

IEC 60076 does not define a method for utilising a thermal model to determine a dynamic asset rating. For the majority of this project work, sustained ratings of the transformers have been considered together with a sustained limit temperature of 98°C.

"Of the moment" Ampacity for the transformer (using ambient conditions for a moment in time to determine ampacity at that same moment) may be estimated by repeatedly incrementing the input load current to the model until a hot-spot temperature limit is reached. This is then set as a continuous dynamic rating for that moment in time assuming an unvarying load. Standards typically state that 98°C is the unit life winding temperature for non-thermally upgraded paper. This means that the winding temperature can reach 98°C without there being any noticeable additional loss-of-life beyond a nominal design rate.

The dynamic rating calculated in this way is most appropriate for the aims of the FALCON project in looking at DAR of transformers as a planning tool and therefore studying the rating appropriate to operation without loss of transformer life.

Some work has also been conducted on investigating the impact of cyclic loads in comparison to the quoted (summer) rating of 19MVA, cyclic load shape, with a limiting temperature of 120°C. This work is briefly reported in Section 5.4.

[7] Table 1, IEC60076-2 2011 Medium power transformer values

5.3 Primary transformer trial DAR results

Calculated Primary transformer DAR results are shown in Figure 18 as a long term trace over time, with comparison to the ONAN (98°C) static rating.

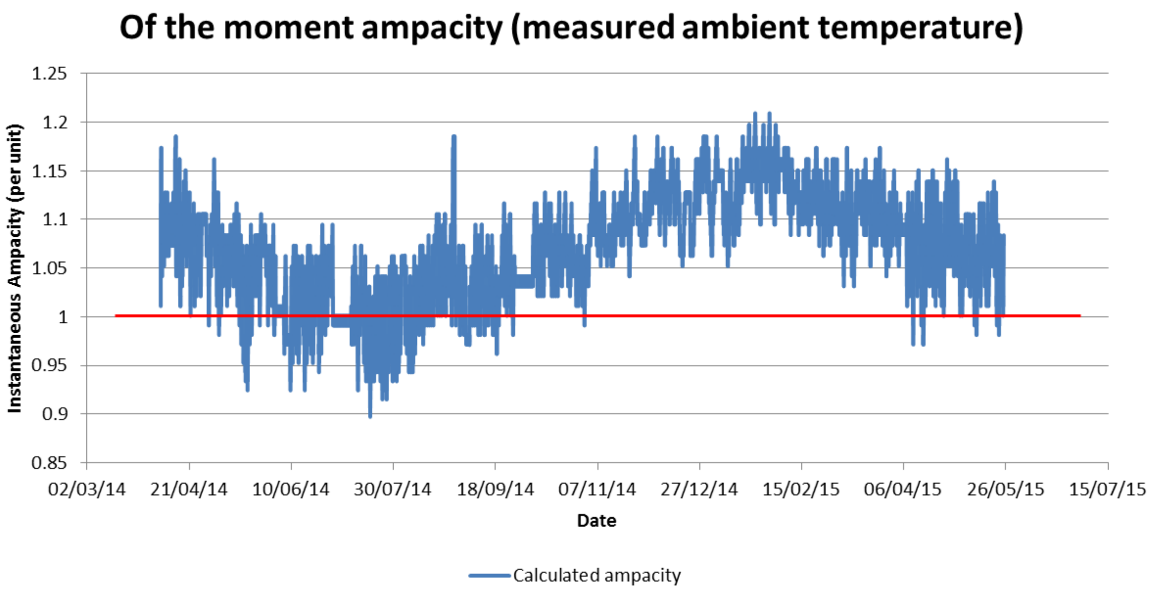

Figure 18 : Dynamic rating for unit loss-of-life operation (98°C limit) with ONAN cooling over trial period

From Figure 18 it can be seen that:

- Analysed data covered the period April 2014 to May 2015;
- DAR values vary on a broadly seasonal basis – this is clearly founded on transformer temperature being dependant on ambient air temperature;
- Significant variation in DAR values occurs around this seasonal trend;
- DAR values are mostly above the ONAN 98°C static rating;
- Peak DAR value over the period is around 1.2pu (14.4MVA);
- DAR values of less than the ONAN 98°C static rating are mainly seen in the summer period, though a small number of occurrences are seen in the Spring 2015 period;
- Minimum DAR value over the period is around 0.9pu (10.8MVA).

As with other DAR techniques, sample one week periods, representing different seasons, have been used to present higher (time) definition views of the data. The sample periods are shown in Table 7. Charts of DAR and ambient temperature values are shown in Appendix H for each of the weeks in Table 7.

Season	Date (w/c)
Spring	21st April 2014
Summer	23rd June 2014
High Summer	21st July 2014
Autumn	13th October 2014
Winter	19th January 2015

Table 8 :Seasonally representative weeks

The DAR and ambient temperature chart for week commencing 21st July 2014 is shown in Figure 19.

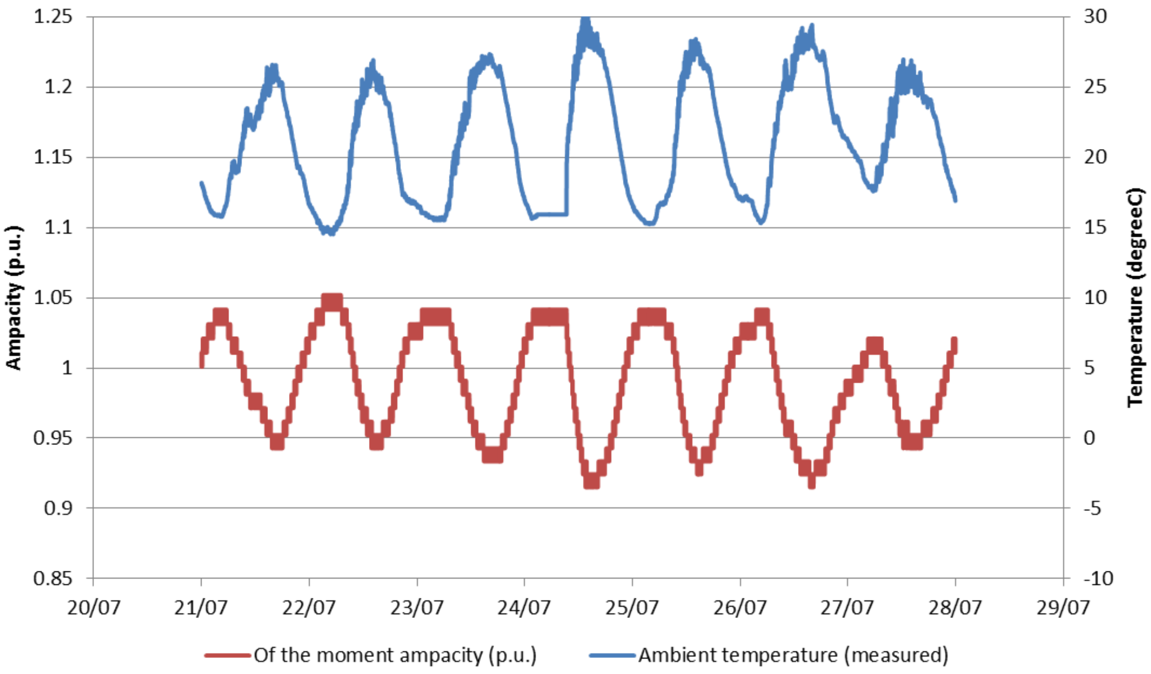

Figure 19 : Dynamic rating and ambient air temperature for w/c 21/07/2014 – High summer.

From Figure 19 it can be seen that:

- DAR values are clearly in antiphase to diurnal variation seen in ambient air temperature; and
- Peak DAR values occur in the early hours of the morning, which might provide some support to morning pickup load, but would not assist with evening peaks.

The same underlying DAR data from Figure 18 is presented in Figure 20, averaged over month periods, with maximum and minimum DAR values shown as error bars.

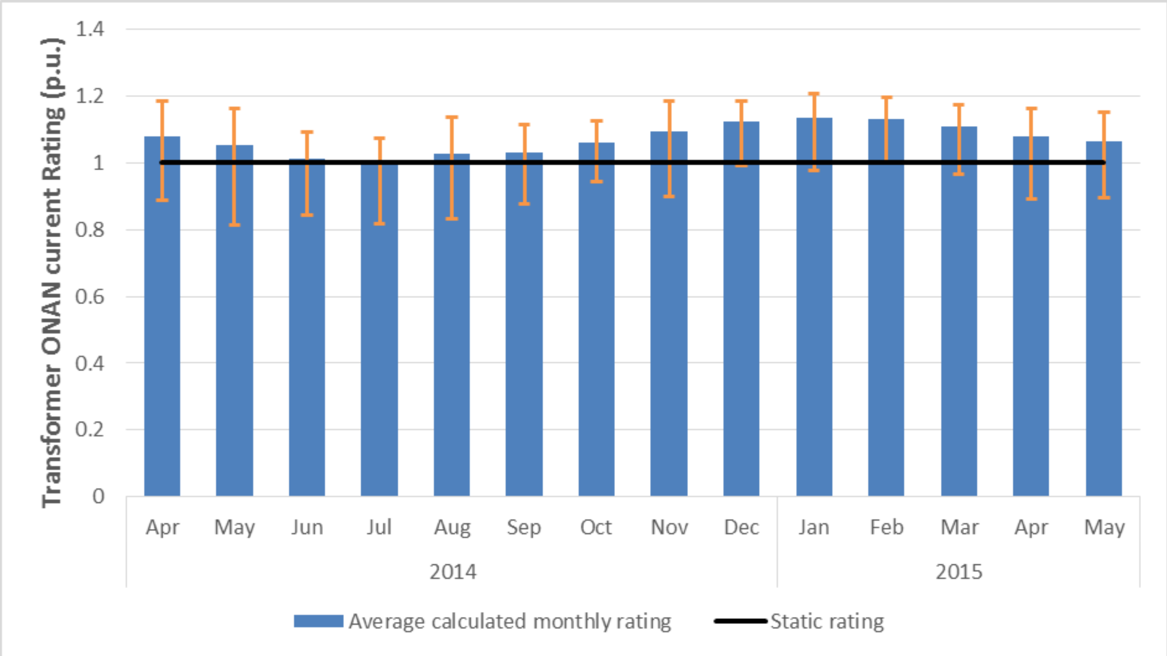

Figure 20 : Primary transformer T1 monthly dynamic rating limits under ONAN cooling for unit loss-of-life operation (98°C limit)

From Figure 20 and the underlying data it can be seen that:

- The mean monthly DARs are above the ONAN 98°C static rating, with the exception of July 2014;
- Transformer DAR is 107% of the ONAN 98°C static rating over the 14 month period;
- Minimum DAR values during the colder months (October to March) are greater than the ONAN 98°C static rating, with the exception of November 2014;
- The mean DAR over the colder months is 111% of ONAN 98°C static rating. This improvement over the static rating is not surprising, given the rating is based on 20°C.
- Minimum DAR values during the warmer months (April – September) are all less than the ONAN 98°C static rating;
- The mean DAR over the warmer months is 103% of ONAN 98°C static rating;

LP 23.	DAR values from the trial suggests that there is scope to run at up to 20% higher continuous current in the winter months under ONAN operation.

LP 24.	DAR values from the trial suggests that during the warmer summer months continuous rating of the transformer may be restricted to around 85% of the 12MVA rating if ONAN operation is maintained, and a hot spot limit of 98^{o}C is also maintained. In reality this circumstance would not occur because pumps and fans operation would be initiated.

5.4 Summer cyclic rating

The transformer has a reported cyclic summer rating of 19MVA with OFAF cooling. A limited investigation of this rating, using a cyclic load shape, OFAF cooling and a limiting temperature of 120^{o}C has been undertaken.

For the purposes of the investigation:

- the measured weekly load curve was normalised with respect to the maximum value and then set as the cyclic load curve with a peak at 19MVA for that week;
- The model was run with this cyclic load and the measured ambient temperatures for the week concerned; and
- It should be noted that the investigation was based on modelling parameters that are not fully validated through operation of the transformer at hotspot temperatures approaching 98^{o}C; and should therefore be seen as directionally indicative.

The results of the assessment for week commencing 21 July 2014, shown in Figure 21, are a trace of hotspot (and top oil) temperatures associated with the modelled load current (peaking at 19MVA equivalent), with the experienced ambient air temperatures (peaking at around 30^{o}C).

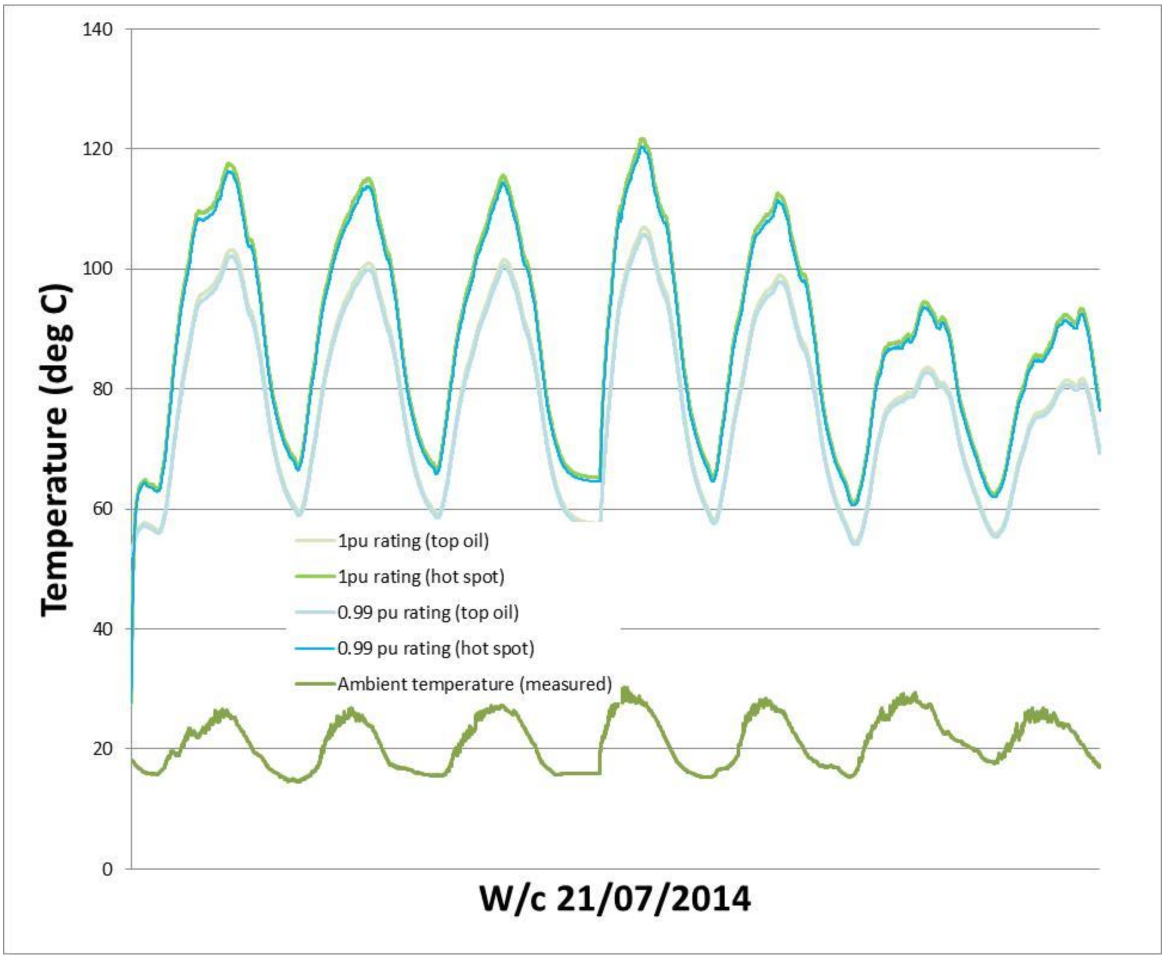

Figure 21 : of hotspot (and top oil) temperatures associated with the modelled load current (peaking at 19MVA equivalent), with the experienced ambient air temperatures)

LP 25.	Model investigation of the summer cyclic rating of 19MVA suggests that this load can be carried under OFAF cooling to a hotspot temperature of 120°C.

This modelling approach was also run for the period week commencing 19th January 2015, which contained the winter peak demand day for 2014/15. The results are shown in Figure 22.

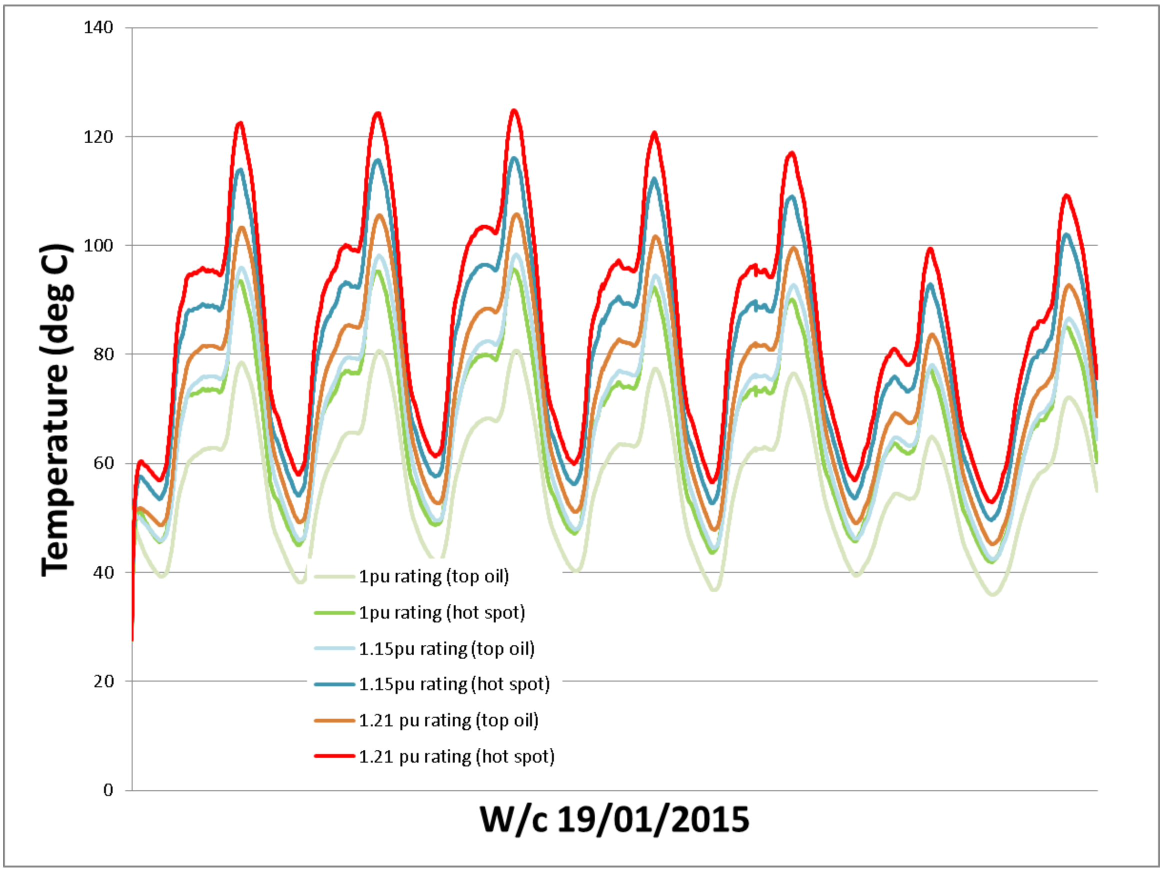

Figure 22 : of hotspot (and top oil) temperatures associated with the modelled load current (peaking at 19MVA equivalent), with the experienced ambient air temperatures)

Figure 22 shows that with a load of 19MVA, hotspot temperatures rose to a maximum of around 98°C (assuming OFAF operation), with a minimum ambient air temperature recorded as around -2°C. Further modelling suggests that a load of 22-23MVA would lead to limiting temperatures of 120°C.

LP 26.	Model investigation of the (summer) cyclic rating of 19MVA under peak winter ambient air conditions suggests that 22-23MVA might be carried with OFAF cooling and a hotspot temperature of 120°C.

This cyclic rating investigation also suggests that:

LP 27.	The indicative winter gains in sustained rating may also apply to cyclic loads, though further work in this area is recommended.

SECTION 6

Forward Ampacity based on forecast ambient conditions

6.1 Overview of forward ampacity, including:

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

6.2 Approach to estimation of forward cable ampacity

The IEC60076-7 model and the DAR estimation process (described in Section 5) are used for the calculation of forward ampacity. Actual air temperature measurement are replaced in the assessment with forecast values.

The ambient air temperature forecast values are taken from the BBC forecast (day ahead and week ahead) in 2014/2015. Hourly day-ahead temperature data was then interpolated to provide 48 half-hour values per day [3]. Maximum and minimum temperatures values from the week-ahead forecasts were sinusoidally shaped to provide 48 half-hour values per day [6].

As with the DAR estimation process, forward ampacity estimates are estimated by working with the forecast air temperature, and repeatedly incrementing the input load current to the model until a hot-spot temperature limit is reached. This limiting current is then set as a raw continuous forward dynamic rating (ampacity) for that period ahead, assuming an unvarying load.

Differences between raw forward ampacity and measured of-the-moment ampacity are then considered (ultimately related to the differences between forecast temperatures and the experienced measured values). This assessment leads to the inclusion of an uncertainty margin applied to the raw forward DAR estimate to arrive at a forward ampacity estimate that accounts (with a specified level of confidence) for experienced differences between forecast and actual air temperatures over the course of the trial.

This estimated forward ampacity is then compared against the ONAN 98^{o}C rating of the transformer (12MVA).

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

6.3 Calculated Forward Ampacity

6.3.1 Development of day-ahead estimates

Figure 23 shows the estimated raw day-ahead ampacity values for the period May 2014 to May 2015 (inclusive) as a single trace over time, compared to the static rating (12MVA ONAN 98^{o}C).

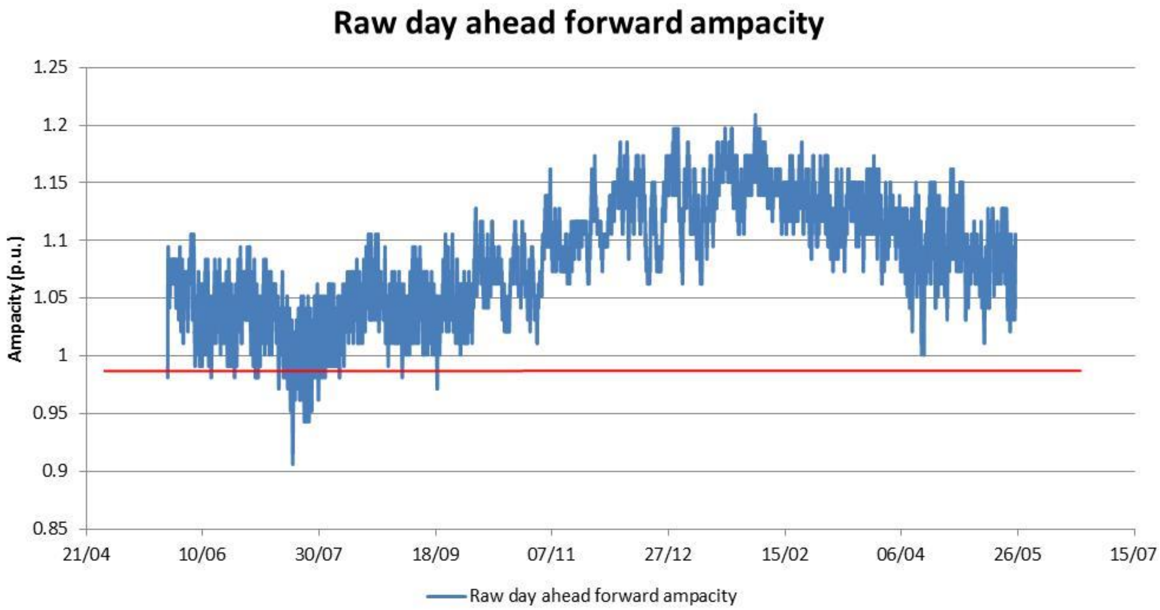

Figure 23 : Raw day-ahead forward ampacity for unit loss-of-life operation (98°C limit) with ONAN cooling using BBC day-ahead data

The data in Figure 23 is also presented as monthly averages with minimum and maximum monthly value indicators in Figure 24.

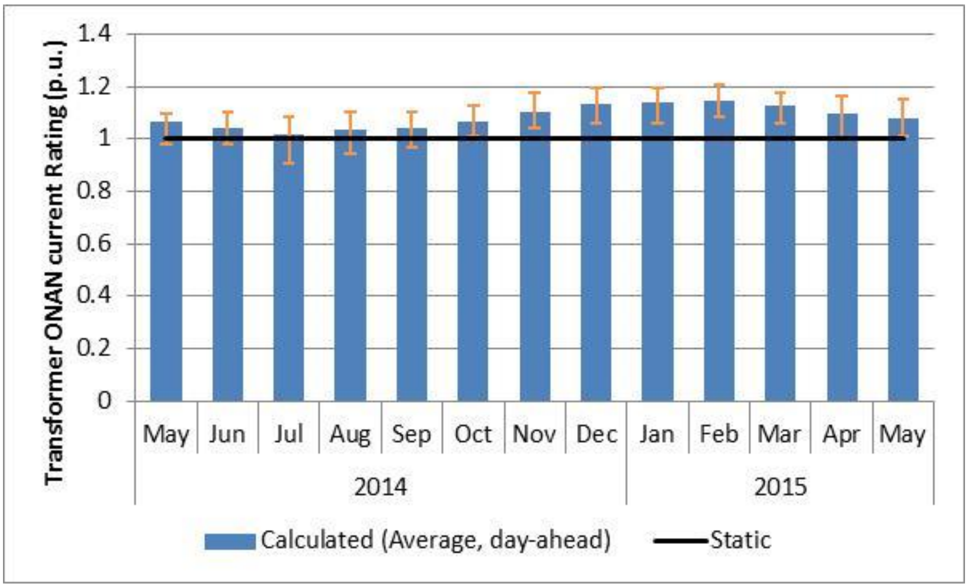

Figure 24 : Raw day ahead forward ampacity as monthly averages with maximum and minimum indicators

The differences between raw day-ahead forecast ampacity values (based on forecast air temperature - Figure 23) and of-the-moment ampacity values (using measured air temperature values - Figure 18, page 48) are shown in Figure 25 as a frequency distribution chart.

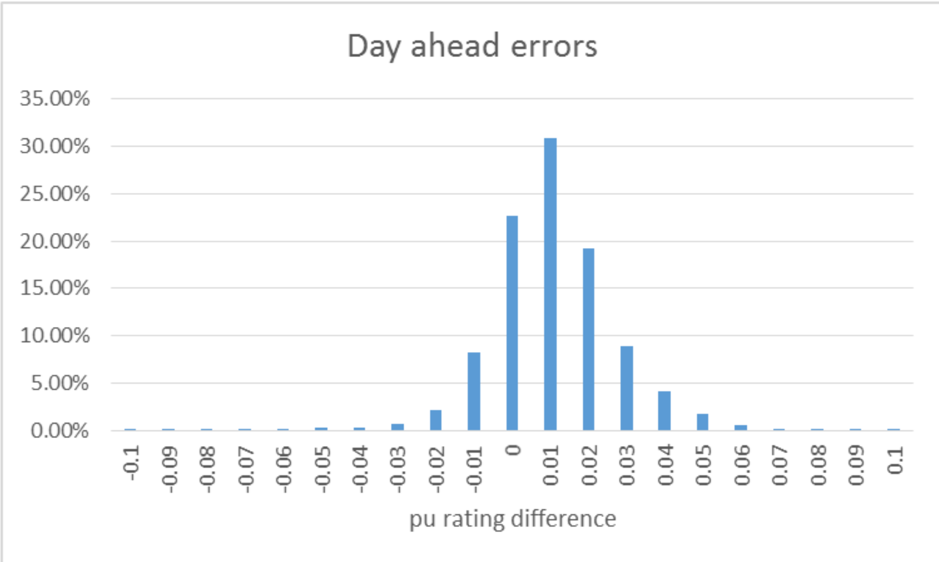

Figure 25 : Raw day ahead forward ampacity as monthly averages with maximum and minimum indicators

Within Figure 25, positive differences indicate raw forward ampacity values were larger than the comparable of-the-moment ampacity i.e. actual temperature was higher than forecast. Examination of cumulative frequency data shows that 95% of comparisons between raw day-ahead and of-the-moment ampacities have a difference of +0.04pu or less. Therefore if raw day-ahead ampacity estimates are each reduced by 0.04pu

(0.48MVA), then 95% of the resulting day-ahead ampacity estimates will not exceed ampacity that was actually experienced.

