Flexible Networks for a Low Carbon Future

Technical note on calibration of IEC60076-7 model performance based on primary transformer load test

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1 Summary and Learning Outcomes

This technical note proposes improved values for three parameters of the IEC 60076-7 transformer model based on load and temperature measurements taken at Liverpool Road primary substation in January and February 2014. The proposed values are:

- $\Delta\theta_{hr} = 19.5^{o}C$
- $\Delta\theta_{or} = 44.3 \pm 2.7^{o}C$
- $\tau_o = 388$ minutes

No changes to other parameters are proposed.

Comparison of the observed and modelled behaviour suggests that some aspect of transformer behaviour are not fully represented by the IEC model. These include small differences between the rates of heating and cooling during the daily load cycle (which are assumed in the model to be governed by a common time constant) and long-term cooling of the transformer following a period of abnormally high load. There are also indications of variations of oil flow in the transformer which lead to changes in the measured oil temperature. Nevertheless, it is concluded that, when suitably calibrated, the IEC model adequately represents the main aspects of transformer thermal behaviour of interest for the calculation of enhanced and dynamic thermal ratings. I

It is recommended that a margin of 8.5ºC should be allowed in the maximum permitted transformer temperature when using this model, to account for these uncertainties.

As in the previous calibration exercise, little data was available in relation to the thermal behaviour of the transformer windings and hotspot. Therefore, this note reiterates the recommendation that additional information about hotspot behaviour (such as manufacturers' test reports) should be sought.

This report forms part of work package 2.1, fulfils action 136, and contributes to Strathclyde deliverable DU2.1.2.

2 Motivation

An enhanced thermal rating calculation tool has been developed by TNEI with input from the University of Strathclyde and DNV GL. This tool uses the transformer thermal model specified by the IEC 60076-7 standard, together with historical measurements of transformer load patterns and assumptions about ambient temperature to calculate the peak load which can be supported by a transformer without exceeding limits on insulation temperature.

Although the TNEI tool has been initially parameterised using suggested values from the IEC standard, it is highly desirable that these should be verified and/or modified in order to conform as closely as possible to the behaviour of actual primary transformers in the SP Energy Networks asset base. It is particularly important that the model be verified at high load, since aging of the transformer insulation is highest under these conditions.

An initial exercise in model parameter validation [1] was undertaken based on data recorded in November 2014. No special interventions were made in support of that study: the maximum recorded transformer load was less than 75% of nameplate rating. It is therefore desirable that an experiment be undertaken to temporarily increase the loading on the transformer and to use the resulting measurements to adjust the model's parameters to better represent transformer thermal behaviour at high load.

3 Summary of Method

The objective of this work is to improve the accuracy of the model recommended by IEC60076-7 in estimating the thermal state of the transformer at Liverpool Road primary substation when operating close to and above its nameplate thermal rating.

3.1 Experimental Method

An electronic winding temperature monitor (Ashridge Engineering model 852Plus[2]) had previously been installed on the Liverpool Road primary transformer. This device functions in an analogous way to traditional mechanical WTIs, in that the measurement is derived from an oil temperature measurement and a current-based offset.

During the week beginning 26 January 2015, the load on the Liverpool Road primary transformer was increased by transferring additional load from adjacent primary substations. This was achieved by closing mid-feeder normally open points and then opening the corresponding circuit breakers at the remote primary substation. The following transfers were made:

- Whitchurch feeder 1 (Chester Road)
- Whitchurch feeder 4 (Barnfield Close)
- Yockings Gate feeder 1 (Station/Nantwich Road)
- Yockings Gate feeder 4 (St Ivel/Hill Valley)
- Yockings Gate feeder 5 (Shakespeare Way)

The load transfer was made at 0930 on Monday 26 January 2015, and was removed at 2100 on Thursday 29 January 2015.

Measurements of transformer current, real and reactive power flow and temperature were made at ten minute intervals at Liverpool Road (although the period covered does not correspond to the complete test – see Section 4 below). In addition, measurements of load on the transferred feeders, taken at the primary substation remote from Liverpool Road, were taken before and after the experiment.

It must be emphasised that no direct measurements of transformer winding temperature (such as a resistance-based measurement of average winding temperature) were made. No manufacturer’s data on winding temperature behaviour under load was available.

3.2 Transformer Thermal Model

The IEC-recommended thermal model is shown in Figure 1; suggested parameters from the non-normative Appendix E to the standard for an ONAN-cooled transformer in excess of 1MVA rating are given in Table 1:

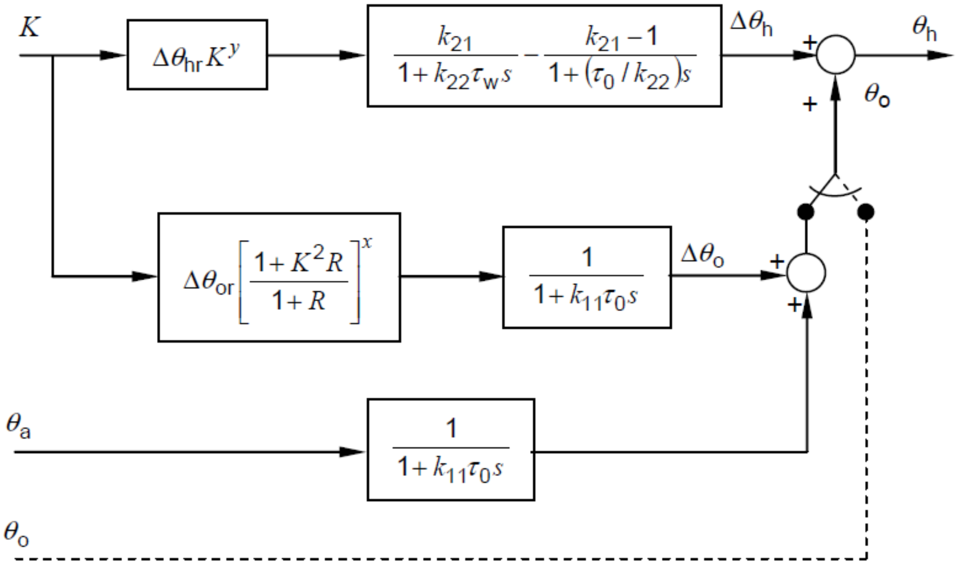

Figure 1: Transformer thermal model

Parameter	**Symbol**	**Value**
Oil exponent	x	0.8
Winding exponent	y	1.3
Loss ratio	R	6
Oil time constant (min)	τ_o	210
Winding time constant (min)	τ_w	10
Hot-spot temperature rise over top oil at rated load (ºC)	$\Delta\theta_{hr}$	26
Top oil temperature rise over ambient at rated load (ºC)	$\Delta\theta_{or}$	52
Time response shaping parameter	k_{11}	0.5
Time response shaping parameter	k_{12}	2.0
Time response shaping parameter	k_{13}	2.0

Table 1: Suggested model parameters applicable to Liverpool Road from IEC60076-7

In Figure 1, K is the transformer load as a per-unit value on rating, θ_a is the measured ambient temperature, θ_o is the top oil temperature (which, if measured, may be substituted for the two lower model branches), $\Delta\theta_o$ is the top oil temperature rise over ambient, $\Delta\theta_h$ is the hotspot temperature rise over top oil, and θ_h is the hotspot temperature.

A previous transformer model tuning exercise [1] undertaken using measurements taken at normal loading levels in November 2014 suggested the following revised parameter values:

- $\Delta\theta_{hr}$ = 15ºC
- $\Delta\theta_{or}$ = 43ºC

No other changes were recommended to the parameter values suggested by IEC60076-7.

However, it is now understood that the temperature sensor provides an estimate of the top winding temperature rather than the winding hotspot. IEC60076-7 recommends that, for power transformers larger than 1MW, a 'hotspot factor' of 1.3 should be applied to the difference between the oil and winding temperatures, as shown in equation (1).

$$\theta_h = H(\theta_w - \theta_o) \qquad (1)$$

where θ_h is the hotspot temperature, θ_w is the top winding temperature, θ_o is the top oil temperature, and H is the hotspot factor.

On this basis, a revised value of $\Delta\theta_{hr}$ of 19.5ºC will be used in the work described here, while the previously identified value of $\Delta\theta_{or}$ will be used as the starting point of the tuning exercise.

It should be noted that the temperature reported by the monitoring device at Liverpool Road is not a true measurement. Rather, it is obtained by adding an offset based on the blue-phase current to the measured top oil temperature. The offset is linear from 0ºC at no load to 15ºC at full load current. It is unclear as to whether the offset is capped at the full load value, or extends linearly beyond it. A sensitivity analysis of this uncertainty will be undertaken. However, because of the nature of this measurement, and the fact that the true hotspot temperature cannot be observed, no further optimisation of $\Delta\theta_{hr}$ will be undertaken.

