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# Factory Acceptance Tests
# Stage 2

## Post-FAT Loadsense Analysis

ea technology

RIIO NIC NETWORK INNOVATION COMPETITION

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# Contents

# Glossary

| Term | Definition |
|---|---|
| **ALVIN** | Automated Low Voltage Intelligent Network |
| **CB** | Circuit Breaker – in the context of this report, this refers to an Alvin Reclose™ device, containing a controllable circuit breaker |
| **FAT** | Factory Acceptance Test |
| **Loadsense** | Logic based control software developed by the OpenLV Project and tested as part of the Stage 2 FATs |
| **LV** | Low Voltage |
| **NOP** | Normally Open Point |
| **SAT** | Site Acceptance Test |
| **SS** | Substation |

# 1 Introduction

This document provides additional detail to support the Stage 2 Factory Acceptance Tests (FATs) undertaken at EA Technology's Capenhurst Offices on July 12th, 2018.

These tests demonstrated the successful control of the Alvin Reclose™ hardware by the LV-CAP™ platform but it was not practicable to provide the detail necessary to explain the operation of the Loadsense application.

The information below, provides a 'walkthrough' of the operation process of the Loadsense application, and details the data gathered, generated and utilised, to drive the behaviour demonstrated in the Stage 2 FATs.

# 2 Test Environment

## 2.1 Software

The following software versions were used in the FAT:

- Modbus RTU Sensor Application 2404-SWREL-S011-V03.07.00 production
- Transformer Thermal Ratings 2579-SWREL-S011-V00.02.01 production
- Peer to Peer communications 2661-SWREL-S011-V00.05.00 production
- Load Profiler 2662-SWREL-S011-V00.02.06 production
- OpenLV Operating System configuration 2826-SWREL-V00.01.08

## 2.2 Network Configuration

The LoadSense software works with a pair of LV substations on the same 11kV feeder (with no normally-open point between them), which are also interconnected at LV via a "meshing" feeder which has a link box on it. Traditionally this link box would be a normally open point with the links not fitted, except under fault conditions when a back-feed could be established.

For the OpenLV project the links will be permanently fitted to the link box, forming a continuous feeder between the two substations. Alvin Reclose™ LV Circuit Breakers will be fitted in place of the LV board fuses at both ends of the feeder.

At substation Site (Substation) 2, the Circuit Breaker will always be closed (unless there is a fault on the feeder, which will trip it) and so this substation will contribute to powering the meshing feeder. At Site (Substation) 1, the Circuit Breaker will be controlled by LoadSense. If the Circuit Breaker at Site 1 is open, then the complete meshing feeder load will be supplied from Site 2. If the Circuit Breaker at Site 1 is closed, then the meshing feeder load will be shared between Sites 1 and 2.

The default state is to operate with the Site 1 Circuit Breaker open (Figure 1). However, if this will cause an overload at Site 2[1], then LoadSense may decide to close this Circuit Breaker (Figure 2). This will reduce the transformer load (and hence in time transformer temperature) at Site 2 but increase the load (and hence temperature) at Site 1.

[1] Within the OpenLV project this is guaranteed through setting the 'overload threshold' to a lower level than would be utilised in a business-as-usual scenario.

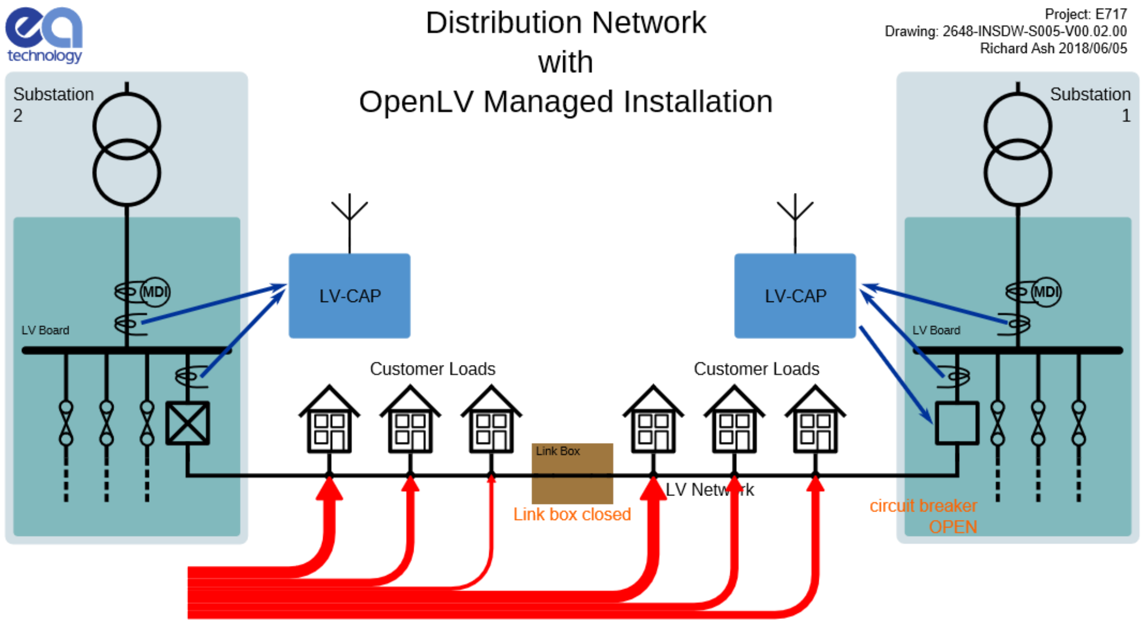


**Figure 1: Distribution network with OpenLV managed installation – Energised from Substation 2**

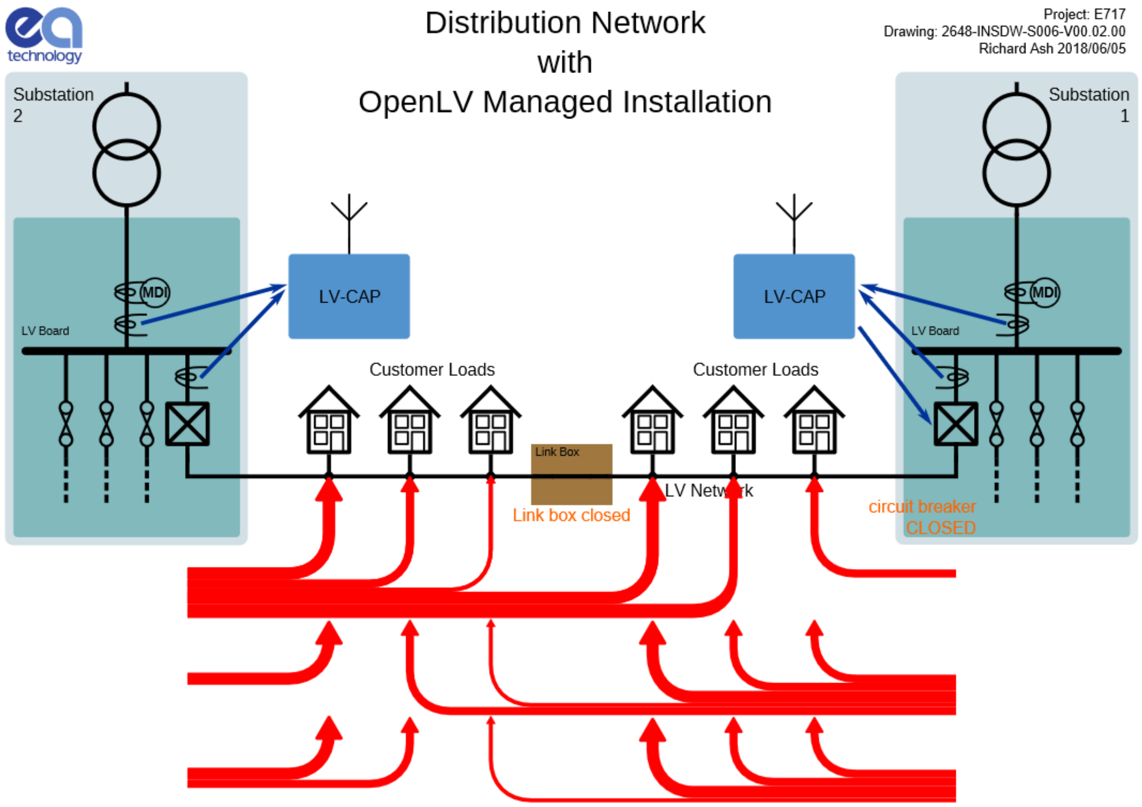


**Figure 2: Distribution network with OpenLV managed installation – Energised from Substations 1 & 2**

The logic for the operation of the switch is shown in below in Figure 3.

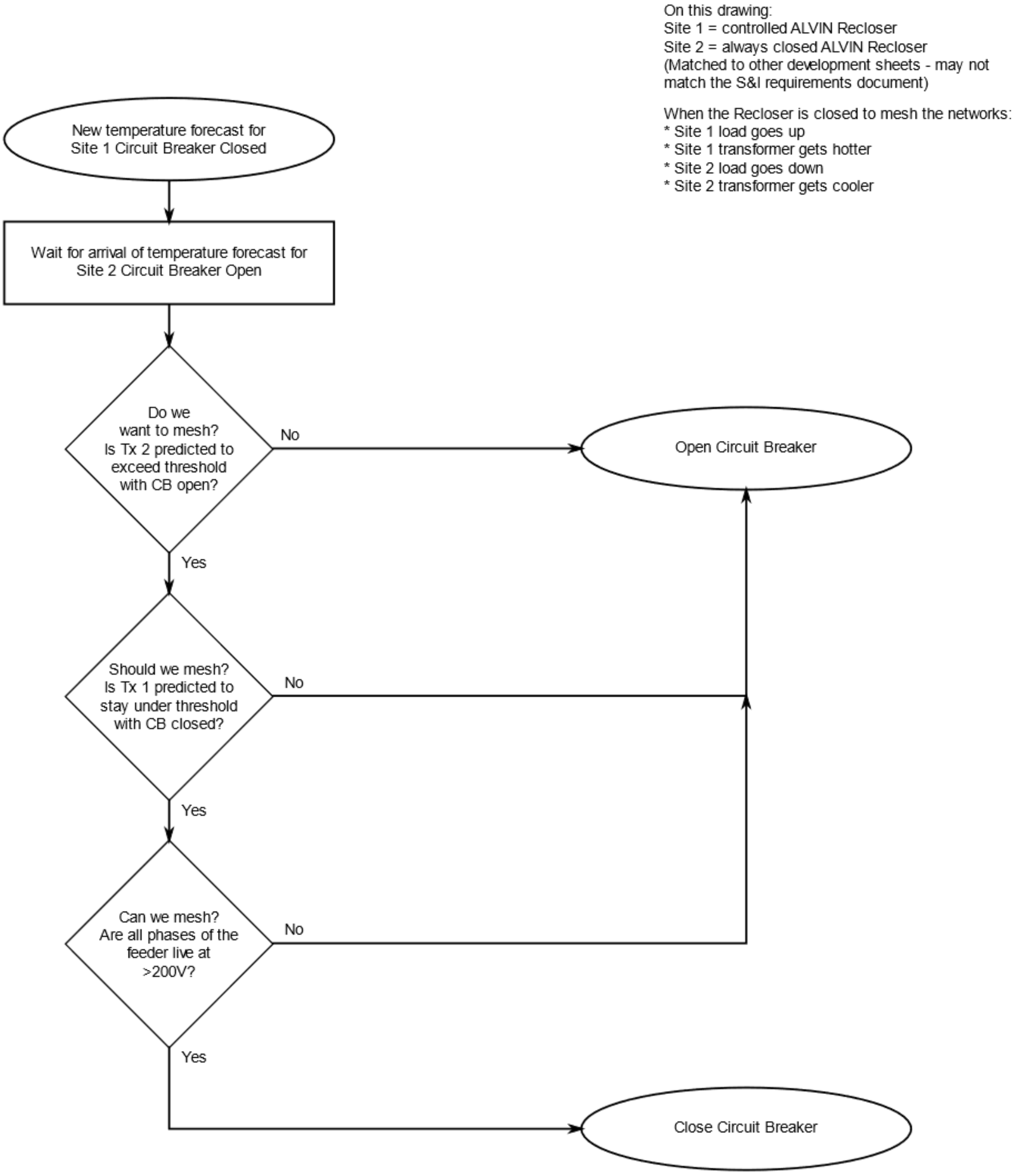


**Figure 3: Operation logic for Loadsense**

## 2.3 Test Data

The test data for the FAT was generated from the following spreadsheets:

- 2930-TSTDC-S001-V00.08.00 – load-current-generator-site1
- 2930-TSTDC-S002-V00.08.00 – load-current-generator-site2

Note that in this version (V00.08.00) the ALVIN output topics have been disabled by prefixing them with "-" so that they are not picked up by LoadSense. Edit the "output" sheet first row to reverse this if real ALVIN hardware is not available for testing.

These sheets can be made available if requested but are not included within this document.

### 2.3.1 Site 1

The load at each site is split into two components:

1. the meshed feeder load (which is affected by the position of the Alvin Reclose™ Circuit Breaker); and
2. the "other" load on the other feeders at the site, which is not affected by the Alvin Reclose™ Circuit breaker position.

Each load is made up of a load curve in 10-minute steps, taken from the LV Network Templates project spreadsheet.

The "other" load at Site 1 uses the LV Template 4 (High Domestic Dominance (~90%) (Low Customer Size ~70)) Winter load curve, scaled for a maximum current of 250A per phase.

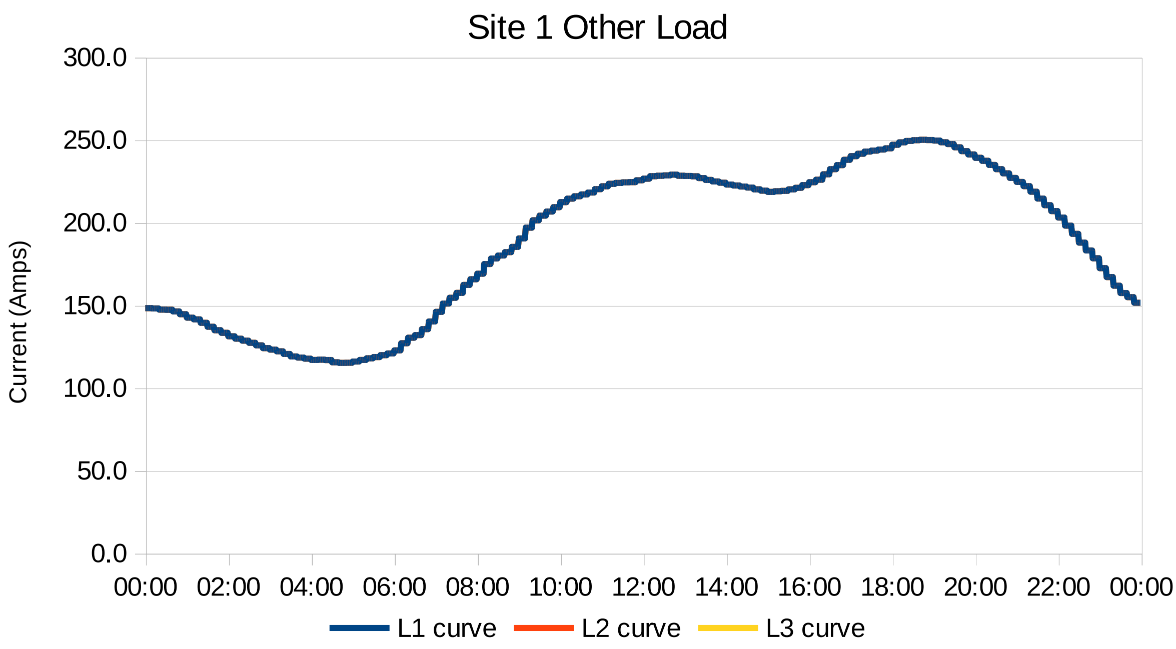


Figure 4: 'Other' Load Profile – Site 1

### 2.3.2 Site 2

The "other" load at Site 2 uses the LV Template 2 (Modest Domestic Dominance (~60%) (Suburban)) Winter load curve, scaled for a maximum current of 250A per phase.