If a reduction in value is not undertaken there is a risk that the transformer will have accelerated aging in these periods.

In terms of loss-of-life, it is expected that with the hot-spot temperature at 98^{o}C, the loss-of-life over the total period of time is around unity. This is calculated by firstly calculating the relative aging rate V as defined in equation 2:

$$V = 2^{(\theta_{hs}-98)/6}$$ **Equation 2**

The relative aging rate is very sensitive to the hot-spot temperature θ_{hs}.

Then the loss-of-life L over a certain period of time is described by Equation 3:

$$L = \int_{t_1}^{t_2} V dt \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n$$ **Equation 3**

Where V_n is the relative aging rate during interval n; t_n is the nth time interval.

Day-ahead ampacities, with a range of confidence levels are presented in Section 6.3.3.

6.3.2 Development of week-ahead estimates

Figure 26 shows the estimated raw week-ahead ampacity values for the period May 2014 to May 2015 (inclusive) as a single trace over time, compared to the static rating (12MVA ONAN 98^{o}C).

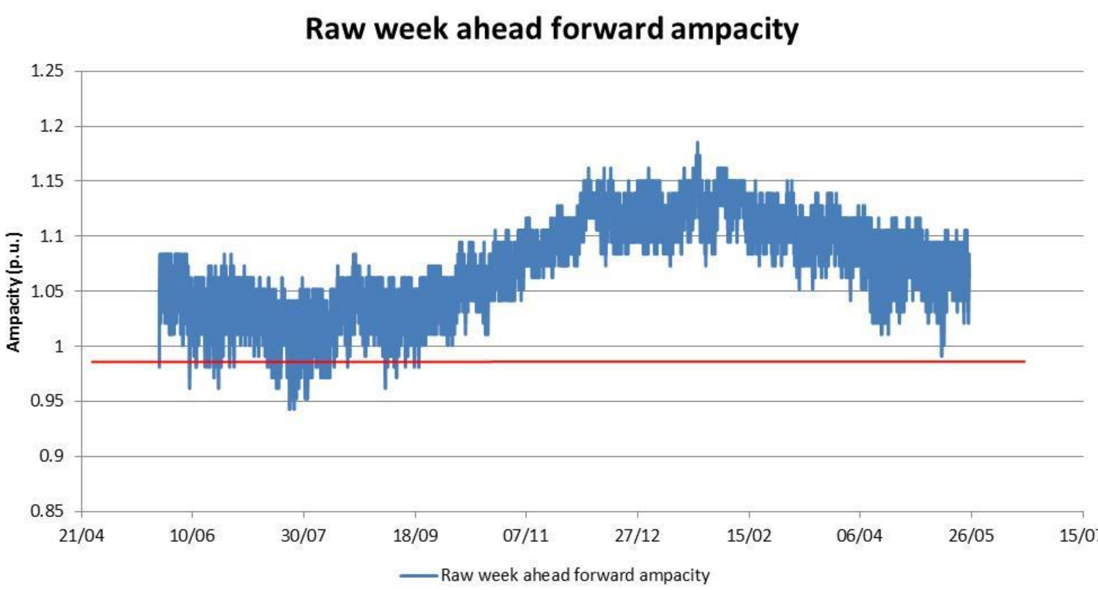

Figure 26 : Raw week-ahead forward ampacity for unit loss-of-life operation (98°C limit) with ONAN cooling using BBC day-ahead data

The data in Figure 26 is also presented as monthly averages with minimum and maximum monthly value indicators in Figure 27.

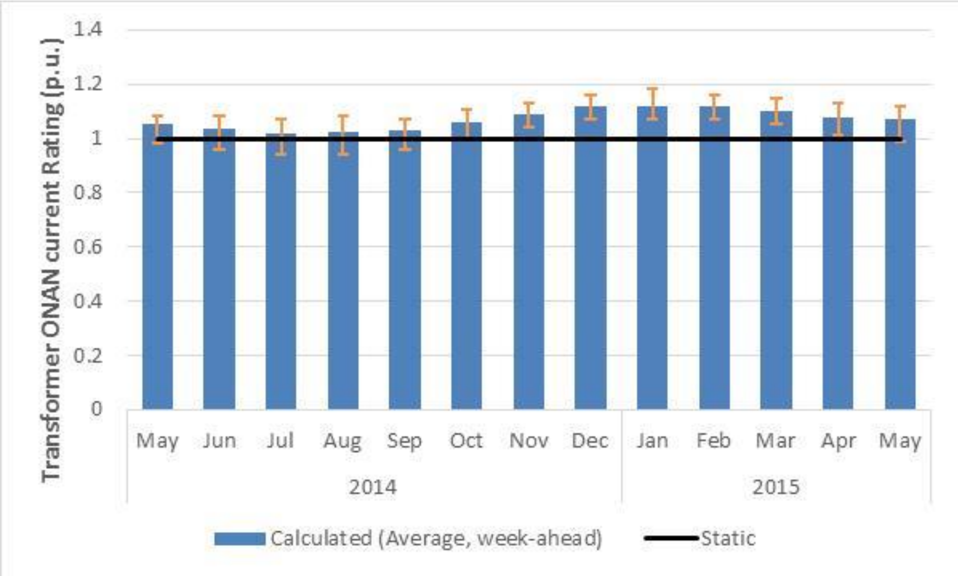

Figure 27 : Raw week ahead forward ampacity as monthly averages with maximum and minimum indicators

The differences between raw week-ahead forecast ampacity values (based on forecast air temperature - Figure 26) and of-the-moment ampacity values (using measured air temperature values - Figure 18, page 48) are shown in Figure 28 as a frequency distribution chart.

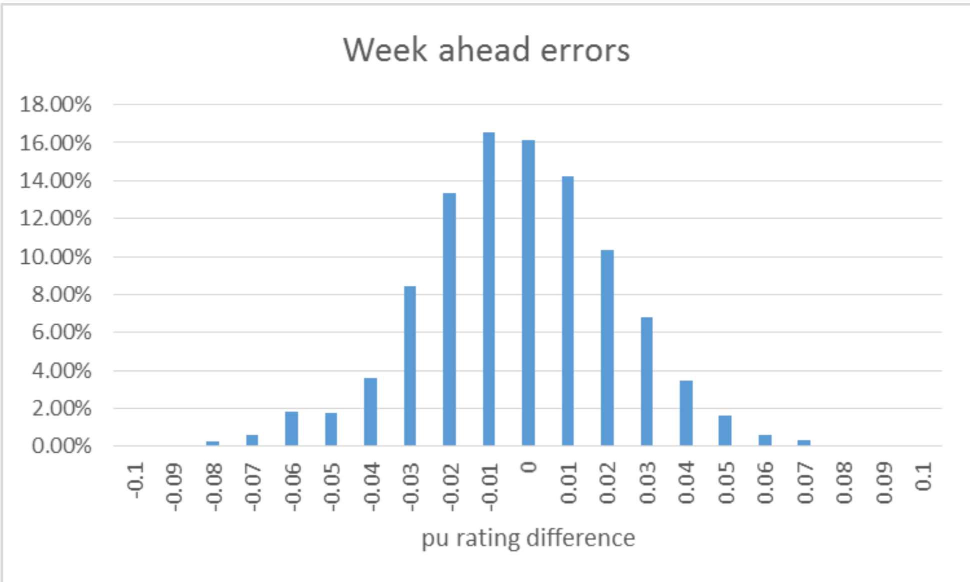

Figure 28 : Raw week ahead forward ampacity as monthly averages with maximum and minimum indicators

As before, within Figure 28, positive differences indicate raw forward ampacity values were larger than the comparable of-the-moment ampacity i.e. actual temperature was higher than forecast. Comparison between the day-ahead and the week-ahead differences shows a wider spread, as would be expected from a longer range weather forecast. Examination of cumulative frequency data shows that around 95% of comparisons between raw week-ahead and of-the-moment ampacities have a difference of +0.04pu or less. Therefore if raw week-ahead ampacity estimates are each reduced by 0.04pu (0.48MVA), then 95% of the resulting week-ahead ampacity estimates will not exceed ampacity that was actually experienced.

Week-ahead ampacities, with a range of confidence levels are presented in Section 6.3.3.

6.3.3 FALCON Primary transformer forward ampacity estimates

As described in Sections 6.3.1 and 6.3.2 above, differences between raw forward ampacity values and outturn of-the-moment values have been analysed to produce forward ampacity estimates (day-ahead and week ahead). These estimates are presented as monthly bar charts, with various levels of confidence included: Day-ahead Forward Ampacity (Figure 29) and Week-ahead Forward Ampacity (Figure 30).

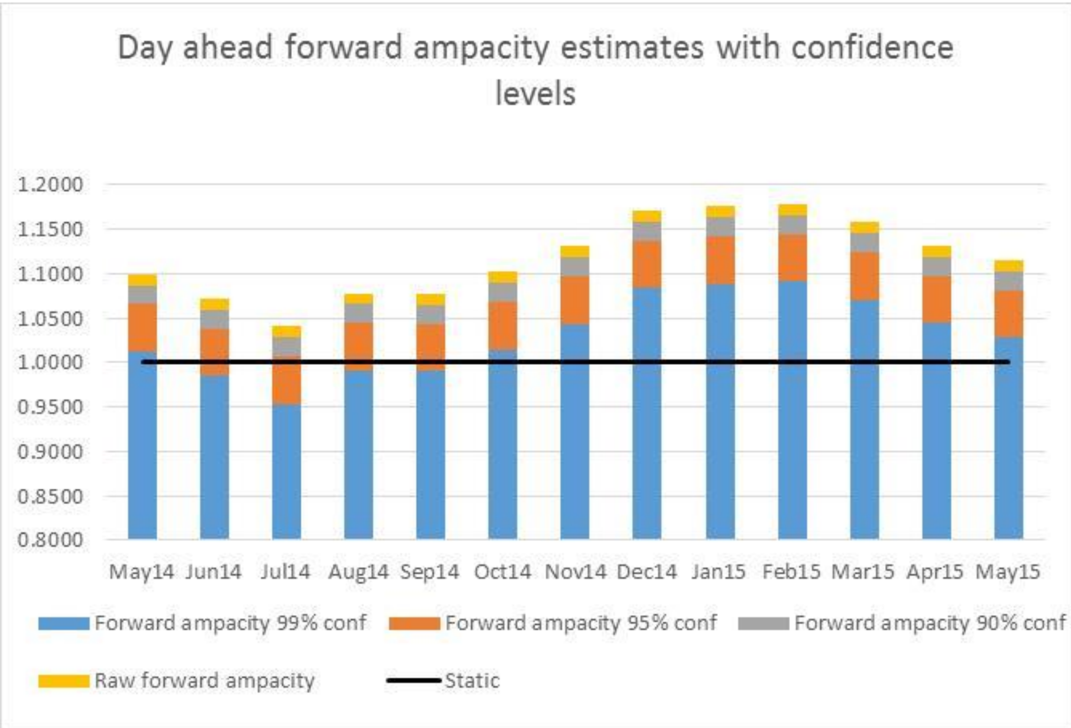

Figure 29: Day ahead predicted rating confidence

From Figure 29 it can be seen that:

- during the colder months 90% confidence day-ahead forward ampacity was always above the static rating (12MVA, ONAN, 98^{o}C);
- during the warmer months (October to March inclusive), 95% confidence day-ahead forward ampacity was always above the static rating (12MVA, ONAN, 98^{o}C); and
- for the conventional peak load periods of December, January and February, the mean 95% confidence day-ahead forward ampacity was around 108% of the static rating (12MVA, ONAN, 98^{o}C).

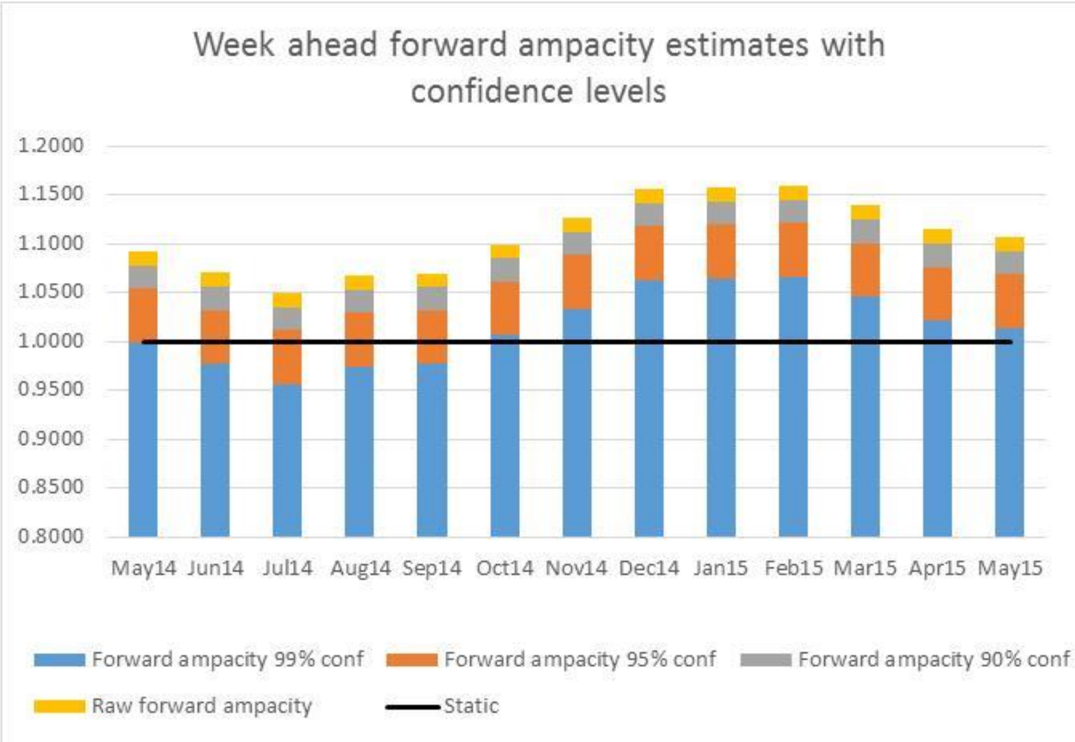

Figure 30: Week ahead predicted rating confidence

From Figure 30 it can be seen that:

- during the cooler months 90% confidence week-ahead forward ampacity was also always above the static rating (12MVA, ONAN, 98^{o}C);
- during the warmer months (October to March inclusive), 95% confidence week-ahead forward ampacity was also always above the static rating (12MVA, ONAN, 98^{o}C); and
- for the conventional peak load periods of December, January and February, the mean 95% confidence week-ahead forward ampacity was around 107% of the static rating (12MVA, ONAN, 98^{o}C).

6.4 Pre-emptive cooling

Instead of relying on forecast data and cooler temperatures to generate ampacity benefit, pre-emptive cooling may be considered. Pre-emptive cooling is potentially beneficial to the control room if the requirement for additional capacity is known, and the effect can be quantified in advance.

Defining the requirement in advance is a short-term load forecasting challenge that includes forward indicators (such as day of the week, week of the year, forecast temperatures etc.), and is outside the scope of FALCON project.

Quantifying the potential ampacity benefit has been briefly investigated as part of FALCON.

To illustrate the potential of pre-emptive cooling a modelling exercise was undertaken. The exercise included two transformers, and initially:

- Both transformers were given a 1pu load step;
- One of the transformers was operating with ONAN cooling;
- One transformer was operating with OFAF cooling.

The results of modelling are shown in Figure 31.

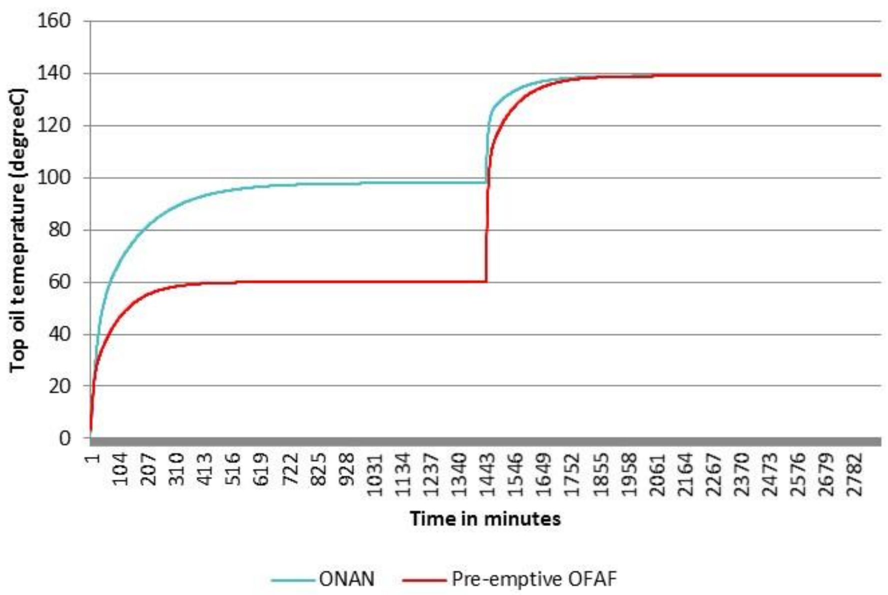

Figure 31: Pre-emptive cooling modelling exercise

Initially it can be seen that the transformers settle at different hot-spot temperatures, as would be expected given the different cooling regimes. This effectively shows the difference in transformer temperature that can be achieved if OFAF cooling is employed (as would operationally be the case). This difference is approximately 38^{o}C, and can be considered as the pre-cooling benefit under this exercise.

With stable hot-spot temperatures the exercise continued to its final stage:

- a further load step change was implemented, both transformer loads changed to 2pu;
- At the time of the load change, the cooling mode on the ONAN transformer was changed to OFAF – both transformers were therefore cooling under OFAF.

From Figure 31 it can be seen that:

- the transformers tend to the same ultimate (limiting) temperature of 140°C – a expected given the 24MVA 140°C emergency rating; and
- There is a difference in time taken to reach this temperature – the initially pre-cooled transformer takes an additional 72 minutes to reach limiting temperature.

The modelling exercise suggests that:

LP 28.	Pre-emptively cooling a transformer ahead of a step load/cyclic load increase does not change the ultimate temperature that the unit reaches, but beneficially does increase the time that it takes to reach this temperature (compared to no pre-emptive cooling)

LP 29.	Further work could be undertaken with in-service cyclic loads to further quantify operational benefits that may be achieved with pre-emptive cooling.

Some further work was also undertaken to consider the potential to load a transformer above the emergency rating (2pu/24MVA) without breaching the 140°C temperature limit applicable under such circumstances. Notes on this work are contained in Appendix J. Consideration of pre-emptive cooling and short term overload concluded that possible benefits are not large enough to be significant and therefore pre-emptively cooling a transformer for the purposes of a high short term overload is not deemed useful.

SECTION 7

Cross-technique Comparison[8]

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

Table 9 provides a high level summary of which techniques impact what network metric, with the remainder of the section providing comparison of the DAR Cable technique with other trials, on a network-metric basis.

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

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

Table 9: Cross-technique comparison of impact.

Network capacity:

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

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

Voltage:

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

Fault level:

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

Power Quality (PQ):

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

Enablement of DG:

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

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

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

Losses

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

CIs and CMLs

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

Grid/network Services:

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

SECTION 8

Conclusions and recommendations

Transformer DAR is dependent on thermal models. These models have parameters whose values are necessary for accurate modelling. In the case of Primary transformers, data that allowed initial estimation of parameter values was readily available from asset specific test certificates (in contrast to Distribution transformers in the FALCON engineering trials).

Model outputs using these initial parameter values were further improved upon through the application of a parameter tuning method developed specifically for the Distribution transformers in FALCON. The majority of top oil calculated results were within approximately 6^{o}C of the measured value, and the models tend to marginally overestimate the top oil temperature (by design). This is important and beneficial as it leads to conservative (marginally lower) estimated ampacity, preventing potential operation of the transformers at hotspots greater than limit values.

Ampacity values from the trial (based on real time air temperature measurements, and current thermal state of the transformer) suggests that there is scope to run at up to 20% higher continuous current in the colder months under ONAN operation, with a mean DAR over the colder months of 111% of ONAN 98^{o}C static rating.

Thermal modelling work with cyclic load shapes supports the 19MVA OFAF 120^{o}C rating of the transformer, and suggests that similar levels of improvement in cyclic load ratings (i.e. around 110% in the colder months) would also be achievable, though further work is required in this area to validate this.

A new method of estimating forward ampacity has been developed and validated within the FALCON project, and applied to Primary transformers. Because Primary transformers use only (external) ambient air temperature, and forecasting of this parameter is relatively accurate, forward forecasts of ampacity are only marginally reduced compared to of-the-moment assessments of ampacity. This is in contrast to all other DAR techniques. For the conventional peak load periods of December, January and February, the 95% confidence day-ahead forward ampacity was around 108% of the static rating (12MVA, ONAN, 98^{o}C). For the conventional peak load periods of December, January and February, the 95% confidence week-ahead forward ampacity was around 107% of the static rating (12MVA, ONAN, 98^{o}C).

Investigation of pre-emptively cooling a transformer ahead of a step load/cyclic load increase suggests that this could be a marginally beneficial technique. Further work could be undertaken with in-service cyclic loads to clarify an operational procedure, and to quantify benefits in operational circumstances.

Future DAR development could be targeted at existing (indoor/outdoor) transformers that are approaching thermal/load limits, involve limited installation of temperature & load monitoring, tuning of transformer specific models, and assessment of potential to run at higher than nominal ratings. Such development would include addressing the issue of risk management with respect to transformer life. With this method, there will be a small number of days were the ambient temperatures are materially above seasonal averages, and accelerated (vs par) life usage will occur on such days.

Appendices

A References

[1] International Electrotechnical Commission (IEC). "Power transformers - Part 7: Loading guide for oil-immersed power transformers," *IEC 60354,* pp. 1-110, (1991).

[2] International Electrotechnical Commission (IEC). "Power transformers - Part 7: Loading guide for oil-immersed power transformers," *IEC 60076-7,* pp. 1-110, (2005).

[3] Transformers Committee of the IEEE Power & Energy Society. "IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators," *IEEE Std C57.91-2011 (Revision of IEEE Std C57.91-1995),* pp. 1-123, (2012).

[4] FALCON Distribution Transformer DAR report

[5] Marlborough Street Transformer Test Certificate

[6] FALCON OHL DAR report

B Learning Objectives

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

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

- C6 - Required post-fault running conditions;
- B7 - Running conditions required during adjacent outages.

C Notes on thermal models

There are three main mathematical models from three common standards that apply to mathematical modelling of transformers, see Table 10.

Standard	Load	Model	Time constant	Cooling mode	Used in	Year
IEEE C57.91 [3]	Step	Exponential	Variable	√		2011
IEC 60354 [1]	Step	Exponential	Fixed	√	Alstom relay	1991
IEC 60076-7 [2]	Dynamic	Multi-exponential-function-based differential	Fixed	√	Recommended for SIM	2005

Table 10: Summary of the transformer thermal models under review.

Note: IEC 60354 is an earlier standard than IEC 60076-7, and has largely been superseded by IEC 60076-7. As the Alstom relay used IEC60354 this was also considered within the modelling. All three models were coded to enable comparison between them and against measured results.

The model validation was process was undertaken as follows;

1. An Excel spreadsheet and MATLAB were used to code the models and check the results against the examples given in the standards.
2. The three models were compared against a theoretical load step scenario.
3. Measured data of electrical load current and ambient temperature (outdoor depending on transformer location) were received and used within the model to generate calculated top oil temperatures for comparison with measured values and relay reported values.
4. The validation process of comparing the measured and calculated oil and hot-spot temperatures between modelled values and experimental values was undertaken to understand which model was most appropriate and how the constants for use in the models should be established.
5. Although primary transformers are not part of the SIM, learning from this process has been used to inform the SIM development of Distribution transformers (IEC60076-7 implemented model choice).

The three standards use different models but these models are dependent on parameters within each model. Table 11 shows a breakdown of some of those key parameters within each model that are contained within the derivation of each model described below. A description of these parameters is given within the summary description of each model below.

Standard	Standard defined constants	Input variables	Transformer specific model parameters
IEEE C57.91	*n,2m*	K,T_a	$R, \Delta T_{tor}, \Delta T_{hsr}, \tau_o, \tau_{hs}$
IEC 60354	*x,y*	K,θ_a	$R, \Delta\theta_{tor}, \Delta\theta_{hsr}, \tau_o, \tau_{hs}$
IEC 60076-7	*x,y*, k_{11}, k_{21}, k_{22}	K,θ_a	$R, \Delta\theta_{or}, \Delta\theta_{hr}, \tau_o, \tau_{hs}$

Table 11 : Parameters in Transformer Thermal models

A complication with the input variable K (rating of measured current to rated current) and transformer specific variables, $R, \Delta T_{tor}, \Delta T_{hsr}$,$\Delta\theta_{tor}, \Delta\theta_{hsr}, \Delta\theta_{or}, \Delta\theta_{hr}$ are that they are all dependent on the rating of the transformer. There is no one specific rating for a primary transformer, and in this instance there are three ratings dependent on the ambient temperature and cooling regime. The standard defined constants change depending on cooling mode and these are not defined for every conceivable cooling mode.

C.1 IEC60354 exponential model

In the IEC60354 standard, the model used for the hot-spot temperature calculation is as follows [1].

$$\theta_{hs} = \theta_a + \Delta\theta_o + \Delta\theta_{hs}$$ **Equation 1**

where, θ_{hs} = Hot spot temperature (°C)

θ_a = Ambient temperature (°C)

$\Delta\theta_o$ = Top oil rise over ambient temperature (°C)

$\Delta\theta_{hs}$ = Hot spot rise over top oil temperature (°C)

Under natural cooling, the hot spot temperature T_{HS} can be calculated by equation 2.

$$\theta_{hs} = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R} \right)^x + \Delta\theta_{hsr} K^y$$ **Equation 2**

Where in equation 2,

x = Oil exponent (no unit)

y = Winding exponent (no unit)

R = Ratio of no load losses to rated losses (no unit)

K = Load ratio = MAX (I_A RMS, I_B RMS, I_C RMS) / I_{rated} (no unit)

I_{rated} = The nominal steady state current rating value for the transformer, the following temperature-rise values are estimated based on this nominal current (A)

$\Delta\theta_{or}$ = Top oil rise over ambient temperature at rated load (°C)

$\Delta\theta_{hsr}$ = Hot spot rise over top oil temperature at rated load (°C)

The dynamic temperature can be calculated from equations 3 and 4, by replacing the ultimate oil and hot spot temperature with the above calculated values.

$$\theta_o(t+\Delta t)=\theta_{o,u}-\left(\theta_{o,u}-\theta_{o,i}(t)\right)\cdot e^{-\Delta t/\tau_o} \quad \textbf{Equation 3}$$

Where in equation 3,

τ_o = Thermal time constant of oil temperature rise (s)

$$\theta_{hs}(t+\Delta t)=\theta_{hs,u}-\left(\theta_{hs,u}-\theta_{hs,i}(t)\right)\cdot e^{-\Delta t/\tau_w} \quad \textbf{Equation 4}$$

Where in equation 4,

τ_w = Thermal time constant of winding temperature rise (s)

Δt = time step (s)

C.2 IEEE C57.91 exponential model

This model uses the same expressions as the IEC60354 model (3 and 4 - single exponential function) [3]. However, parameters used with the expressions are different for example, the time constants are variable depending on conditions rather than fixed.