3.3 Simulation and Fidelity Assessment Method

The transformer top oil temperature θ_o is selected as the parameter to be compared between the model and the physical transformer. For the physical transformer, this is derived from the recorded measurement by reversing the current compensation step described above.

At the start of the period over which model performance it to be assessed, it is necessary that the internal state of the model is in a stable condition, and that any initialisation effects have been eliminated. In the Excel-based model developed by TNEI, this is achieved by calculating the internal state of the model as if it had been constantly loaded at the initial load value. As in the November assessment exercise, such an approach is difficult here because of the nature of the Matlab/Simulink model used, and instead an approach of ‘preconditioning’ the model by starting it without explicit state initialisation, and running it using load and ambient temperature data from before the comparison period so that the internal state settles to the value dictated by the load and temperature.

As discussed in more detail below, measurement data was not available for Liverpool Road for the early part of the experimental period. As a result, model performance can only be assessed for the part of the period when temperature measurements are available. The initialisation of the model is also complicated by this deficiency, since the load transfer must (as discussed in more detail below) be represented by estimated data. Thus, it is possible that the state of the model at the point at which data becomes available during the experimental period does not match that of the physical transformer because of inaccuracies in the load estimation. To ensure that the model is properly initialised, it was decided that the early part of the available data from the experimental period should be used to complete initialisation of the model, and would therefore be excluded from the comparison.

Two comparison periods were therefore selected: one including the experimental period from 1630 on 28 January until the transformer has cooled to its ‘low load’ state at 0800 on the morning of 30 January, and a second extending further into the ‘low load’ period until 1200 on 1 February. Differences in model performance between these cases will indicate whether the behaviour of the transformer differs significantly between ‘high load’ and ‘low load’ operation.

3.4 Parameter Optimisation

Two parameters are selected for optimisation: $\Delta\theta_{or}$ is expected to be the most significant influence on the maximum oil and winding temperature produced by the model, while τ_o governs the rate at which the modelled temperature increases and decreases in response to changes in load and ambient temperature.

For both parameters, a process of repeated simulation with adjustment to the value of this parameter was adopted, as discussed in more detail below. In this process, the value of the sum of the squares of the differences ('errors') between measured and modelled oil temperature at each point in the simulation was to be minimised. This approach results in a model whose oil temperature profile is closest to the measured temperature profile.

It should be noted that the previous optimisation experiment, which focused only on $\Delta\theta_{or}$, found that there was little difference between optimisation of the error and the squared-error, and preferred the former on the grounds of minimising long-term offset of average oil temperature, and thus improving estimation of aging over the life of the transformer. In this case, however, it was found that this approach was not effective in optimising the oil time constant in particular – the optimisation process tended to produce very long time constants which had the effect of giving a very low average error over the optimisation period, but very poor estimates of temperature at particular instants. For this reason, minimisation of the squared error has been used as the optimisation objective in this case.

Following identification of the optimum values of $\Delta\theta_{or}$ and τ_o, a further simulation was run with these values. The measured and simulated top oil and winding temperatures are compared in a number of ways, including side-by-side comparison of the time series and of the estimate and measurement of maximum daily temperature.

4 Source Data

Real and reactive power data, blue-phase current data and transformer temperature measurements were obtained via iHost from the Liverpool Road Primary substation monitor for the period 1 January 2015 to 17 February 2015 inclusive. In addition, measurements of real and reactive power flow into the five feeders listed in Section 3.1 above from Whitchurch and Yockings Gate primary substations were obtained from iHost for the same period. Finally, measurements of ambient temperature were obtained from the weather station at Liverpool Road primary substation for the same period. This data was complete, without interruption.

In practice, little data was available from the Liverpool Road substation monitor before approximately 1200 on 22 January, and no data was recorded between 1700 on 1 February and 1630 on 2 February. In order to focus on the period of the test, it was decided to restrict the data analysed to the period from 00:00 on 24 January 2015 to 12:00 on 1 February 2015.

Within the selected period, there were two intervals during which no measurement data was available from the substation monitor at Liverpool Road:

- Monday 26 January 2015 09:10 – Tuesday 27 January 2015 08:30 inclusive
- Thursday 29 January 2015 14:30 – Thursday 29 January 2015 14:40 inclusive

It will be noted that the first of these periods begins just before the switching to increase the transformer load, and includes almost all of the first 24 hours of the experiment. No transformer temperature measurement or blue phase current is available during these periods, and they have therefore been excluded from the analysis. However, in order that the measured and simulated transformer temperature can be compared over the remainder of the period, it is necessary to synthesise a representative transformer load for these periods. This will ensure that, at the end of the gap in the data, the model is in a state similar to that in which it would have been had measurements been continuously available. The time taken to settle to a fully representative state is thus reduced, and the ability to use the available measurements for comparison is maximised.

4.1 Synthesis of Representative Load Data

In the previous study, gaps in the transformer load data had been filled using average load profiles for the relevant day of the week calculated from transformer load measurements taken over a number of weeks surrounding the study period. This approach was considered partly impractical here for a number of reasons:

- The substation monitor at Liverpool Road had exhibited significant reliability problems in the weeks preceding the experiment. This meant that any average profile would be very inconsistent in the periods represented.
- Synthesised load measurements during the load transfer period would need to be constructed from estimates of load on the individual transferred feeders derived from measurements at Yockings Gate and Whitchurch substations.
- A long-term problem with the substation monitor at Whitchurch meant that no load measurements for feeder 4 were available until the normal configuration was restored at the end of the experiment.
- The HV customer connection at Cold Store was transferred from Yockings Gate feeder 5 to Liverpool Road during the study period.

In the light of these considerations, an alternative approach was devised, making use of measurements from throughout the period over which they were obtained. For each non-Liverpool Road feeder other than Whitchurch feeder 4 and Yockings Gate feeder 5, a daily average load profile for Mondays, Tuesdays and Thursdays was calculated from measurements taken during the weeks beginning 12 January to 2 February inclusive, but excluding the week of the experiment, and any zero measurements. As an example, the recorded loads for Whitchurch feeder 1 are shown in Figure 2. The period of the experiment (during which no load was recorded at Whitchurch for this feeder) is bounded by the vertical turquoise lines. The trace for the week beginning 9 February is somewhat lower than the weeks more closely surrounding the experiment and was therefore excluded.

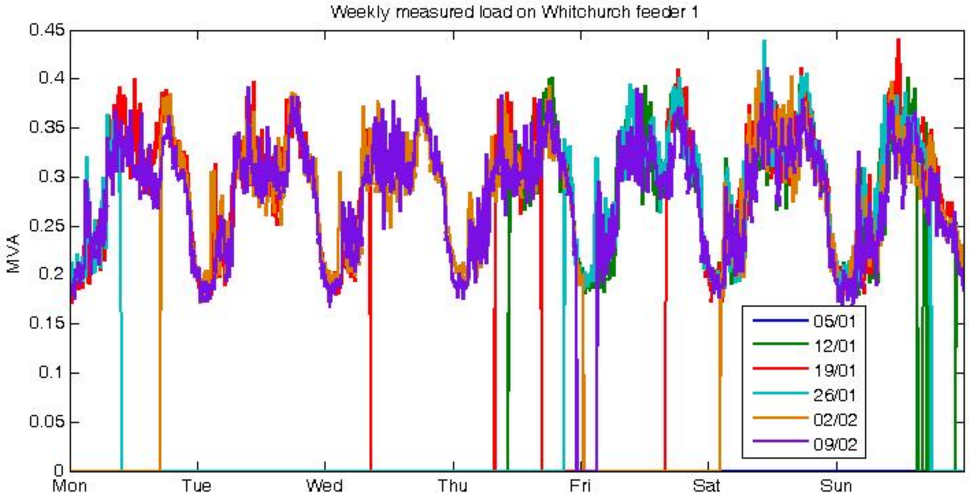

Figure 2: Weekly measured load on Whitchurch feeder 1

For Whitchurch feeder 4, a similar process was undertaken using the weeks beginning 2 February and 9 February. The relevant portions of these profiles were extracted and used to represent the transferred loads during the experiment.

Weekly load traces for Yockings Gate feeder 5 are shown in Figure 3. The Cold Store load supplied during the week beginning 19 January and on 26 January until the start of the experiment is clearly visible. The experiment ends during the overnight minimum on Thursday evening, and it is apparent that the Cold Store load remains supplied from Liverpool Road and does not return to this feeder.