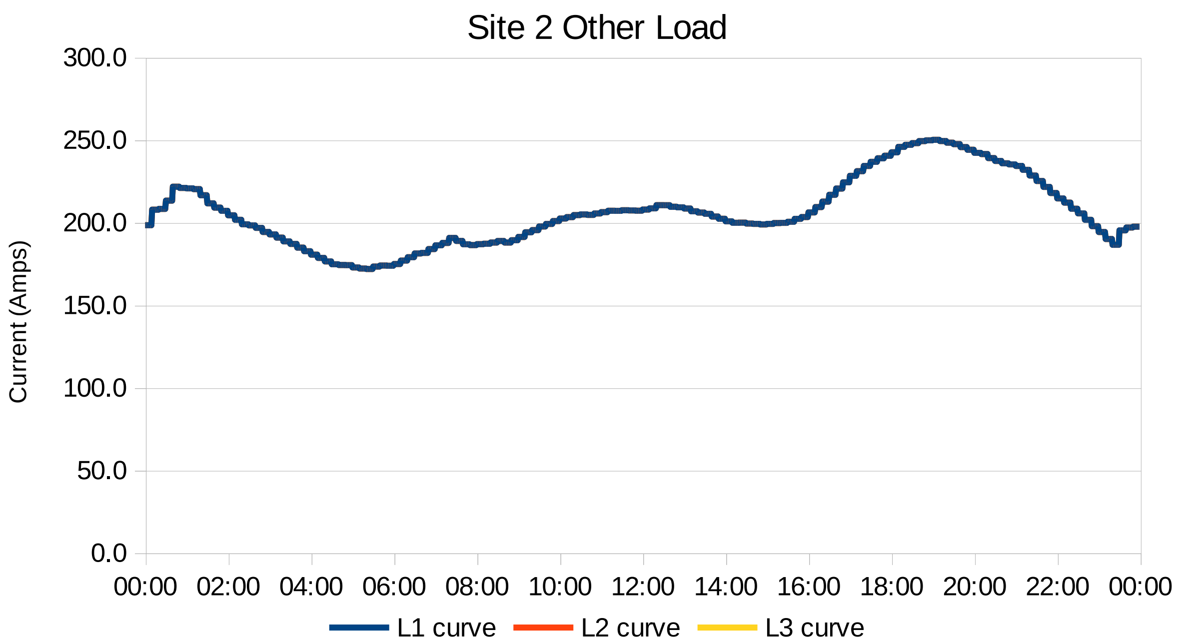


Figure 5 - 'Other' Load Profile – Site 2

### 2.3.3 Meshing Feeder

The meshing feeder load uses the LV Template 9 (Domestic Economy 7 Dominance (~65%)) Winter load curve, scaled for a maximum current of 150A per phase.

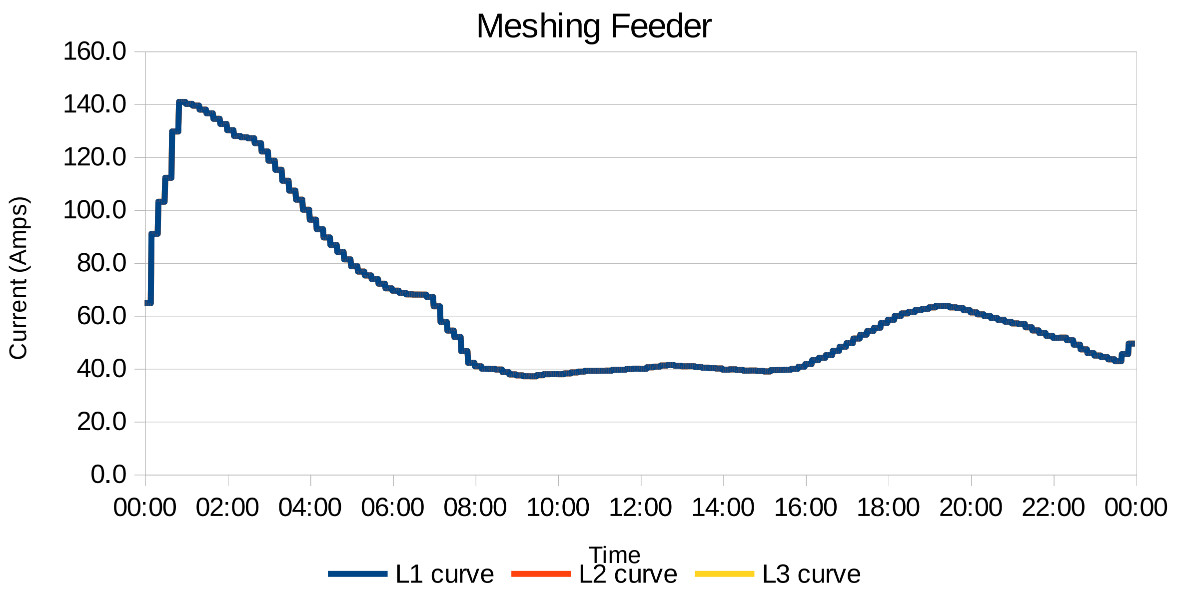


Figure 6: Load Profile - Meshing Feeder

# 3 Loadsense verification

Successful operation of the Loadsense software was demonstrated in the Stage 2 FATs through the use of simulated data in each LV-CAP™ platform. It was shown that the implementation of the Loadsense control system reduces load at Site 1 at peak times when Loadsense is operational.

The below sections (3.1 – 3.3) detail:

- Transformer load and temperatures in an unmeshed (circuit breaker open) system;
- Transformer load and temperatures in a meshed (circuit breaker closed) system; and
- Transformer load and temperatures in an automatically unmeshed system.

Section 3 of this report is intended to simply demonstrate that the control system operates to transfer load from one substation to another, whilst greater detail, expanding on the specific operation of the Loadsense process is provided in the appendix.

## 3.1 Open circuit breaker operation

The plots in this section (3.1) show the load profiles for each transformer (Site 1 and Site 2), the connecting feeder, and the resulting transformer 'HotSpot' temperature.

Key points are:

- The circuit breaker at Site 1 is open, without any automatic control;
- The full load of the connecting feeder is fed from Site 2.

***Site 1: Circuit Breaker – Open***

Figure 7 shows the overall load of the Site 1 Transformer, when the Alvin Reclose™ circuit breaker is permanently open; it peaks and dips to approximately 255A and 115A respectively.

As a result of the open circuit breaker, the measured load on the connecting feeder is zero due to it being fed entirely from Site 2.

The Transformer HotSpot temperature ranges from approximately 45 to 70 degrees Celsius.

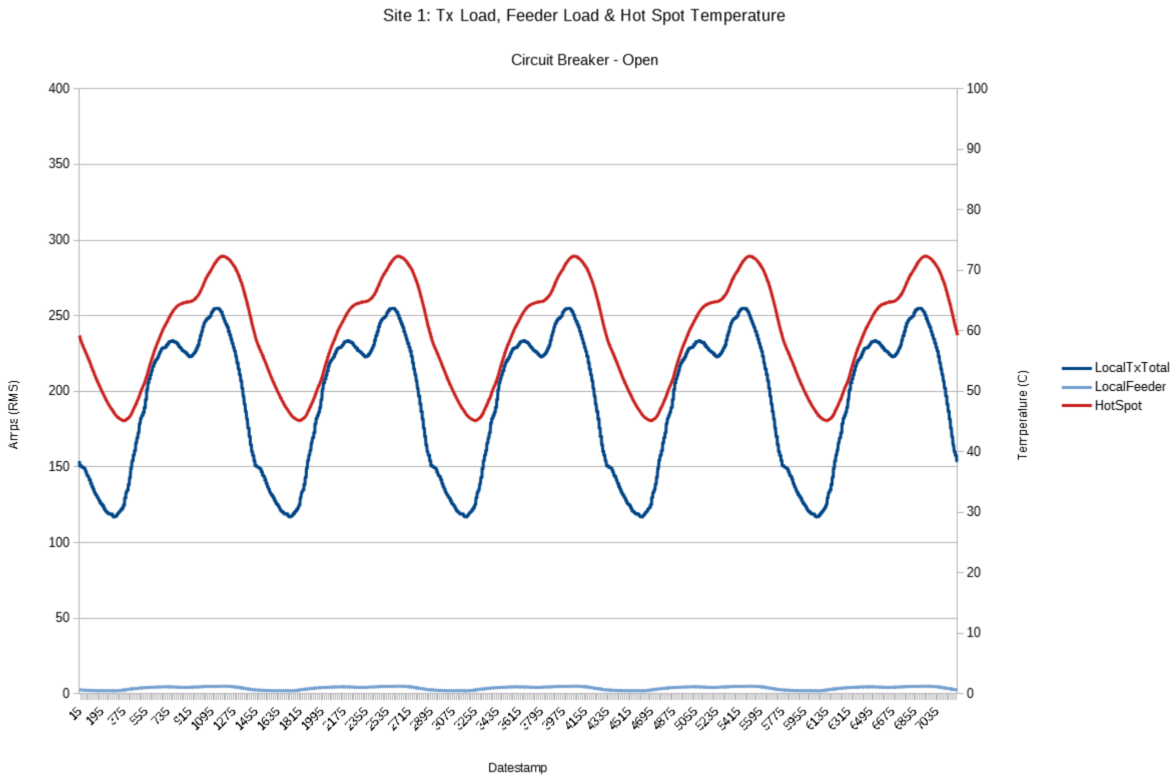


**Figure 7: Site 1 - Circuit Breaker - Open**

## *Site 2: Circuit Breaker – Open*

Figure 8 shows the overall load of the Site 2 Transformer when the Alvin Reclose™ circuit breaker (at Site 1) is permanently open; it peaks and dips to approximately 360A and 225A respectively.

As a result of the open circuit breaker, the measured load on the connecting feeder is moderate, with a high overnight peak, due to it being fed entirely from Site 2, ranging from approximately 35A to 140A.

The Transformer HotSpot temperature ranges from approximately 75 to 95 degrees Celsius.

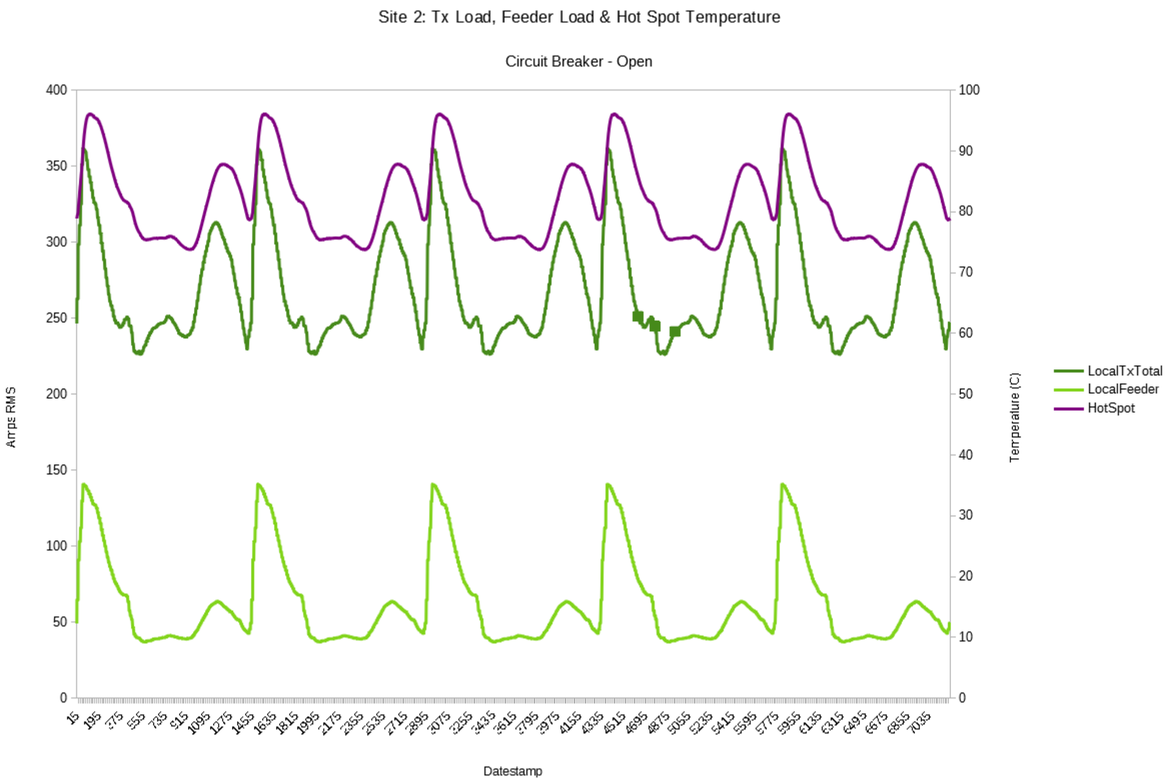


**Figure 8: Site 2 - Circuit Breaker - Open**

### *Site 1 & Site 2: Circuit Breaker – Open*

When the plots are combined, it can be seen that the Site 2 transformer load is significantly higher than that of Site 1 and is significantly influenced by the connecting feeder load and the overnight peak.

Similarly, the Site 2 transformer temperature is both higher than at Site 1, but whilst similar in shape, is also offset to later each day as a result of the Economy 7 profile.

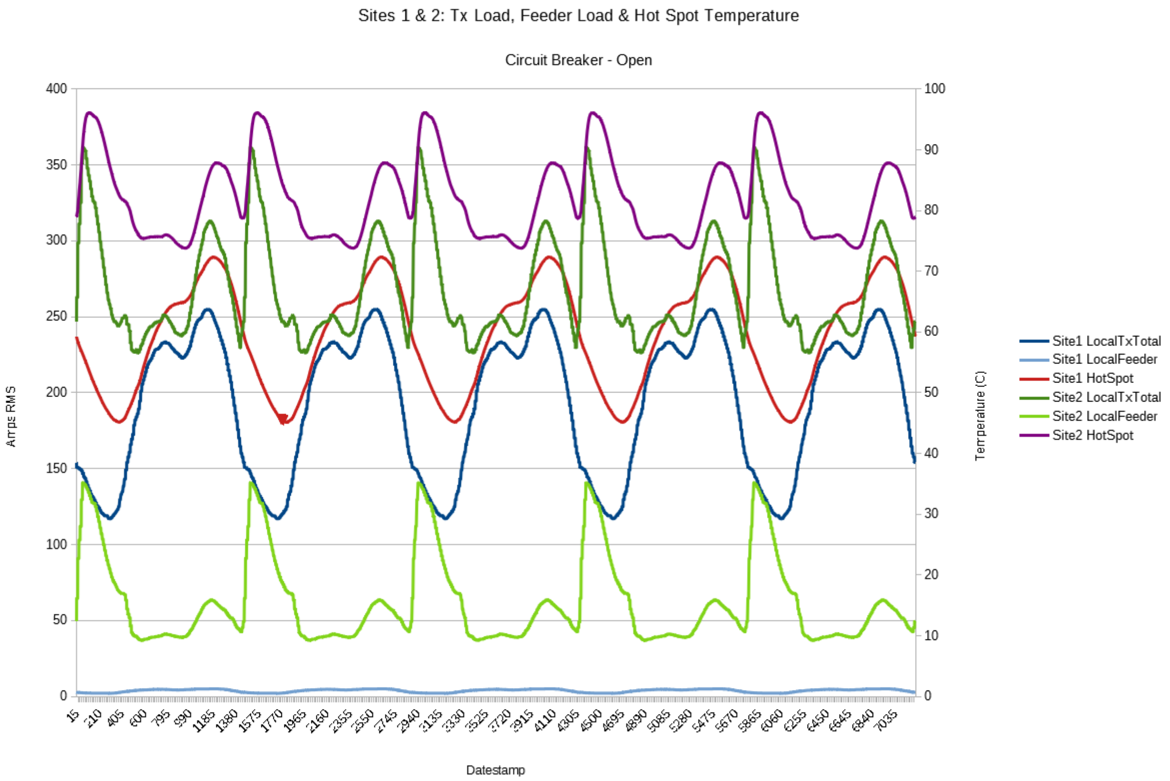


**Figure 9: Site 1 & Site 2 - Circuit Breaker - Open**

## 3.2 Closed circuit breaker operation

The plots in this section (3.2) show the load profiles for each transformer (Site 1 and Site 2), the connecting feeder, and the resulting transformer 'HotSpot' temperature.

Key points are:

- The circuit breaker at Site 1 is closed, without any automatic control;
- The full load of the connecting feeder is shared, at an assumed distribution of 50%/50% between Site 1 and Site 2.

This results in an increase in Site 1 load and a decrease for Site 2, with equivalent impact on the transformer temperatures as the feeder load is shared between the transformers.

***Site 1: Circuit Breaker – Closed***

Figure 10 shows the overall load of the Site 1 Transformer, when the Alvin Reclose™ circuit breaker is permanently closed and thus sharing the load of the connecting feeder; it peaks and dips to approximately 280A and 155A respectively.

With the circuit breaker closed, the measured load on the connecting feeder fluctuates between 18A and 70A.

The Transformer HotSpot temperature ranges from approximately 55 to 80 degrees Celsius.