C.3 IEC60076 differential model

In standard IEC60076-7 [2], section 8.2.3, the time-domain differential equations are given by:

$$\Delta\theta_{hs}=\Delta\theta_{hs1}-\Delta\theta_{hs2} \quad \textbf{Equation 5}$$

$$k_{11}\tau_o\frac{d\theta_o}{dt}+\theta_o=\theta_a+\Delta\theta_{or}\left(\frac{1+K^2R}{1+R}\right)^x \quad \textbf{Equation 6}$$

$$k_{22}\tau_w\frac{d\Delta\theta_{hs1}}{dt}+\Delta\theta_{hs1}=k_{21}K^y\Delta\theta_{or} \quad \textbf{Equation 7}$$

$$\frac{\tau_o}{k_{22}}\frac{d\Delta\theta_{hs2}}{dt}+\Delta\theta_{hs2}=\left(k_{21}-1\right)K^y\Delta\theta_{or} \quad \textbf{Equation 8}$$

Where the variables have the same description as IEC60354 model.

Re-writing in standard form for input into MATLAB (Modelling package) gives:

$$\frac{d\theta_o}{dt} = -\frac{1}{k_{11}\tau_o}\theta_o + \frac{1}{k_{11}\tau_o}\theta_a + \frac{1}{k_{11}\tau_o}\Delta\theta_{or}\left(\frac{1+K^2R}{1+R}\right)^x$$ **Equation 9**

$$\frac{d\Delta\theta_{hs1}}{dt} = -\frac{1}{k_{22}\tau_w}\Delta\theta_{hs1} + \frac{1}{k_{22}\tau_w}k_{21}K^y\Delta\theta_{or}$$ **Equation 10**

$$\frac{d\Delta\theta_{hs2}}{dt} = -\frac{k_{22}}{\tau_o}\Delta\theta_{hs2} + \frac{k_{22}}{\tau_o}(k_{21}-1)K^y\Delta\theta_{or}$$ **Equation 11**

These differential equations are approximated by using difference models assuming that calculation for each time step is linear. Therefore the ultimate temperature values may be slightly different from an exponential model, even if previous step result is used as initial value for the next step calculation. This model, as mentioned in the standard [2], "is suitable for arbitrary time-varying loading and time-varying ambient temperature, which is particularly applicable for on-line monitoring, especially as it does not have any restrictions concerning the load profile."

C.4 IEC60076 multi-exponential model

This is a more advanced version of a single exponential model to represent transients between calculated values in more detail. . However, as stated in the IEC 60076 standard that: "Exponential equations suitable for load variation according to a step function. It yields proper results in the following cases: 1) Each of the increasing load steps is followed by a decreasing load step or vice versa; 2) each first steps has to be long enough for the hot-spot-to-top-oil gradient to obtain steady state." In addition, there are different expressions for temperature increase and decrease.

The temperature increases to a level corresponding to a load factor K is given by:

$$\theta_{hs} = \theta_a + \Delta\theta_{oi} + \left\{\Delta\theta_{or}\cdot\left(\frac{1+R\cdot K^2}{1+R}\right)^x - \Delta\theta_{oi}\right\}f_1(t) + \Delta\theta_{hsi} + \left(\Delta\theta_{hsr}K^y - \Delta\theta_{hsi}\right)f_2(t)$$ **Equation 12**

The temperature decreases to a level corresponding to a load factor of K is given by:

$$\theta_{hs} = \theta_a + \Delta\theta_{or}\cdot\left(\frac{1+R\cdot K^2}{1+R}\right)^x + +\left\{\Delta\theta_{oi} - \Delta\theta_{or}\cdot\left(\frac{1+R\cdot K^2}{1+R}\right)^x\right\}f_3(t) + \Delta\theta_{hsr}K^y$$

Equation 13

The function f_1(t) describes the relative increase of the top-oil temperature rise according to the unit of the steady-state value:

$$f_1(t) = 1 - e^{-\frac{t}{k_{11} \times \tau_o}}$$ **Equation 14**

The function f_2(t) describes the relative increase of the hot-spot-to-top-oil gradient according to the unit of the steady-state value. It models the fact that it takes some time before the oil calculation has adapted its final value to correspond to the increase load level:

$$f_1(t) = k_{21}\left(1 - e^{-\frac{t}{k_{22} \times \tau_w}}\right) - (k_{21} - 1)\left(1 - e^{-\frac{t}{\tau_o / k_{22}}}\right)$$ **Equation 15**

The function f_3(t) describes the relative decrease of the top-oil-to-ambient gradient according to the unit of the total decrease:

$$f_3(t) = e^{-\frac{t}{k_{11} \times \tau_o}}$$ **Equation 16**

Where

k_{11}, k_{21}, k_{22} are constants defined within the standard.

Once the modelled values for top oil temperature have been validated through comparison to measured top oil temperatures, for a range of ambient/load conditions, assessment of the potential benefits of the technique can commence.

C.5 Step function model comparison

A large load step was simulated to understand how each of the models behaved transiently with time following this event. To fit the IEC60076 multiple exponential model requirement, the loading applied is a step increase followed by a step decrease after reaching steady states: from 1.0 p.u. to 1.5 p.u., then 0.5 p.u. under a constant 20°C ambient temperature. Results of the top-oil temperature and hot-spot temperature are shown in Figure 32 and Figure 33 respectively.

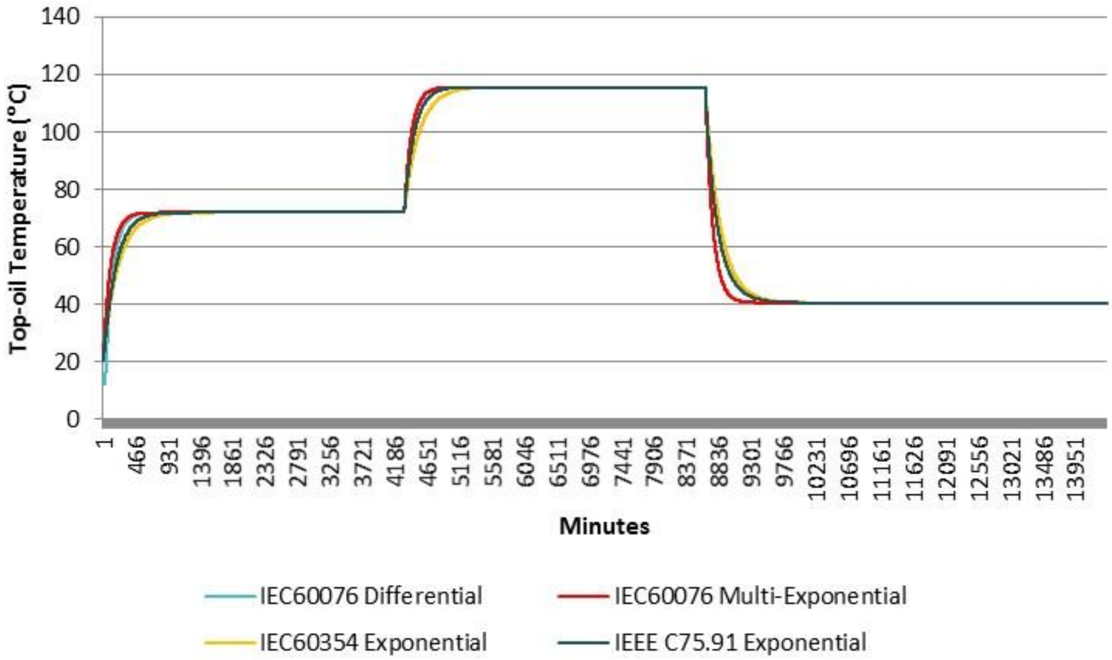

Figure 32: Top oil temperature calculation with different models (long-term step loading)

The parameter $\Delta\theta_{or}$ used for all models is 52°C as the typical example value in IEC standard. Therefore results at 1.0 p.u. loading are all the same showing a top oil temperature of 72^{o}C (20^{o}C ambient plus top oil temperature rise of 52°C at rated load). The oil temperature exponent x value is 0.8 for all models. Hence all eventual values for 1.5 p.u. and 0.5 p.u. loadings are the same for all models. However, the transients are different. This is due to two aspects: the mathematical models and the parameter τ_o. IEC60076 differential and IEC60076 multi-exponential models are nominally the same mathematical expressions but the former uses a difference solution [2] while the latter uses exponential solution. Still for this long-term step loading they generate very close results. The transient differences between IEC60076 models and IEC60354/IEEEC57.91 models are more noticeable because of the multi-exponential functions used for IEC60076 models. For IEEE exponential models, the same single exponential expressions are used., but the transients have different oil time constant values, which subject to changes according to different oil temperature and power loss as equation 18 [3]:

$$\tau_o = \frac{C \times \Delta\theta_{om} \times 60}{P}$$ **Equation 17**

Where C is the transformer thermal capacity; $\Delta\theta_{om}$ is the average oil temperature rise above ambient temperature at the load considered; P is the supplied losses at the load considered.

Due to the fact that it’s difficult to measure P for all loading conditions, for all IEC models an example typical value 210-minute constant is used for τ_o. In the IEEE C57.91 exponential model a variable time constant, is adjustment as per equation 18 [3]:

$$\tau_o = \tau_{or} \frac{\left(\frac{\Delta T_{to,u}}{\Delta T_{to,r}}\right) - \left(\frac{\Delta T_{to,i}}{\Delta T_{to,r}}\right)}{\left(\frac{\Delta T_{to,u}}{\Delta T_{to,r}}\right)^{1/x} - \left(\frac{\Delta T_{to,i}}{\Delta T_{to,r}}\right)^{1/x}}$$

Equation 18

Where $\tau_{or} = \frac{C\ x\ \Delta T_{or}\ x\ 60}{P_r}$ is the time constant for rated load beginning with an initial top-oil temperature rise of 0°C (note ΔT and $\Delta\theta$ are the same variable). Here we assume the value of τ_{or} is the same as previously set (52°C). P_r is the total loss at rated load which is given in the test certificate (71052W for T1 [5]).

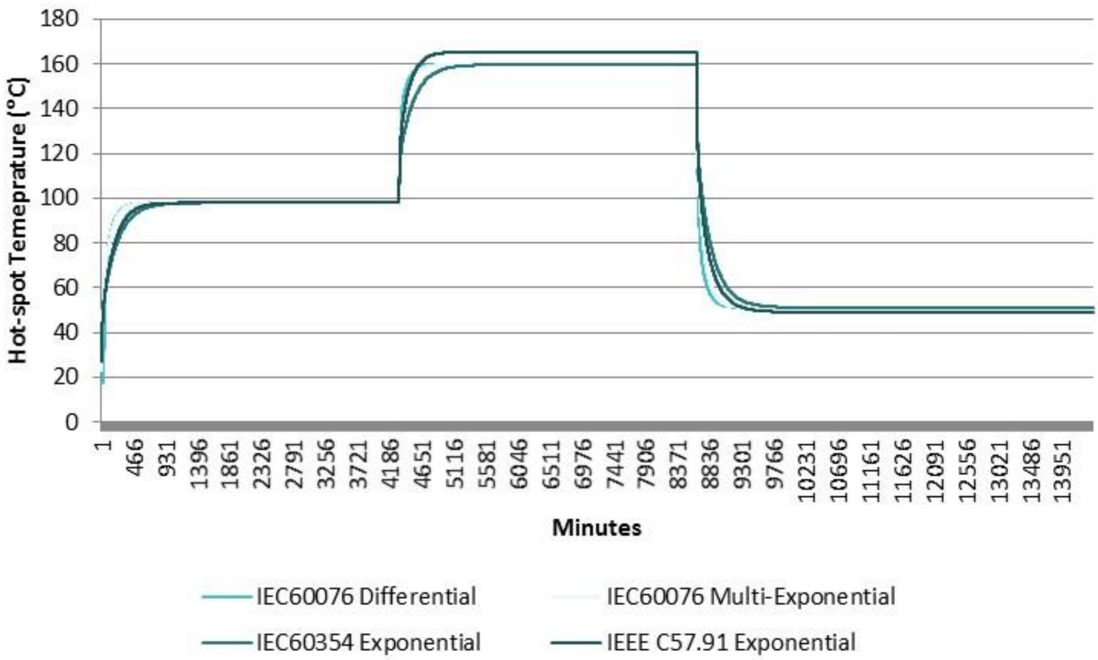

Figure 33: Hot-spot temperature calculation with different models (long-term step loading)

For hot-spot temperature calculations, similar observations can be made as above. However in Figure 33 the ultimate value differences of IEEE C57.91 model are higher under 1.50p.u. and 0.50 p.u. loadings. This is due to the fact that the y exponent value used in IEEE standard is 1.6 (compared to 1.3 in all IEC standards [1, 2]). Therefore any eventual hot-spot temperatures under non-unit loadings will be higher.

C.6 Notes on thermal model parameter value estimation

In the context of DAR and transformer thermal modelling, parameter estimation is a crucial first step in accurately modelling individual transformers. If initial estimates of parameter values do not deliver adequate accuracy to measured values, then various forms of regression analysis may be applied to identify improved model parameter values.

Within published literature, regression has been applied specifically to improve (primary) transformer modelling:

- Least-squares regression [5] is applied to estimate parameters for a primary transformer in the US using the IEEE Clause 7 model [4];
- Parameter estimation using genetic algorithms to find the relevant values for a single transformer [6]. As a measure of model effectiveness they apply a fitness function, which they define as the error between modelled and measured top oil temperature and also bottom oil temperature. This approach ensures a similar output to a least squares method, as in [5].

Parameter estimation for complex differential equations has also been applied in other fields [7]–[9] with various numerical methods used depending on the circumstances. Typically, parameter values are iterated and the difference of least squares is found for each set, but in some situations a weighted function can provide a more tailored solution.

For instance, [10] employs a weighted function based on the difference between various quantiles. This is due to the fact that some parts of a distribution or model are deemed more important than others. [11] discusses weighted regression generally, observing that certain local conditions may require specific weighting, or that other parts of a distribution may require a lesser weight – such as at boundaries or for initial values of a curve.

As a result of this work it was found that:

LP 30.	For transformer thermal models it is prevalent to ensure the maximum modelled daily values closely match the actual maximum values – as these values are key to determining the load allowance/life of insulation in the transformer. By extension other parts of the curve may be seen as less crucial – and so a better regression at these points may not always be desirable (especially if the accuracy at the maximum is jeopardised). This indicates a weighted method of tuning is preferred.

C.7 Notes on cooling mode trials

In Table 11 there are three columns; standard defined constants; input variables and transformer specific parameters. The standard defined constants are dependent on cooling mode and the input variables and transformer specific parameters are function of the “nominal” rating chosen.

In order to understand the impact on the cooling mode offered by the pumps and fans a set of test were planned which allowed the effect of different cooling to be studied in more detail. Table 12 shows the trial dates and associated cooling mechanism. The cooling was manually applied to ensure the status of the pumps and fans was known.

Day	Load on Tx1	Cooling on Tx1	Load on Tx2	Cooling on Tx2	Cooling of T1
Day 1 (8th June 2015)	In-service, prevailing load	3 hours fans ON, then return to auto	In-service, prevailing load	Normal auto operation	ONAF
Day 2 (9th June 2015)	In-service, prevailing load	3 hours pumps ON then return to auto	In-service, prevailing load	Normal auto operation	OFAN
Day 3 (10th June 2015)	In-service, prevailing load	3 hours fans & pumps ON then return to auto	In-service, prevailing load	Normal auto operation	OFAF

Table 12: Cooling mode trials in June 2015.

In the IEC60076-7 standard [2], example values given for top-oil temperature rises are similar for ONAN, ONAF, and OFAF cooling modes. This indicates that the rated current for different cooling modes is different to obtain the same observable cooling effect in temperatures. This is also demonstrated by the three listed ratings of each transformer 12/19/24MVA (sustained ONAN 98^{o}C/ summer cyclic OFAF 120^{o}C/ emergency continuous winter OFAF 140^{o}C) as shown in Table 13.

What is not specified therefore is the rating of the transformer under ONAF or OFAN modes of operation. The model relies on the rating for two purposes; the user inputting the load current as a per unit value of the rating and to tie up with the difference in top oil temperature above ambient at rated value for calculation purposes, if the rating is not explicitly known then this process is more complex as it is not clear at which current the 98^{o}C hot spot temperature would be reached.

LP 31.	The calculation techniques rely on knowing a value for top oil and hot spot temperature rise under rated conditions. If these conditions are not known or specified – then the methodology will not allow accurate calculation and an estimate of rating must be used.

The stated ratings of the transformer under different cooling modes are shown in Table 13. There is no explicit rating stated for the transformer operating under ONAF or OFAN modes.

Therefore the rated current for load factor calculation under different cooling mode has to be trialled at different values under different cooling modes. A 19MVA and 12MVA rating were used as estimates in ONAF and OFAN modes while 24MVA was used as the rating for OFAF modes. For ONAN mode, the previously applied parameters, i.e. 52°C for top-oil temperature rise and 340 minutes for oil time constants are retained.

Cooling mode	Rated current	MVA
ONAN	602.5A	12 (sustained)
ONAF		
OFAN		
OFAF	953.9A 1205A	19 (summer cyclic) 24 (continuous winter emergency)

Table 13: Rated current for different cooling modes.

LP 32.	The rating of the transformer under different cooling conditions needs to be known to accurately calculate hot spot temperature – this information is not traditionally available for anything other than ONAN and OFAF operation.

Results for the three trial periods are shown from Figure 34 to Figure 36. These results use 19MVA and 12MVA (shown by 602.5A label) as the rated current for the ONAF and OFAN cooling condition under test. Under the second condition (602.5A), the ratio of the load to rated current will be approximately the same before and after the cooling is applied. Therefore in order to replicate the cooling effect the top oil temperature at rated load would need to be reduced below a level that is meaningful in the context of the modelling. Keeping this value the same as for ONAN means that using a rating of 602.5A current results in insignificant cooling effect. Increasing the rating allows a more reasonable graph match to be obtained. A 24MVA rating was used in the OFAF test.

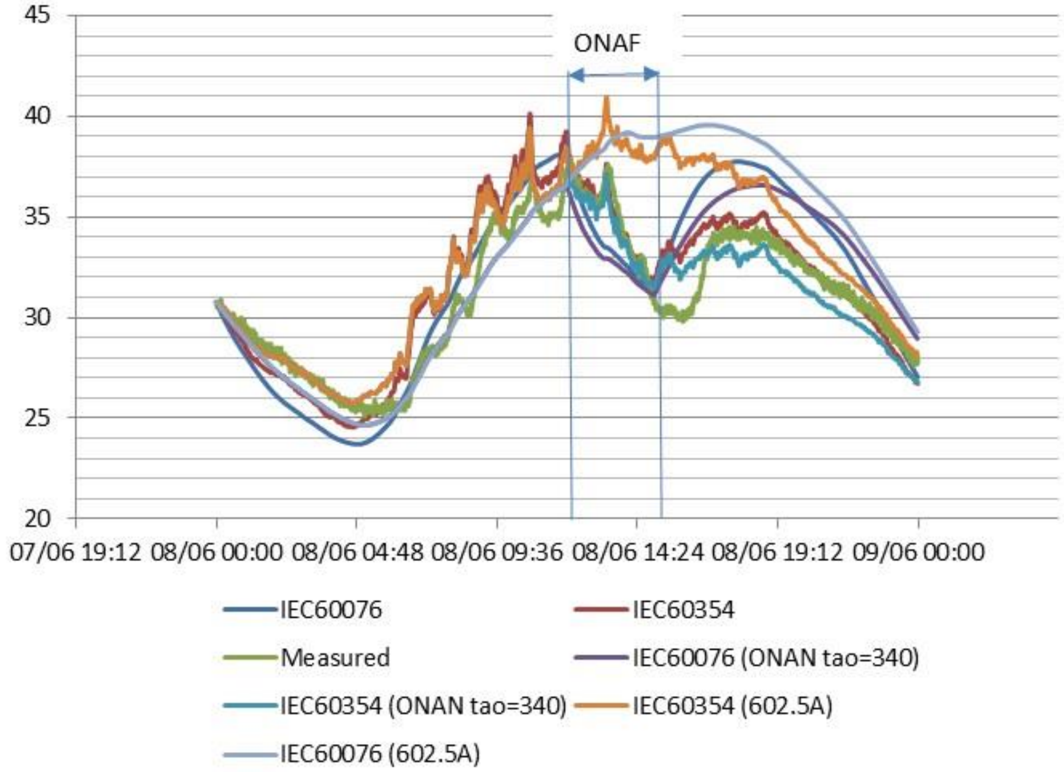

Figure 34: Top-oil temperature comparison, T1, ONAF trial 12.00 – 15.00, 8th Jun 2015

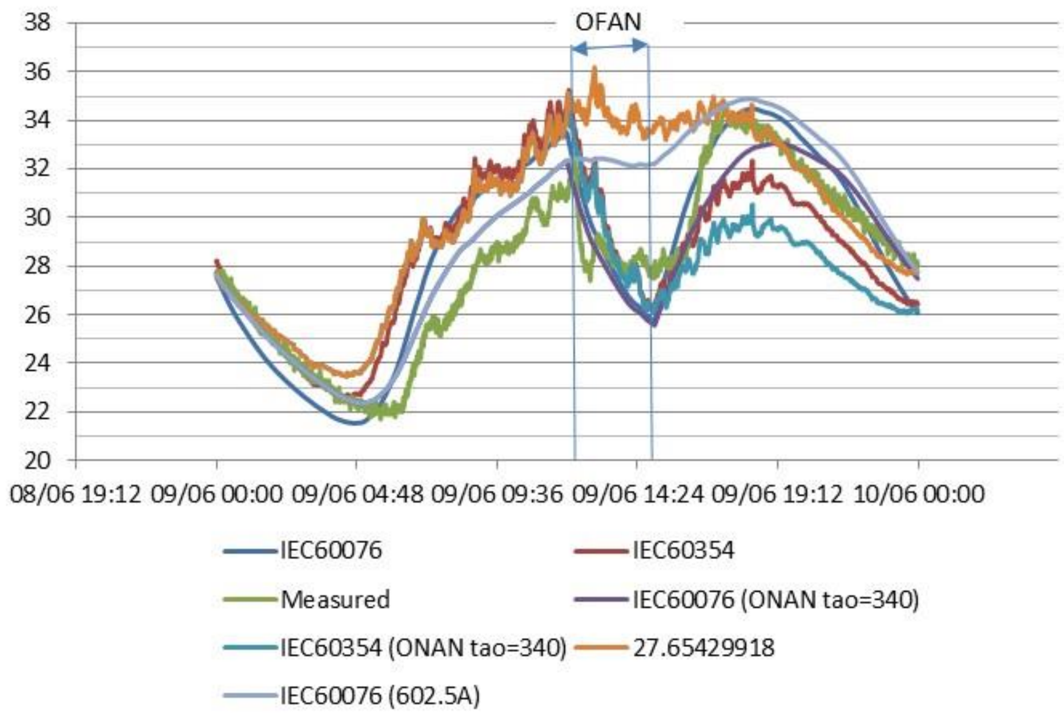

Figure 35: Top-oil temperature comparison, T1, OFAN trial 12.00 – 15.00, 9th Jun 2015

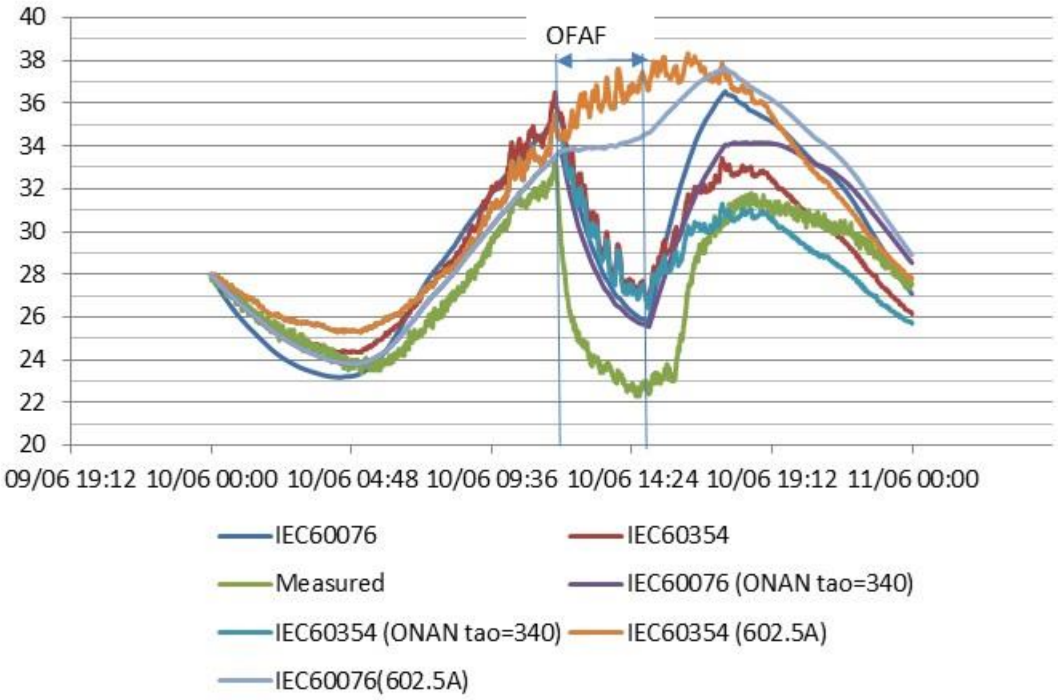

Figure 36: Top-oil temperature comparison, T1, OFAF trial 12.00 – 15.00, 10th Jun 2015

LP 33.	OFAN and ONAF trail results show a similar level of cooling (temperature drop with time) for approximately the same load, but the OFAN cools quicker as expected.

LP 34.	Where the transformer rating is not explicitly known for a cooling condition a further degree of uncertainty is added which further complicates the determination of the transformer specific data.

LP 35.	There is some indication that using the summer cyclic rating under OFAF operation can be used to represent the rating for Sustained ONAF and OFAN cooling.

Once a transformer rating value has been settled on a curve fitting technique with measured data can be used to estimate the transformer specific parameters. In this instance the Root-mean-square error (RMSE) is used for cooling mode parameters fitting. This is because the weighted method can only be used when there is significant data with clear peaks and troughs. The results of the three trial periods are shown in

Figure 37, Figure 38, and Figure 39 show the results over the day. The cooling parameters are summarised in Table 14.