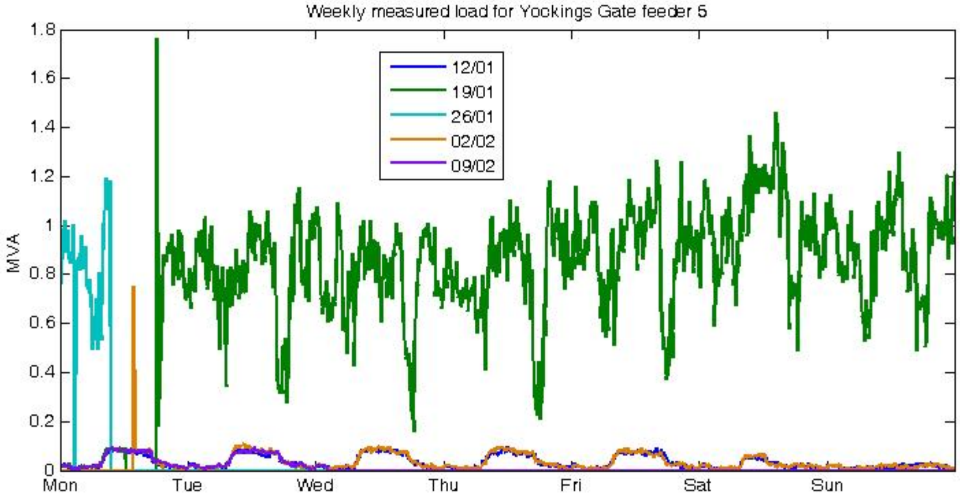

Figure 3: Weekly measured load on Yockings Gate feeder 5

It is clear that no representative load measurement is available for a Monday on which Cold Store is supplied from this feeder between mid-morning and evening, and that Cold Store must usually be supplied from Liverpool Road.

Weekly load traces for the Liverpool Road primary transformer are shown in Figure 4. The period of the experiment in the week beginning 26 January is clear, as is the gap in measurements from Monday morning to Tuesday morning. A load transfer on the previous Monday can also be seen. The effect of Cold Store being supplied from Yockings Gate in the latter part of the week beginning 19 January and on the Monday of the experiment can be seen in the reduction in load in comparison to other weeks.

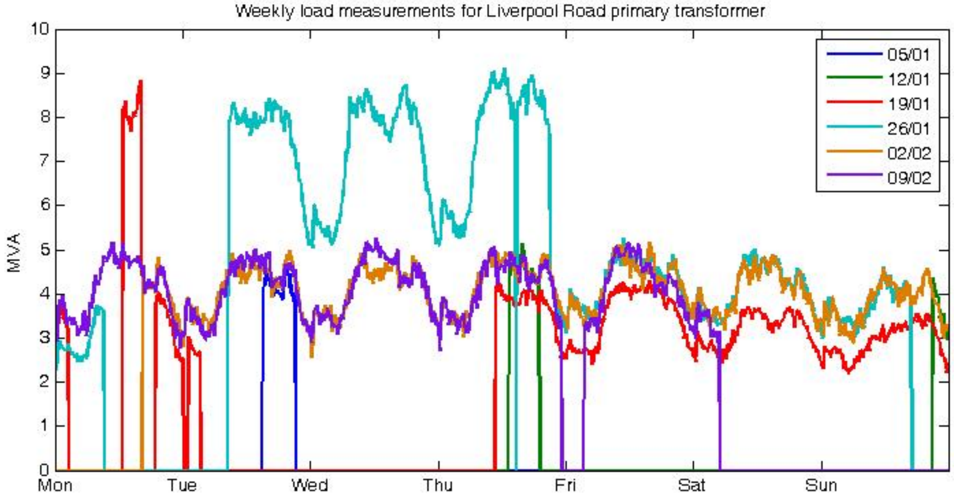

Figure 4: Weekly load measurements on Liverpool Road primary transformer

Based on these observations, the load on Yockings Gate feeder 5 and the load normally supplied from Liverpool Road were modelled as follows: Yockings Gate feeder 5 load was represented using data from the week beginning 12 January, when Cold Store was supplied from Liverpool Road. Core Liverpool Road load was represented using measurements taken in the week beginning 9 February, since this data is complete for the days and times of interest, and includes Cold Store load. However, since Cold Store was *not* supplied from Liverpool Road for the period between loss of measurements on 26 January and the start of the experiment, the difference in Yockings Gate feeder 5 load between 26 January (when Cold Store was fed from Yockings Gate) and 9 February (when it was not) was subtracted for that period. It need not be added to the Yockings Gate load, since Cold Store is not fed via Liverpool Road during that time, and should therefore not be included in the synthesised load.

The synthesised load profile for the Liverpool Road primary transformer is therefore constructed as follows:

- From 0915 on 26 January until the start of the experiment: representative core Liverpool Road load
- From the start of the experiment until 0830 on 27 January: representative core Liverpool Road load *plus* representative transferred feeder load.
- From 1430 until 1440 on 29 January: representative core Liverpool Road load *plus* representative transferred feeder load.

The synthesised load profile is shown in Figure 5.

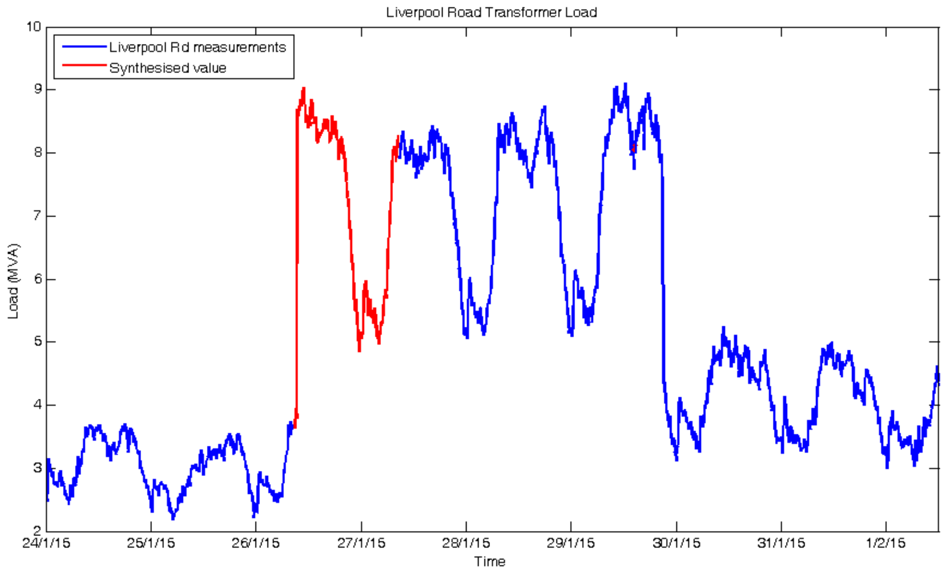

Figure 5: Synthesised and measured Liverpool Road load

The peak measured load during the test is 9.11MVA, which is 121% of nameplate rating. The minimum overnight load measured during the test was 5.06MVA, 67% of nameplate rating. The minimum load on the transformer during the test is similar to the daily peak load during the previous exercise in November 2014.

4.2 Measured Transformer Temperature

Measurements of Liverpool Road transformer temperature are available for the same periods of time as load measurements at that substation, as shown on page 6. As previously noted, the recorded measurement is derived by adding an offset based on the measured blue-phase current to the measured oil temperature. For comparison purposes, this offset was reversed by application of equation (2):

$$\theta_o = \theta_w - 15\frac{I_C}{I_{FL}} \qquad (2)$$

where θ_o and θ_w are respectively the top oil and measured winding temperatures, I_C is the measured C-phase current and I_{FL} is the phase current at rated load.

Figure 6 shows the recorded temperature value and calculated oil temperature for the period of interest.

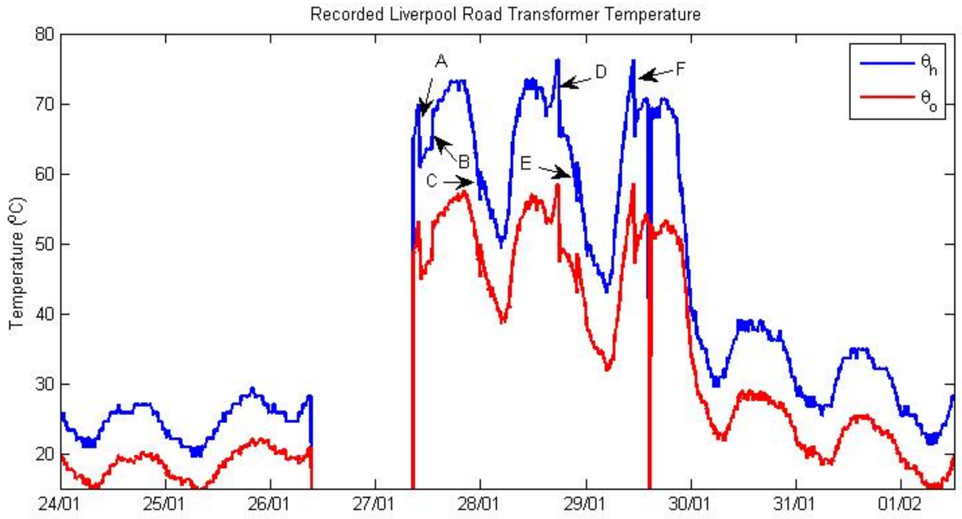

Figure 6: Recorded transformer temperature at Liverpool Road

Five features are identified in Figure 6 using the letters A–E. Each of these is a large difference between adjacent temperature measurements (i.e. over a period of 10 minutes). They are described in more detail in Table 2:

Feature	Time	Direction of change	Magnitude (ºC)
A	27/1/2015 10:00	Fall	8.6
B	27/1/2015 13:00	Rise	4.0
C	28/1/2015 00:00	Rise	4.2
D	28/1/2015 17:50	Fall	10.8
E	28/1/2015 22:00	Rise	5.5
F	29/1/2015 11:00	Fall	11.0

Table 2: Anomalous features in recorded transformer temperature

It is unlikely that these features represent actual changes in the thermal state of the transformer. The relatively long time constant of the transformer oil means that a very unusual pattern of loading would be required in order to achieve a sudden heating of the oil (whose temperature is measured) or to suddenly add a large offset through the current-based adjustment carried out by the measurement device. Such a change would be likely to have a large effect on the thermal behaviour of the transformer over the following hours. Similarly, the even larger downward steps could not, in an ONAN transformer, be achieved by sudden removal of heat from the oil and windings. Achieving such a reduction through the measurement device's offset mechanism would require a reduction of over 70% in the blue-phase current: such a drop in current would be very obvious, and is not observed.