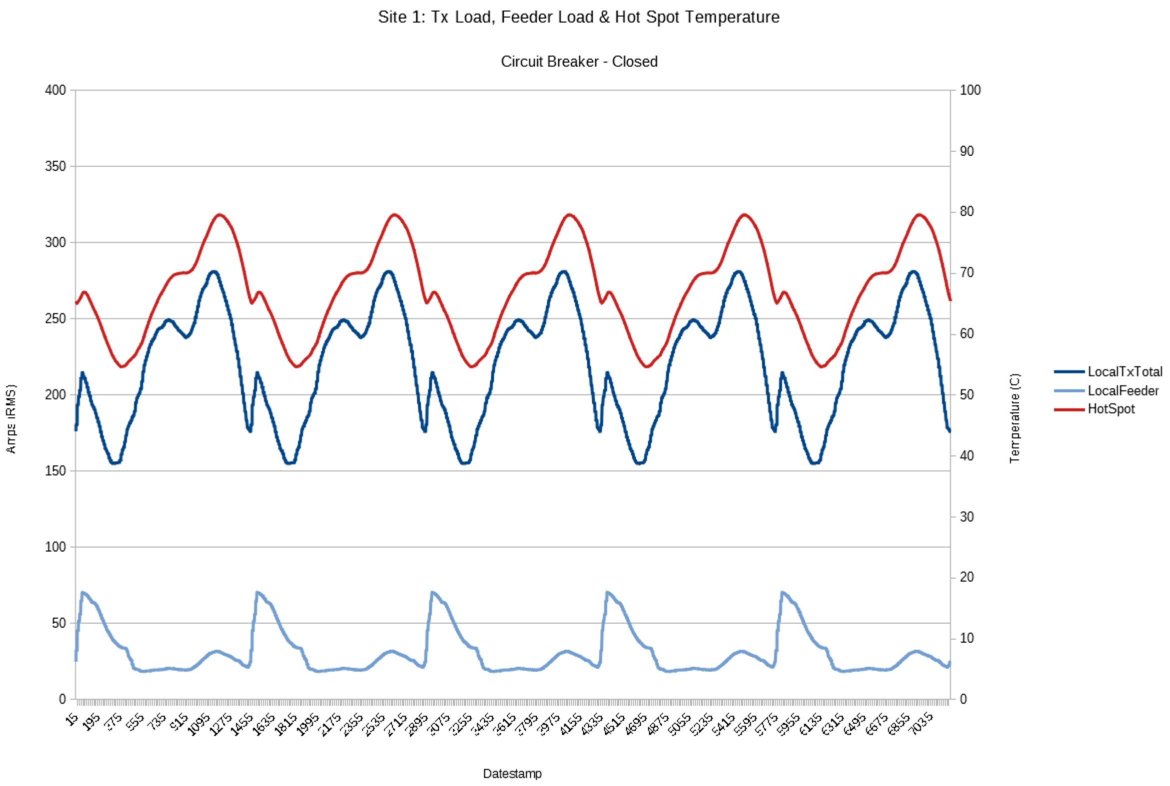


**Figure 10: Site 1 - Circuit Breaker - Closed**

### *Site 2: Circuit Breaker – Closed*

Figure 11 shows the overall load of the Site 1 Transformer, when the Alvin Reclose™ circuit breaker is permanently closed and thus sharing the load of the connecting feeder; it peaks and dips to approximately 290A and 205A respectively.

With the circuit breaker closed, the measured load on the connecting feeder matches that experienced by Site 1 and fluctuates between 18A and 70A.

The Transformer HotSpot temperature ranges from approximately 65 to 80 degrees Celsius.

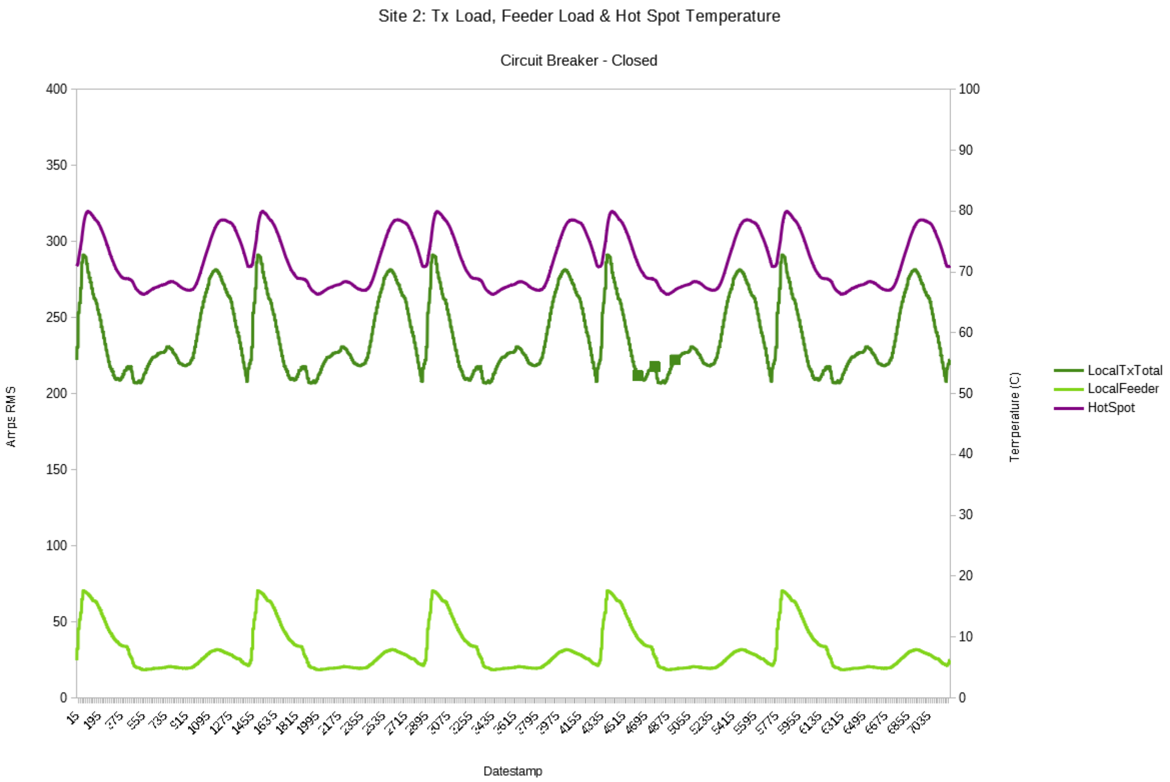


**Figure 11: Site 2 - Circuit Breaker - Closed**

### *Site 1 & Site 2: Circuit Breaker – Closed*

When the plots are combined, it can be seen in Figure 12 that when the circuit breaker is permanently closed, in comparison to Figure 9, the load experienced by each transformer is more evenly distributed.

The connecting feeder load is assumed to be equal for each transformer (with Site 1 LocalFeeder underneath the Site 2 LocalFeeder line on the below plot).

Having the circuit breaker closed, reduces the overall load, and subsequent transformer temperature at Site 2, whilst increasing both at Site 1.

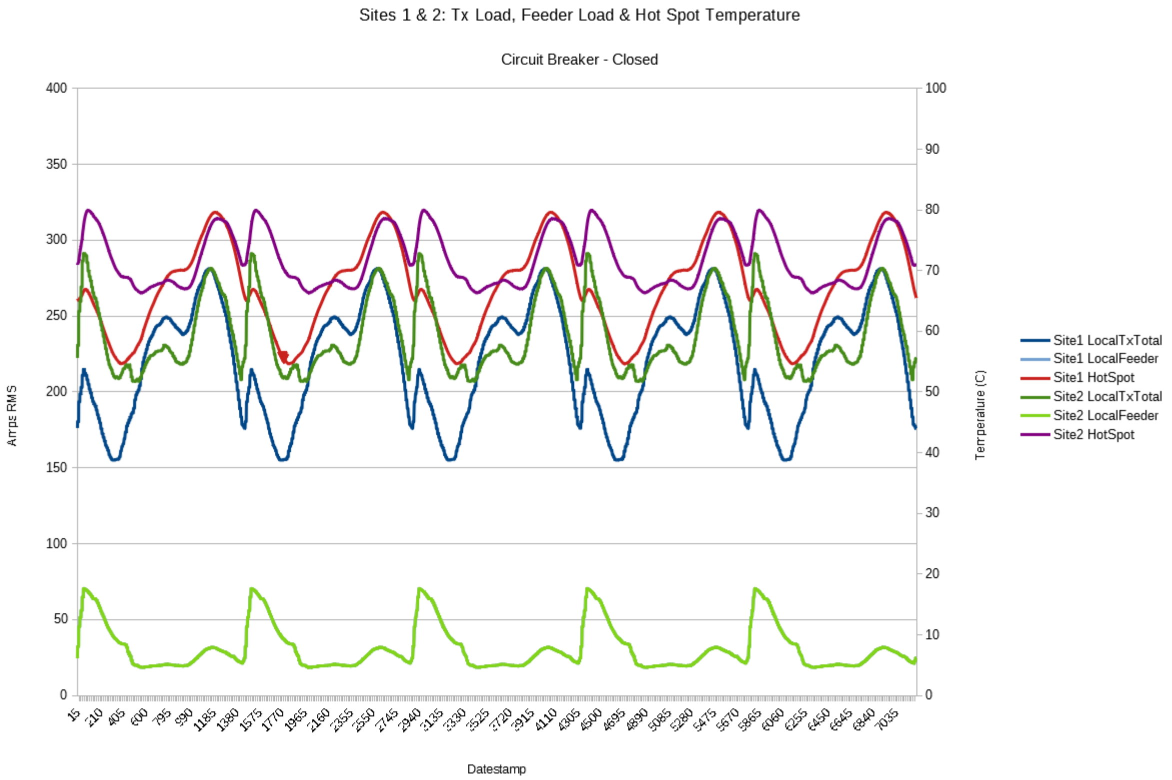


**Figure 12: Site 1 & Site 2- Circuit Breaker - Closed**

## 3.3 Autonomous circuit breaker operation

The plots in this section show the load profiles for each transformer (Site 1 and Site 2), the connecting feeder, and the resulting transformer 'HotSpot' temperature.

Key points to note in this situation are:

- The circuit breaker at Site 1 is allowed to operate autonomously, as determined by the Loadsense control algorithm;
- The full load of the connecting feeder is shared, at an assumed distribution of 50%/50% between Site 1 and Site 2, when the circuit breaker at Site 1 is closed.

The breaker is closed to share load of the connecting feeder between the substations across the overnight peak when Site 2 load is at its peak, resulting in an increase in Site 1 load and a decrease for Site 2.

The benefits demonstrated to the Site 2 transformer in Figure 12 are less significant when the circuit breaker operates autonomously, due to the circuit breaker only occasionally being closed to alleviate peak loading forecasts.

### *Site 1: Autonomous Circuit Breaker Operation*

Figure 13 shows the overall load of the Site 1 Transformer, when the Alvin Reclose™ circuit breaker operates autonomously, under the control of the Loadsense application; it peaks and dips to approximately 255A and 115A respectively.

The orange trace shows the circuit breaker position, (where ‘high’ is closed and ‘low’ is open), having a clear effect on the Site 1 transformer load. The measured load on the connecting feeder is zero, except during the periods where the breaker is closed. The smooth reduction in transformer load shown in Figure 7 is broken by the increase in load from the connecting feeder when the breaker is closed.

The Transformer HotSpot temperature ranges from approximately 50 to 70 degrees Celsius, showing that the closing of the circuit breaker prevents the transformer from cooling as far as was managed previously.

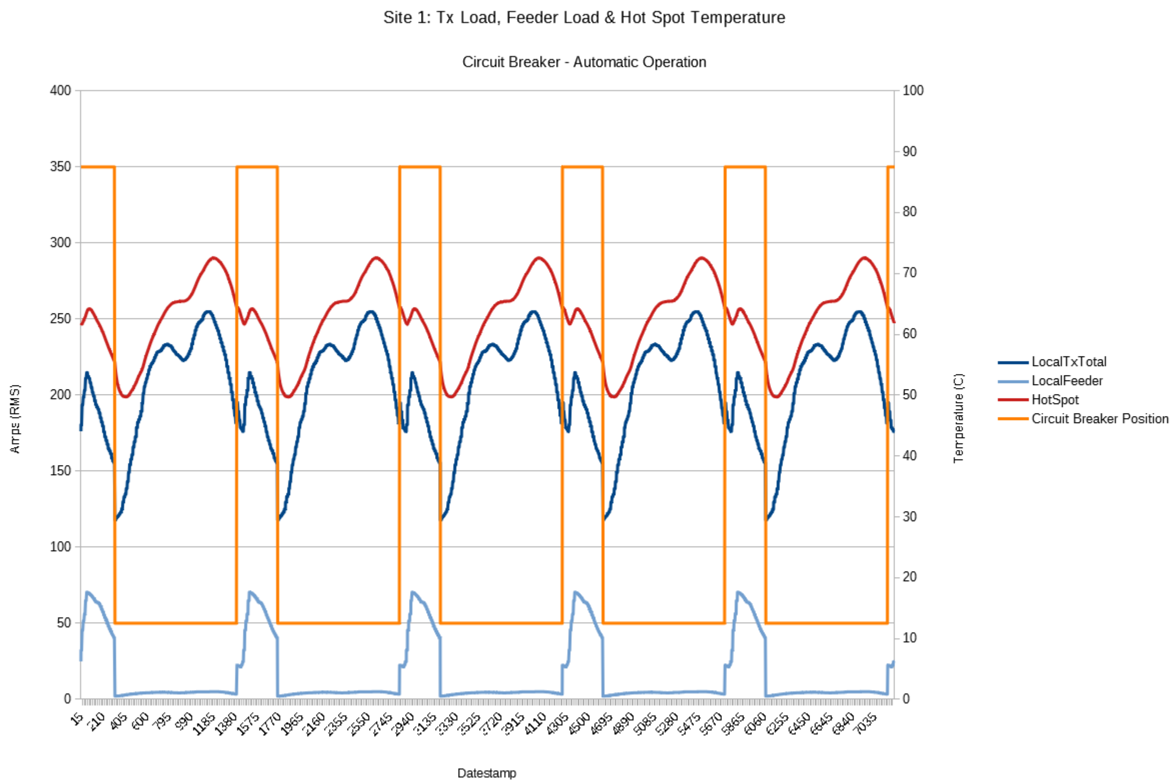


**Figure 13: Site 1 - Circuit Breaker - Autonomous**

It can be seen in Figure 14 that where the circuit breaker is allowed to operate autonomously, it closes to share the load between Sites 1 and 2 across the LocalFeeder connection.

This results in a sharp increase in current through the LocalFeeder at Site 1, subsequently reversing the steady decline experienced at that point. As the load begins to drop at Site 2, the downtrend resumes, until the circuit breaker opens and a sharp drop to the 'Circuit Breaker Open' profile occurs.

The difference in total transformer load can be seen, along with the impact on the overall transformer temperature, which never quite drops to the lowest temperature experience in a 'Circuit Breaker Open' scenario, although the maximum temperature is unchanged.

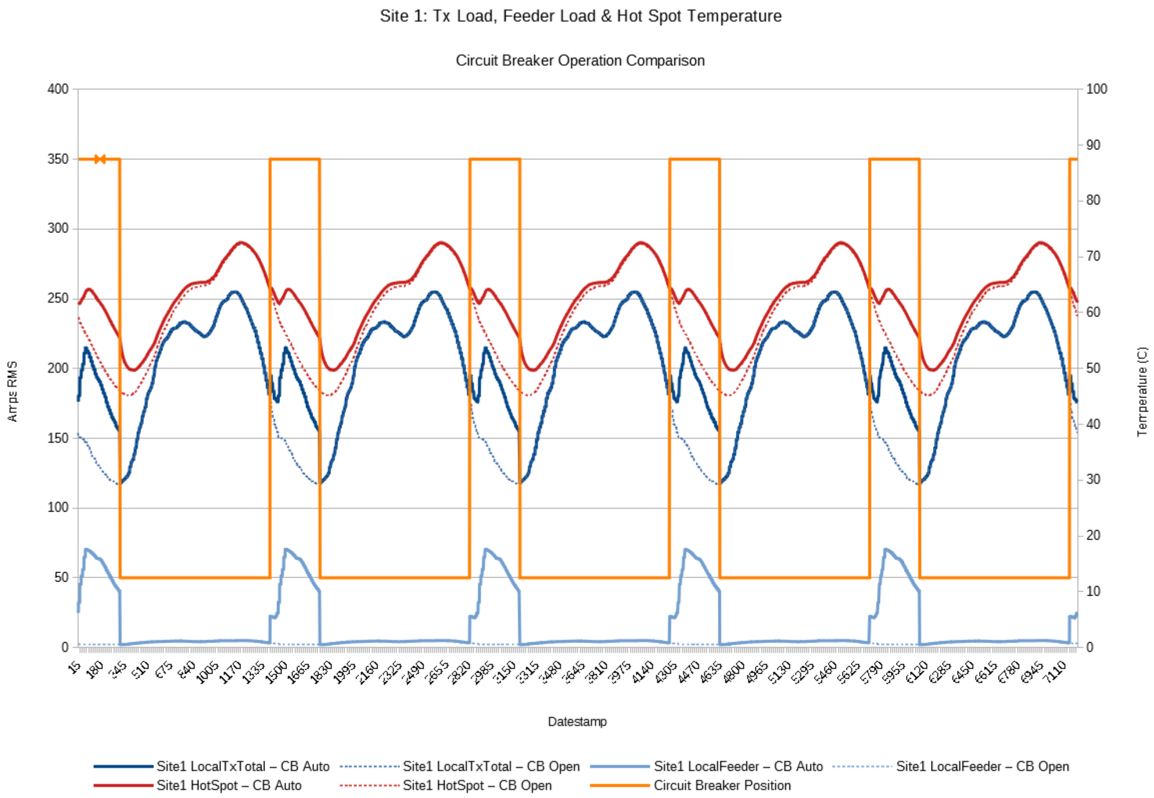


Figure 14: Site 1 - Circuit Breaker Comparison – Open to Autonomous

### *Site 2: Autonomous Circuit Breaker Operation*

Figure 15 shows the overall load of the Site 2 Transformer, when the Alvin Reclose™ circuit breaker operates autonomously, under the control of the Loadsense application; it peaks and dips to approximately 315A and 208A respectively.