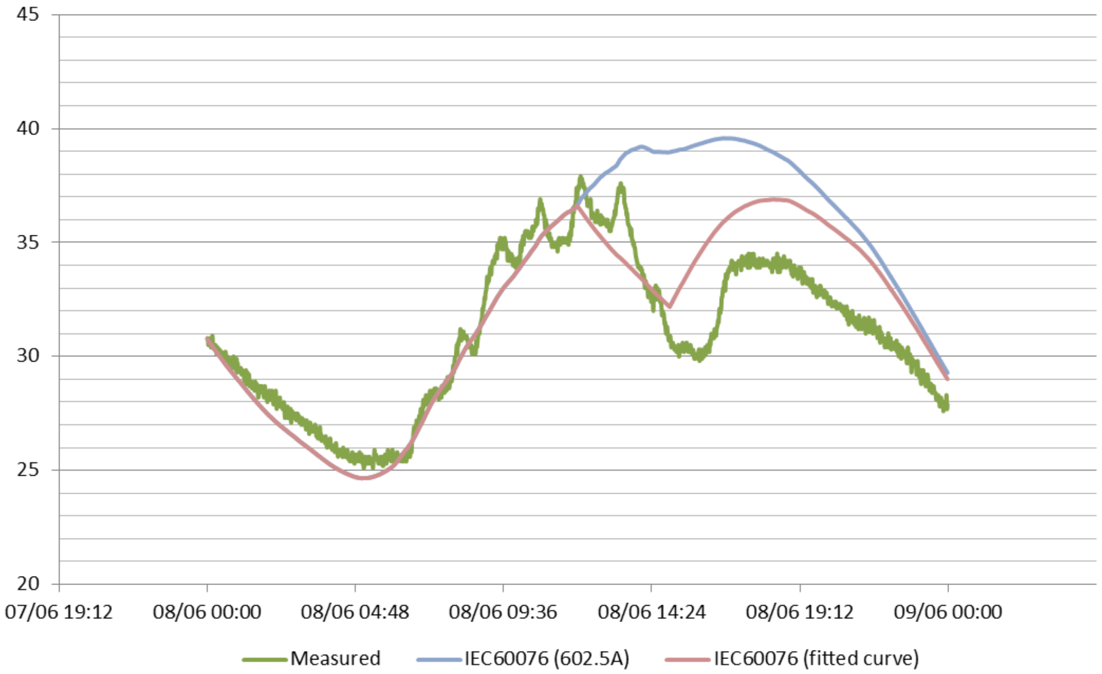

Figure 37: Top-oil temperature comparison with curve fitting results, T1, ONAF trial 12.00 – 15.00, 8th Jun 2015

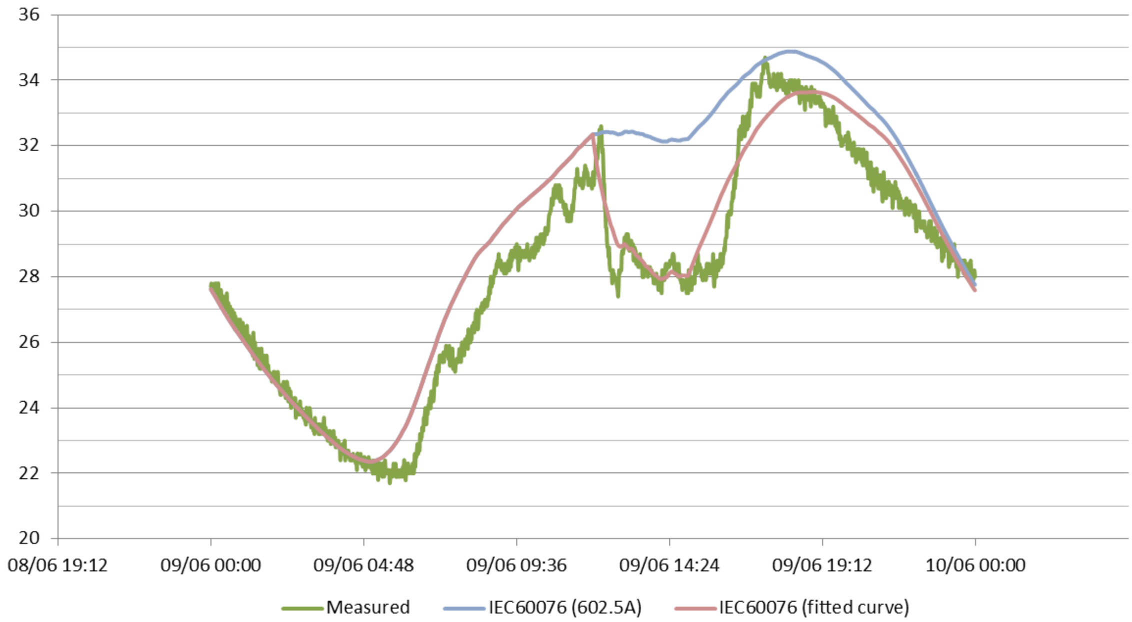

Figure 38: Top-oil temperature comparison with curve fitting results, T1, OFAN trial 12.00 – 15.00, 9th Jun 2015 using ONAF standard constant values

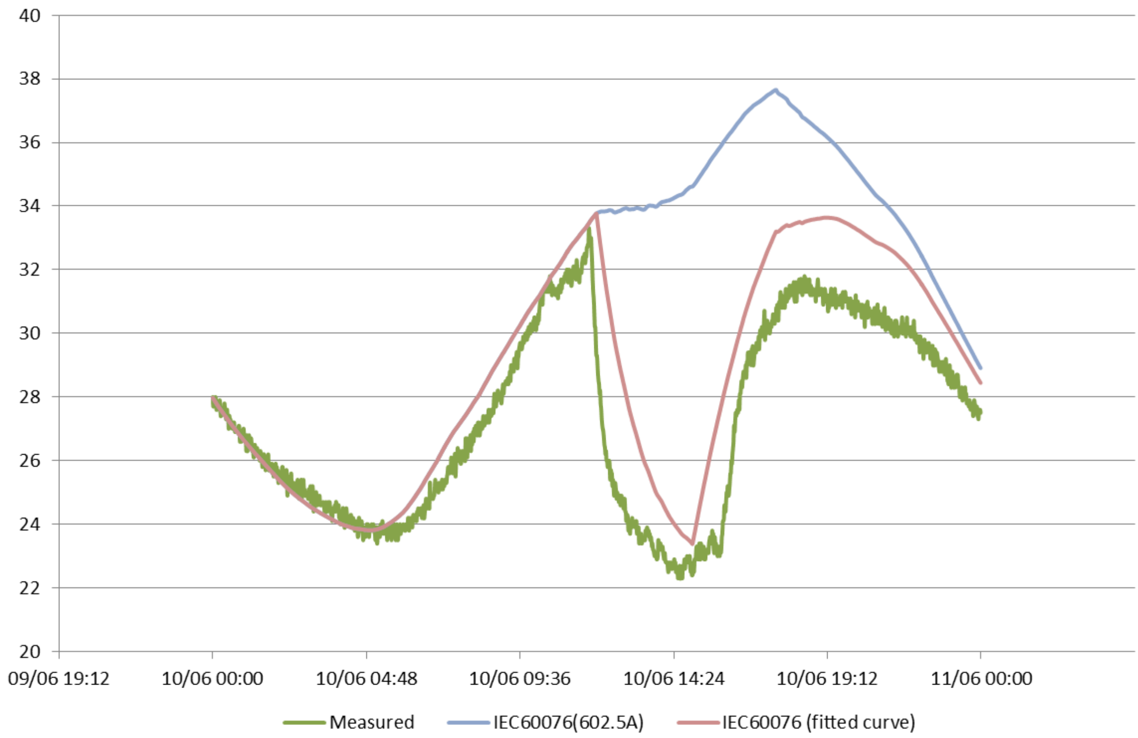

Figure 39: Top-oil temperature comparison with curve fitting results, T1, OFAF trial 12.00 – 15.00, 10th Jun 2015

Cooling	Ambient temperature (°C)	Hot-spot temperature limit (°C)	ΔT_{or} (°C)	τ_o (minutes)
ONAN	20	98	52	340
ONAF	20	-	20	700
OFAN	20	-	34	60
OFAF	20	140	16	100

Table 14: Summary of parameters fitted for different cooling modes.

The values in the table should not be relied upon because they were produced with limited amounts of poor quality data and should be used as indicative only. In addition, OFAN is not a cooling mode mentioned in the IEC standards [1, 2] therefore there are no standard defined values given for use in the calculations. A RMSE curve-fitting was used to compare which of ONAF and OFAF standard defined parameters give "better" results. With the same rated current of 953.9A as shown in Figure 40. Using OFAF parameters of x, y, k11, k21, k22 parameter values, gives a calculated value of $\Delta\theta_{or}$ of 42°C, and τ_o of 50min, for which a total RMSE score is 0.72 was calculated; using ONAF parameter values of x, y, k11, k21, k22 parameter values, gives a calculated value of $\Delta\theta_{or}$ of 34°C, and τ_o of 60min, with a total RMSE score 0.67. This indicates that the ONAF parameters could be used for this particular period for the fitting of OFAN oil rise and time constants.

LP 36.	After fixing on a rating transformer specific parameters need to be determined. These are not on test certificates or necessarily included in standards as example values and should be determined from test

LP 37.	Curve fitting in this circumstance is complicated by changing load current and ambient temperature and therefore with this level of data the results and benefits are purely indicative of the values expected.

LP 38.	In addition to transformer specific data there is standard specific data needed for the calculations which is unspecified for OFAN cooling. An estimate of this has been made – an initial indications are that ONAF constants could be used in the first instance to aid investigations

LP 39.	Spot testing under a single condition doesn't allow the impact of system non-linearity to be taken into account.

LP 40.	Modelling with the different cooling modes indicates that different cooling modes can offer up to 35^{o}C of cooling at rated load.

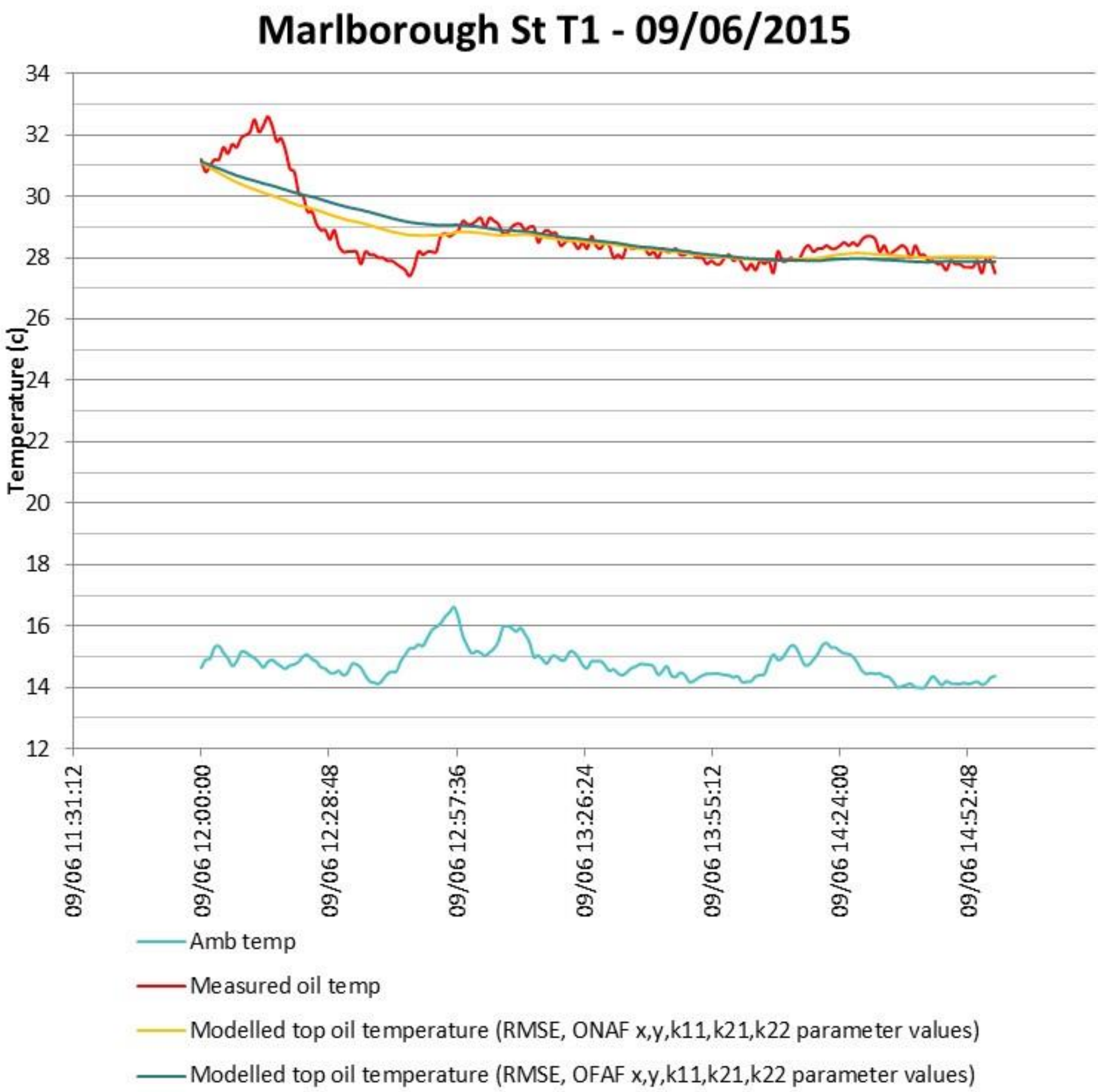

Figure 40: OFAN fitting results using ONAF or OFAF model parameters.

The cooling status of the transformer needs to be captured and substantial amount of trial data is required to be fed into the transformer thermal relay and model. Without this the model does not produce a reliable indication of the practical operational thermal state.

LP 41.	A method of parameter fitting cooling techniques not dealt with in the standards has been described. Values are based on curve fitting at one point with variable load and ambient temperature data so are indicative rather than accurate. Accurate measurements under controlled conditions would allow more confidence in benefits to be made.

D Top oil temperature comparison

Measurement of T2 temperatures are only available from July 2014.

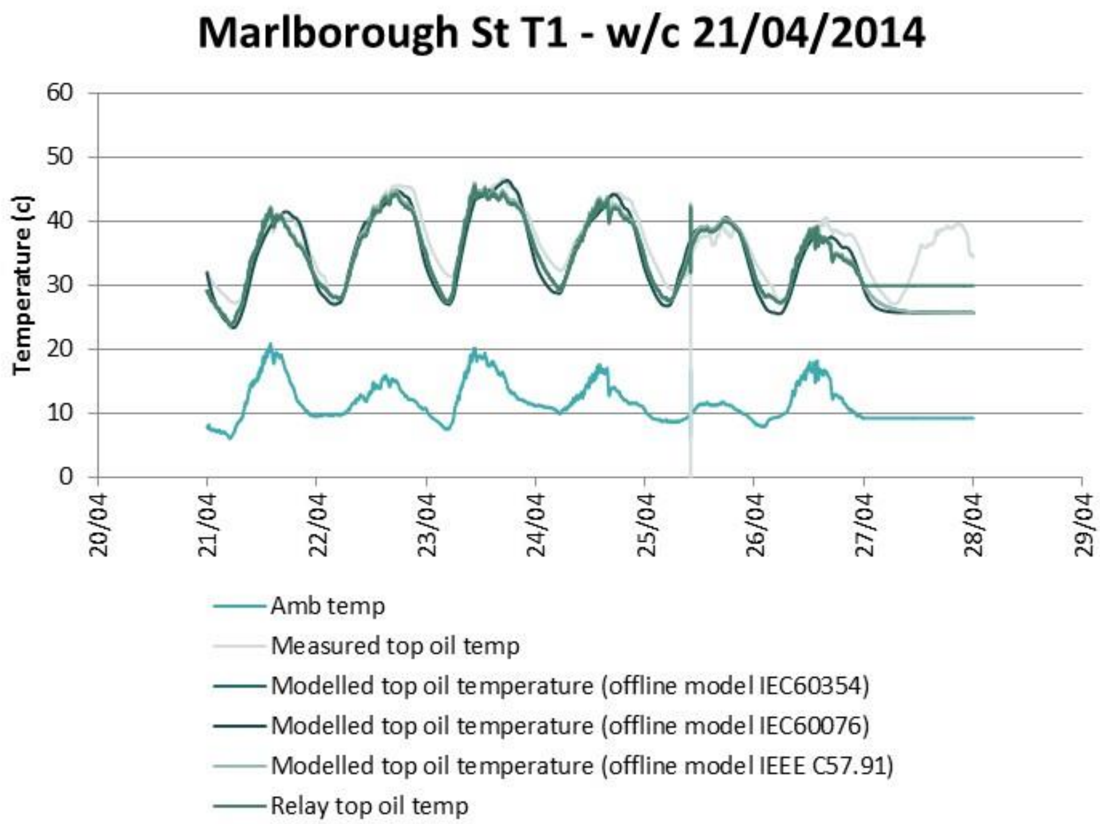

Figure 41 : Top-oil temperature modelling results with different models compared to measured and relay values (T1, w/c 21/04/2014).

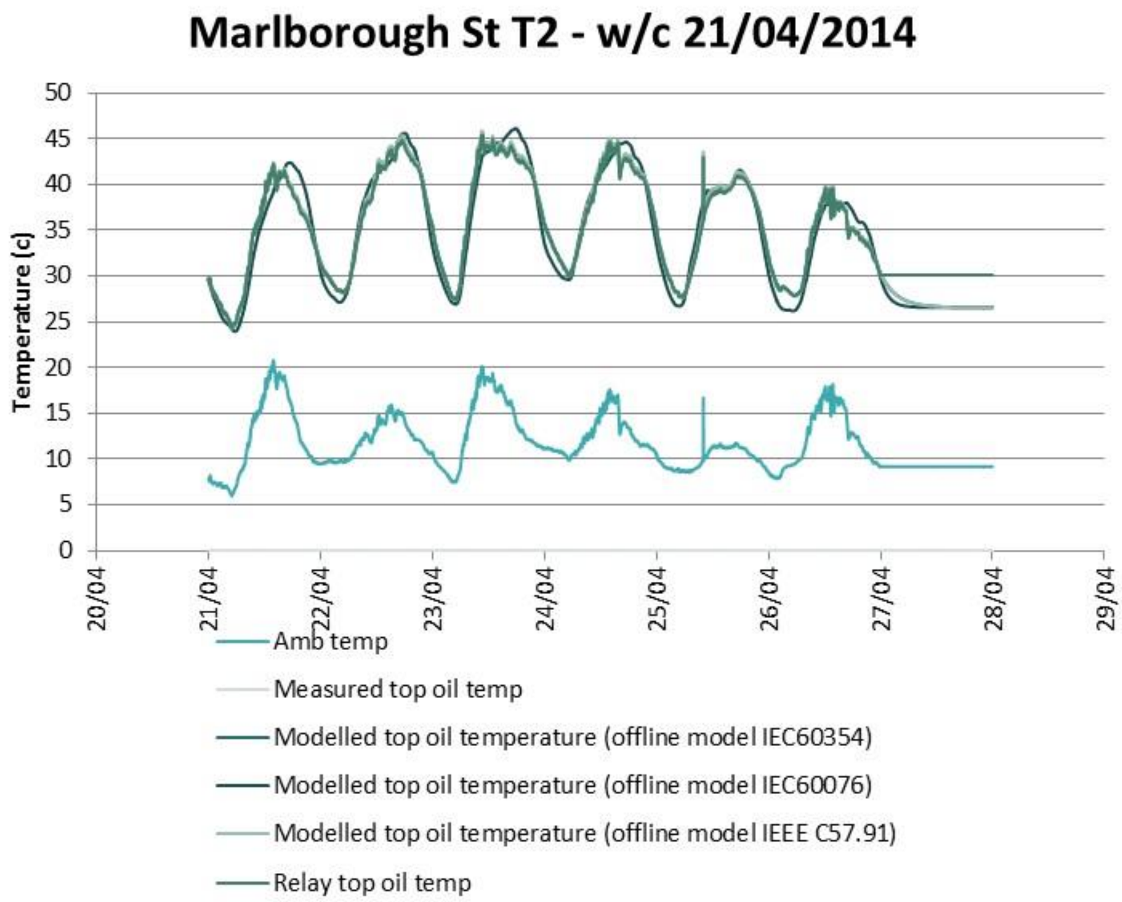

Figure 42 : Top-oil temperature modelling results with different models compared to measured and relay values (T2, w/c 21/04/2014).

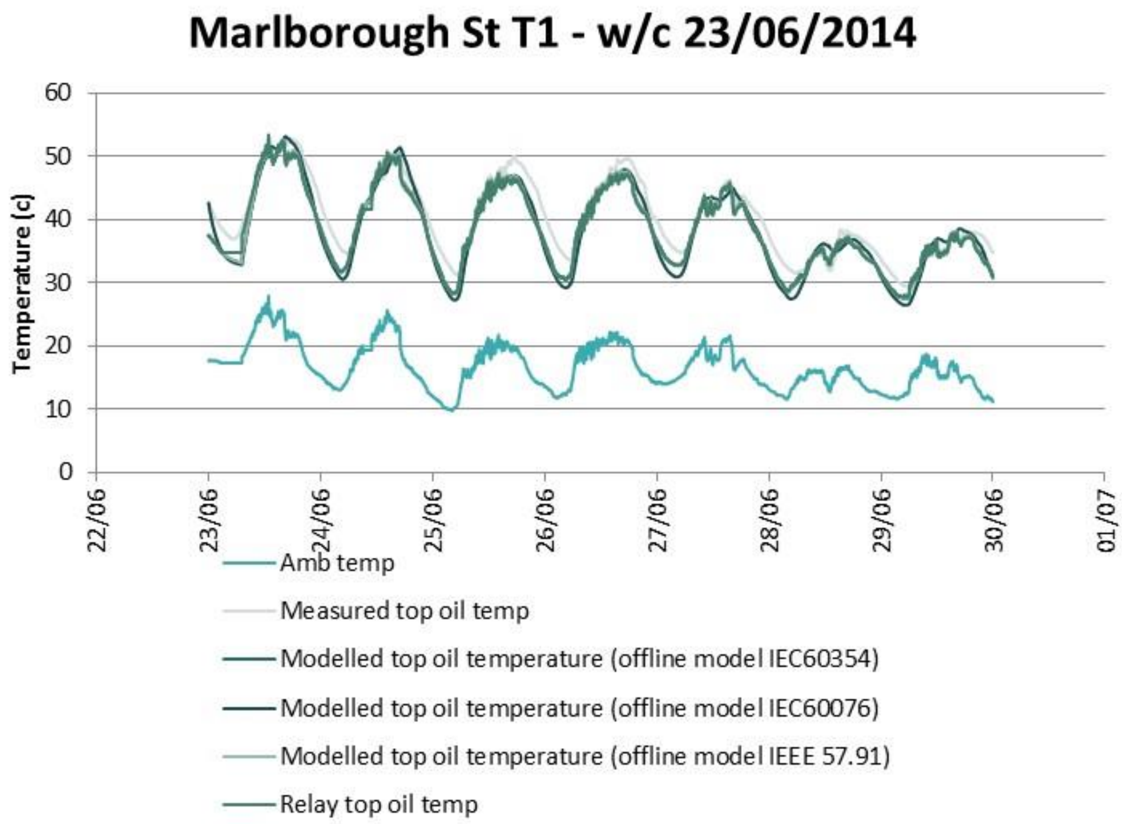

Figure 43 : Top-oil temperature modelling results with different models compared to measured and relay values (T1, w/c 23/06/2014).

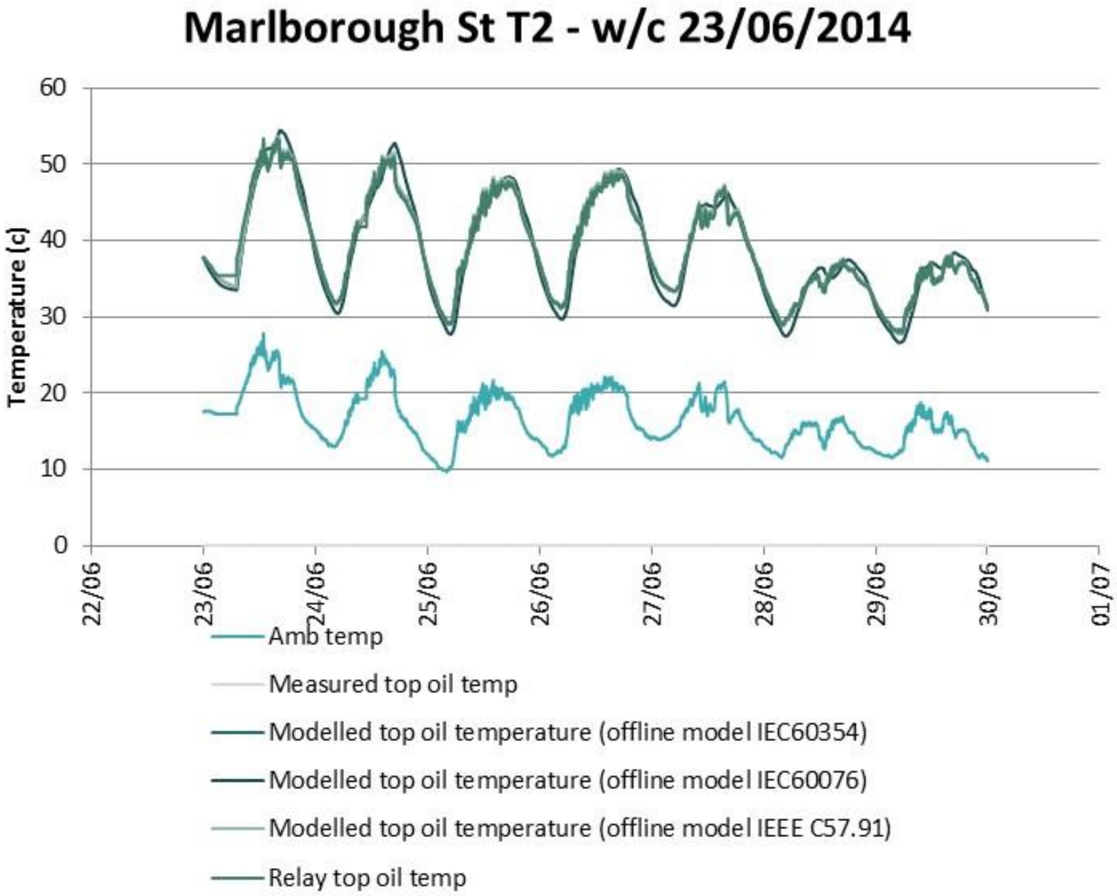

Figure 44 : Top-oil temperature modelling results with different models compared to measured and relay values (T2, w/c 23/06/2014).

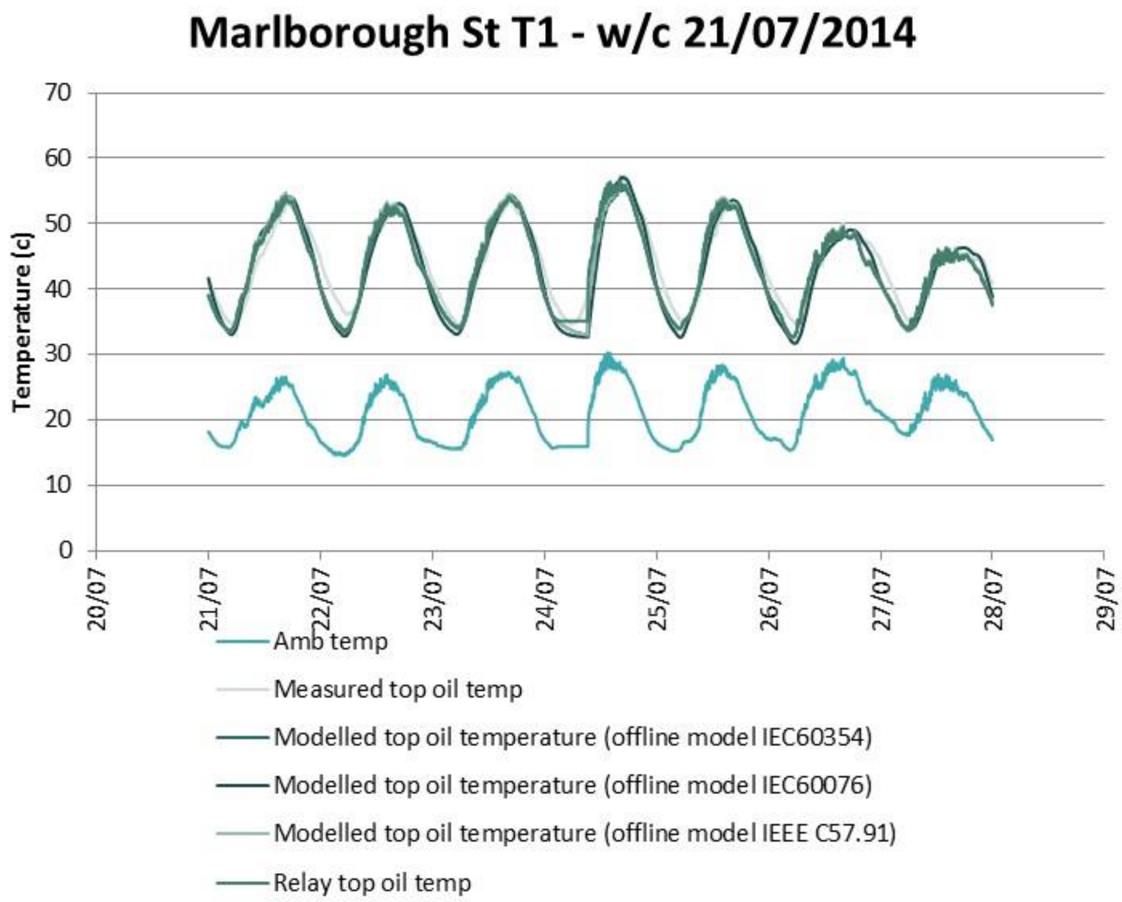

Figure 45 : Top-oil temperature modelling results with different models compared to measured and relay values (T1, w/c 21/07/2014).