It is therefore likely that these steps are either an artefact of the measurement process, resulting from interference or error in the measurement, or a change in the internal behaviour of the transformer so that the temperature to which the sensor is exposed suddenly changes. For example, it is possible that the flow pattern of the oil changes so that, at times the sensor pocket is in a flow of hot oil emanating directly from the windings, while at others this flow is directed elsewhere and the sensor is in cooler mixed oil. This would result in two measurement regimes, one in which the measurement is ‘high’ in relation to the true thermal state of the transformer and one in which it is ‘low’.

It is notable that the upward steps in measured temperature generally take place while the transformer is cooling towards its overnight minimum temperature, although B takes place during the day while the transformer load and temperature is high. The downward steps appear to occur when the transformer temperature is high and close to a peak, either at the end of the rise to morning peak temperature (A and F) or close to the evening peak (D). On this basis, it might be expected that a further upward step would take place on the evening of 29 January or early on the morning of 30 January. Although such a feature is not immediately apparent from Figure 6, close examination of the recorded transformer temperature shows a rise of 1.5ºC at 21:30, which may play an analogous role to features C and E. Although there is therefore some evidence that the thermal state of the transformer influences these features, there is too little data to accept or reject any hypothesis in explanation. The presence of the two rising steps B and C in succession is evidence against the idea of there being two distinct operating states of the transformer driven by temperature.

The complete set of transformer temperature measurements taken since the installation of the sensor at Liverpool Road has been reviewed, and no similar features occur in measurements taken outside the period of this experiment. This indicates that they only occur when the transformer is operating at abnormally high load.

Since the Liverpool Road primary transformer is ONAN-cooled, the observed features cannot be the result of changes in the activity of forced cooling systems. However, in ONAF- and OFAF-cooled transformers, the effect of such changes might be observed in the measured temperature. In particular, starting and stopping of oil pumps might be expected to result in changes to the internal flow pattern; changes in the temperature of the oil to which the sensor pocket is exposed are therefore possible. Analysis of future measurements from force-cooled transformers should be carried out with this possibility in mind.

For the analysis described here, the effect of excluding the suspect features and the data immediately surrounding them from the parameter optimisation will be tested. No attempt will be made to derive parameters based on hypotheses of the underlying transformer behaviour.

4.3 Ambient Temperature

Ambient temperature measurements made at Liverpool Road weather station are shown in Figure 7. The temperature measurement set completely covered the period of interest. No further processing of this data was carried out.

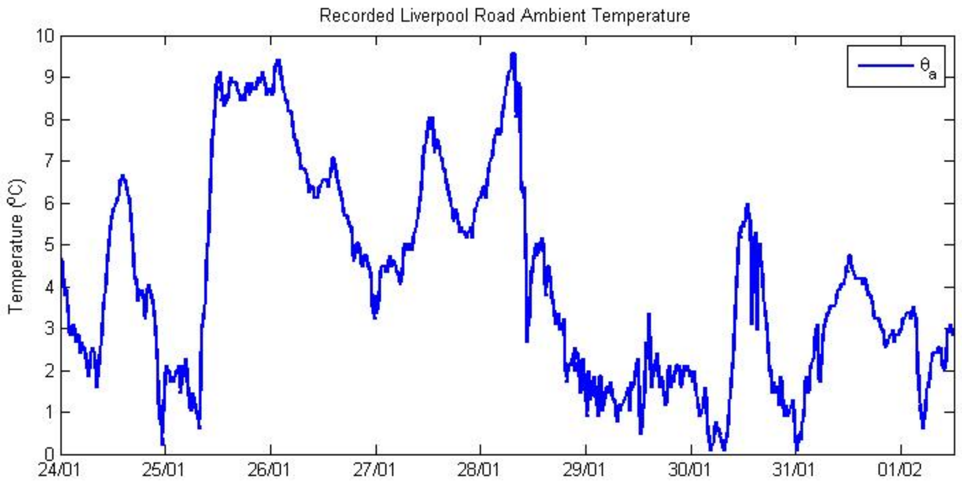

Figure 7: Measured ambient temperature at Liverpool Road

5 Optimisation of Parameters

5.1 Transformer Thermal Model

The optimisation process used the Matlab/Simulink implementation of the IEC thermal model developed for the initial assessment of the model, and discussed in the previous technical note. The model is shown in Figure 8, and was parameterised using the values in Table 1, with the exception that the proposed values of 19.5ºC and 43°C previously noted were used for $\Delta\theta_{hr}$ and $\Delta\theta_{or}$ respectively.

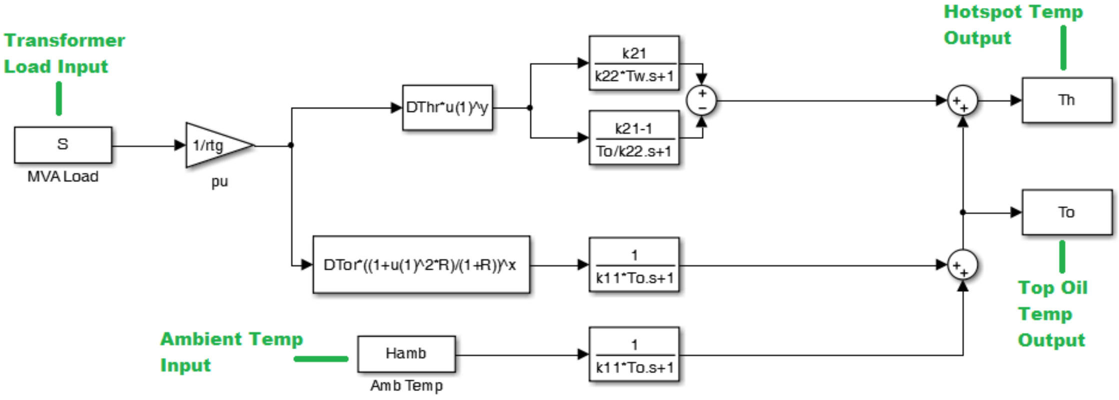

Figure 8: Transformer thermal model

The model was initialised by simulating the transformer behaviour for the period from 00:00 on 24 January 2015 to 16:30 on 27 January 2015 using the load profile and temperature measurements from the sources listed in section 4 above. This process includes synthesised load data during and following the network reconfiguration. It is therefore expected that the transformer model will, at the point where measurement data in the highly-loaded state becomes available, be in approximately the thermal state that it would have been had measurement data been available throughout. However, to reduce the effect of any error, a further eight hours of measured data are applied.

Model outputs from this initialisation period were discarded; they were not used in the optimisation of $\Delta\theta_{or}$ and do not appear in the subsequent comparisons.

5.2 Optimisation Process

An initial estimate of the aggregate temperature error over the study period was calculated by running a simulation with $\Delta\theta_{or}$ set to 43°C and τ_o set to 210 minutes. For each point for which an oil temperature measurement was available, the difference $\delta\theta$ between the simulated value and the measured value was calculated, the sums of these differences and their squares were obtained. The measured and modelled temperature profiles for this initial test are shown in Figure 9.