The orange trace shows the circuit breaker position, (where 'high' is closed and 'low' is open), having a clear effect on the Site 2 transformer load. The measured load on the connecting feeder shows an immediate drop when the breaker is closed, and an increase when opened.

The Transformer HotSpot temperature ranges from approximately 70 to 90 degrees Celsius, showing that the closing of the circuit breaker reduces the overall transformer temperature, in comparison to the situation in Figure 8 where the circuit breaker is open.

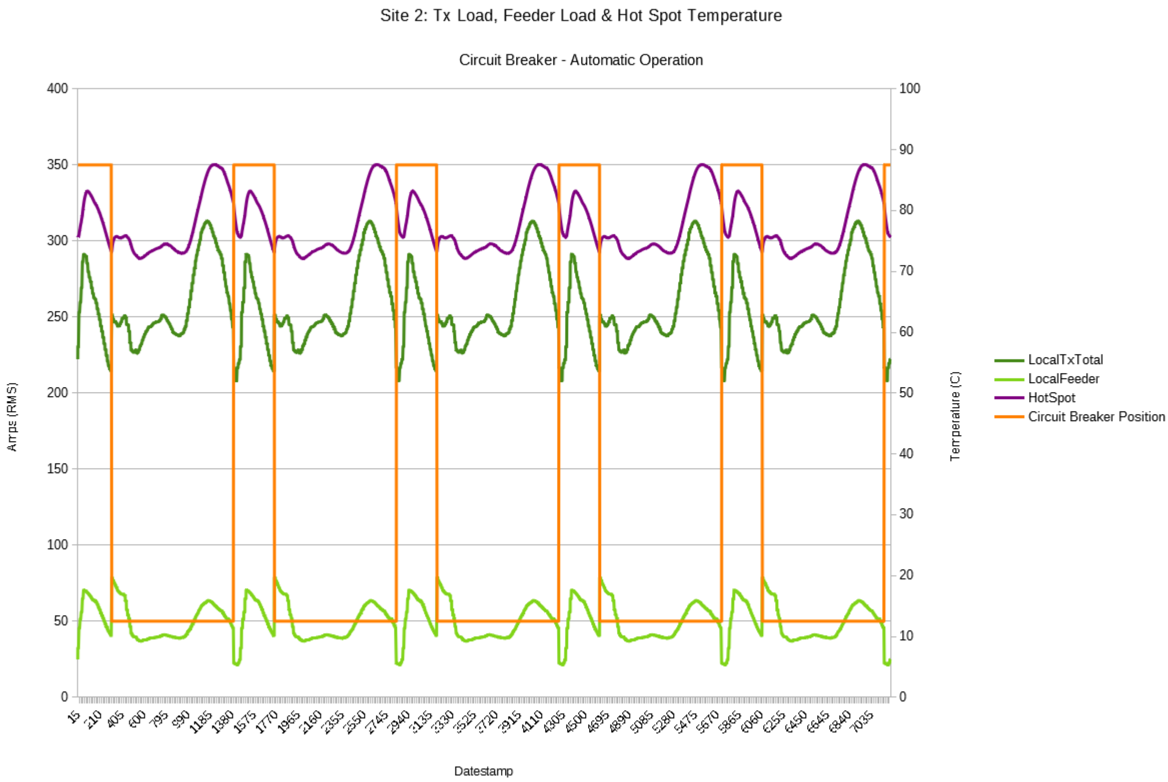


**Figure 15: Site 2 - Circuit Breaker - Autonomous**

It can be seen in Figure 16 that where the circuit breaker is allowed to operate autonomously, it closes to share the load between Sites 1 and 2 across the LocalFeeder connection.

This results in a short decrease in current through the LocalFeeder at Site 2, before the sharp load increase predicted by the system occurs. The increase is not as significant as anticipated for a 'Circuit Breaker Open Scenario' as Site 1 is sharing the load.

The difference in total transformer load can be seen, along with the impact on the overall transformer temperature, seen with a notable decrease in the maximum and a marginal decrease in the minimum operating temperatures.

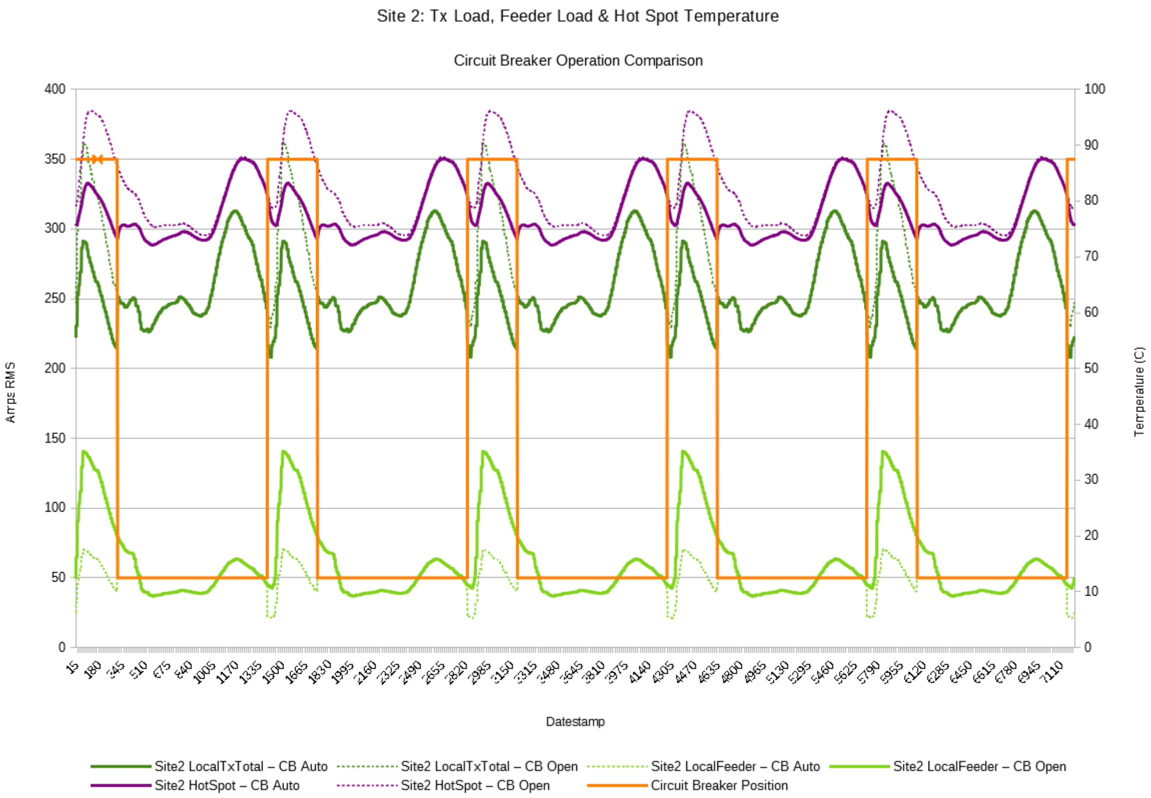


**Figure 16: Site 2 - Circuit Breaker Comparison – Open to Autonomous**

### *Site 1 & Site 2: Autonomous Circuit Breaker Operation*

In comparison to Figure 9, it can be seen in Figure 17 that with the circuit breaker at Site 1 operating automatically, the load experienced by each transformer is more evenly distributed during period of peak network loading.

The connecting feeder load is assumed to be equal for each transformer (with Site 1 LocalFeeder underneath the Site 2 LocalFeeder line on the below plot), when the circuit breaker is closed.

Figure 17 clearly shows that the automatic operation of the circuit breaker is transferring some load from the connecting feeder, initially energised from the transformer at Site 2, to the transformer at Site 1.

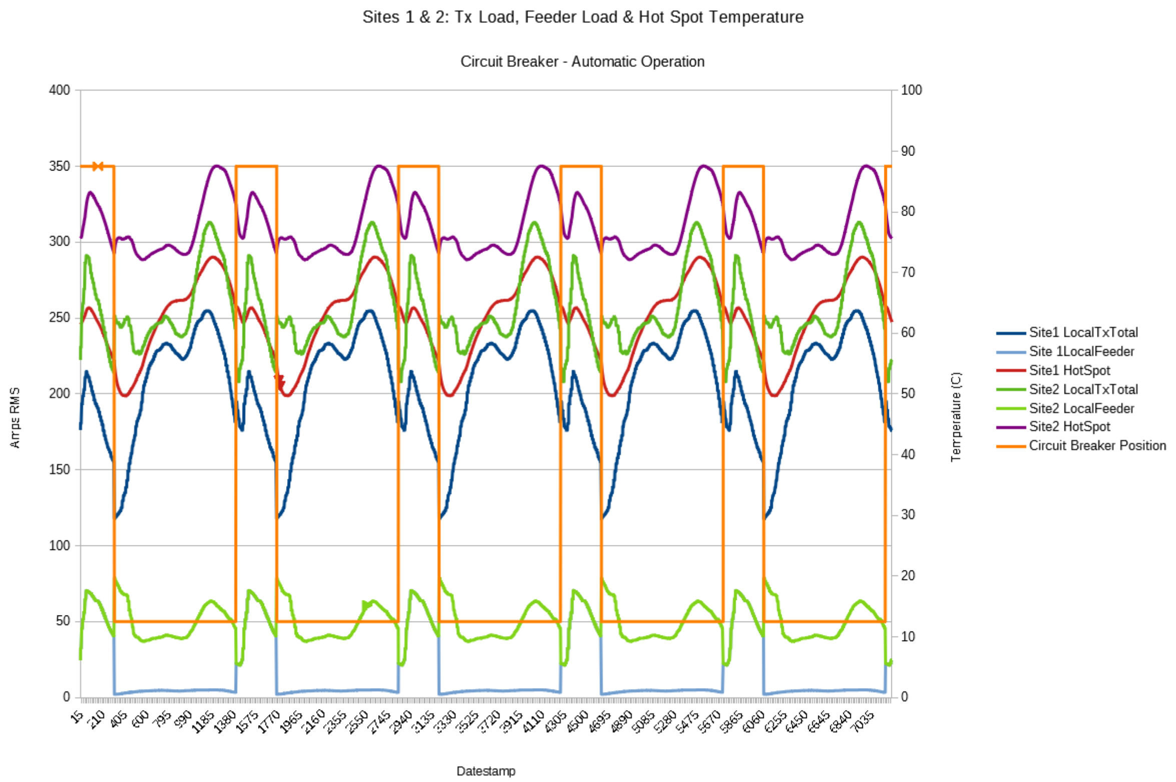


**Figure 17: Site 1 & Site 2 - Circuit Breaker - Autonomous**

Appendix 1 details the operational characteristics of the Loadsense software, providing a step by step process of how the forecasting and decision process is implemented.

Figure 21 shows the decrease in load, and subsequently, transformer operating temperature, in response to the control system operating autonomously and enabling a transfer of load from Site 2 to Site 1 along the connecting feeder. It is assumed that 50% of the total feeder load will be transferred.

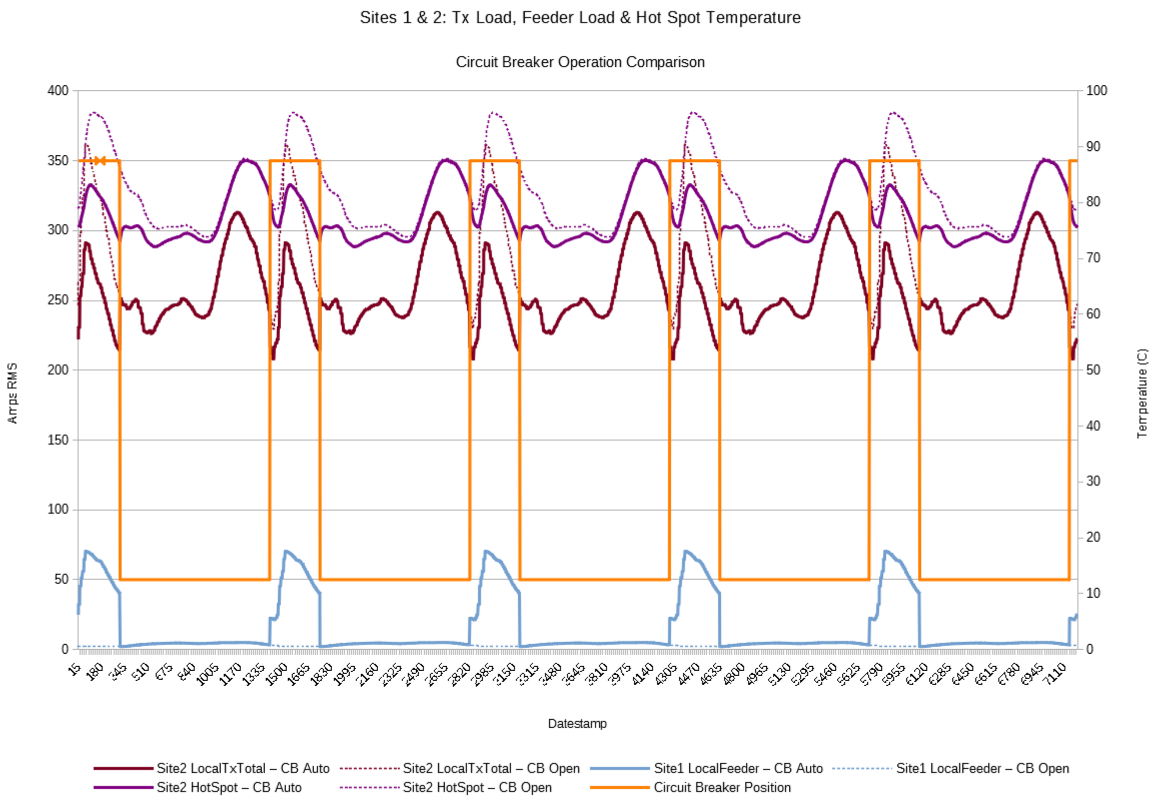


Figure 18: Site 2 & Site 1 Feeder- Circuit Breaker - Autonomous

The test successfully demonstrated the system's ability to transfer load between interconnected substations and hence, deliberately reduce load and overall operating temperature for a more heavily loaded asset. At the same time, consideration of the 'supporting' asset was maintained to protect both transformers.

# Appendix 1. LoadSense Operation

The LoadSense software consists of several connected elements; the full implementation in Figure 19 looks complex but most of this is due to data flows appearing in triplicate for all three phases.

The first stages are identical at Site 1 and Site 2.