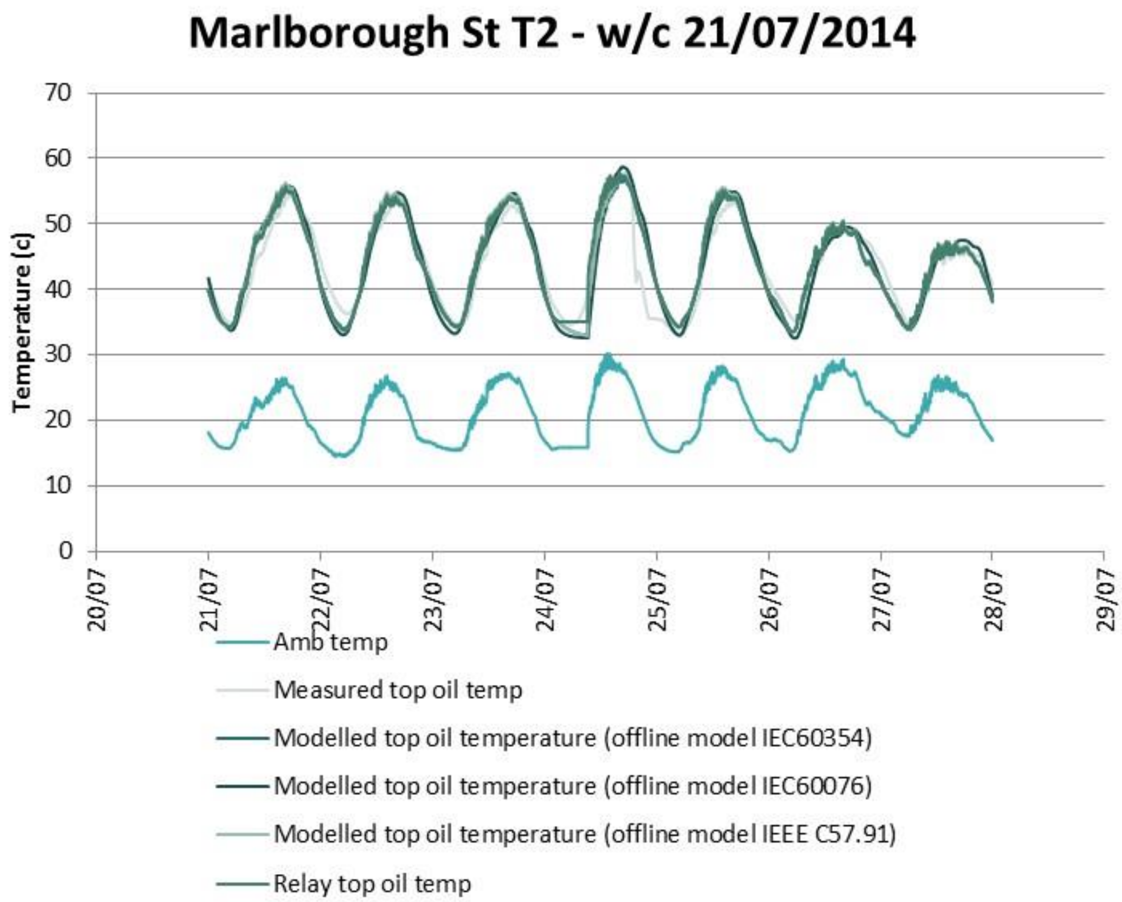

Figure 46 : Top-oil temperature modelling results with different models compared to measured and relay values (T2, w/c 21/07/2014).

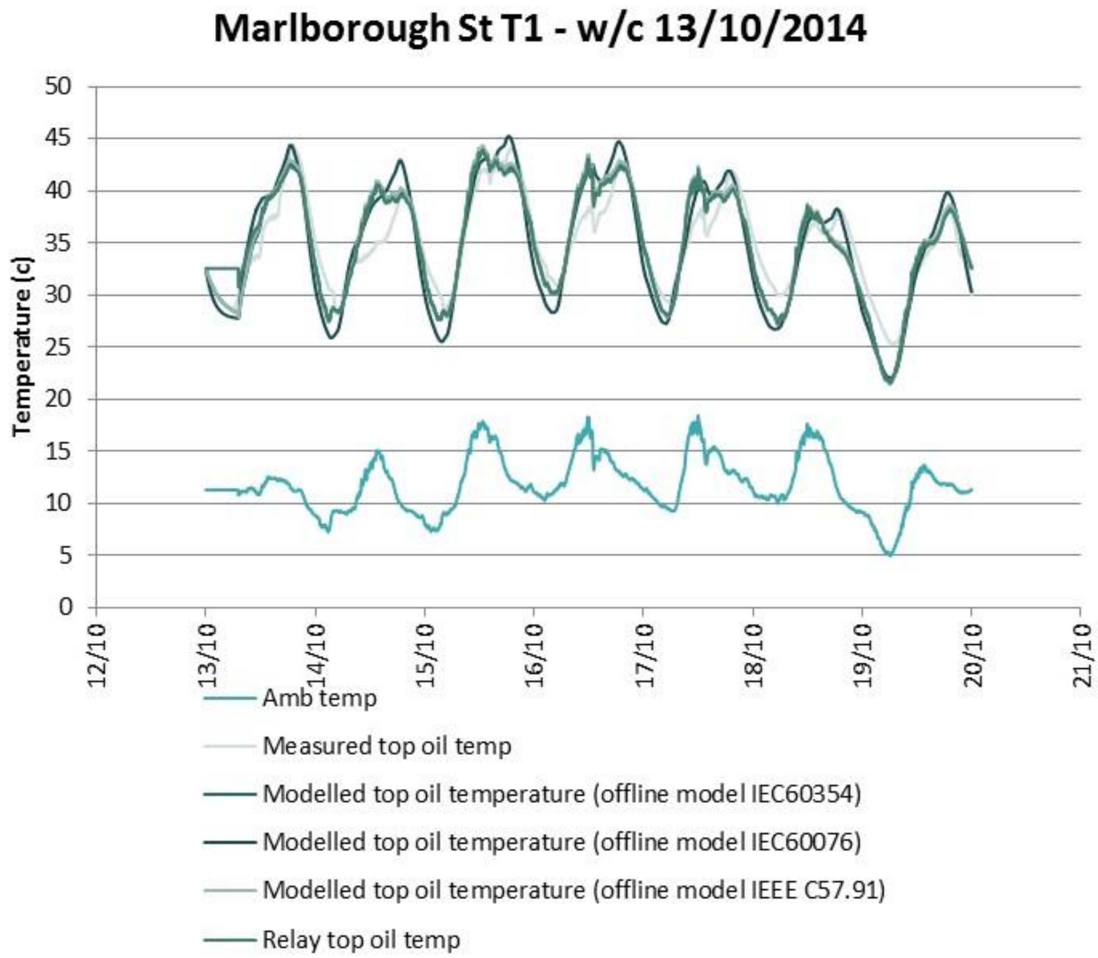

Figure 47 : Top-oil temperature modelling results with different models compared to measured and relay values (T1, w/c 13/10/2014)

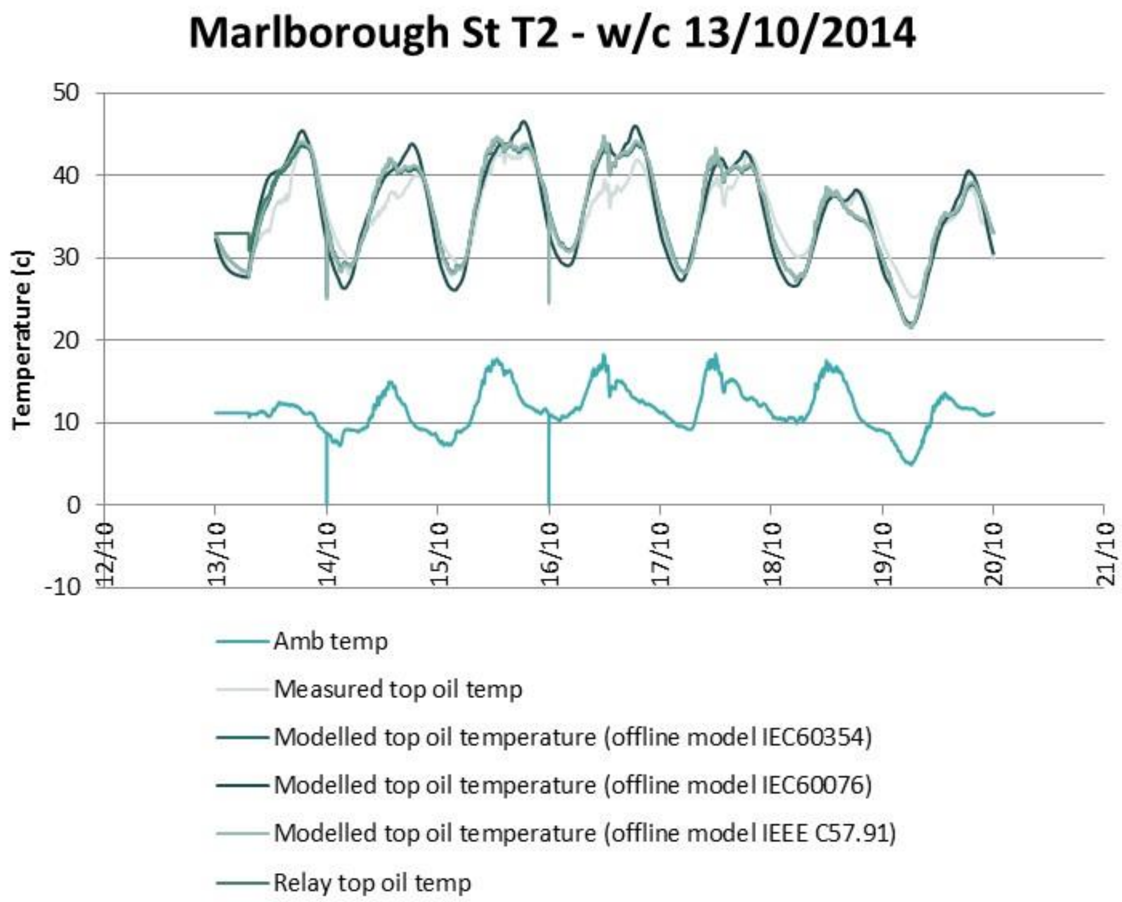

Figure 48 : Top-oil temperature modelling results with different models compared to measured and relay values (T2, w/c 13/10/2014)

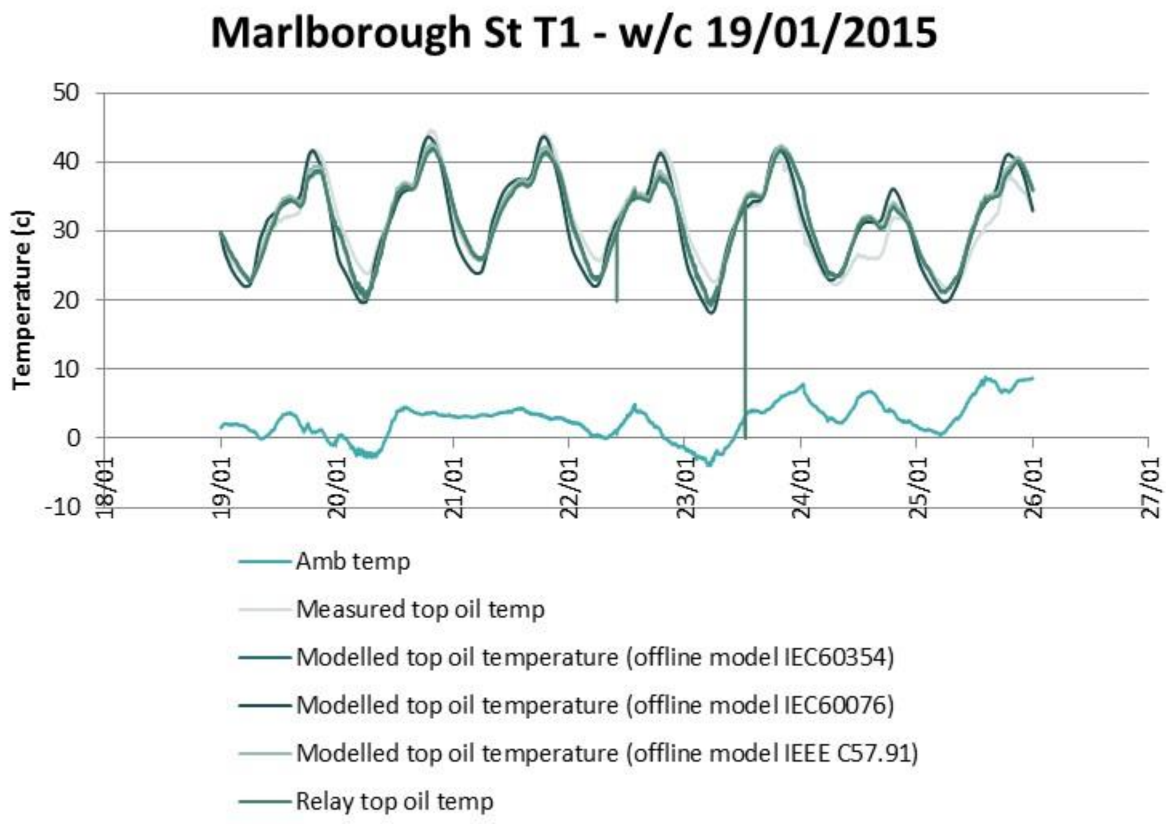

Figure 49 : Top-oil temperature modelling results with different models compared to measured and relay values (T1, w/c 19/01/2015).

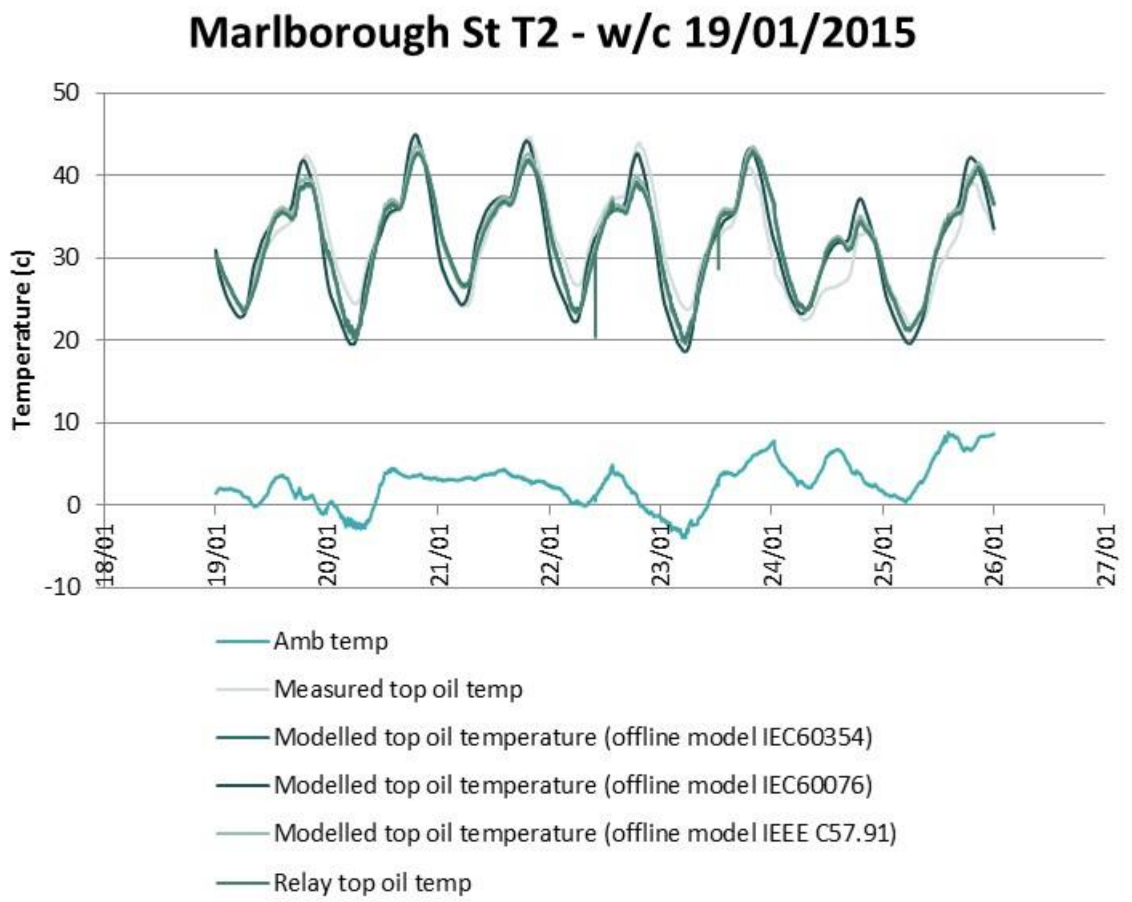

Figure 50 : Top-oil temperature modelling results with different models compared to measured and relay values (T2, w/c 19/01/2015).

E Bottom oil temperature comparison

Measurement of T1 bottom temperature available from June 2014;

Measurement of T2 bottom temperature available from July 2014.

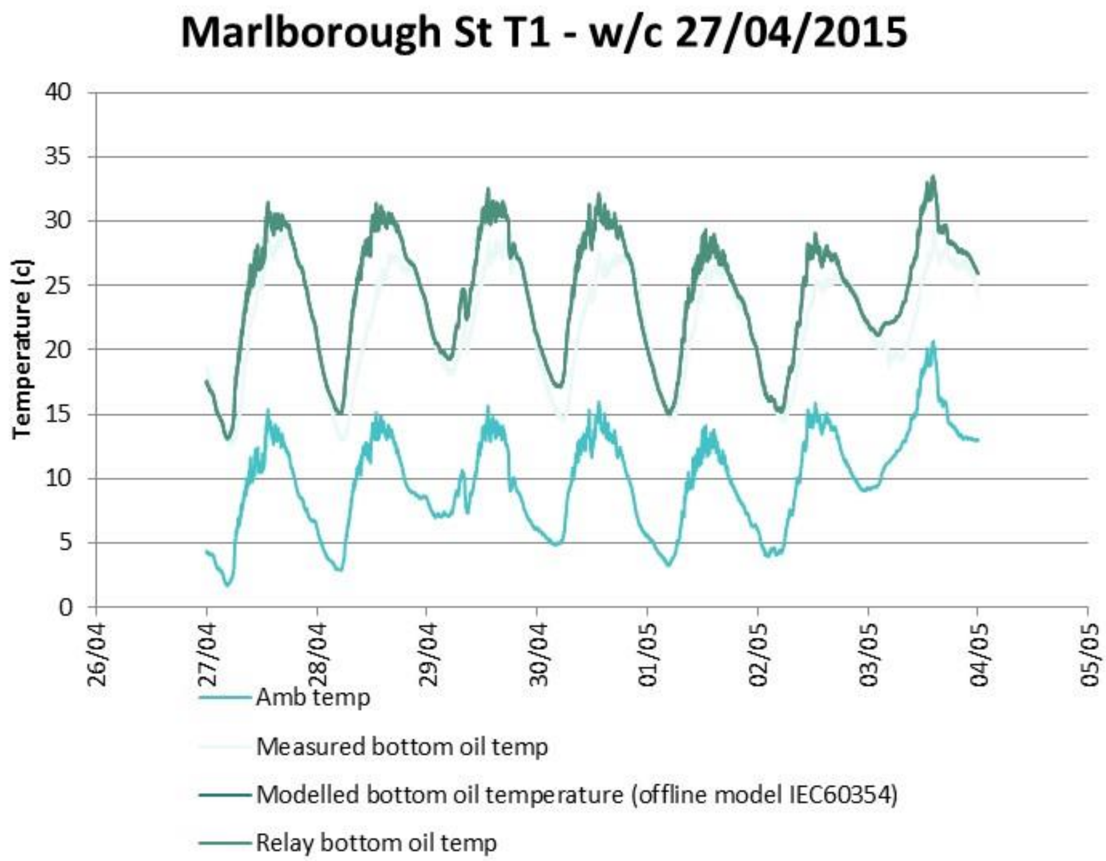

Figure 51 : Bottom-oil temperature modelling results compared to relay values (T1, w/c 27/04/2015).

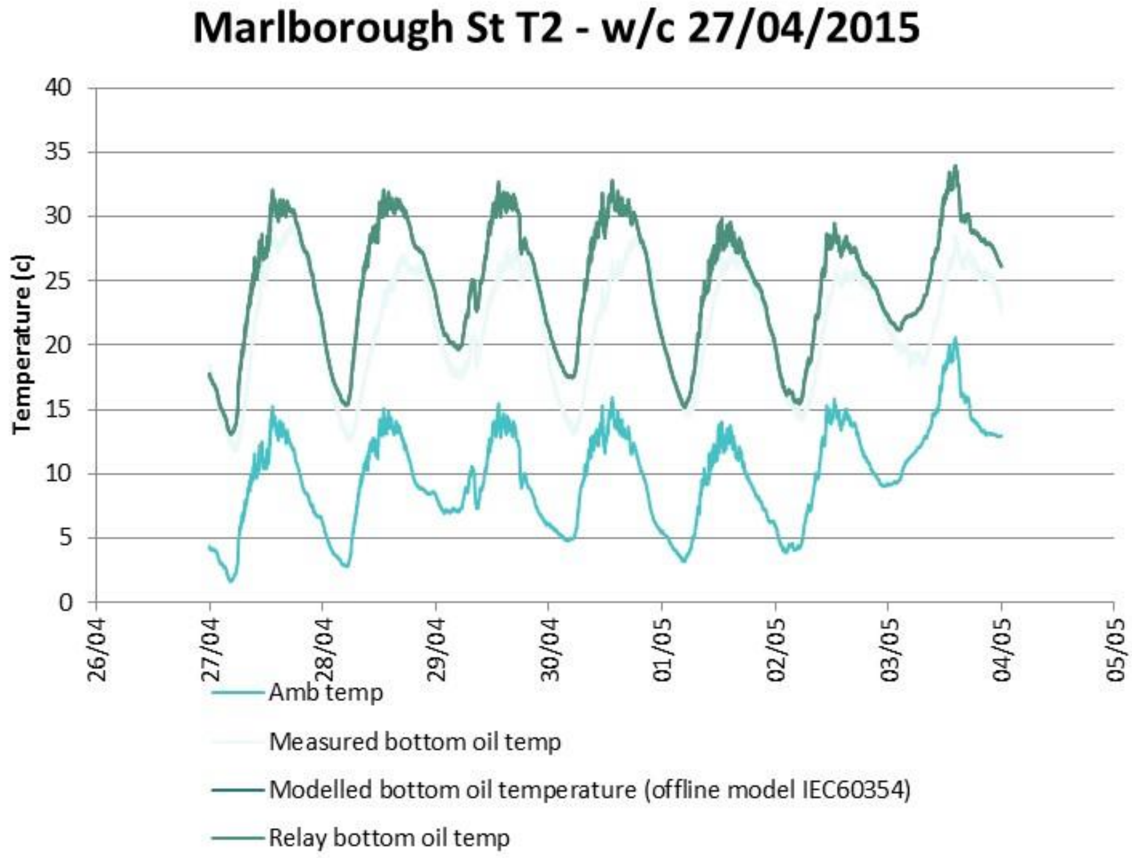

Figure 52 : Bottom-oil temperature modelling results compared to relay values (T2, w/c 27/04/2015).

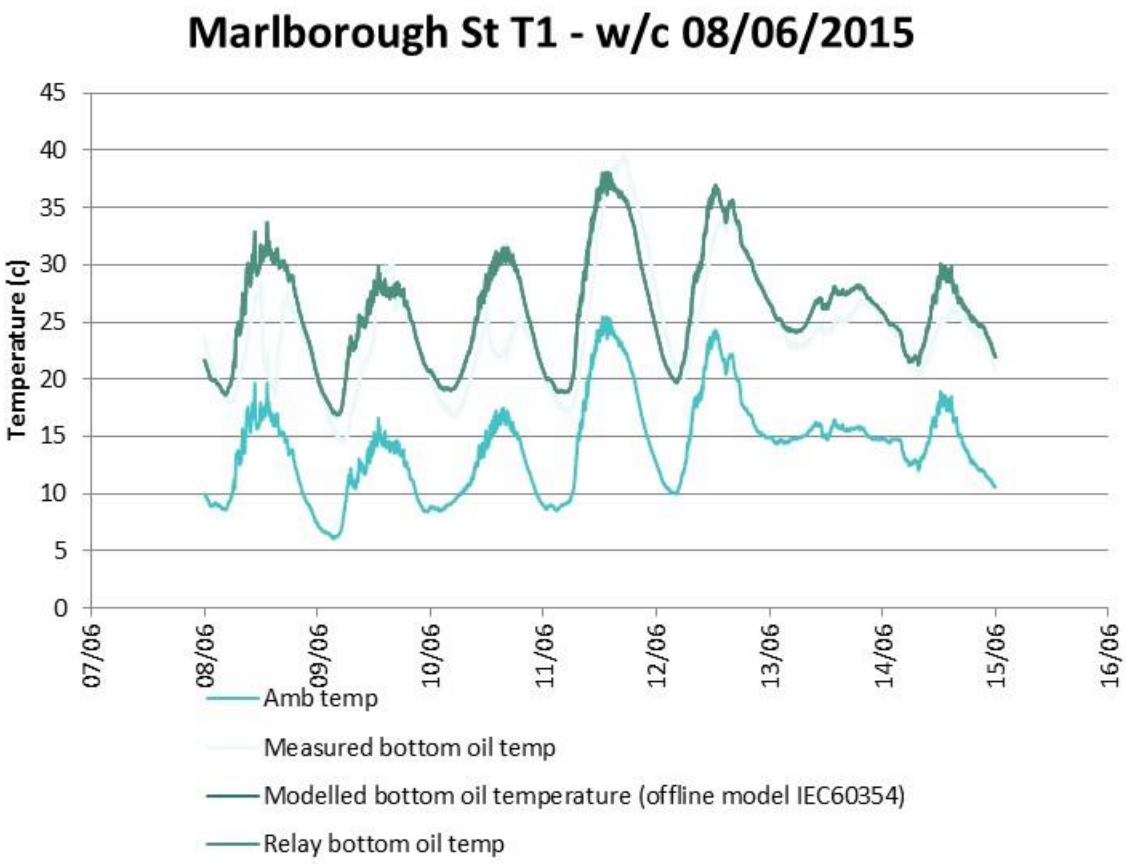

Figure 53 : Bottom-oil temperature modelling results compared to measured and relay values (T1, w/c 08/06/2015).