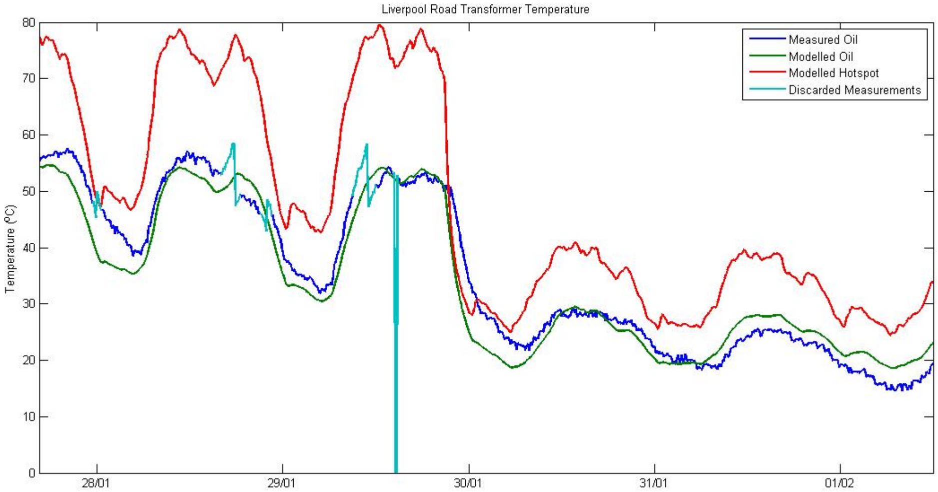

Figure 9: Measured and simulated hotspot temperature using parameters from previous tuning exercise

Figure 9 also shows the regions around the suspect data points discussed in section 4.2 above, whose exclusion is to be investigated.

Figure 9 suggests that, in comparison to the measured behaviour, the model of the transformer achieves broadly the correct temperature, but heats and cools too rapidly, particularly during the return to normal operating temperature at the end of the experiment. It is thus expected that optimisation will not result in a significant change to the value of $\Delta\theta_{or}$, but that the value of τ_o will increase.

To optimise the model parameters, the simulated value of $\Delta\theta_{or}$ was repeatedly adjusted by 0.1ºC in the direction which reduced the sum of $\delta\theta^2$ until minimum magnitudes of the summation was observed. This process was repeated for τ_o in steps of 1 minute using the new value of $\Delta\theta_{or}$. The same process was then used to optimise $\Delta\theta_{or}$ and τ_o in turn until neither changed. In general, it was found that only small adjustments took place after the initial iteration.

For the simulation period and measurement exclusions outlined above, it was found that the smallest sum of $\delta\theta^2$ was observed at **$\Delta\theta_{or}$ = 44.3ºC and τ_o = 388 minutes**.

The value of $\Delta\theta_{or}$ is somewhat larger than that found during the previous exercise at lower load. This may indicate that the cooling efficiency of the transformer is lower when operating about its nameplate rating. Although it might be expected that the heat transfer processes from winding to oil and oil to ambient air would improve with increasing temperature gradient across these boundaries, this may be offset by other factors, such as sub-optimal oil flow when operating above the transformer's design rating. As previously noted, there appears to be some evidence of changes in oil flow which are not observed at lower load. As discussed in section 8.2.3 below, it is also possible that heat transfer to and from the core is attenuating the oil and winding temperature profiles in the low load case.

6 Simulation Results

The period from 1630 on 27/1/2015 to 12:00 on 1/2/2015 was simulated using the revised values of the parameters $\Delta\theta_{or}$ and τ_o. Results are shown in Figure 10 below.

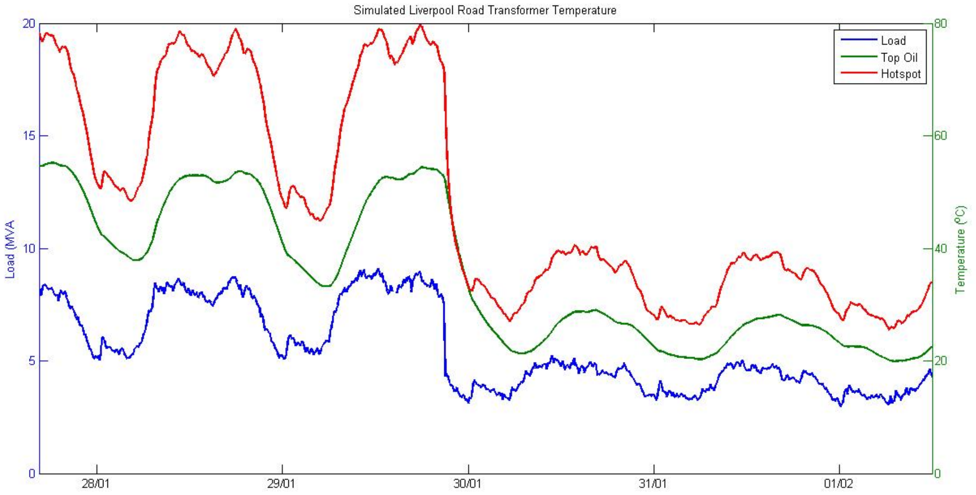

Figure 10: Simulated transformer temperatures

The maximum simulated oil temperature was 54.4ºC shortly after 1800 on 29 January. The maximum simulated hotspot temperature was 79.8ºC, a few minutes before 1800 on the same date.

6.1 Comparison with Measured Temperature Data

The measured and simulated transformer hotspot and top oil temperatures for the study period are shown in Figure 11 and Figure 12. The 'measured' hotspot temperature is reconstructed from the measured load and winding temperature using equations (1) and (2):

$$\theta_h = \theta_w + 15(H-1)\frac{I_C}{I_{FL}} \qquad (3)$$

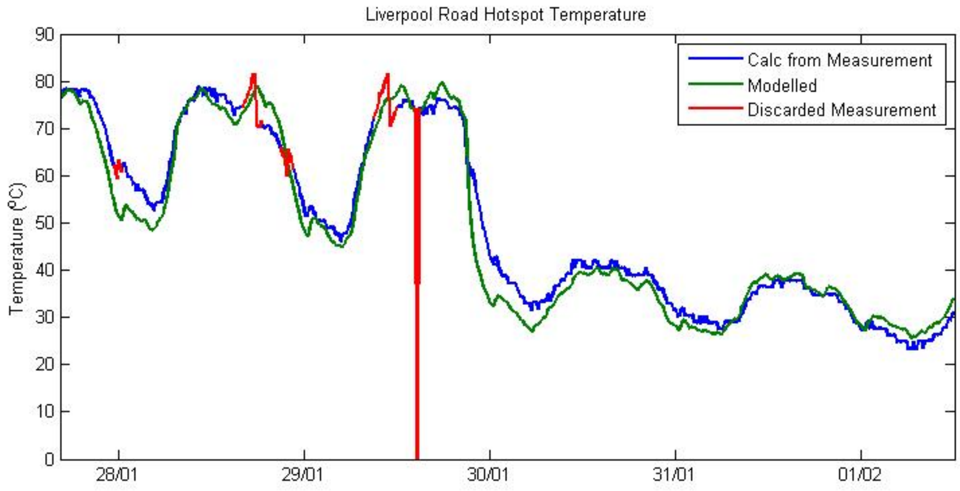

Figure 11: Measured and modelled hotspot temperature at Liverpool Road

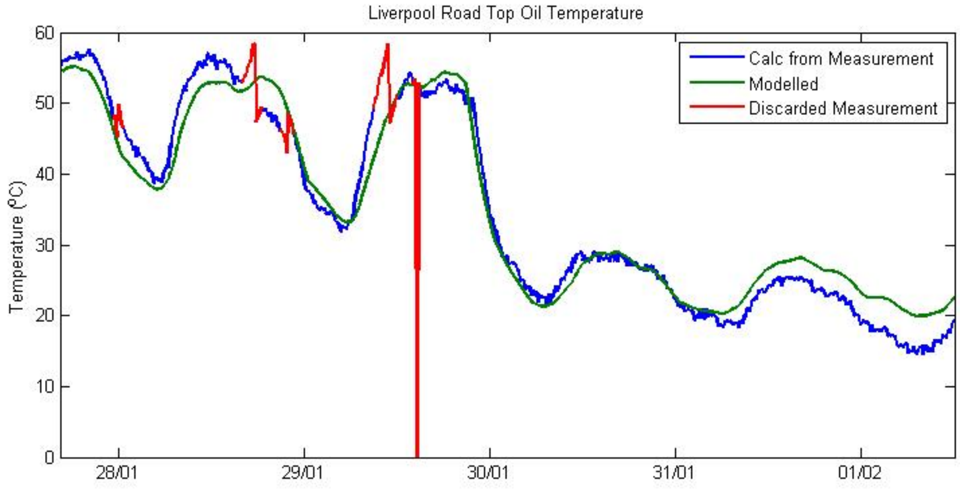

Figure 12: Measured and modelled top oil temperature at Liverpool Road

The simulated hotspot temperature is reasonably similar to that calculated from measurements. The simulated daily peak values during the experiment are slightly higher than those measured, particularly on the evening of 29 January. The model generally appears to heat up at a similar rate to the actual transformer, but cools more rapidly, particularly during the overnight cooling period following the end of the experiment. The maximum overestimate of hotspot temperature is 6.3ºC, which occurs immediately after the first sudden drop in measured temperature. The maximum underestimate of hotspot temperature is 14.8ºC, which occurs during the overnight cooling period following the end of the experiment. For comparison, the equivalent results using the values from the previous tuning exercise are 5.0ºC and 19.3ºC respectively.