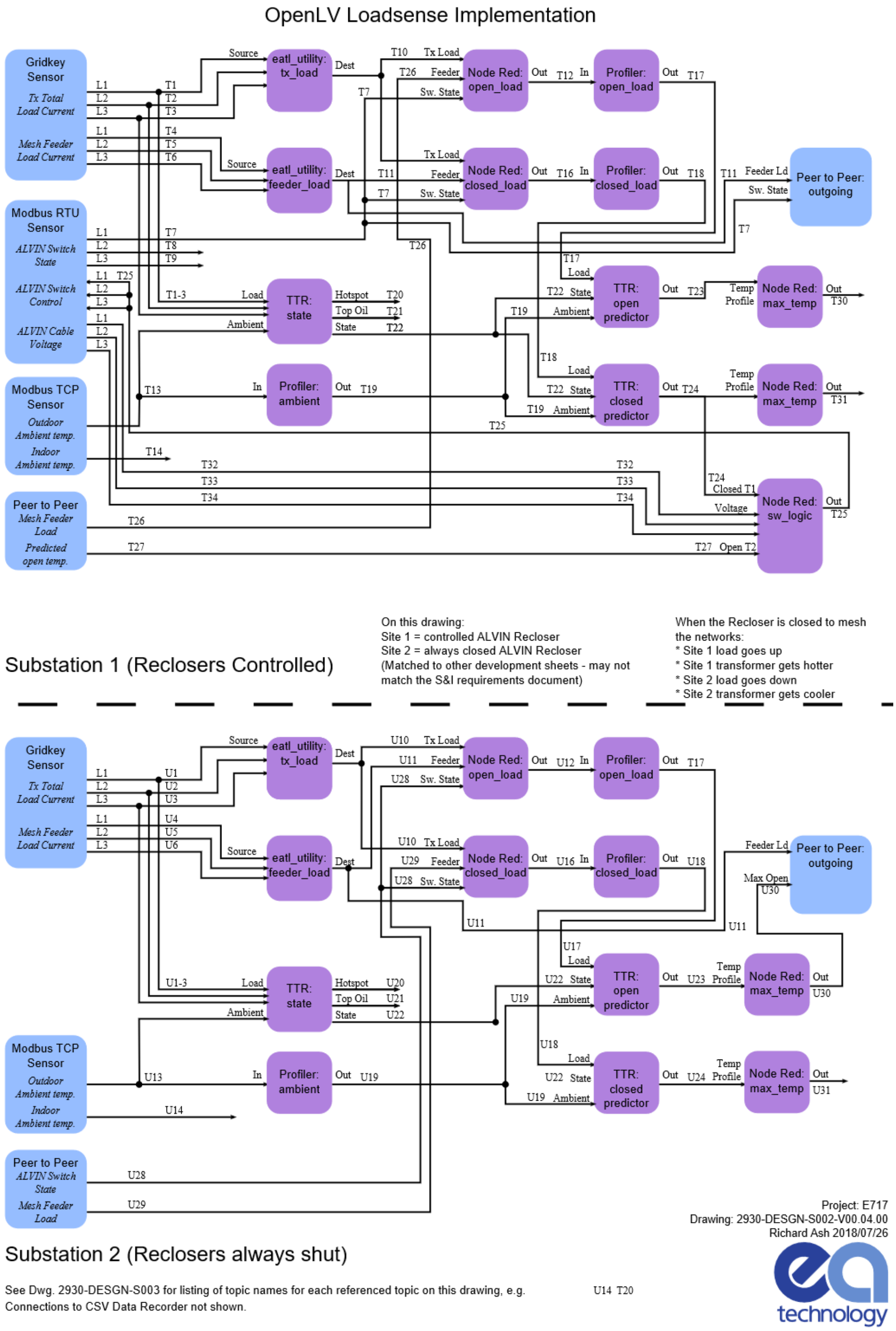


**Figure 19: Loadsense implementation**

## 3.4 Predicted Loads

To make decisions in the LoadSense Application, it is necessary to be able to predict the transformer temperature for four hours into the future. This first requires predicting the load current for the same period.

Two predictions are carried out, one for the case where the Alvin Reclose™ Circuit Breaker at Site 1 is open, and the other for the case where the Alvin Reclose™ Circuit Breaker at Site 1 is closed. These predictions consider the state of the circuit breaker when the measurements were made, hence why the meshing feeder current as well as the measured transformer load current is considered.

### 3.4.1 Site 1

For Site 1 with the Alvin Reclose™ Circuit Breaker held (always) open, we have the "other" load but a negligible feeder load, (Figure 20).

- Blue trace (LocalTxTotal) – The 'other load' comprising all load on the Site 1 transformer except for that introduced from the 'meshing feeder'.
- Red trace (LocalFeeder) – The load introduced to the Site 1 transformer from the 'meshing feeder'.

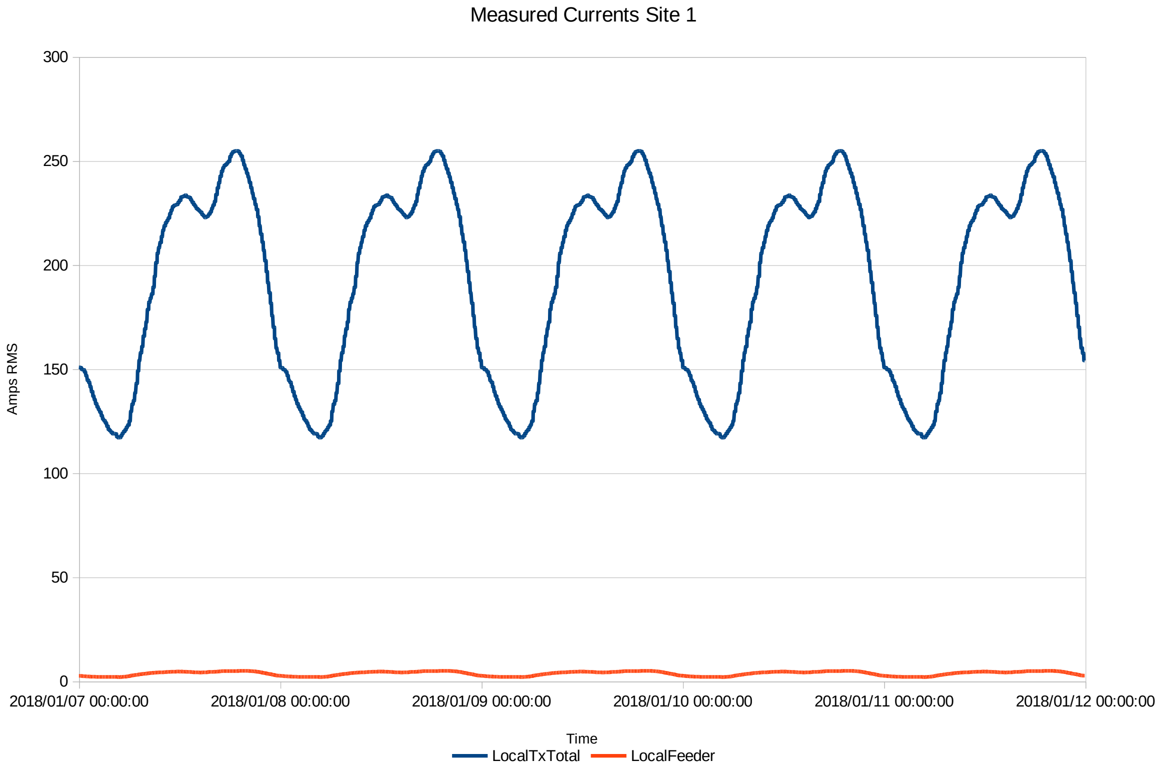


**Figure 20: Measured Currents – Site 1**

As the days are all identical in the test, Figure 21 shows the first day in more detail.

We can overlay the predicted transformer current when the Alvin Reclose™ Circuit Breaker is open, onto the graph of actual current. Taking the prediction made at 01:00:00 UTC on 2018/01/08, we can see that it lies on top of the actual transformer load. The orange hour-glass denotes the point in time at which the prediction (shown as the green line) was issued. At the point the blue line on the graph would have stopped at the orange marker. As time carried on we can see that the blue (actual) line lies very close to the green prediction.

Again, with the prediction made at 18:00:00 UTC on 2018/01/08 the same happens confirming we have predictions of the load with the circuit breaker open. The accuracy of the prediction in this scenario is enhanced by the unchanging load profile from day-to-day.

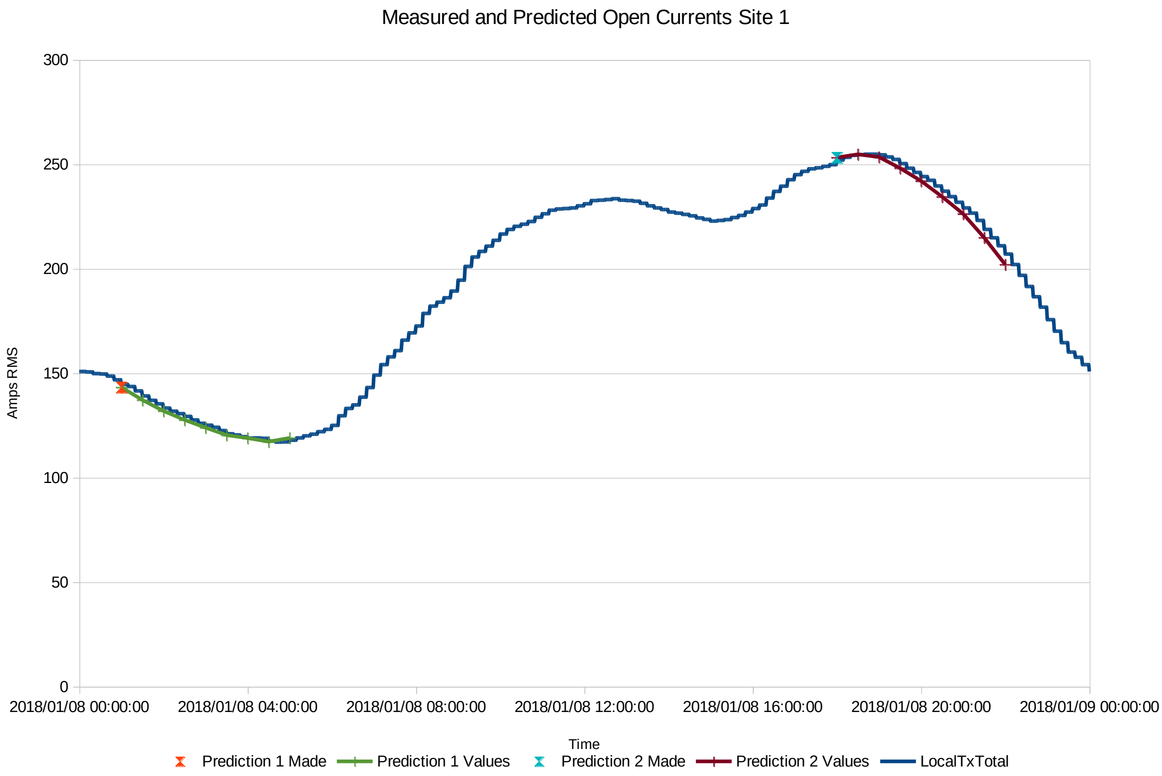


**Figure 21: Site 1_CB-Open – Measured & Predicted Currents**

With respect to the prediction of the loading at Site 1, if the Site 1 Alvin Reclose™ Circuit Breaker were to be closed, an assumption is required about the sharing of the meshing feeder load between the two transformers. For this analysis[2], we assume that 50% of the meshing feeder load will be transferred to Site 1.

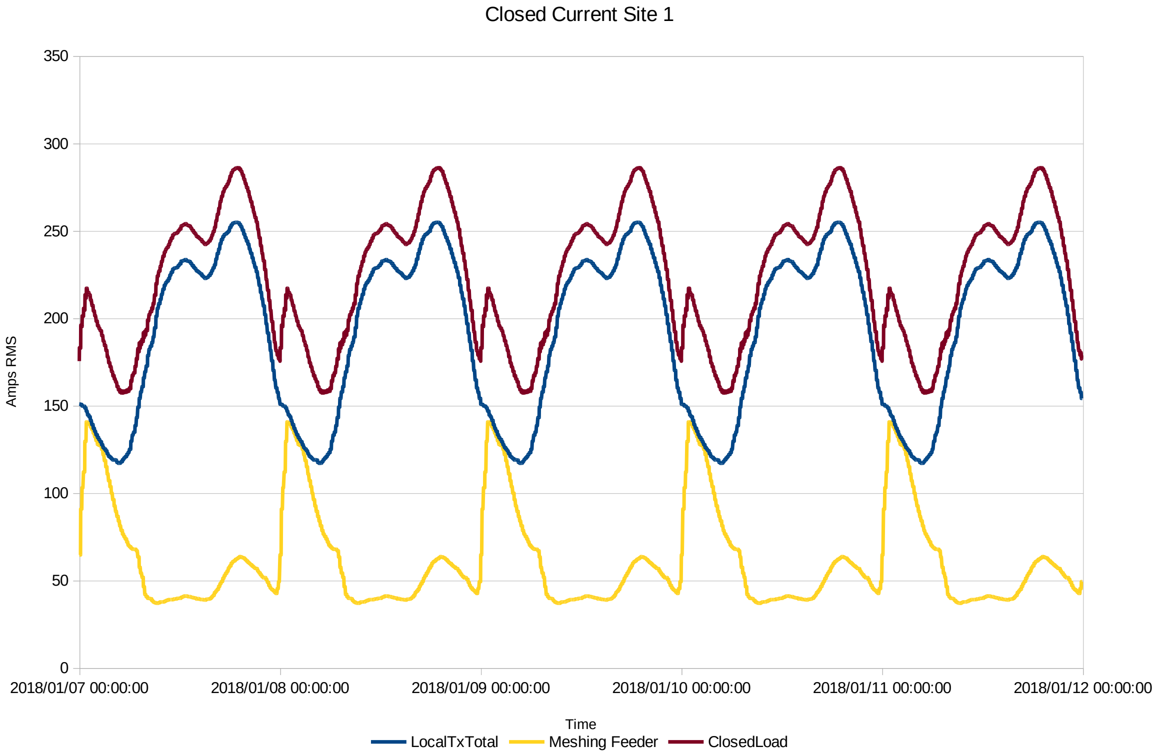


**Figure 22: Closed Current – Site 1**

Here (Figure 22), we see the following:

- Blue trace (LocalTxTotal) – The total load experienced by the Site 1 transformer with the Site 1 Circuit Breaker 'open'.
- Yellow trace (Meshing Feeder) – The total load associated with the meshing feeder.
- Brown trace (ClosedLoad) – The total load that would be experienced by the Site transformer if the Site 1 Circuit Breaker were closed, thus taking 50% of the meshing feeder load.

[2] Refinement of the feeder load distribution has been allowed for within the project, as more information becomes available as the trials progress.

Looking again at 1 day, 2018/01/08, (Figure 23) we can show the predicted loads and the outcome closed load. Again, the data matches up very well thanks to the repetitive nature of the testing load curve.

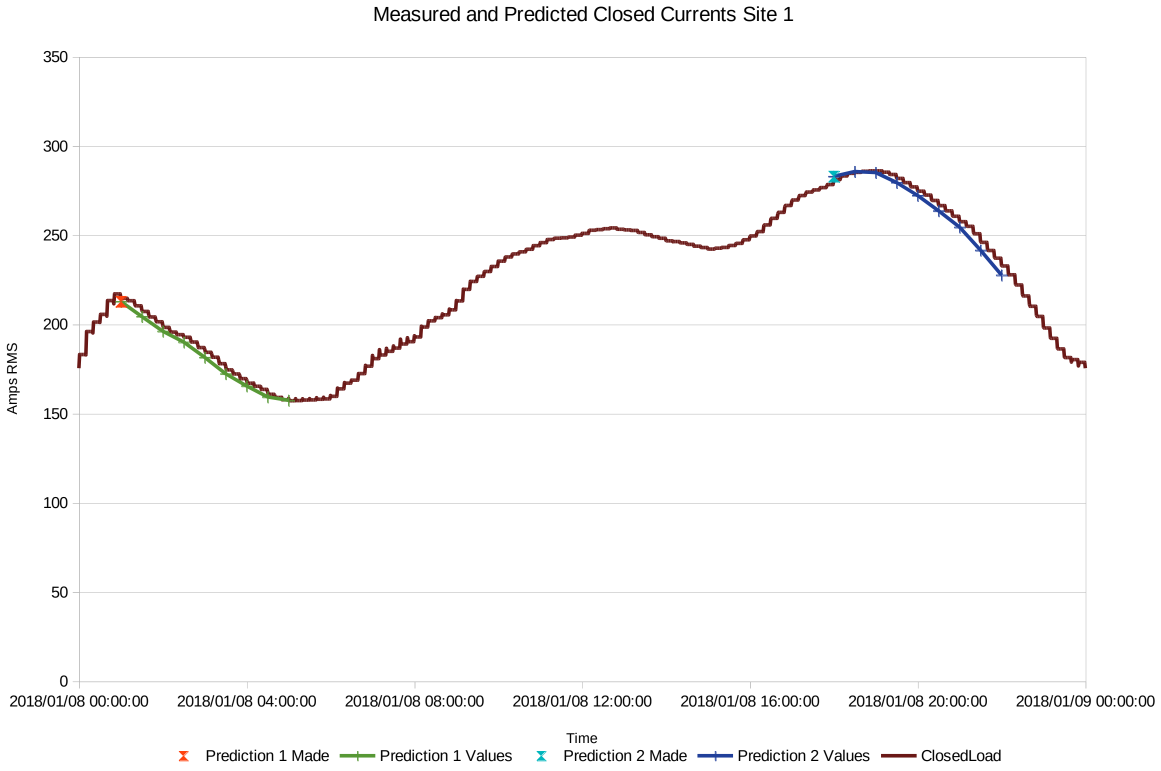


**Figure 23: Site 1_CB-Closed – Measured and Predicted Closed Currents – Site 1**

Turning now to a situation where the Site 1 Alvin Reclose™ Circuit Breaker is held closed and the network is always meshed, the measurements show the meshed feeder drawing half (as before) of it’s current from Site 1. and bringing an overnight peak into the Site 1 curve (Figure 24).