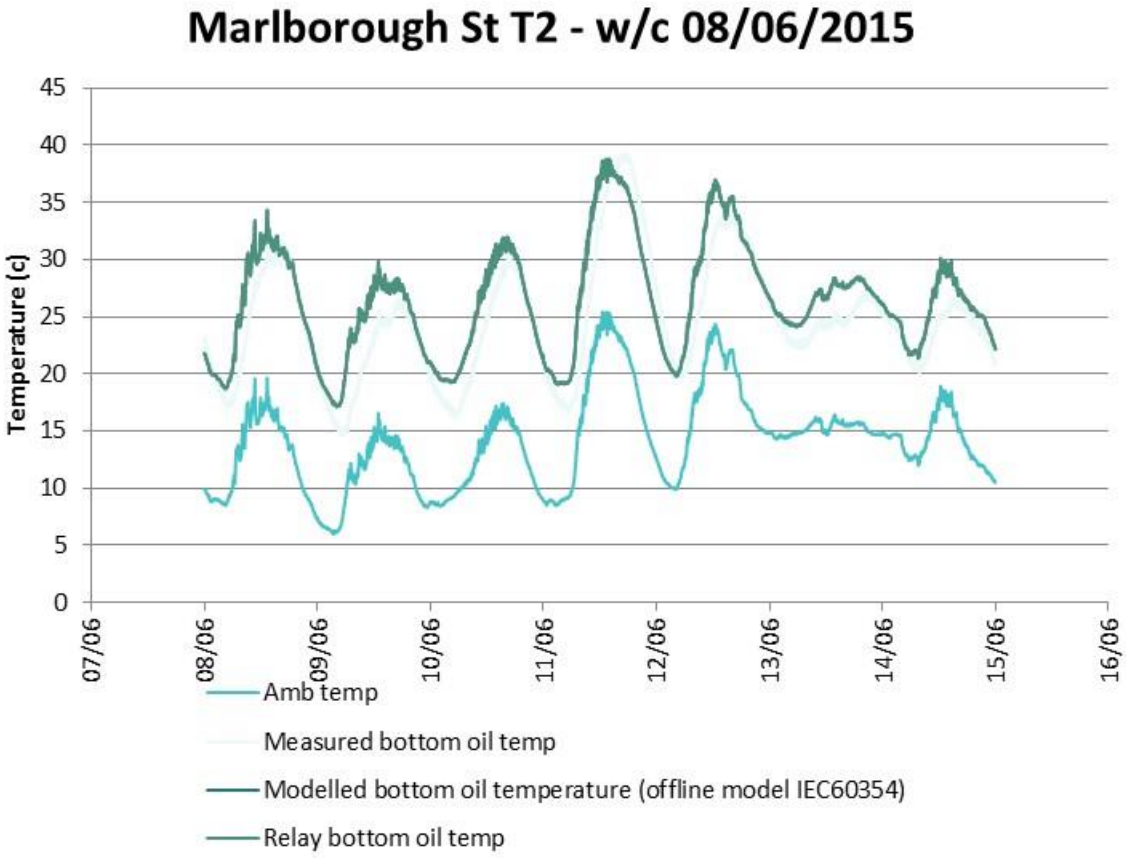

Figure 54 : Bottom-oil temperature modelling results compared to relay values (T2, w/c 08/06/2015).

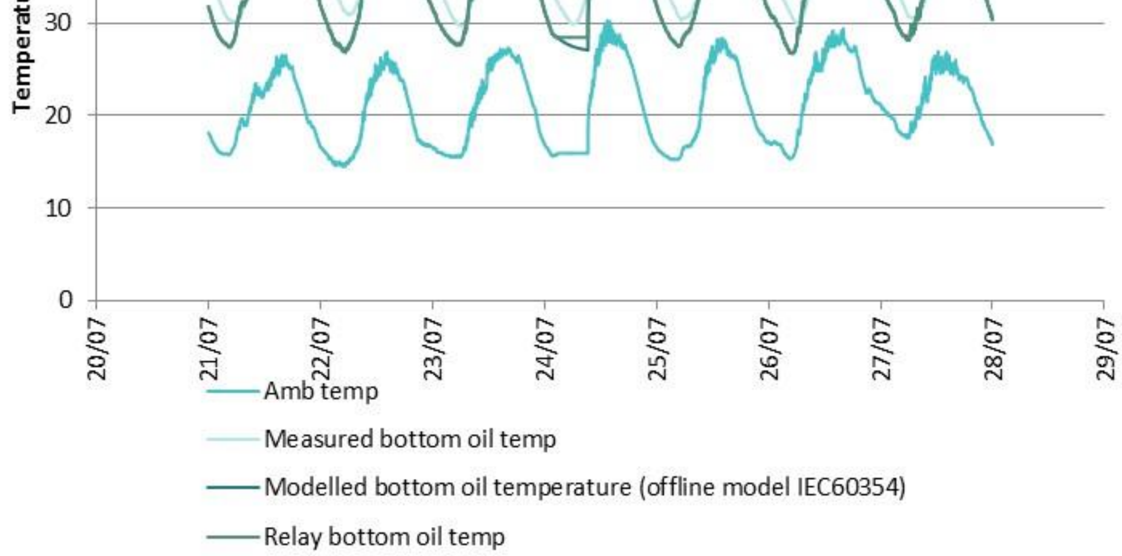

Figure 55 : Bottom-oil temperature modelling results compared to measured and relay values (T1, w/c 21/07/2014).

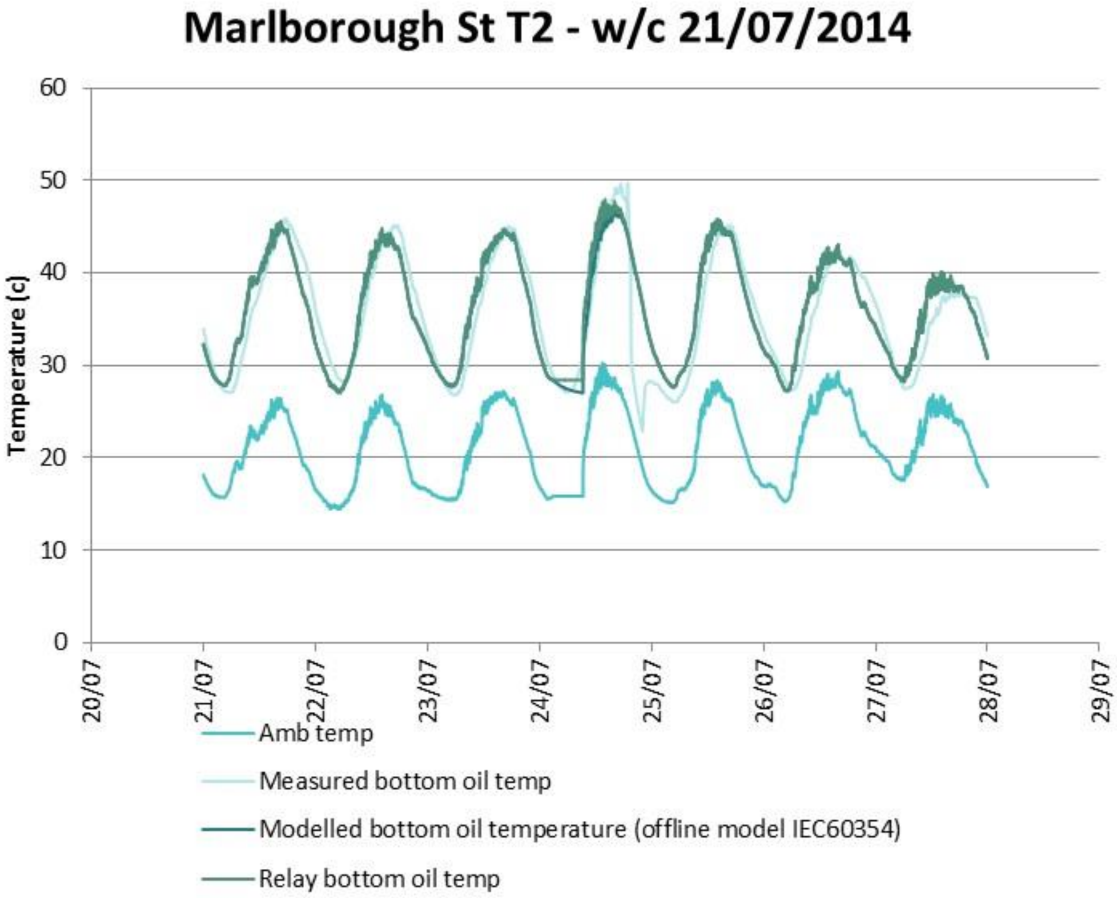

Figure 56 : Bottom-oil temperature modelling results compared to measured and relay values (T2, w/c 21/07/2014).

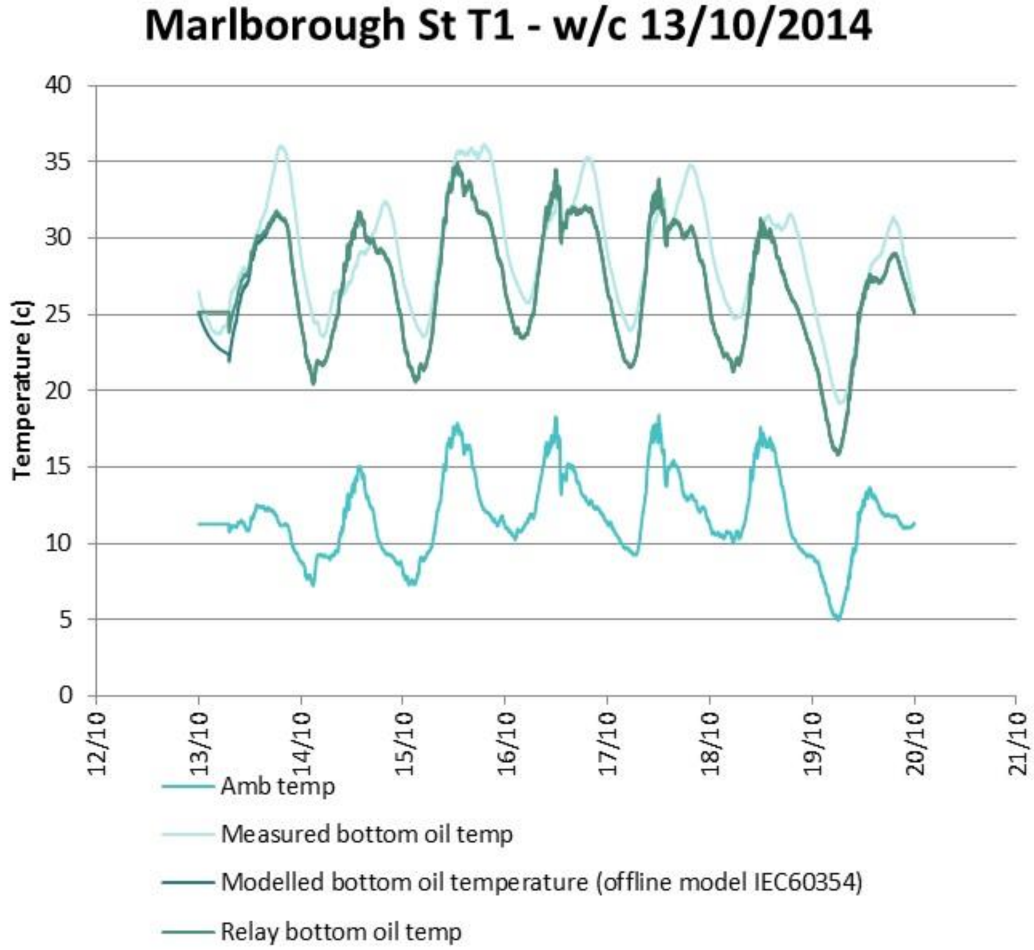

Figure 57 : Bottom-oil temperature modelling results compared to measured and relay values (T1, w/c 13/10/2014).

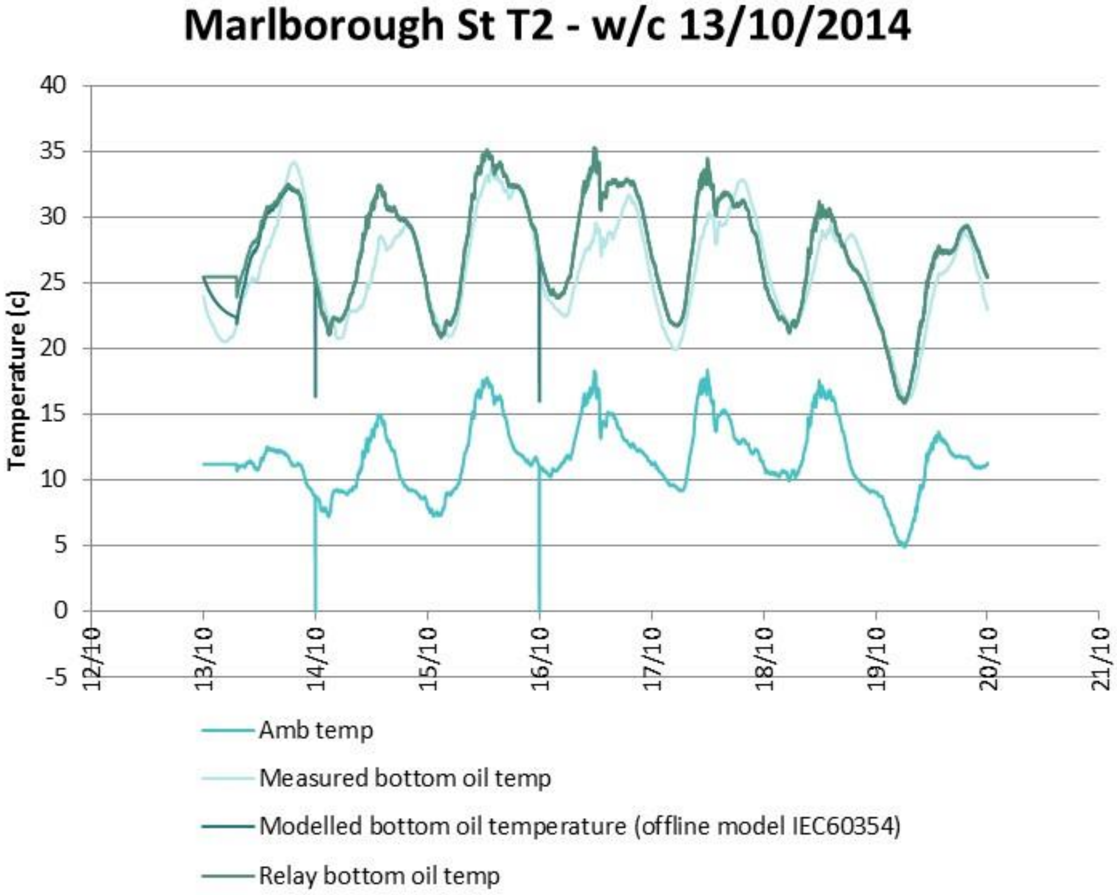

Figure 58 : Bottom-oil temperature modelling results compared to measured and relay values (T2, w/c 13/10/2014).

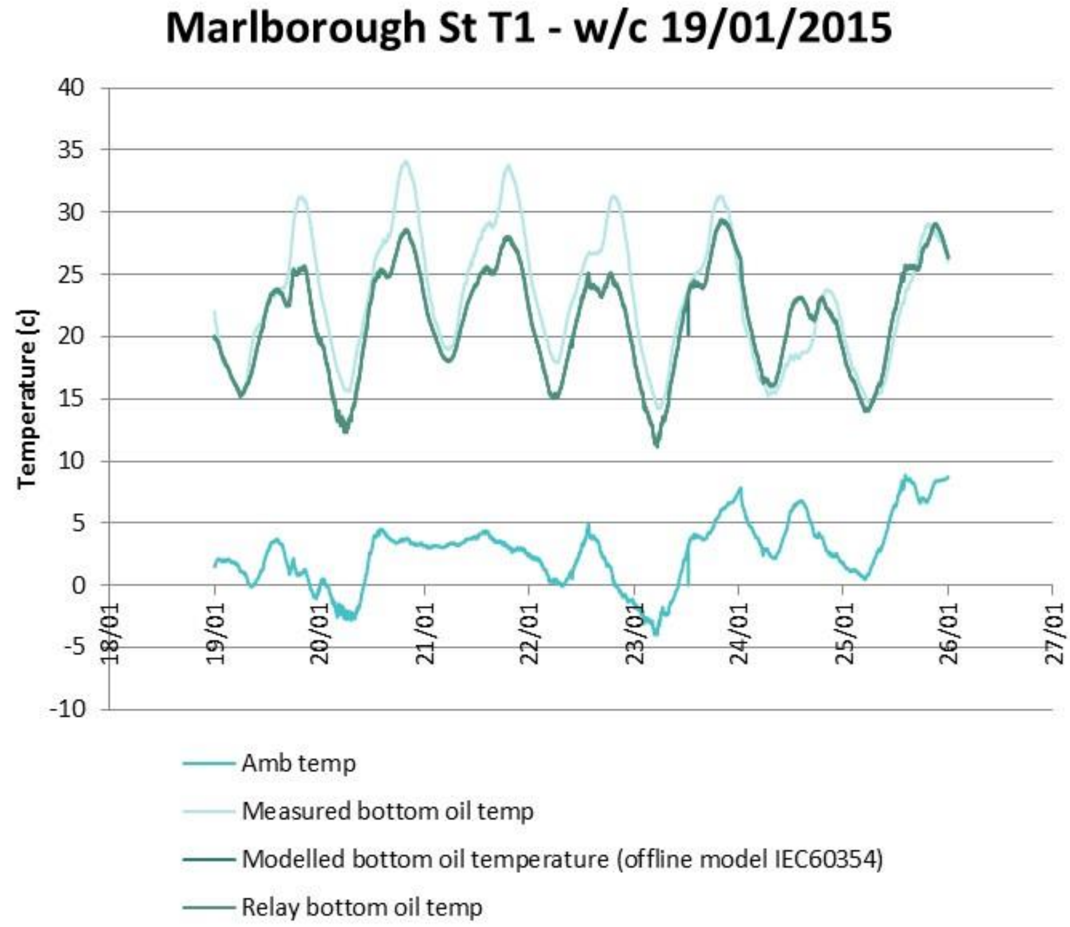

Figure 59 : Bottom-oil temperature modelling results compared to measured and relay values (T1, w/c 19/01/2015).

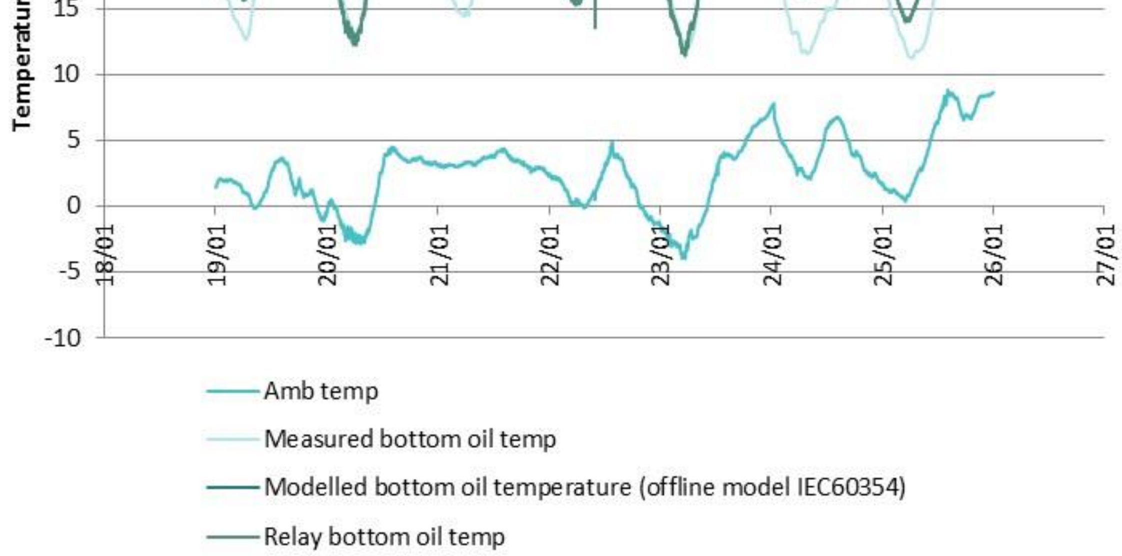

Figure 60 : Bottom-oil temperature modelling results compared to measured and relay values (T2, w/c 19/01/2015).

F Hot spot temperature comparison

Measurement of hot-spot temperatures not available therefore only relay outputs are used for comparison.

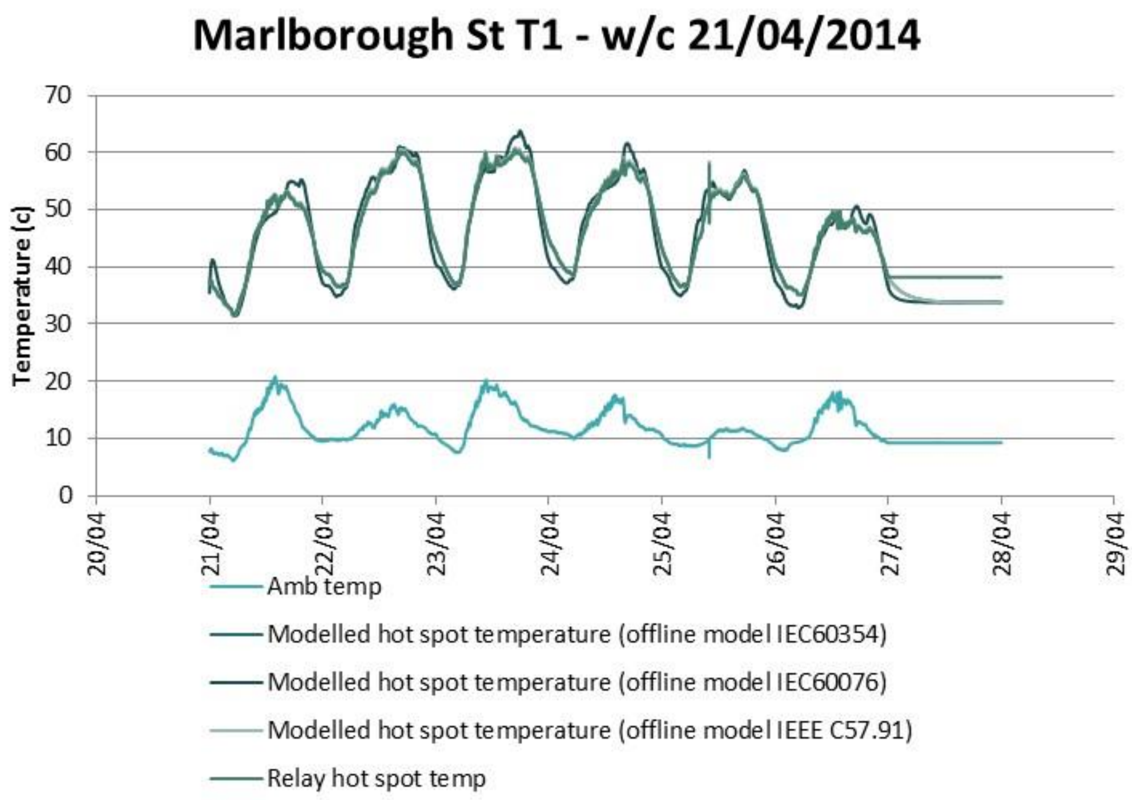

Figure 61 : Hot-spot temperature modelling results with different models compared to relay values (T1, w/c 21/04/2014).

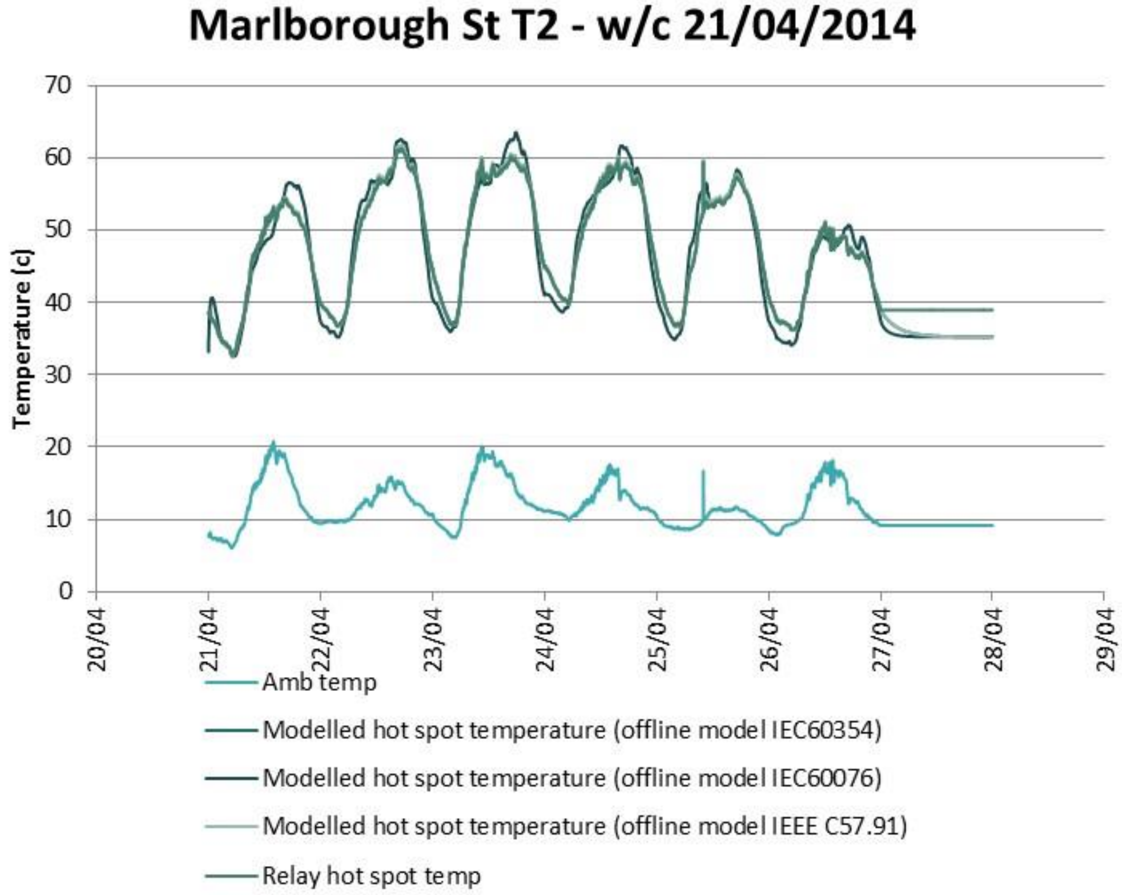

Figure 62 : Hot-spot temperature modelling results with different models compared to relay values (T2, w/c 21/04/2014).

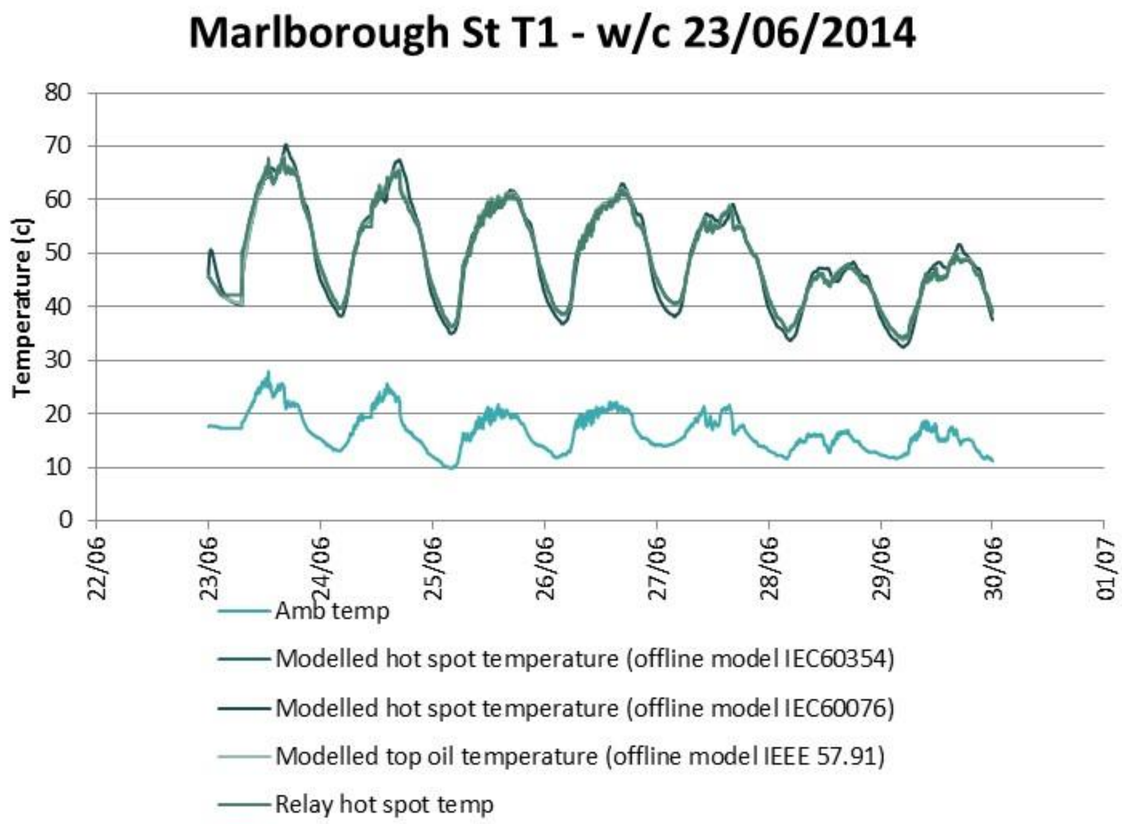

Figure 63 : Hot-spot temperature modelling results with different models compared to relay values (T1, w/c 23/06/2014).