The simulated oil temperature is generally similar to the value calculated from measurements, but with significant divergences on 28 January and from 31 January until the end of the study period. On 28 January, the model is too cool in the early part of the day (in which the 'high' measurement regime applies) and too warm in the later part of the day, in which the ‘low’ regime applies). From 31 January onwards, the model fails to replicate a slow continued cooling of the oil, during which the oil-to-hotspot temperature difference remains largely constant. During and immediately after the experiment, the model appears to correspond well to the cooling phase of transformer operation, but heats up more slowly than the physical transformer.

The largest overestimate of top oil temperature is 5.8ºC, which occurs during the evening of the first sudden drop in measured temperature. The largest underestimate is 6.9ºC, which occurs during the rise from the overnight minimum temperature on the morning of 29 January. The equivalent results using the values from the previous tuning exercise are 4.8ºC and 11.5ºC respectively.

In general, the greatest differences between observed and modelled behaviour occur either when the measured temperature shows a sudden change (which may indicate a change in the behaviour of the transformer) or when the transformer thermal state is changing rapidly in the morning or evening. In this latter case, it is expected that small discrepancies in the modelled rate of heating or cooling will lead to significant errors in modelled temperature, which will reduce as the transformer’s thermal state stabilises. The behaviour after the end of the test suggests that, following the initial cooling at the end of the experiment, there is a further slow cooling phase, perhaps involving the release of heat from the transformer core, which is not represented by the model. It is unfortunate that the lack of measurement data from the first day of the experiment prevents the investigation of any similar behaviour when the transformer becomes heavily loaded – such behaviour might provide additional headroom for short-term emergency loading.

6.2 Assessment of Daily Peak Temperature

The principal restriction on the ability of a transformer to support a particular set of loads is the peak hotspot temperature attained during the daily load cycle. It is therefore useful to assess the accuracy of the model’s representation of the maximum hotspot temperature on each day of the study period. These, together with the values derived from measurements using equation (3), are shown in Table 3. Values calculated using the parameters found during the previous tuning exercise are also shown. As previously, the measurements around the sudden changes in recorded transformer temperature have been excluded from these results.

Date	Max θh (measured) (ºC)	From previous exercise		New values	
		Max θ_h (modelled) (ºC)	Overestimate/ (underestimate) (ºC)	Max θ_h (modelled) (ºC)	Overestimate/ (underestimate) (ºC)
27/1/2015[1]	78.3	77.5	(0.8)	78.2	(0.1)
28/1/2015	78.7	78.7	0.0	78.5	(0.2)
29/1/2015	76.1	79.6	3.5	79.8	3.7
30/1/2015	42.9	40.9	(2.0)	40.5	(2.4)
31/1/2015	38.0	39.5	1.5	39.3	1.3
1/2/2015[2]	31.0	33.8	2.8	33.9	2.9

Table 3: Comparison of modelled and measured peak hotspot temperature

From Table 3, it is clear that the larger differences between modelled and measured values tend to be overestimates: the two underestimates at high load are very small. The sole large underestimate of daily peak hotspot temperature occurs on the day following the experiment. On this day the measured and modelled peak hotspot temperature occurred shortly after midnight, during the transformer's cooling period at the end of the experiment. In comparison to values from the previous tuning exercise, the (small) underestimates of hotspot temperature are reduced, while overestimates increase by a very small amount.

7 Sensitivity Analysis

Earlier sections identified a number of uncertainties and observed phenomena whose effect on the optimised parameters of the transformer model should be investigated. The following sensitivities were studied by repeating the optimisation process using a subset of, or modification to, the measured transformer temperature:

- Saturation of transformer load compensation in the measurement device: the 'measured' transformer top oil temperature was recalculated from the winding recorded temperature on the assumption that the load correction was limited to 15ºC at and above nameplate rating. This has the effect of increasing the oil temperature value at high load.
- The effect of different transformer behaviour at high load was investigated by ending the comparison period at 08:00 on 30/1/2015 – i.e. immediately after the overnight cooling period at the end of the experiment.

7.1 Load Compensation Saturation

In order to investigate the possibility that the load-dependent offset from oil to winding temperature applied by the temperature measurement device saturates at full-load current (i.e. that the maximum offset is 15ºC at full load current), an alternative oil temperature time series was calculated as follows:

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[1] From 16:30 onward

[2] Until 12:00

$$\theta'_o = \begin{cases} \theta_w - 15\dfrac{I_C}{I_{FL}} & : \quad I_C \le I_{FL} \\ \theta_w - 15 & : \quad I_C > I_{FL} \end{cases} \qquad (4)$$

where θ_o and θ_w are respectively the top oil and measured winding temperatures, I_C is the measured C-phase current and I_{FL} is the phase current at rated load. The resulting oil temperature is therefore higher than the base case when the transformer operates above its nameplate rating, as shown in Figure 13.

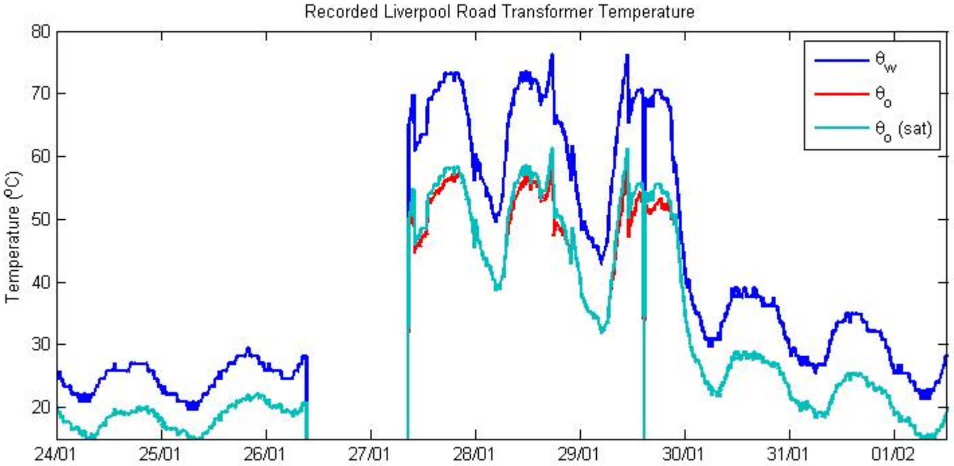

Figure 13: Effect of load offset saturation on calculated oil temperature

As can be seen, the effect of saturation of the load-related temperature offset at 15ºC is to slightly increase the calculated oil temperature by a small amount at the daily temperature peaks during the experiment.

Under these conditions, the optimised values of $\Delta\theta_{or}$ and τ_o were found to be **45.2ºC** and **344 minutes** respectively. The increase in $\Delta\theta_{or}$ and reduction in τ_o are perhaps to be expected since the result of assuming saturation of the load offset is that the true oil temperature is proportionately increased above rated load, and must therefore increase and reduce more rapidly.

The maximum overestimate and underestimate of hotspot temperature are respectively 7.4ºC and 14.6ºC. For the top oil temperature the largest overestimate is 6.7ºC, and the largest underestimate is 5.5ºC. Errors in daily peak hotspot temperature are shown in Table 4:

Date	Max θh (measured) (ºC)	Max θ_h (modelled) (ºC)	Overestimate/ (underestimate) (ºC)
27/1/2015[3]	78.3	79.4	1.1
28/1/2015	78.7	79.8	1.1
29/1/2015	76.1	81.0	4.9
30/1/2015	42.9	41.3	(1.6)
31/1/2015	38.0	39.9	1.9
1/2/2015[4]	31.0	34.4	3.4

Table 4: Comparison of modelled and measured peak hotspot temperature assuming load offset saturation

This assumption results in a transformer model which is generally warmer than that using the ‘base case’ values identified in section 5. This results in smaller maximum underestimates and larger maximum overestimates of oil and hotspot temperatures for the study period. The model generally tends to overestimate the peak daily hotspot temperature of the transformer.