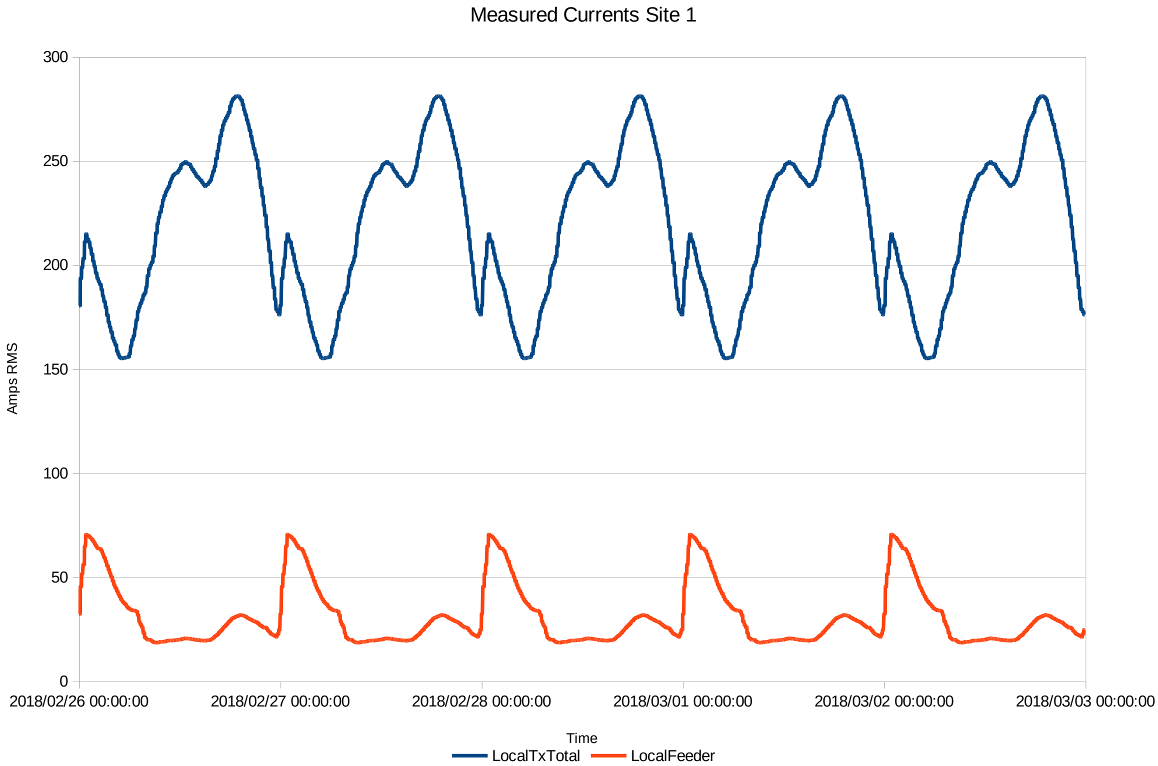


**Figure 24: Site 1_CB-Closed – Measured Currents – Site 1**

The closed load predictions at 13:00 and 23:00 on 2018/02/27 are a straightforward overlay onto the measured load current (Figure 25).

This is because there is no calculation to obtain the closed load when the Site 1 Alvin Reclose™ Circuit Breaker is already closed.

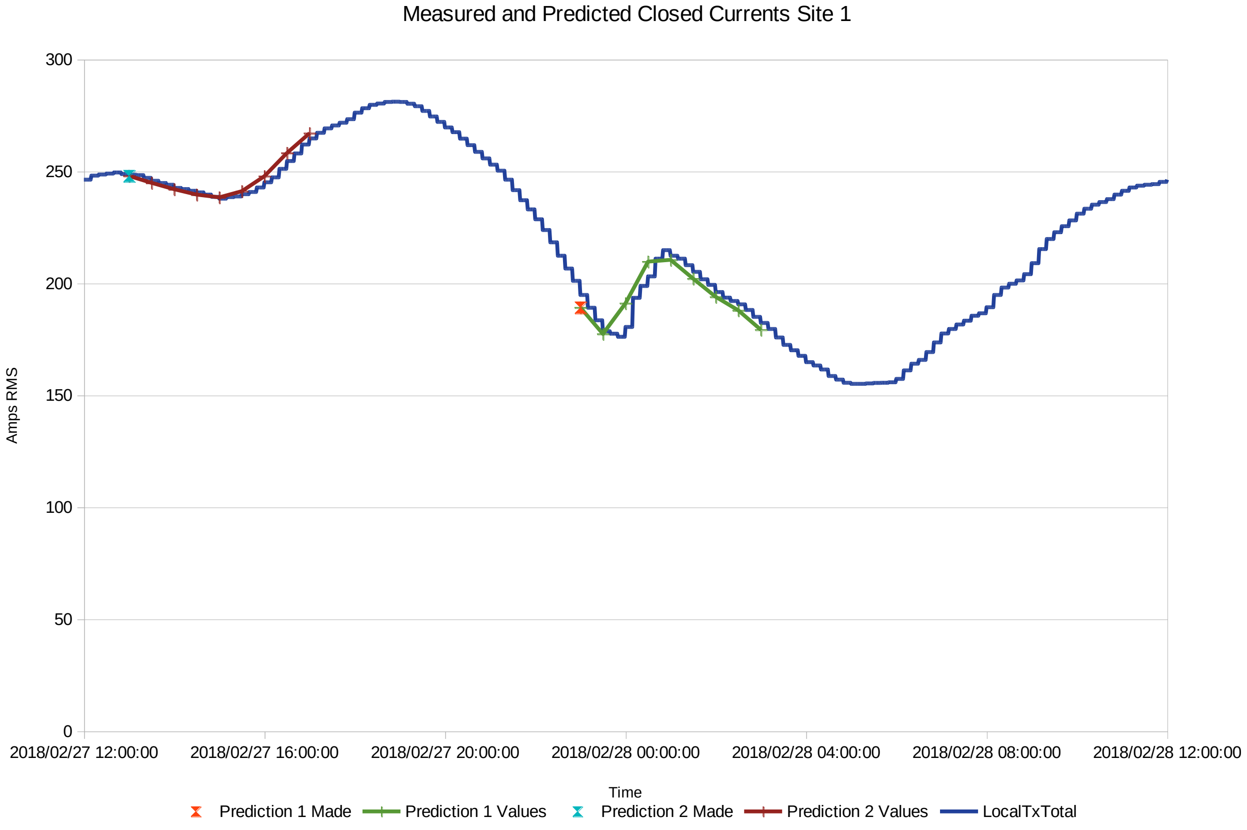


**Figure 25: Site 1_CB-Closed – Measured and Predicted Closed Currents – Site 1**

With the Circuit Breaker closed, we must calculate the loads which would occur if it were opened. This is robust because it simply involves subtracting the feeder load from the total load (both local measurements) to get the remainder of the Site 1 load (Figure 26).

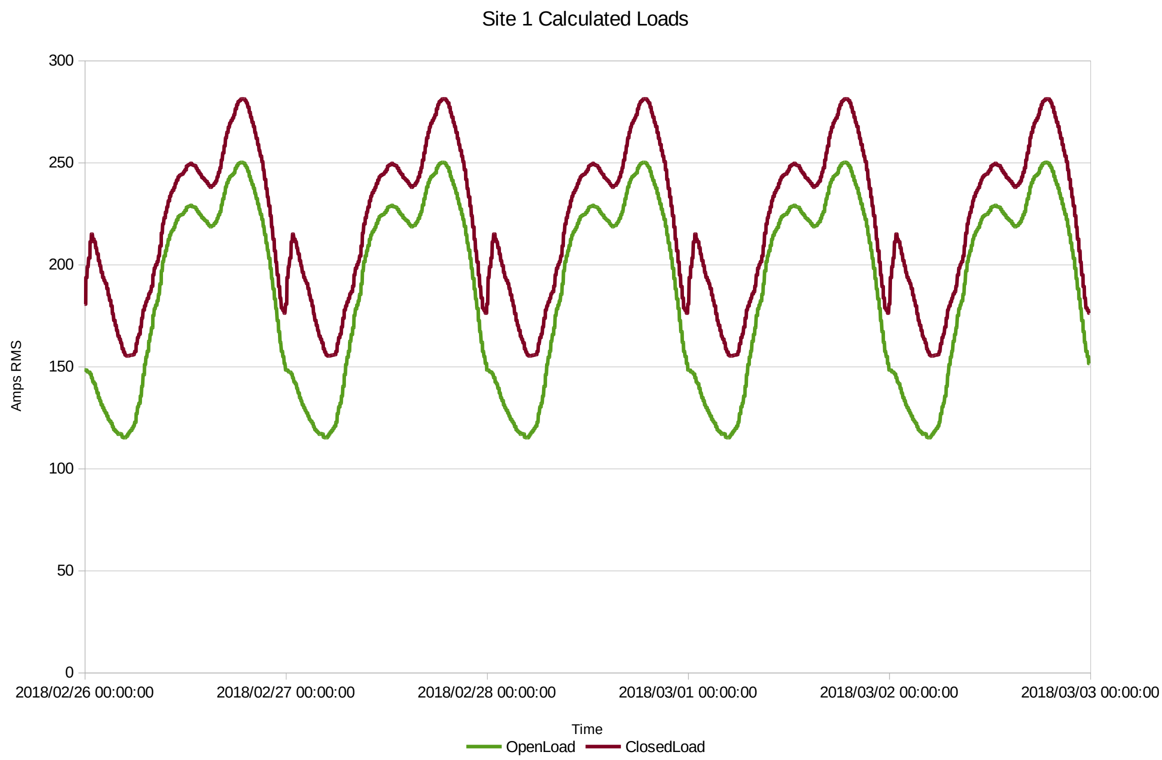


**Figure 26: Site 1_CB-Closed – Calculated Loads – Site 1**

The resulting plots are:

- Brown trace (ClosedLoad) – Total load experienced by the Site 1 transformer where the Site 1 Circuit Breaker is closed.
- Green trace (OpenLoad) – The total experienced by the Site 1 transformer where the Site 1 Circuit Breaker open; equal to:
- the ‘other load’ for Site 1;
- total load less 50% of the meshing load; or
- total load less the monitored load of the meshing feeder at Site 1.

The brown trace is equal to the blue trace shown in Figure 24.

Again, we can plot the predictions of open state load current overlaid on Figure 27 to show they are correct.

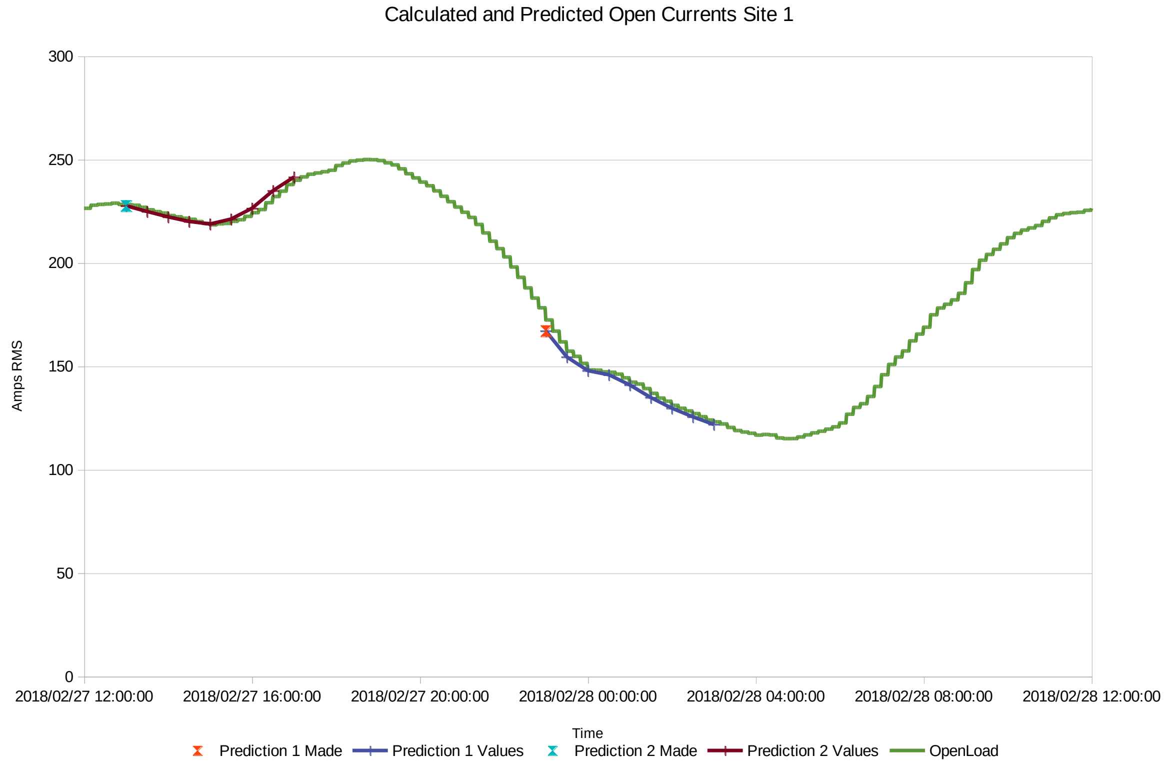


**Figure 27: Site 1_CB-Closed – Calculated and Predicted Currents Circuit Breaker were opened**

Finally, we examine some data with the Site 1 Alvin Reclose™ Circuit Breaker switching in and out over the course of the day (Figure 28).

This results in local feeder load current when the Circuit Breaker is closed, and none when the Circuit Breaker is open. A corresponding increase in the total transformer load when the Circuit Breaker is closed is also shown. A Circuit Breaker Position of "1" indicates that the Circuit Breaker is closed, and "0" indicates it is open.

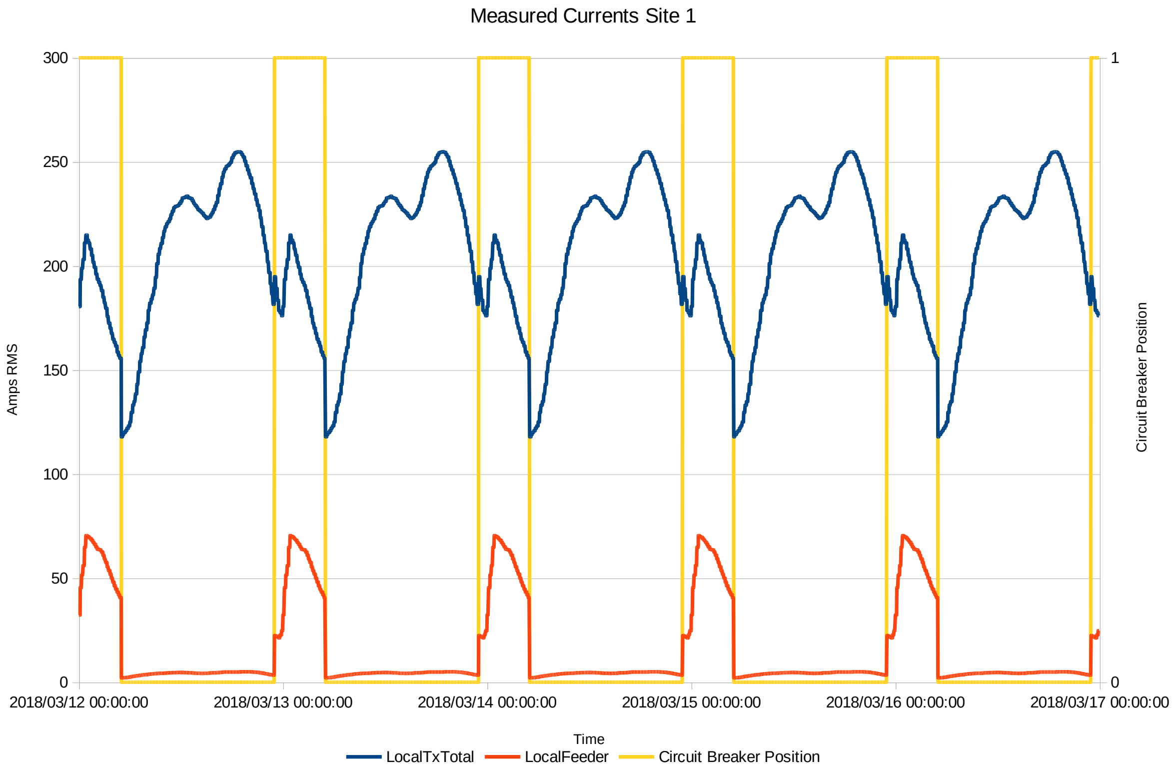


**Figure 28: Measured Currents – Site 1**

This graph just shows the measurements, which demonstrates our test data is correct. The calculations of Open and Closed load currents must be carried out considering the position of the Circuit Breaker at the time.