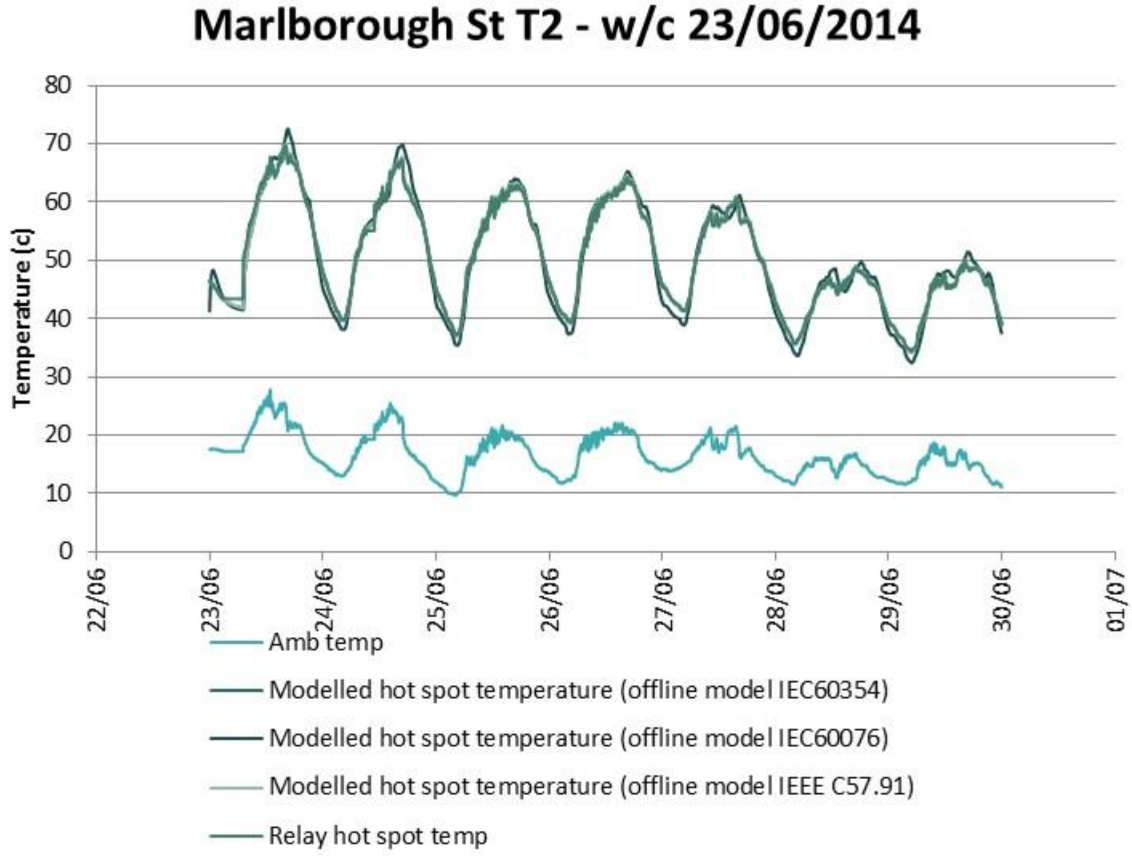

Figure 64 : Hot-spot temperature modelling results with different models compared to relay values (T2, w/c 23/06/2014).

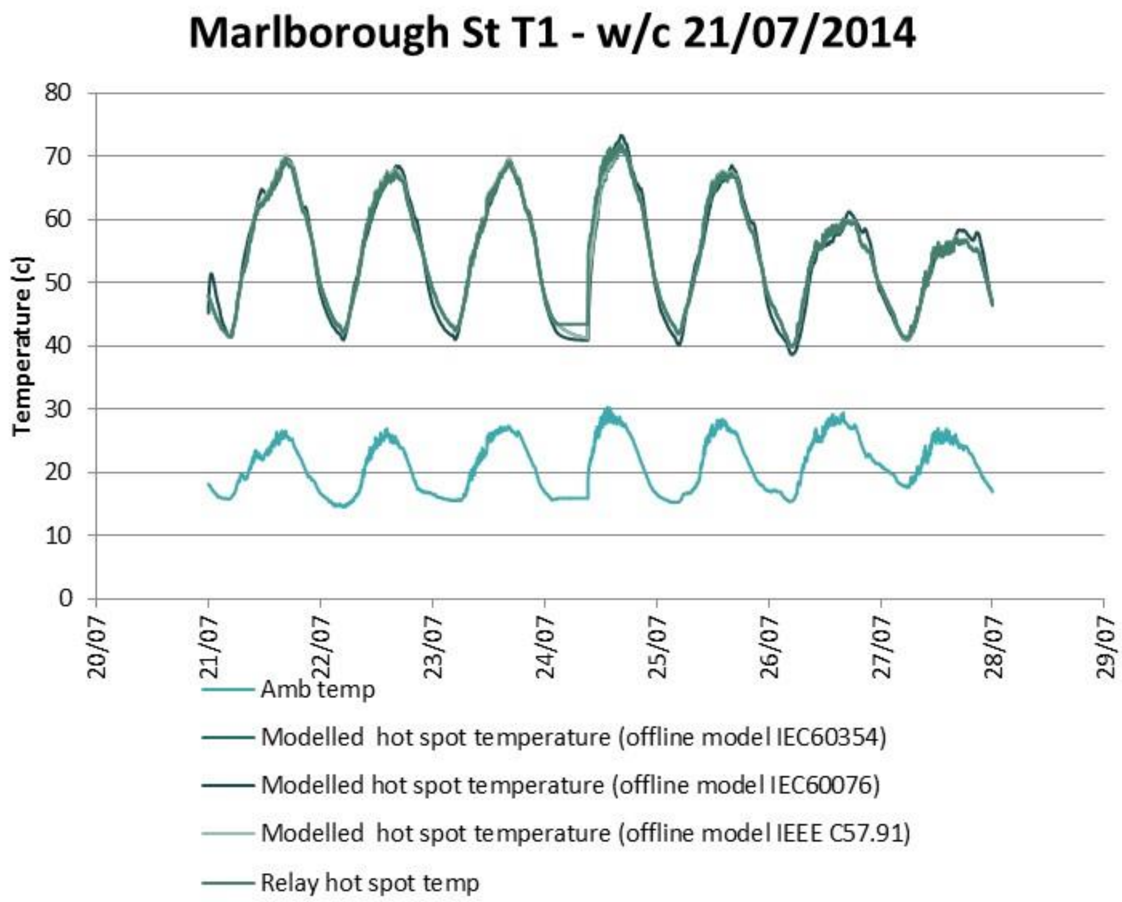

Figure 65 : Hot-spot temperature modelling results with different models compared to relay values (T1, w/c 21/07/2014).

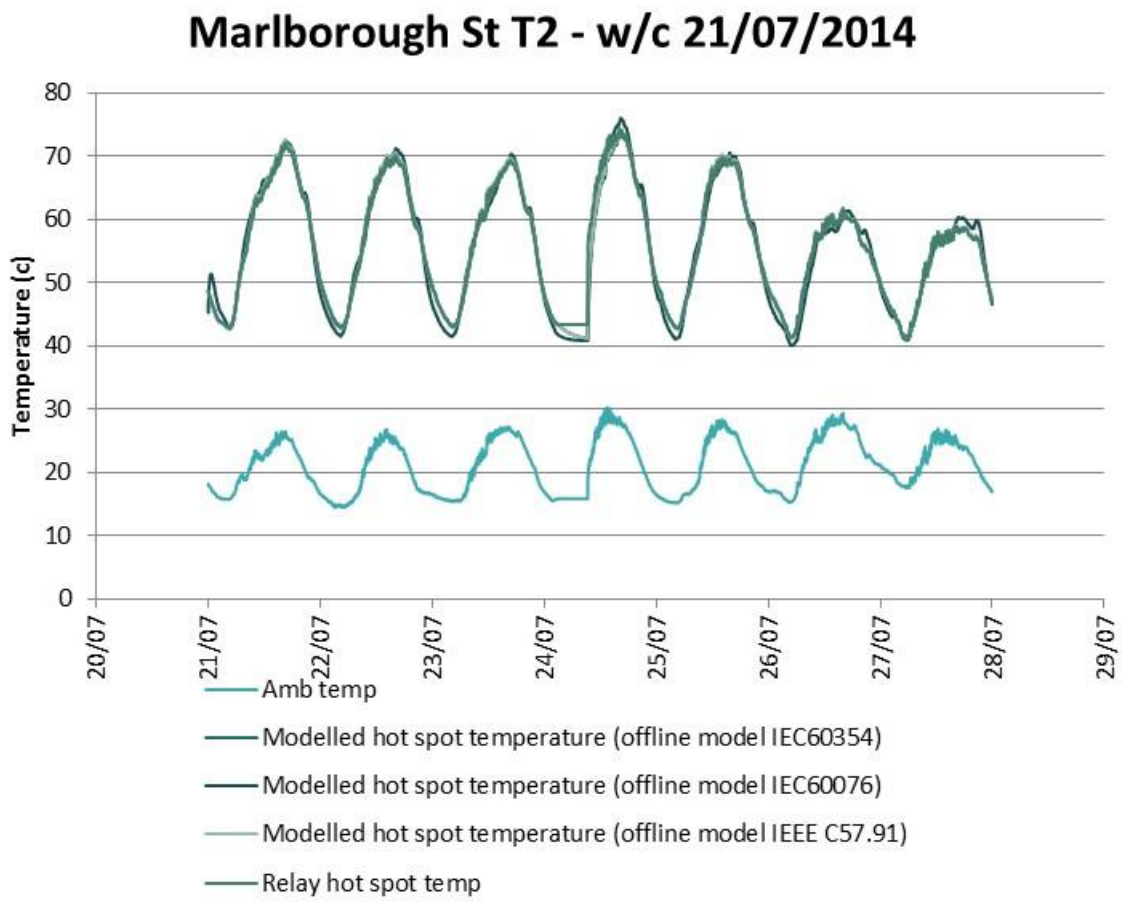

Figure 66 : Hot-spot temperature modelling results with different models compared to relay values (T2, w/c 21/07/2014).

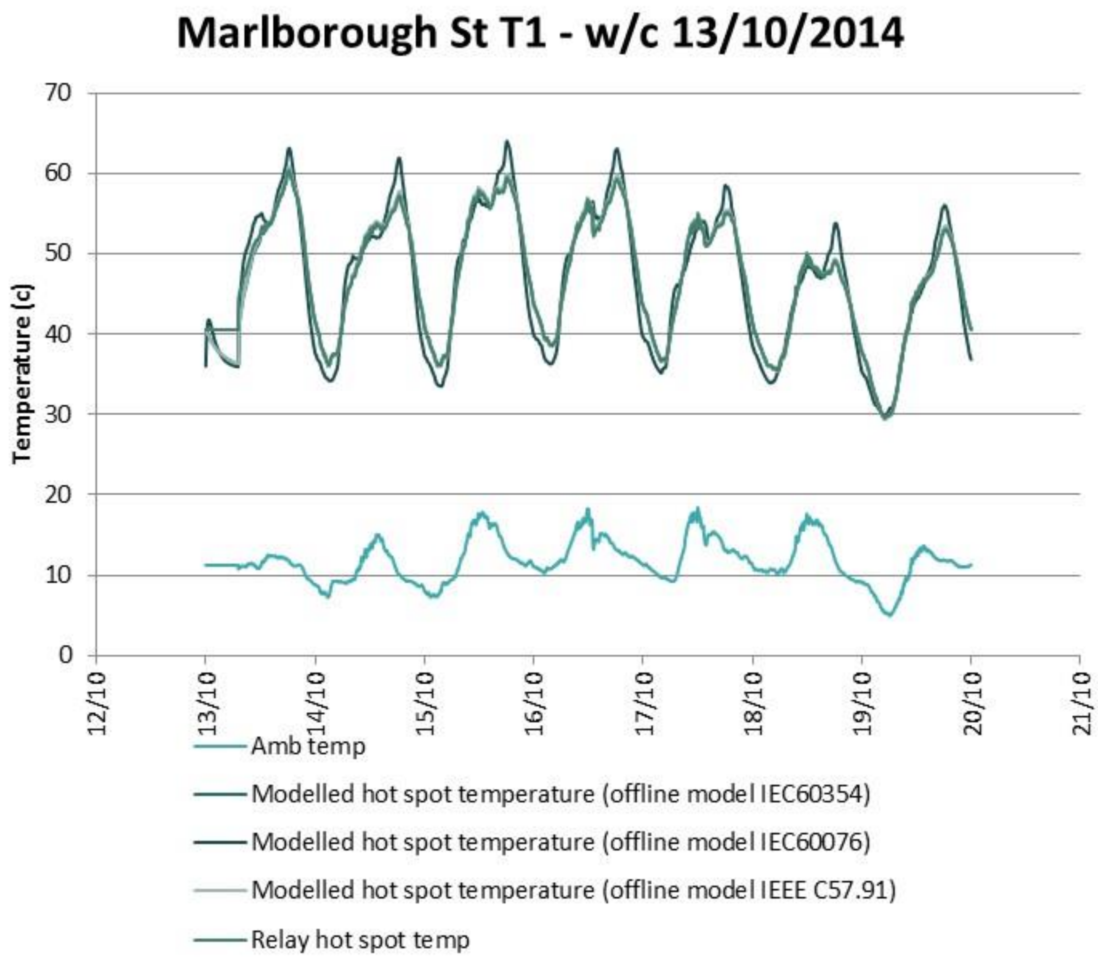

Figure 67 : Hot-spot temperature modelling results with different models compared to relay values (T1, w/c 13/10/2014).

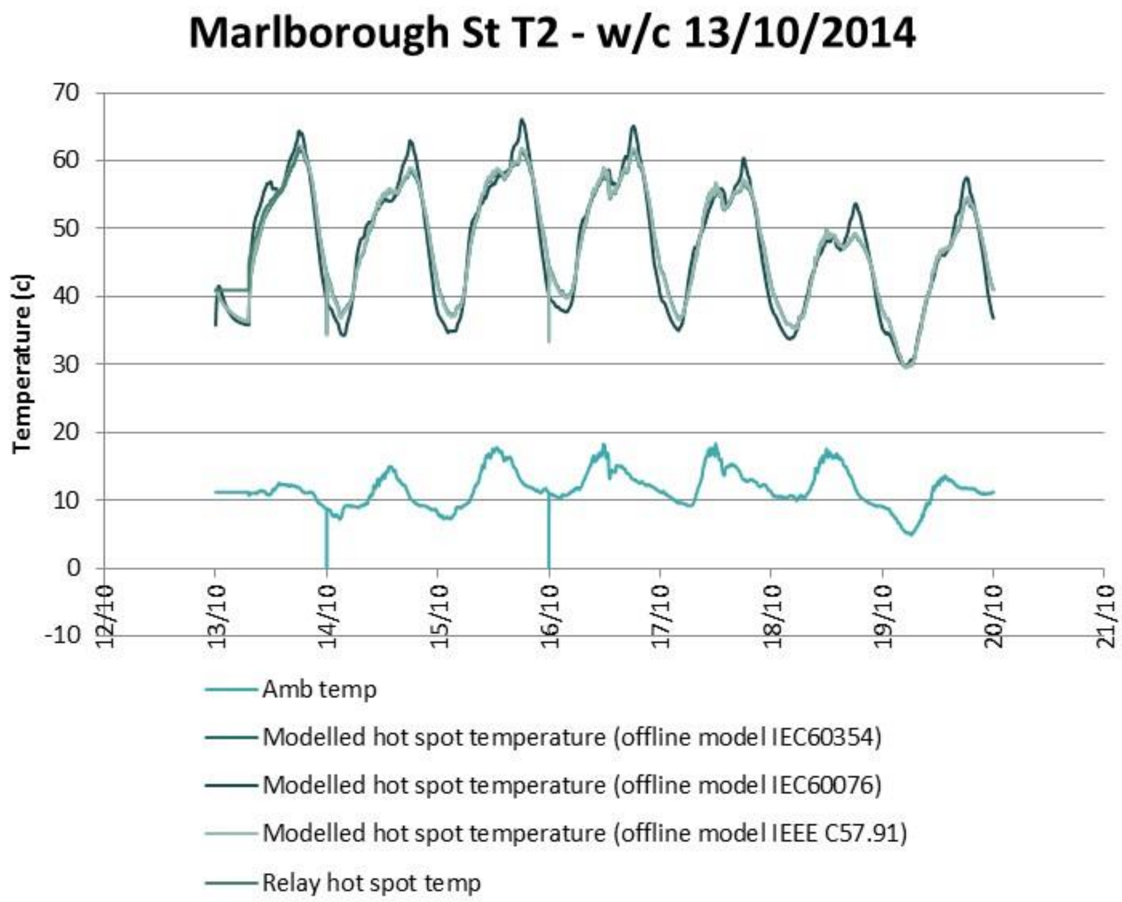

Figure 68 : Hot-spot temperature modelling results with different models compared to relay values (T2, w/c 13/10/2014).

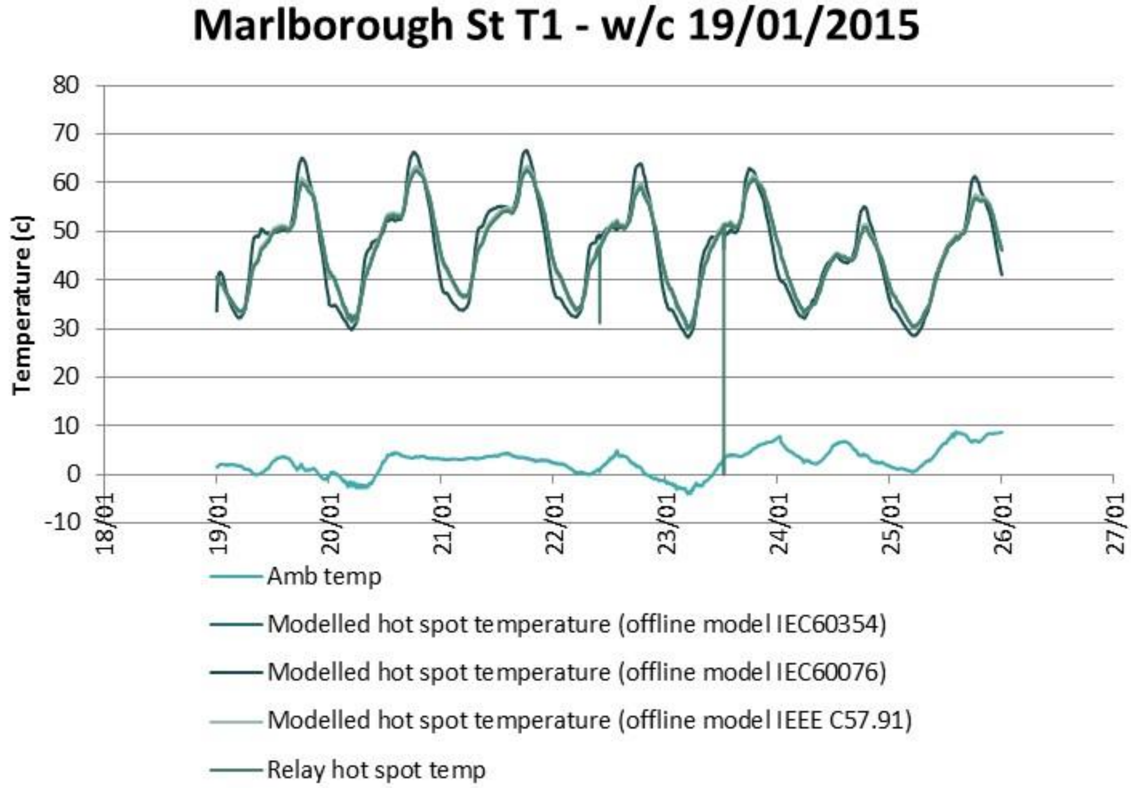

Figure 69 : Hot-spot temperature modelling results with different models compared to relay values (T1, w/c 19/01/2015).

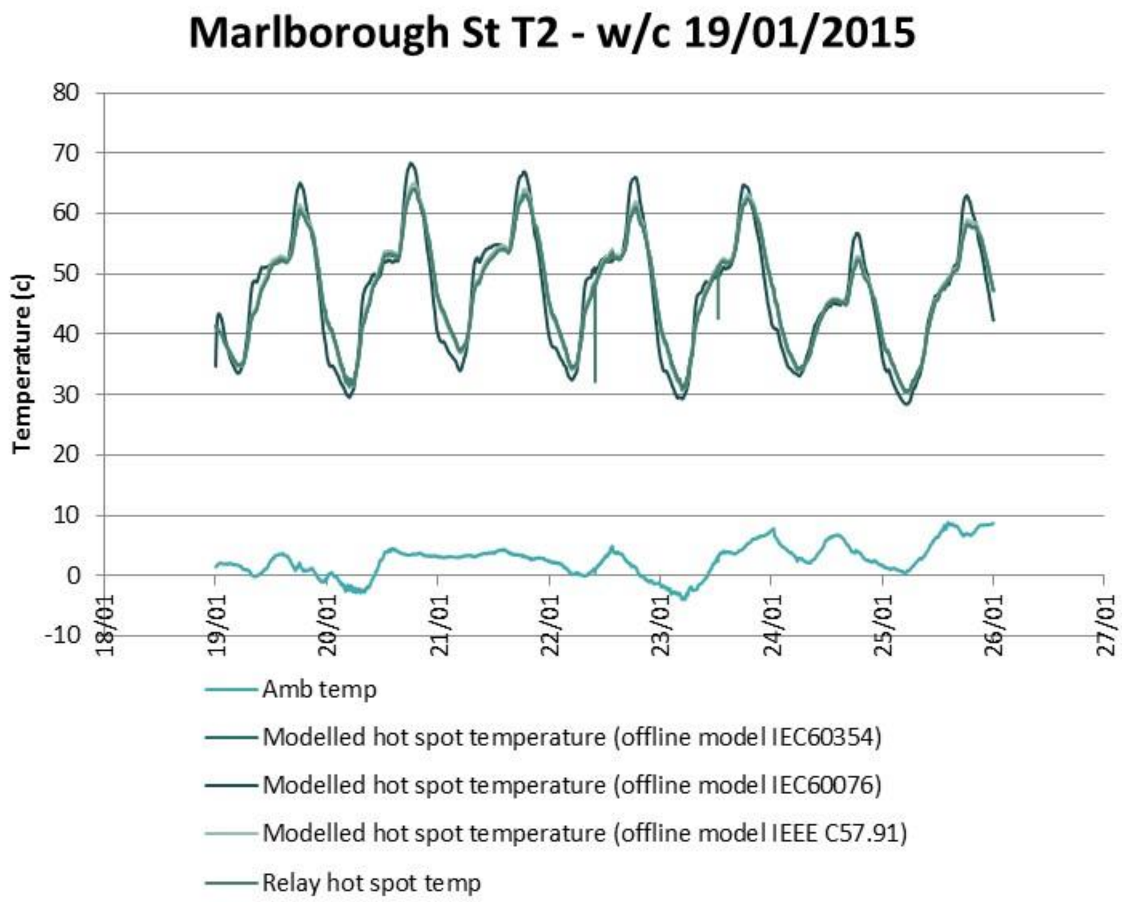

Figure 70 : Hot-spot temperature modelling results with different models compared to relay values (T2, w/c 19/01/2015).

G Notes on ONAN modelling anomalies

There are a small number of days over the course of the year where differences between model-calculated and measured oil temperature values vary unexpectedly by up to 7°C as part of an unexpected pattern. Where this occurs, these weeks were looked at more closely over a weekly period, e.g. w/c 19th January 2015, as shown in Figure 71.

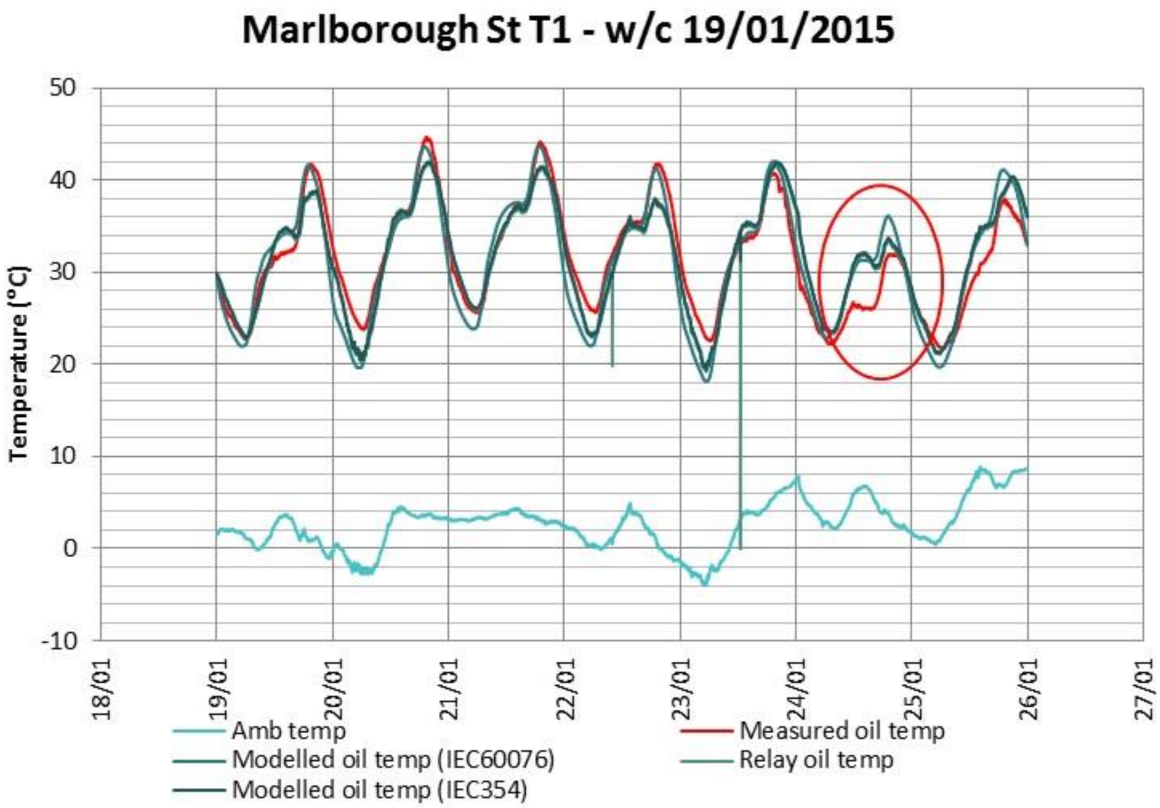

Figure 71 : Modelling results with different models compared to measured values (T1, w/c 19/01/2015).

The vast majority of calculated top oil temperatures are within 6°C of the measured top oil temperature over the course of a year. However, there are a small number of days where larger differences occur. Where this occurs, these weeks were further analysed against other ambient factors, including wind speed (measured at Newport Pagnell substation as part of the FALCON project) and precipitation rate (obtained from the MET office archive and library for the Milton Keynes area). This weather data was used to investigate the correlation between the differences in calculated top oil temperature to measured oil temperature, and weather factors. Figure 72 shows the difference between calculated top oil temperature and measured top oil temperature against wind speed, while Figure 73 shows this difference against historical precipitation.