7.2 High and Low Load Behaviour

As shown in Figure 9, the selected test period includes approximately 2½ days of high substation load, 2 days under normal load conditions, and a further half day which might be considered to cover transformer cooling following the experiment. To determine whether there is a change in transformer thermal behaviour between these two loading regimes, the model parameters were optimised using only measurements from the high load and cooling periods, as shown in Figure 14:

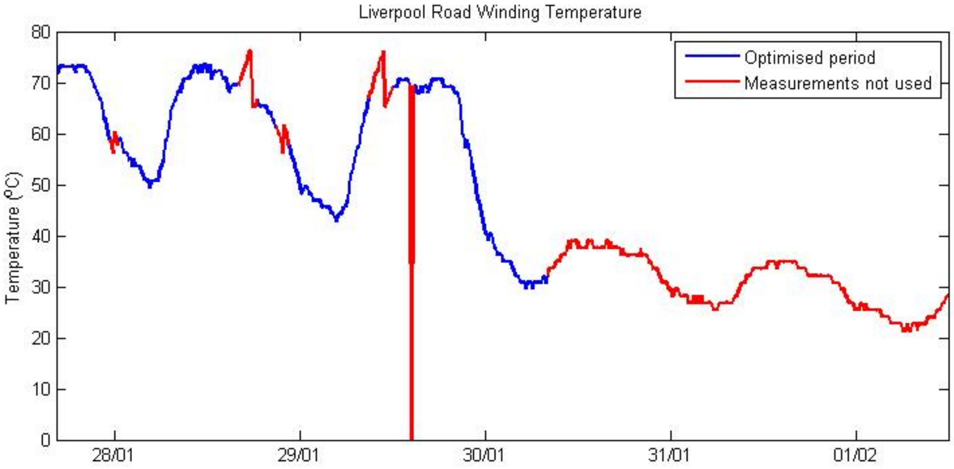

Figure 14: Optimisation of high-load period

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[3] From 16:30 onward

[4] Until 12:00

Under these conditions, the optimised values of $\Delta\theta_{or}$ and τ_o were found to be **45.3ºC** and **388** minutes respectively.

The maximum overestimate and underestimate of hotspot temperature are respectively 7.5ºC and 13.8ºC. For the top oil temperature the largest overestimate is 6.9ºC, and the largest underestimate is 6.0ºC. Errors in daily peak hotspot temperature are shown in Table 5:

Date	Max θh (measured) (ºC)	Max θ_h (modelled) (ºC)	Overestimate/ (underestimate) (ºC)
27/1/2015[5]	78.3	79.3	1.0
28/1/2015	78.7	79.5	0.8
29/1/2015	76.1	80.9	4.8
30/1/2015	42.9	41.1	(1.8)
31/1/2015	38.0	39.8	1.8
1/2/2015[6]	31.0	34.3	3.3

Table 5: Comparison of modelled and measured peak hotspot temperature considering only the high load and cooling parts of the study period

8 Uncertainty

Two sources of uncertainty might be considered to exist in the parameterised model which is recommended in this technical note. The first is the conventional experimental error associated with the calculation of physical or model quantities from a practical experiment, encompassing small unobserved variations in the conditions of the experiment, and small differences between the ‘measured values’ of observed quantities and the true physical values.

Secondly, it must be recognised that the IEC model is an approximation to the true behaviour of the transformer. Differences between modelled and true behaviour are likely to exist for a number of reasons, including that some aspects of behaviour are either not represented or are represented in a simplified manner, and that the measured quantities or conditions of measurement may not correspond exactly to those which appear in the model.

Each of the classes of uncertainty is considered in more detail below

8.1 Experimental Error

Conventionally, the uncertainty in the results of an experiment might be evaluated by conducting a number of experiments under as near identical conditions as possible, or by

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[5] From 16:30 onward

[6] Until 12:00

dividing the period of the experiment into a number of parts and calculating results for each. The statistical distribution of the results obtained would then be analysed to determine the error bounds on the calculated parameters, representing the likely spread of measured transformer behaviour around the central estimate of model parameters.

In this case, the experiment was undertaken over a short period, and there are considerable practical difficulties associated with conducting further experiments under conditions of transformer loading above nameplate rating. As such, there is insufficient experimental data to conduct a meaningful statistical analysis of experimental error in this case. However, it is possible to determine the influence of some important contributors to experimental error from the properties of the measurement systems involved.

The data sheet for the transformer temperature measurement system (Ashridge Engineering 852 Plus [2]) states the input-to-output accuracy of the system is ±2ºC at 20ºC. No indication of variation of this value with temperature is given. Examination of the transformer temperature value recorded by iHost shows that the minimum step between adjacent values is between 1.35ºC and 1.4ºC. Assuming that the measured value is accurately rounded to the nearest available output value, then this suggests a quantisation error in the temperature measurement of ±0.7ºC.

The measured C-phase current is also used in the calculation of the oil temperature profile, since it is used to reverse the load-based conversion from oil to winding temperature. Since no additional CT was installed for the use of the temperature monitor, the measurement accuracy of the CT is not considered. Examination of the current values recorded by iHost suggests that the quantisation step is 1A, giving a maximum quantisation error in the current of ±0.5A. The gradient of the function used to reverse the oil-to-winding conversion is 0.0375ºC/A: the corresponding quantisation error in the calculated oil temperature is therefore less than 0.02ºC, which is considered negligible in comparison to the uncertainty in the recorded temperature measurement.

The worst-case error in the calculated oil temperature constant $\Delta\theta_{or}$, assuming that all measurements are at the limit of both calibration and quantisation error is therefore ±2.7ºC

8.2 IEC Model Limitations

The IEC model is a simplified representation of the behaviour of the transformer, and makes assumptions about the nature of the measured and modelled quantities. Three particular areas of difference in thermal behaviour between the IEC model and measured values are suggestive of either changes in the nature of the measurements being made, or of observed behaviour which is not represented in the simplified model. It is recommended that these differences, should be represented by allowing small margins of uncertainty when setting the maximum permitted temperature for the transformer.

8.2.1 Temperature Measurement Behaviour

The first of these areas of difference is observed in the form of the sudden upward and downward steps in the measured temperature. It is suggested that these represent a change in the oil flow pattern in the transformer, with the upward steps corresponding to a situation in which the temperature transducer becomes exposed to a pocket or stream of hot oil, perhaps emanating directly from the transformer oil. At the downward steps, this hot oil no longer impinges on the transducer, which is immersed in cooler oil. It is interesting that the size of the upward steps (typically in the range 4 – 6ºC) is less than the size of the downward steps (typically 8 – 11ºC). This may indicate that the downward transition places the transducer in a region of unusually cool oil, or that hot oil to cool oil temperature difference increases between upward and downward transitions.

The IEC 60076-7 model describes the top-oil temperature of interest θ_o as the “mixed oil temperature in the tank at the top of the winding” – thus a flow of hot oil directly from the winding would be at a temperature greater than θ_o, and it is possible that regions of oil at a temperature less than θ_o exist at the level of the temperature probe.

The parameter tuning process described here will inherently select model parameters which balance the ‘high oil temperature’ and ‘low oil temperature’ temperature parts of the measurement series. It therefore seems reasonable to define a margin of uncertainty related to the size of the upward and downward steps, on the assumption that the ‘low oil temperature’ measurements may record a temperature lower than that intended by the standard, but that ‘high oil temperature’ measurements involve oil hotter than intended. It appears likely that the difference between actual and expected measurement conditions would be larger if the hot oil is directly heated by the winding, whereas the cooler oil was cooled below average by conduction or convection processes.

The average size of the six temperature steps listed in Table 2 is approximately 7.3ºC. Assuming that the parameter estimation process balances high and low cases well, a margin of half of this value might be considered appropriate. Bearing in mind that the lower oil temperature measurements may be more representative of conditions expected by the standard, it is suggested that the margin should be rounded down to 3.5ºC.

8.2.2 Transient Heating and Cooling Behaviour

Figure 11 and Figure 12 show that there are differences between the rates of heating and cooling of the model and the actual transformer. The modelled oil temperature rises more slowly than the measured temperature, but falls at a very similar rate. This suggests that the oil time constant is too large for the heating process, and that the transformer would respond more rapidly to short but large increases in load, and attain a higher than modelled temperature during them. The optimised time constant is appropriate for the cooling process, suggesting that the actual transformer will cool in the modelled way following a sustained period of high load, such as is found during the daily load cycle or after a day-long spell at high load.

By contrast, the modelled hotspot temperature rises at a rate which closely matches the measured temperature, but cools more quickly. This suggests that the winding time constant is appropriate for the heating process, but is too small for the winding cooling process. It should be recognised, however, that no direct measurement of the hotspot or winding temperature is made, and the true transient behaviour of the winding temperature is therefore difficult to discern.

The most significant risk which should be allowed for in the selection of a temperature margin in respect of transient behaviour is that of a large increase in load of short duration, which might heat the transformer oil to a higher temperature than forecast by the model. Assuming that the oil-to-hotspot relationship is broadly accurate, this would lead to a higher than expected hotspot temperature.

It is unfortunate that the large, fast load transient associated with the start of the experiment was not recorded. However, the temperature rise on the morning of 28 January, which is not interrupted by a sudden temperature change, may provide some indication. From a starting point approximately 1ºC below the measured temperature at the overnight minimum, the modelled temperature at the first peak is 3ºC lower than the measured value. The maximum difference during the temperature rise is 5ºC, which is the largest difference observed during the experiment. It therefore appears reasonable to allow a margin of 5ºC in the permissible hot spot temperature of the transformer.

8.2.3 Long-term Cooling Behaviour

As shown in Figure 12, the transformer oil continues to cool beyond the point at which the modelled oil temperature stabilises. This is indicative of a long-term release of stored heat which maintains the oil at a higher than normal temperature until dissipated into the atmosphere. It seems likely that this heat is stored in the transformer core. The model recommended by IEC60076-7 does not include a representation of the storage and release of heat by the core.