The resulting plots look the same as they always have done, which is the point of these calculations – we can arrive at the load current for each fixed network configuration, even though the actual network configuration is changing over time.

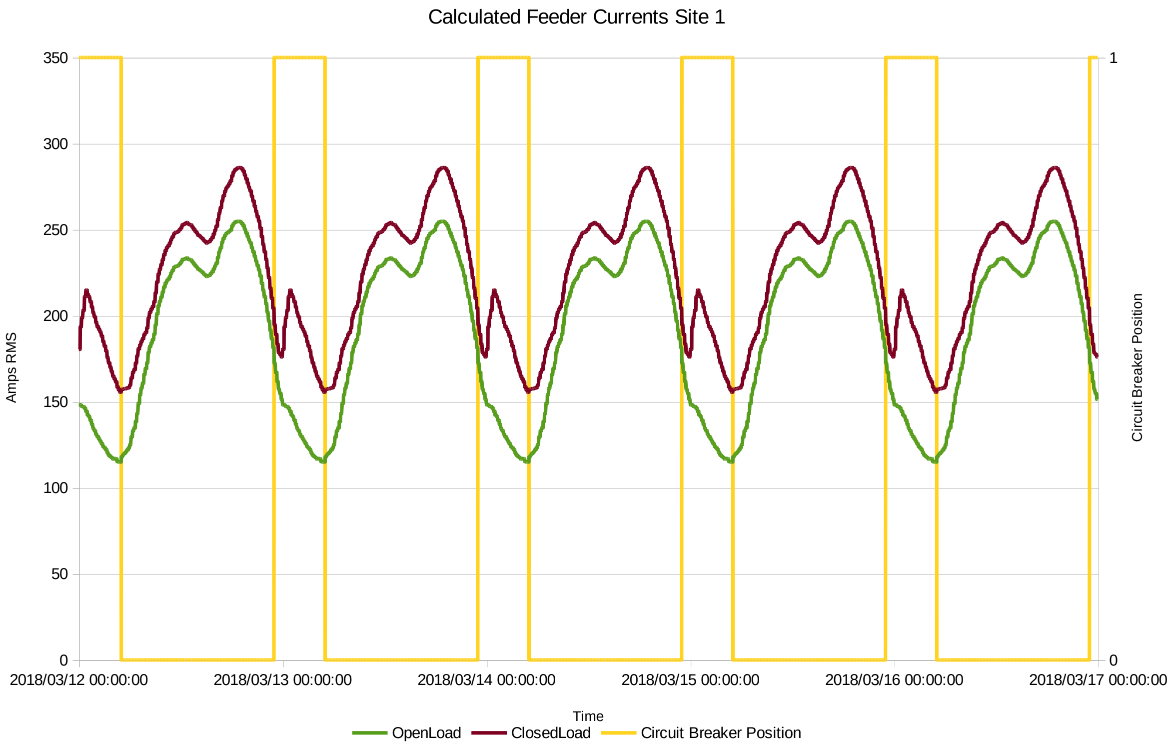


**Figure 29: Calculated Feeder Currents – Site 1**

The prediction of the future open and closed load currents from this data (Figure 29) goes exactly as before, with the graphs looking just the same because they are based on the same open and closed currents.

### 3.4.2 Site 2

The story at Site 2 is similar but requires consideration of the different effect of the meshing feeder. With the Site 1 Alvin Reclose™ Circuit Breaker held (always) open, we have the "other" load and all the meshing feeder load on the Site 2 transformer.

Here, (Figure 30), we see the following plots:

- Blue trace (LocalTxTotal) – Total load on the Site 2 Transformer when the Circuit Breaker at Site 1 is open.
- Red trace (LocalFeeder) – Total load on the meshing feeder.

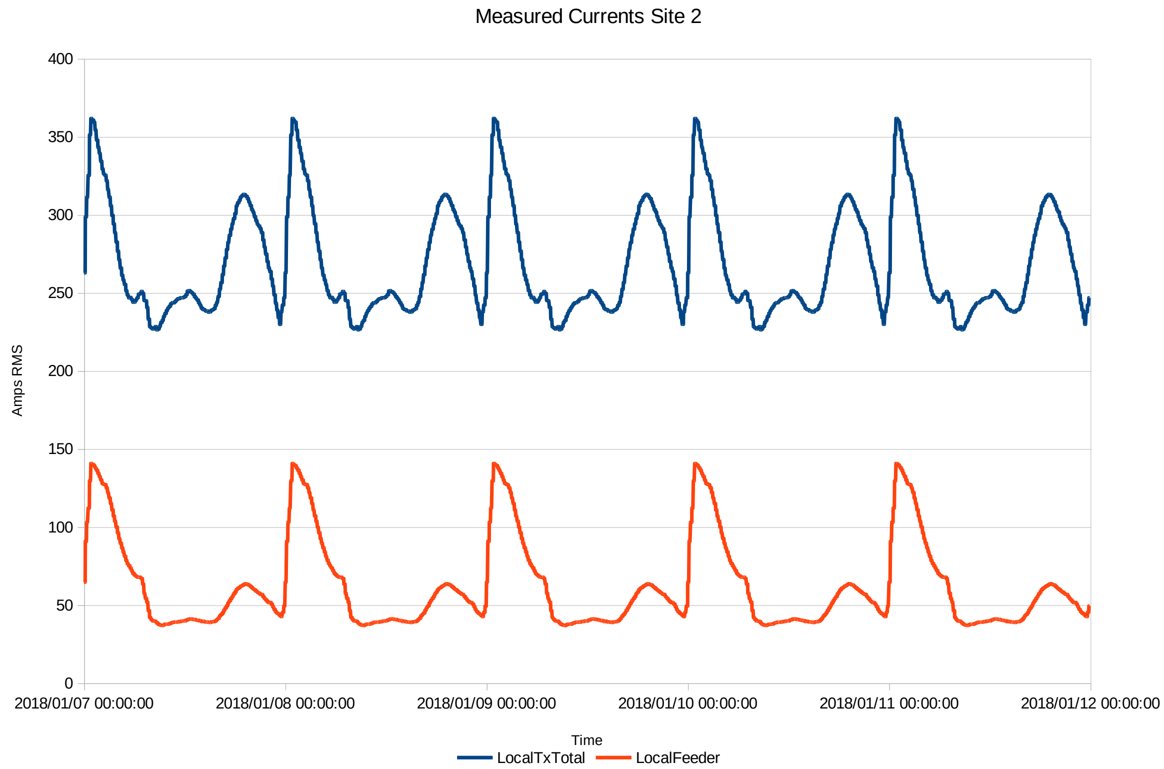


**Figure 30: Site 1_CB-Open – Measured Currents – Site 2**

Next look at the first day in more detail (Figure 31), overlaying the predicted transformer current with the circuit breaker held open onto the graph of actual current. Taking the prediction made at 01:00:00 UTC on 2018/01/08, we can see that it lies on top of the actual transformer load, and again with the prediction made at 18:00:00 UTC on 2018/01/08 the same happens. So, we have predictions of the load with the Site 1 Alvin Reclose™ Circuit Breaker open. As this depends only on the (very predictable) measured load, the accuracy is higher than would be expected in a business-as-usual scenario.

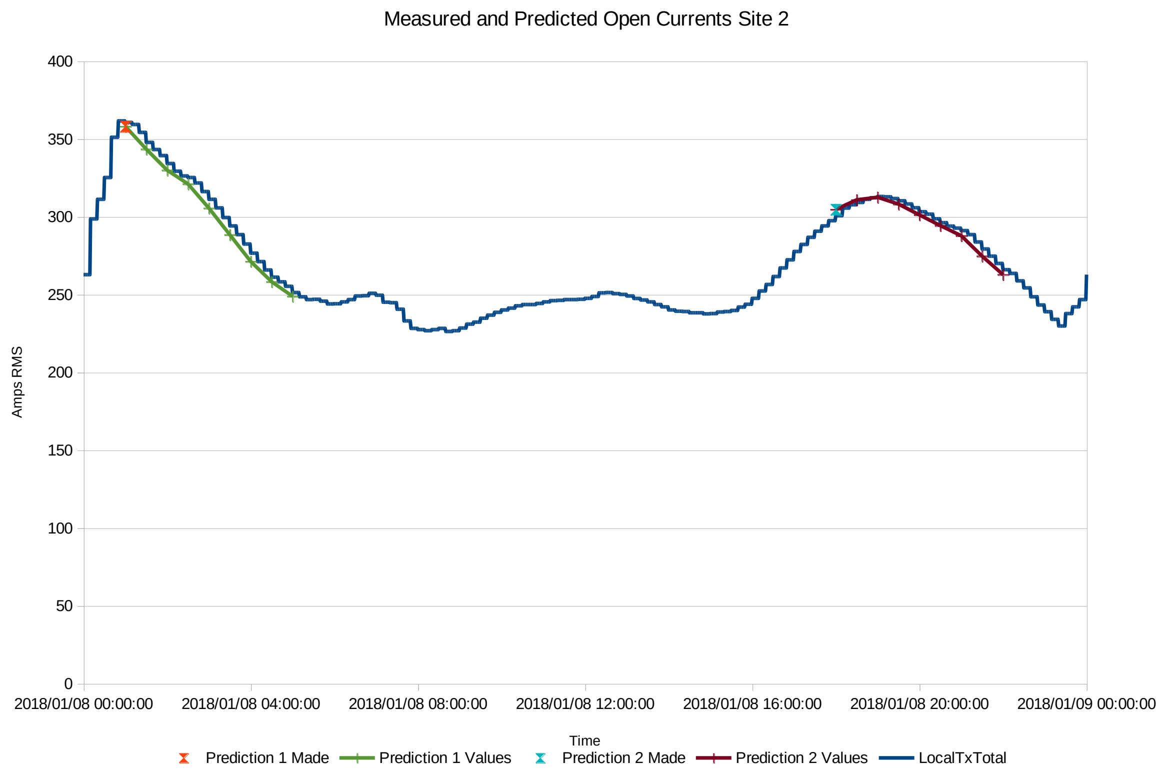


**Figure 31: Site 1_CB-Open – Measured and Predicted Open Currents – Site 2**

Moving on to the prediction of the loading with the Site 1 Alvin Reclose™ Circuit Breaker closed, we must assume about the sharing of the meshing feeder load between the two transformers. For this sequence of project tests, we have assumed that 50% of the meshing feeder load will be transferred to Site 1.

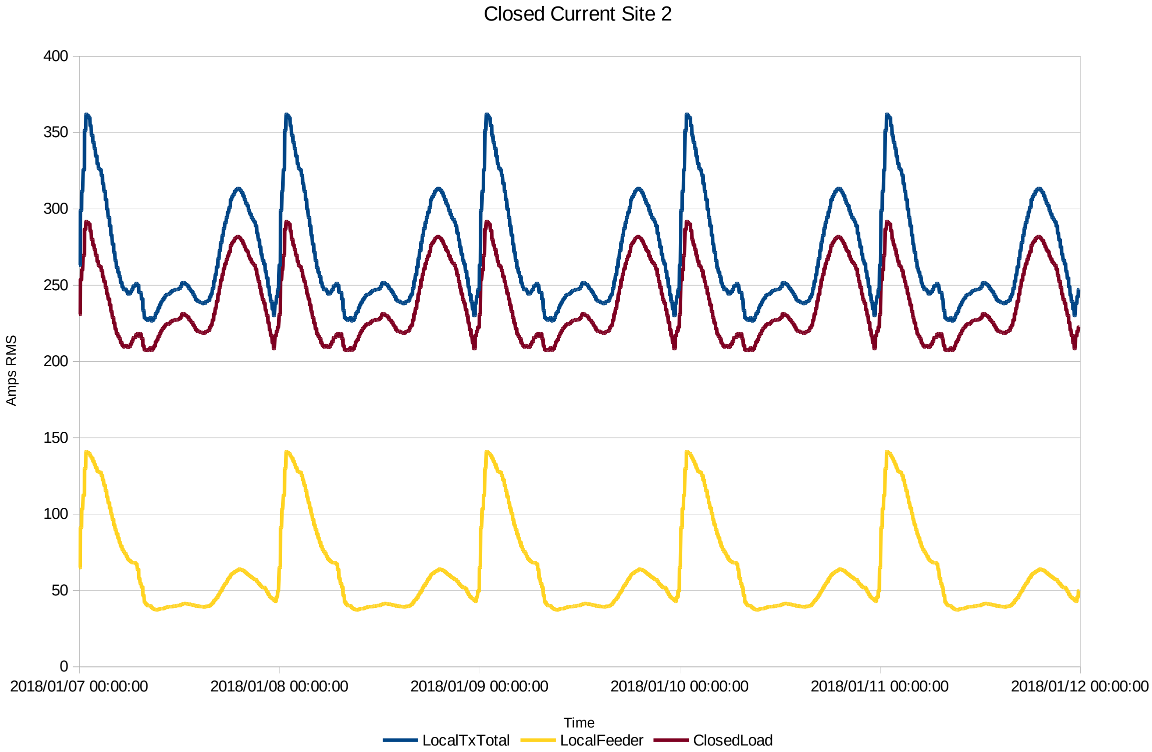


**Figure 32: Measured Currents – Site 2**

Here, (Figure 32), we see the following plots:

- Blue trace (LocalTxTotal) – Total transformer load at Site 2 with the Circuit Breaker at Site 1 open.
- Yellow trace (LocalFeeder) – Total load on the local (meshing) feeder.
- Brown trace (ClosedLoad) – Total transformer load at Site 2 with the Circuit Breaker at Site 1 closed. (In this instance, 50% of the meshing feeder load is transferred from the Site 2 transformer to Site 1.)

Looking again at 1 day, 2018/01/08 (Figure 33), we can show the predictions of closed load and the outcome closed load. The data matches up very well.

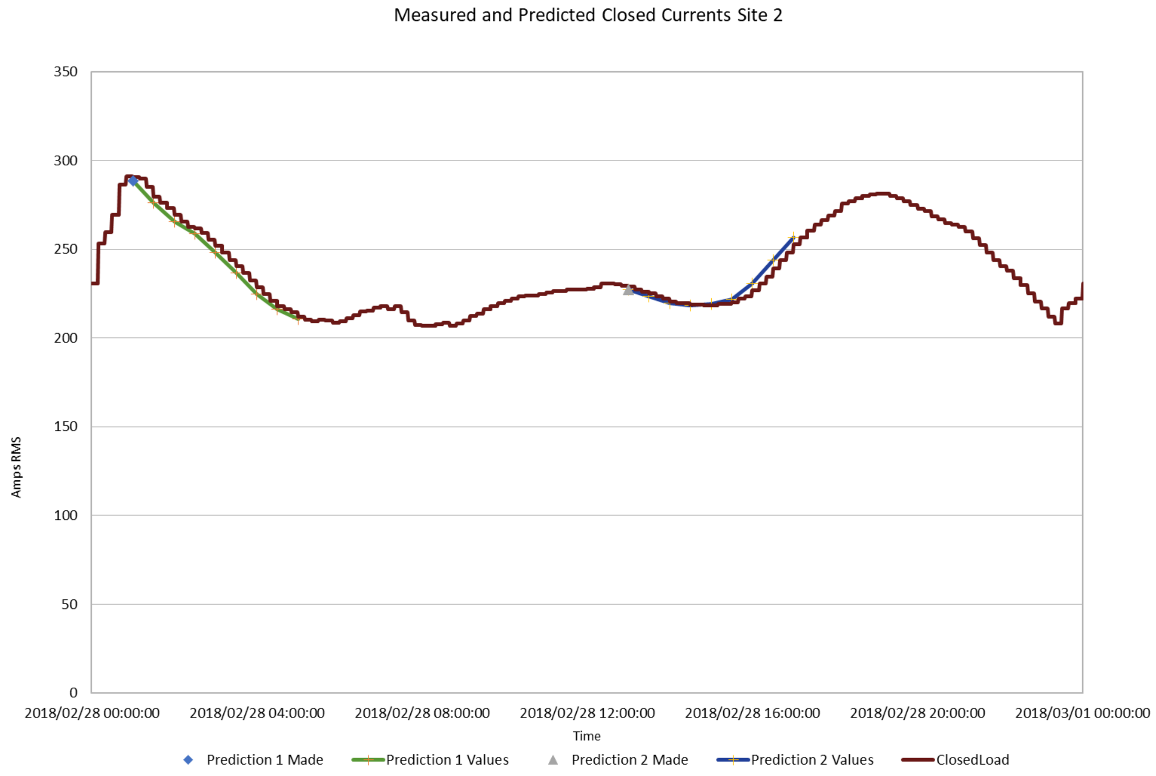


**Figure 33: Measured and Predicted Closed Currents – Site 2**

When the Site 1 Alvin Reclose™ Circuit Breaker is closed, the load on the meshing feeder, at Site 2 is smaller due to Site 1 taking 50% of the load. Consequently, it has a less dominant impact on the site total load as shown in Figure 34.