Other ambient factors looked at include wind speed (historical and BBC forecast data), precipitation rate (historical data). Historical data for the Milton Keynes area was downloaded from http://www.wunderground.com and also provided via the MET Office. This weather data was used to find the correlation between the calculation difference and potential factors. Differences are calculated by subtracting measured values from modelled values, essentially the positive means the calculation is conservative (a top-oil temperature over-estimated); negative means top-oil temperature is underestimated.

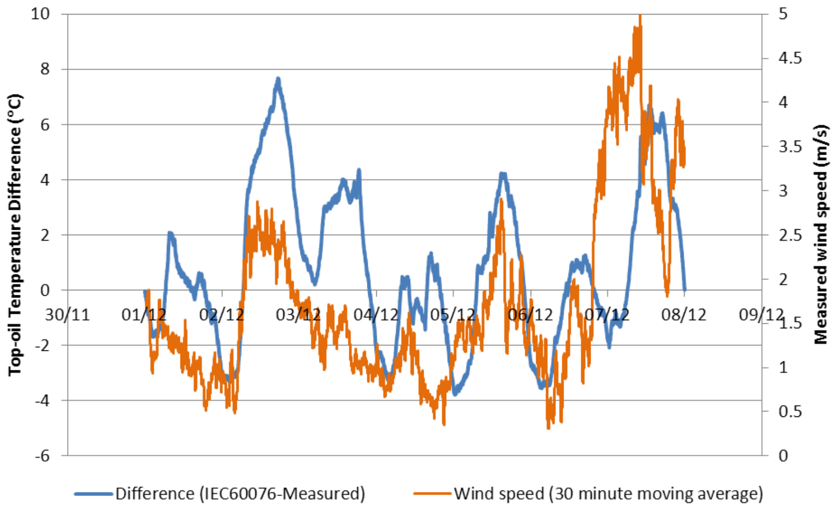

Figure 72: Comparisons between model-calculated and measured oil temperature values with wind speed (w/c 01/12/2014)

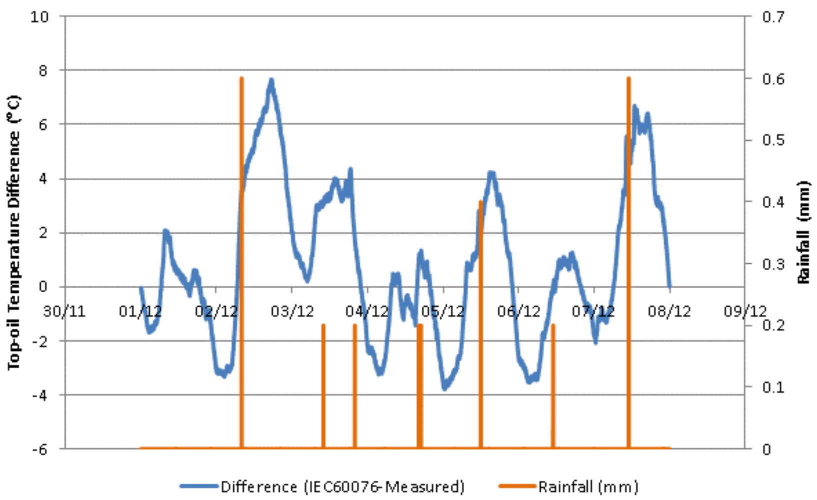

Figure 73: Comparisons between model-calculated and measured oil temperature values with precipitation (w/c 01/12/2014)

From Figure 72 and Figure 73 the wind speed and precipitation rate may be relevant to the temperature difference as there are differences in peaks around rain and wind speed periods. However, other periods studied did not indicate that such a good rainfall correlation existed. For the wind speed, the Pearson's correlation, r, was calculated up to 0.56, indicating the existence of a weak positive correlation between the temperature difference and wind speed. The coincidence of high wind speed and overestimation of calculated transformer top oil temperature suggests that wind speed has a bigger effect on transformer cooling than indicated by the standards. Other weeks also show this trend especially when the wind speed is >9 m/s. However, there is still unexplained discontinuity compared to forecast. Therefore it is suggested that wind speed data can be used to explain some differences between measured and modelled results. Further investigation would be needed to confirm this finding and to establish a mechanism for incorporating this factor into models.

LP 42.	Historically collected data is patchy making it difficult to analyse anomalies accurately against weather such as rainfall

LP 43.	There is some indication that wind speed and/or rainfall may be cooling the transformer in a way that is not picked up by the modelling. This phenomenon is not observable on the Distribution transformers over the same time period and could be a function of the larger size and more exposed nature of the Primary transformers.

H Weekly rating result graphs

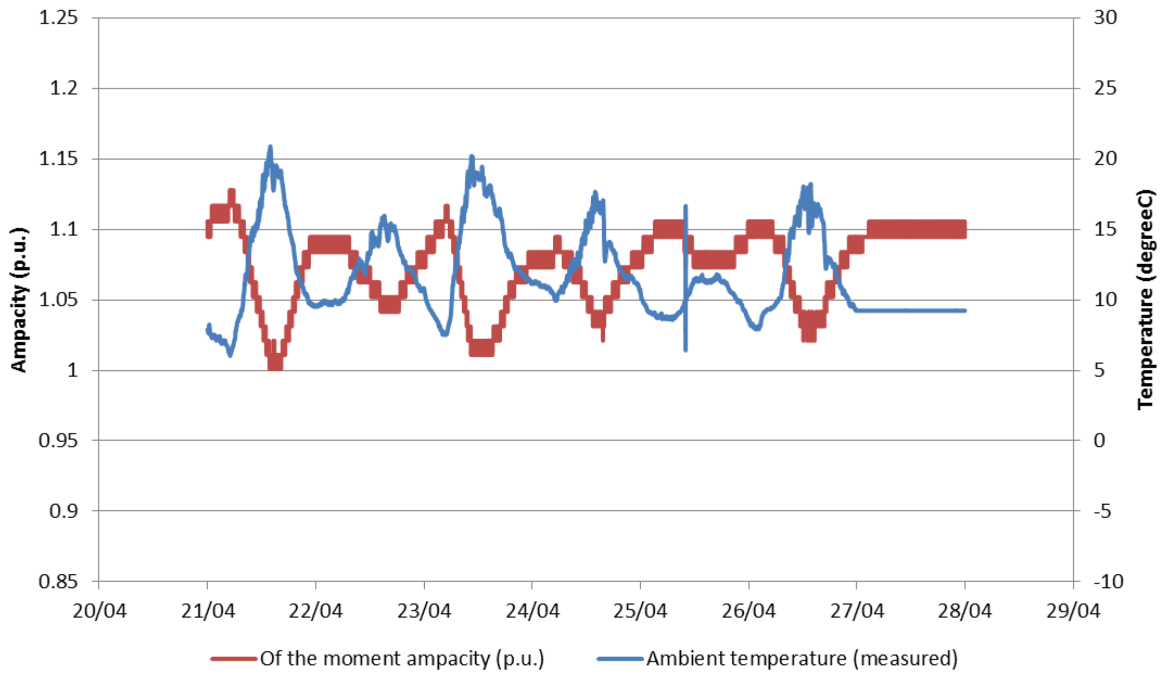

Figure 74: Of-the-moment ampacity (load factor) (ambient temperature w/c 21/04/2014) – Spring.

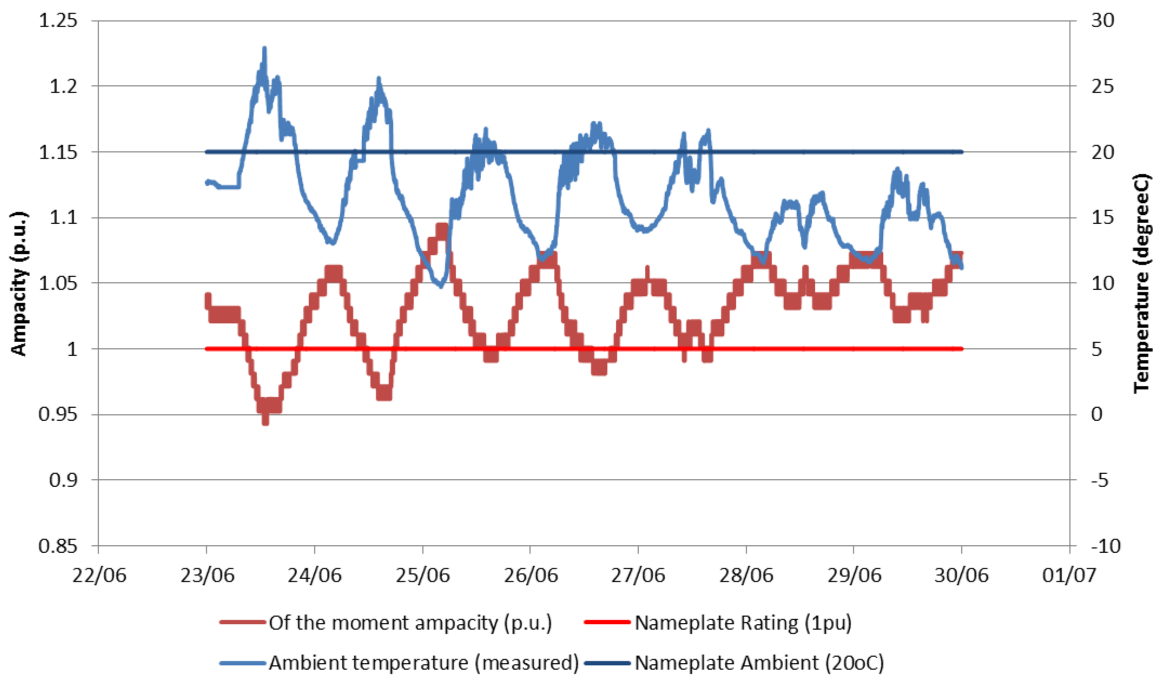

Figure 75: of-the-moment ampacity (load factor) (ambient temperature w/c 23/06/2014) – Summer.

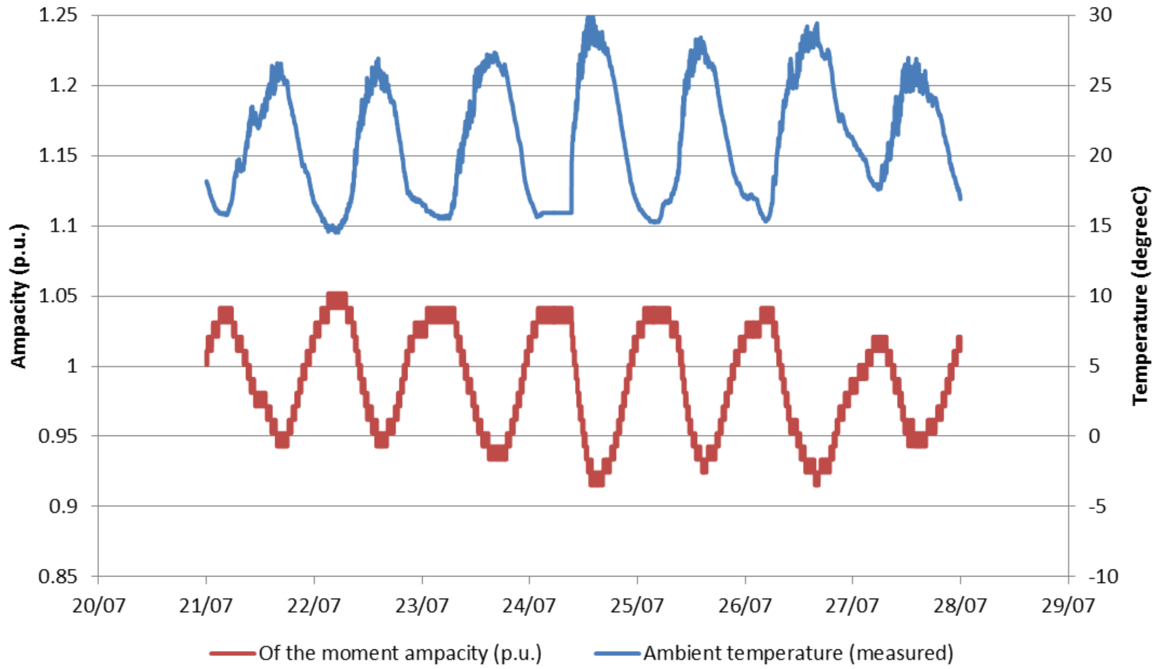

Figure 76: Of-the-moment ampacity (load factor) (ambient temperature w/c 21/07/2014) – High summer.

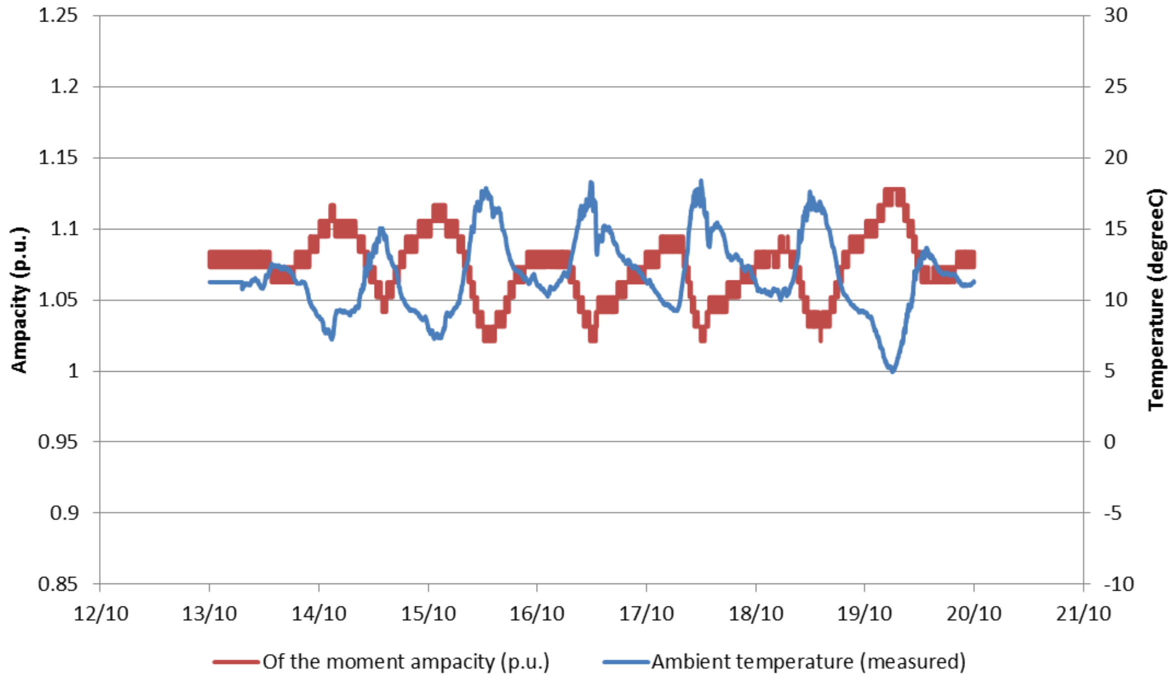

Figure 77: Of-the-moment ampacity (load factor) (ambient temperature w/c 13/10/2014) - Autumn.

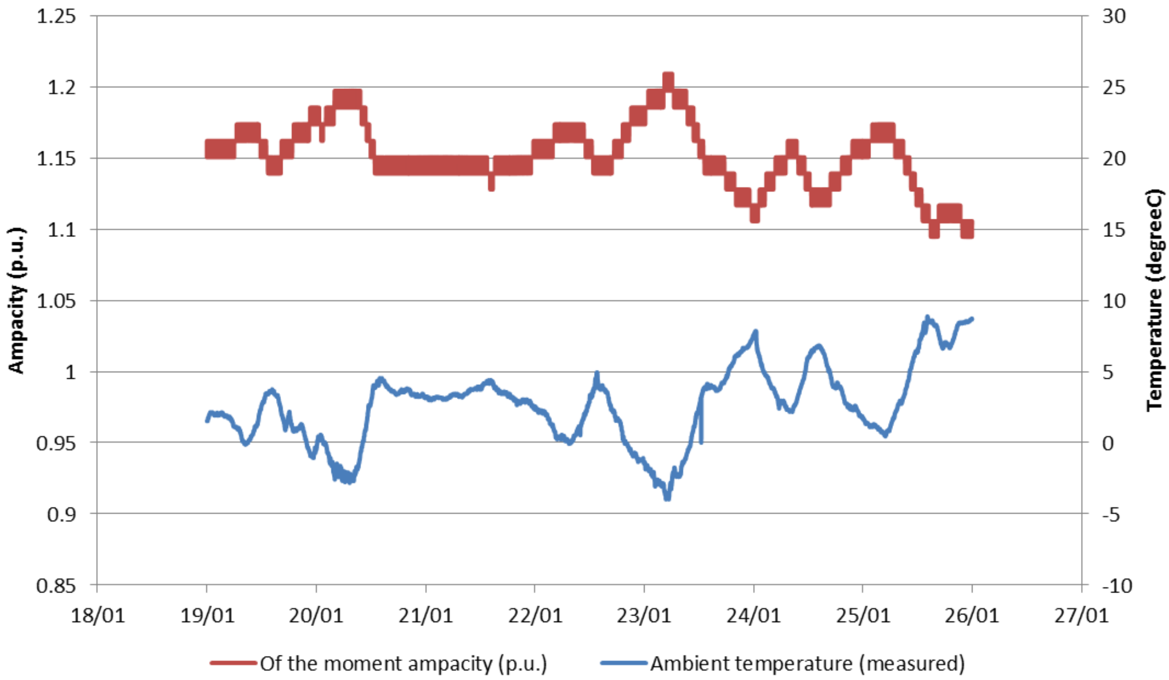

Figure 78: Of-the-moment ampacity (load factor) (ambient temperature w/c 19/01/2015) - Winter.

I Forward Ampacity data

Values used to generate Figure 24 (of-the-moment ampacity page 57), Figure 24 (raw day-ahead ampacity, page 57), and Figure 27 (raw week-ahead ampacity, page 59) are listed in Table 15.

	Min			Max			Average		
Ambient temp data	Measured	BBC day-ahead	BBC week-ahead	Measured	BBC day-ahead	BBC week-ahead	Measured	BBC day-ahead	BBC week-ahead
Apr	0.99	n/a	n/a	1.19	n/a	n/a	1.08	n/a	n/a
May	0.92	0.98	0.98	1.16	1.09	1.08	1.05	1.06	1.05
Jun	0.92	0.98	0.96	1.09	1.11	1.08	1.01	1.04	1.04
Jul	0.90	0.91	0.94	1.07	1.08	1.07	0.99	1.01	1.02
Aug	0.94	0.94	0.94	1.19	1.11	1.08	1.03	1.04	1.02
Sep	0.96	0.97	0.96	1.12	1.11	1.07	1.03	1.04	1.03
Oct	1.01	1.01	1.00	1.13	1.13	1.11	1.06	1.07	1.06
Nov	0.99	1.04	1.04	1.19	1.17	1.13	1.09	1.10	1.09
Dec	1.05	1.06	1.07	1.19	1.20	1.16	1.13	1.13	1.12
Jan	1.05	1.06	1.07	1.21	1.20	1.19	1.14	1.14	1.12
Feb	1.06	1.08	1.07	1.20	1.21	1.16	1.13	1.14	1.12
Mar	1.03	1.06	1.05	1.17	1.17	1.15	1.11	1.12	1.10
Apr	0.97	1.00	1.01	1.16	1.16	1.13	1.08	1.10	1.08
May	0.98	1.01	0.99	1.15	1.15	1.12	1.06	1.08	1.07

Table 15: Min, max and average monthly ampacity

J Notes on short term overload operation (above 24MVA rating)

Under a constant ambient temperature of 20°C condition, different combinations of initial load and overload factors are used to work out a period allowed for short term over loading to assess if there is any advantage to be gained from pre-emptive cooling.

This was done by increasing the load of 140°C and determining how long it took to reach a fixed temperature. Calculated operation under OFAF operation with and without pre-emptive cooling based on initial loading and overload condition is shown in Table 16 and Table 17 and graphically in Figure 79 and Figure 80 respectively.

The results show that when the overload is only just above 2pu there is an additional 15 minutes of benefit before the hot spot temperature is reached. However a larger overload erodes this value. These values are not large enough to offer a significant benefit gain and therefore pre-emptively cooling a transformer for the purposes of a high short term overload is not useful.

LP 44.	Pre-emptive cooling offers limited benefits for short term loading and is not recommended as a practice.

Overload Initial load	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
0.1	151	87	54	35	24	19	16	14	12	11
0.2	152	87	55	35	24	19	16	13	12	11
0.3	150	86	54	34	24	18	15	13	12	10
0.4	147	83	51	32	22	17	14	12	11	10
0.5	143	79	48	30	21	16	14	12	10	9
0.6	136	74	43	26	19	15	12	11	10	9
0.7	128	66	37	23	17	13	11	10	9	8
0.8	117	57	30	19	14	12	10	9	8	7
0.9	104	46	23	16	12	10	8	7	7	6
1	86	33	17	12	10	8	7	6	5	5

Table 16: Short-term overload allowable period (minutes, OFAF).

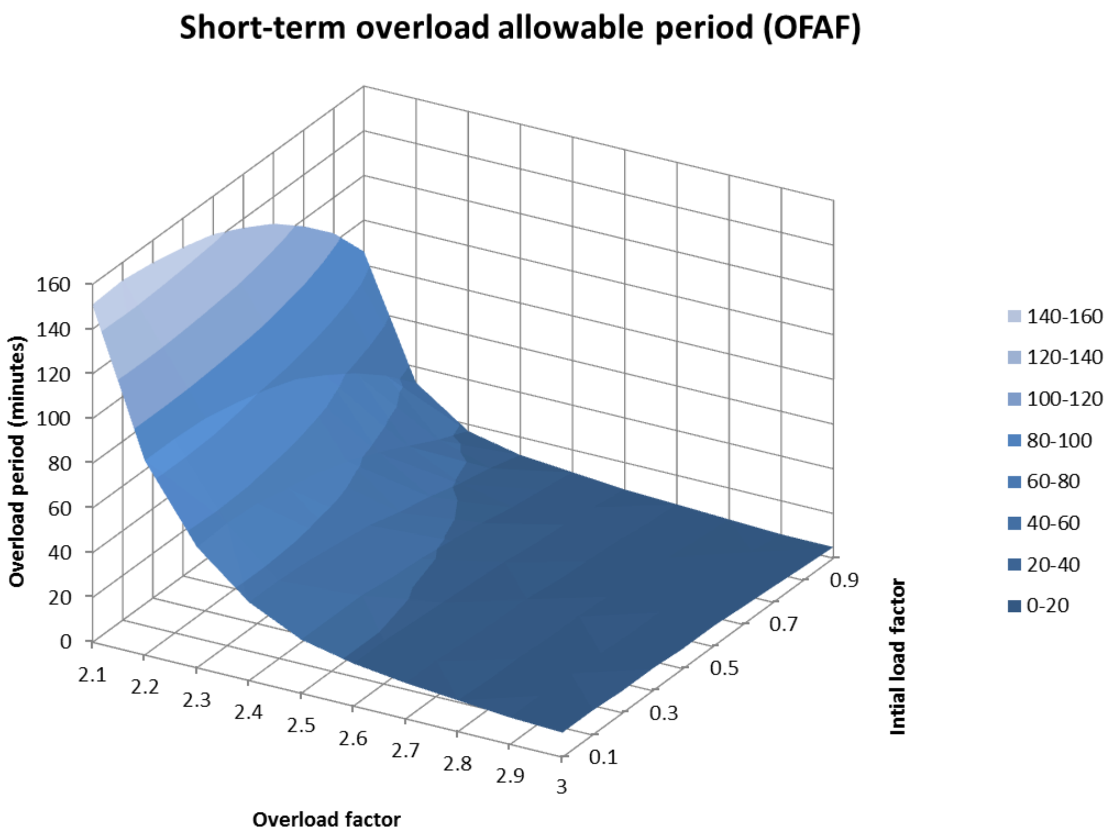

Figure 79: Short-term overload allowable period (OFAF).

Overload Initial load	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
0.1	164	98	64	43	30	22	18	15	13	12
0.2	164	98	65	43	30	22	18	15	13	12
0.3	164	98	64	43	30	22	18	15	13	12
0.4	163	97	64	43	29	22	17	15	13	11
0.5	162	96	63	42	28	21	17	14	13	11
0.6	160	95	61	40	28	21	17	14	12	11
0.7	157	92	59	39	26	20	16	14	12	11
0.8	154	90	57	37	25	19	15	13	11	10
0.9	150	86	54	34	23	18	14	12	11	10
1	146	82	50	31	21	16	13	11	10	9

Table 17: Short-term overload allowable period (minutes, pre-emptive OFAF).

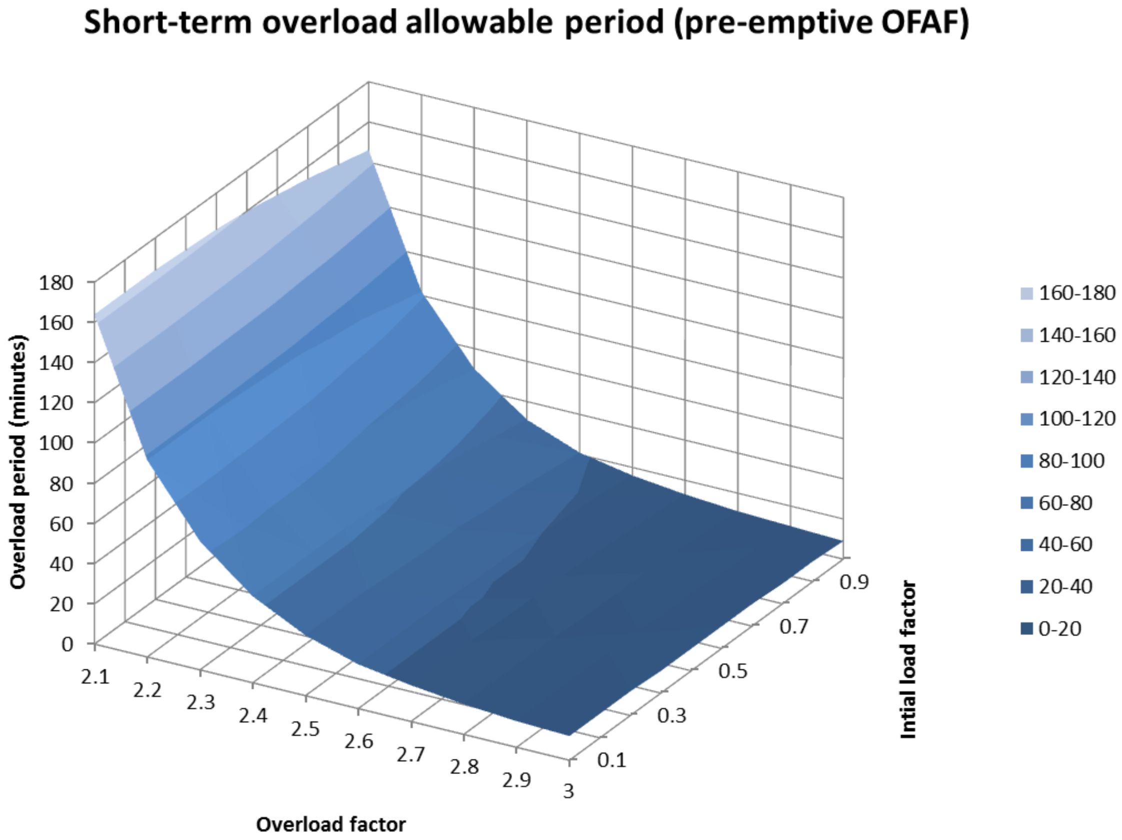

Figure 80: Short-term overload allowable period (pre-emptive OFAF).

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