It might be possible to modify the IEC model to include a representation of the heating and cooling of the transformer core, although the experimental data available here does not provide sufficient basis to do so. It appears from the evidence available that the time constant of the core cooling process is in the order of days. This does not appear consistent with the typical behaviour of transformers under manufacturers' tests, in which the rising transformer temperature is typically allowed to stabilise overnight. It is possible that the difference between heating and cooling time constants observed for the oil and winding is more pronounced in this case. Data would therefore be required from the period immediately after the start of the experiment in order to understand how to represent the process of storing the energy which is observed to be released after the test.

The model parameters resulting from the experiment produce, under 'normal' load conditions, an oil temperature profile which is higher than measured. It is therefore suggested that no additional margin should be allowed in the permissible transformer behaviour for this long-term energy storage, since its effect at high load is already represented in the model parameters. Indeed, it is possible that absorption of energy by the core may slow down the temperature rise associated with a sudden increase in load (as discussed in section 8.2.2), leading to a reduction in the required margin in the acceptable temperature. However, without supporting evidence in the form of measurements from the start of the experiment, no recommendation can be made on this point.

9 Discussion and Conclusions

It is important to acknowledge the limitations of the experiment and associated analysis in determining the thermal parameters of the transformer. Only a short period of experimentation on an in-service transformer was possible, and within this period, some data was lost because of measurement difficulties. Importantly, the large change in temperature following the application of the increased load was not recorded.

In addition, the true hotspot temperature of the transformer, which is the key figure of merit in determining the risk to and aging of the transformer's insulation system, is not recorded. Instead, a synthesised winding temperature is recorded, from which the oil temperature experienced by the sensor is reconstructed. A hotspot temperature has been calculated, but this is dependent on assumptions about the winding temperature inherent in the temperature measurement system, and assumptions from IEC60076-7 about the relationship between the oil, winding and hotspot temperatures. No information is available which would permit the winding temperature time constant to be assessed. The values of $\Delta\theta_{hr}$ and τ_w must therefore be treated with caution. Should further information (for example from transformer acceptance testing or manufacturer's types test) about the thermal behaviour of the winding and hotspot become available, the assessment of those parameters should be revisited.

However, the small change in the optimised value of $\Delta\theta_{or}$ in comparison to the previous tuning exercise – slightly over 1ºC in the base case – suggest that the results of this experiment are consistent with the behaviour of the transformer observed in November 2014. The observed behaviour of the transformer after the test suggests that this difference may reflect energy storage in the transformer core.

Turning to the sensitivity analysis, the optimised values of $\Delta\theta_{or}$ and τ_o for each case are summarised in Figure 16 below, which shows a spread of about 2.5ºC in $\Delta\theta_{or}$ and about 80 minutes in τ_o:

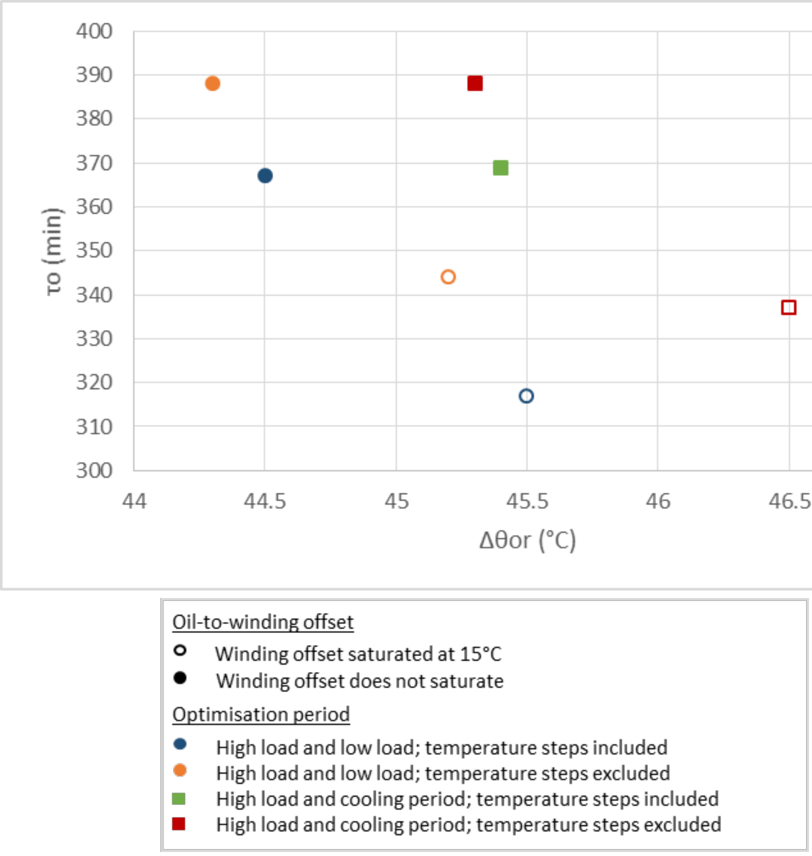

Figure 15: Tuned transformer parameters from sensitivity analysis

From Figure 16 it can be seen that, as previously discussed, the effect of assuming saturation of the oil-to-winding is to reduce the oil time constant and increase the oil temperature rise at rated load – effectively giving a hotter, faster-reacting transformer. Given that the results in section 7.1 show a marginal worsening of the prediction of peak hotspot temperature, there appears to be little support for this assumption of saturation.

The inclusion or exclusion of the periods around the steps in recorded transformer shown in Figure 6 is shown to make a comparatively small difference to the calculated parameters of the transformer. The value of $\Delta\theta_{or}$ reduces by one or two tenths of a degree, suggesting that the oil temperature during these periods is, on balance, higher than average. The oil time constant reduces when these periods are included in the optimisation, reflecting the fact that the measured oil temperature changes suddenly and unrealistically. For this last reason, it is considered that the exclusion of these periods should be preferred.

Considering the difference between the high load and low load periods, as represented in Figure 16 by the round and square pairs of symbols, it appears that the principal difference between these periods is in the value of $\Delta\theta_{or}$, in that in the high-load condition, the transformer is hotter than might be expected from consideration of the entire study period. This is consistent with the results of the November parameter estimation exercise, which was conducted using measurements taken under relatively low load conditions, similar to those observed after the end of the January experiment. The oil time constant seems to be relatively constant under high and low load conditions.

Finally, it must be remembered that the objective of this exercise has been to fit the model specified by IEC60076-7 to the observed transformer behaviour. This is a relatively simple model, and more complex models based on laboratory experiments and/or detailed information about the design and construction of the transformer are reported in the academic literature. While such models may appear attractive, it is unlikely that sufficient design data is available for most if not all transformers currently in service to permit their application. Nevertheless, aspects of the transformer behaviour observed in this experiment, notably the differing heating and cooling rates, and the slow post-experiment cooling shown in Figure 12, clearly indicate that a more complex model could be developed to better represent transformer behaviour. Further experiments, including repeated high and low load cycles would be required to design and calibrate such a model, and it is uncertain whether the benefits of an improved model would outweigh the costs and risks of such a programme of tests.

Consideration has been given to the uncertainties arising from the observed differences between modelled and measured behaviour, and from potential calibration and quantisation errors associated with the measurement process. As a result, it is recommended that the maximum permitted temperature of a transformer modelled using the IEC model with these parameters should be reduced by a small margin of uncertainty. Additionally, an error range corresponding to the maximum error in the measurement process is recommended for the value of $\Delta\theta_{or}$, since this parameter is most directly linked to the measured oil temperature.

Ultimately, the objective of the model considered here is to predict the thermal performance of the transformer at high load for the purpose of dynamically rating it to support peak loads. This must consider both the fidelity of the modelled time series of temperatures and the accuracy of peak temperature prediction. For this reason, it is recommended that the values given in section 5 should be used, as shown in the following table:

Parameter	IEC 60076-7 suggested value	Previous recommendation	New recommendation
$\Delta\theta_{or}$	52°C	43°C	44.3±2.7°C
$\Delta\theta_{hr}$	26°C	15°C	19.5°C
τ_o	210 minutes	210 minutes	388 minutes
τ_w	10 minutes	10 minutes	10 minutes

In addition a margin of 8.5ºC should be allowed in the maximum permitted temperature of the transformer to account for uncertainties relating to sudden observed changes in temperature (thought to be related to oil flow) and model accuracy during large, fast transients.

10 References

[1] Ian Elders, “Technical note on initial calibration of IEC60076-7 model performance based on primary transformer measurements”, Technical note SP/LCNF/TR/2015-001, January 2015.

[2] Ashridge Engineering, “852Plus Transformer Winding Temperature Indicator Data Sheet”, available: http://www.ash-eng.co.uk/wp-content/uploads/downloads/2014/08/852Plus-Datasheet-USB-OPTION.pdf