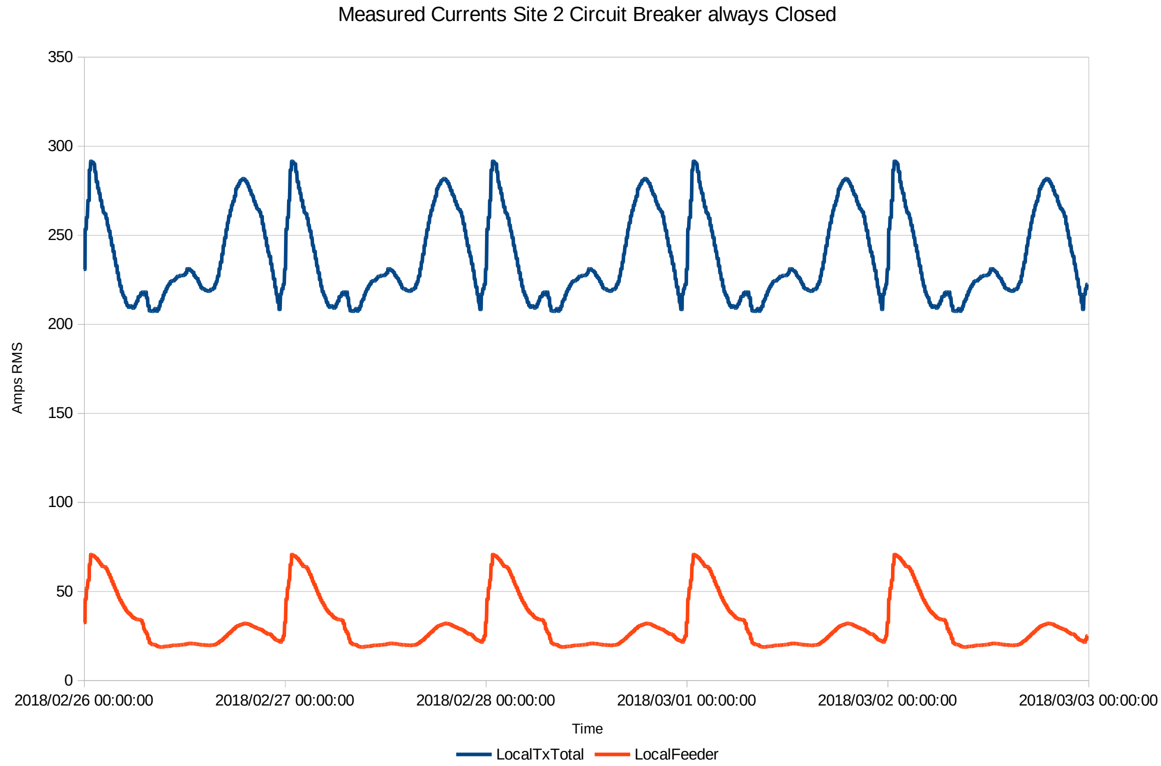


**Figure 34: Measured Currents – Circuit Breaker Closed – Site 2**

Calculating the currents, the pattern reverses – the closed load is the same as the measured transformer load, and for the open load we must add on the additional load we expect to be transferred from the meshing feeder. This results in the same graph (Figure 35) as when the Circuit Breaker is open, despite the different measurement inputs.

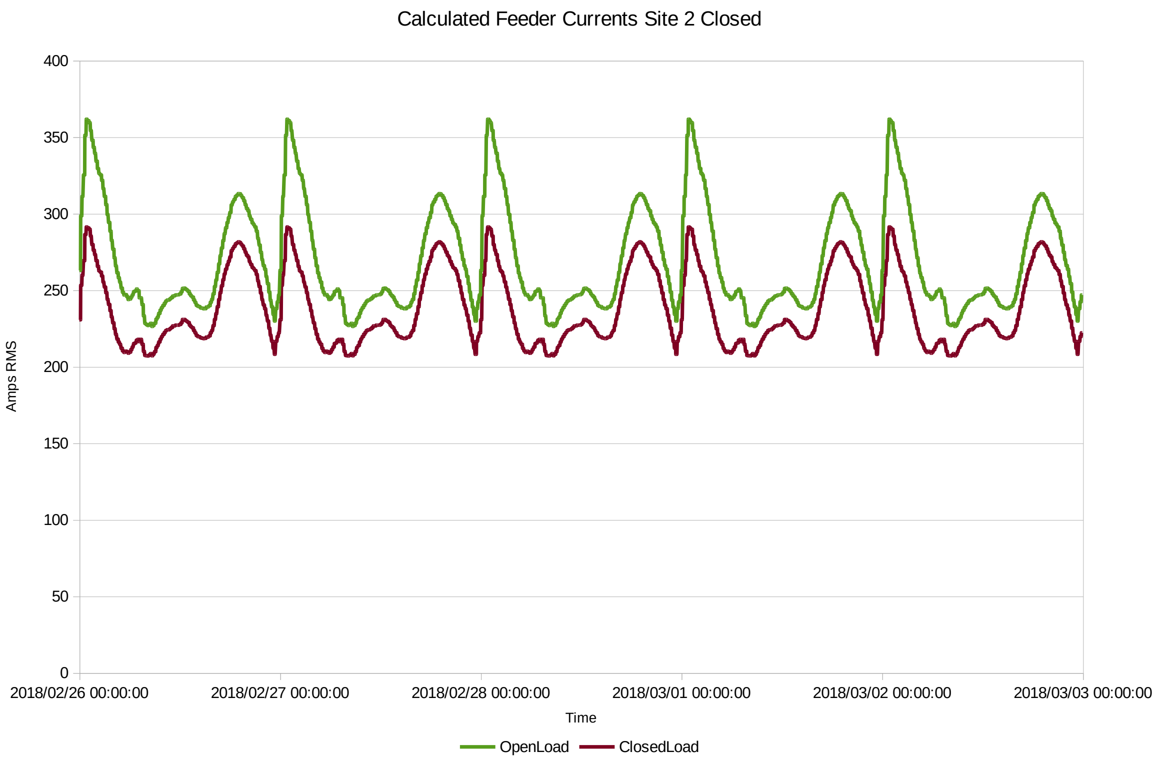


Figure 35: Calculated Feeder Currents – Site 2 - Closed

When the Site 1 Alvin Reclose™ Circuit Breaker is open, the load at Site 2 is increased due to managing the full load of the Meshing Feeder. Due to the meshing feeder load having Economy 7 dominance, the load on the transformer is correspondingly higher still during the Economy 7 peak.

From these calculated currents predictions are made for the two cases(Figure 36 & Figure 37), Circuit Breaker open and closed, as before. These again track the actual curve closely because of the consistent input data.

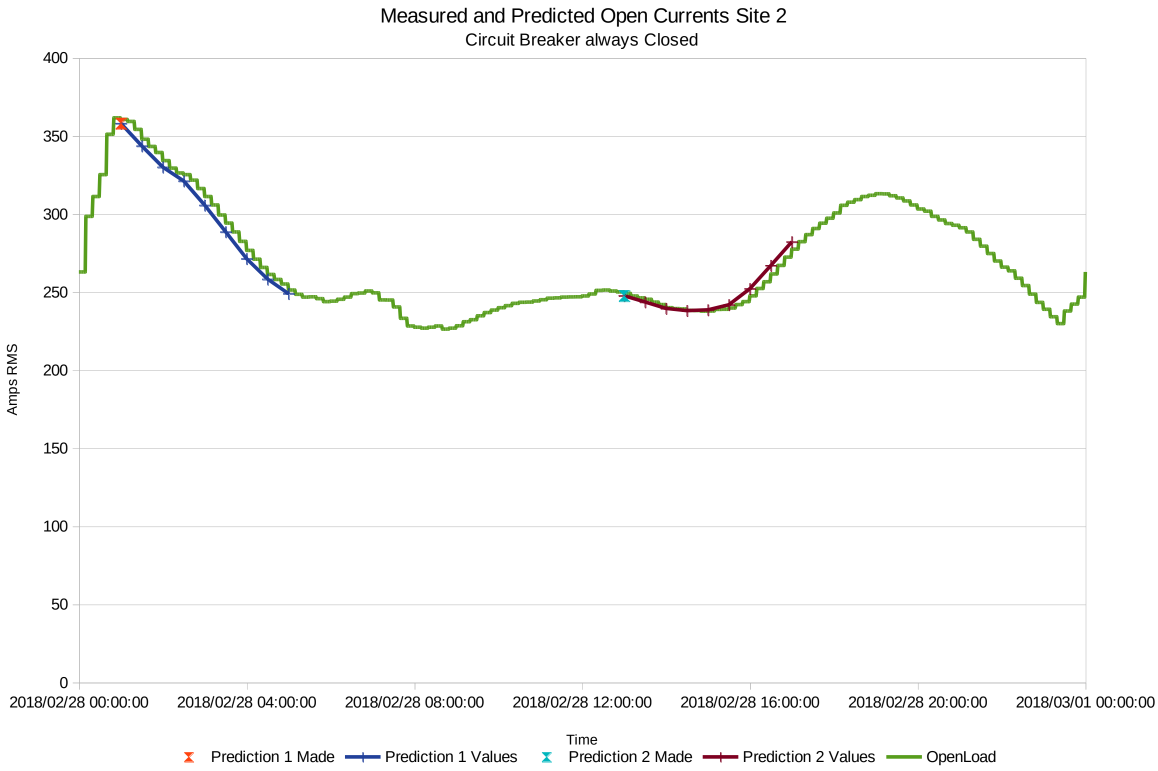


**Figure 36: Measured and Predicted Open Currents – Circuit Breaker Closed – Site 2**

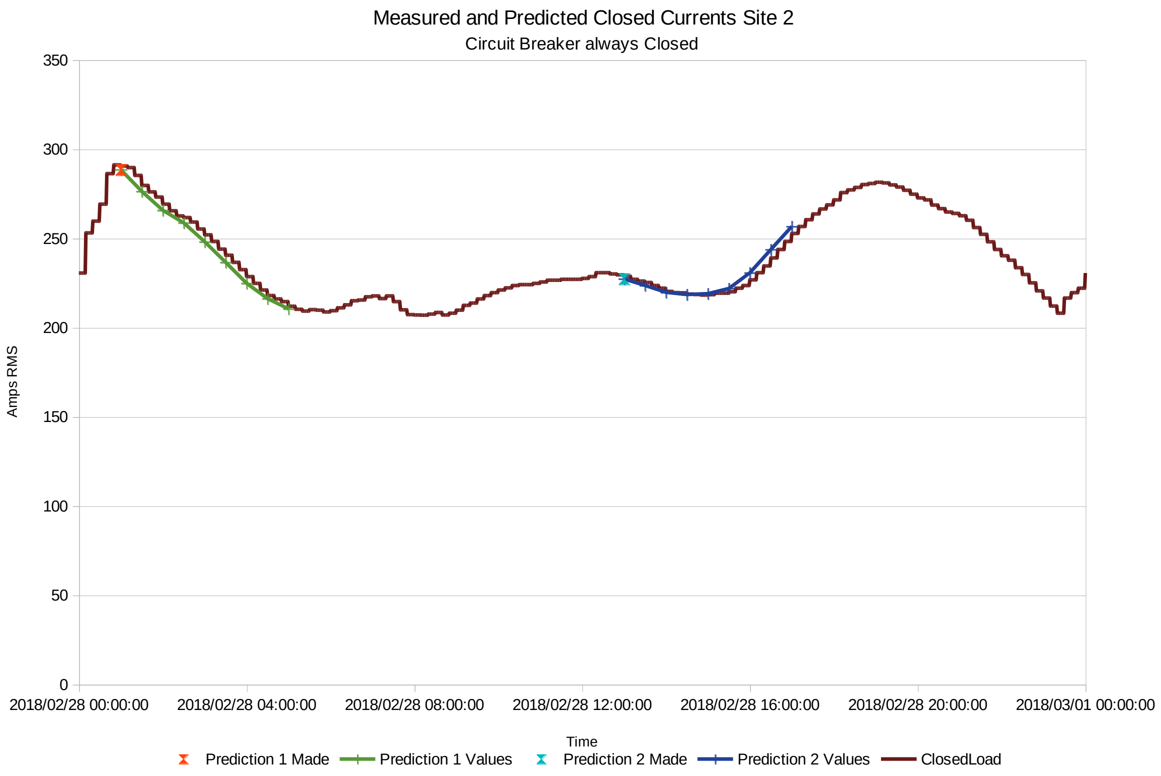


**Figure 37: Measured and Predicted Closed Currents – Circuit Breaker Closed – Site 2**

Finally, we examine some data (Figure 38) with the Site 1 Alvin Reclose™ Circuit Breaker switching in and out over the course of the day.

This results in feeder load current as monitored at Site 2 being lower when the Site 1 Alvin Reclose™ Circuit Breaker is closed compared to when it is open.

A corresponding reduction in the total transformer load when the Site 1 Circuit Breaker is closed is also shown. A Circuit Breaker Position of "1" indicates that the Circuit Breaker is closed, and "0" indicates it is open.

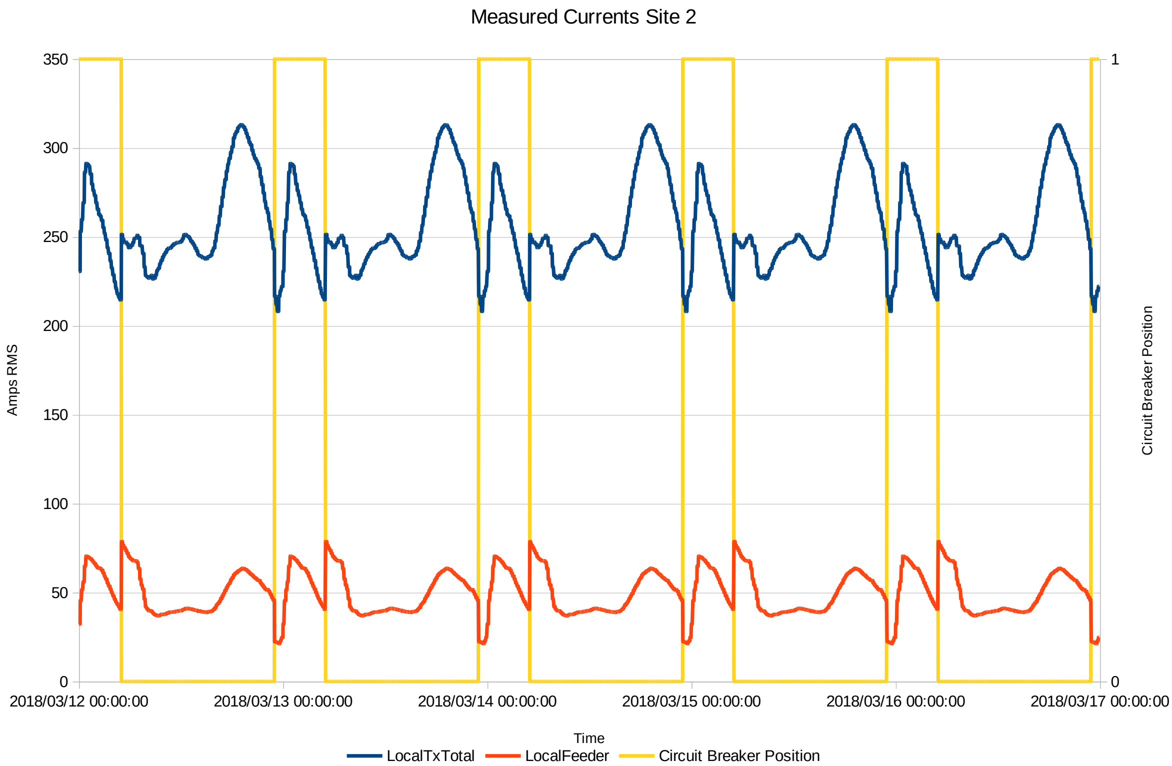


Figure 38: Measured Currents – Site 2

Figure 39 shows the measurements, demonstrating the test data is correct. The calculations of Open and Closed load currents must be carried out considering the position of the Circuit Breaker at the time.

The resulting plots look the same as they always have done, which is the point of these calculations – we can arrive at the load current for each fixed network configuration, even though the actual network configuration is changing over time.

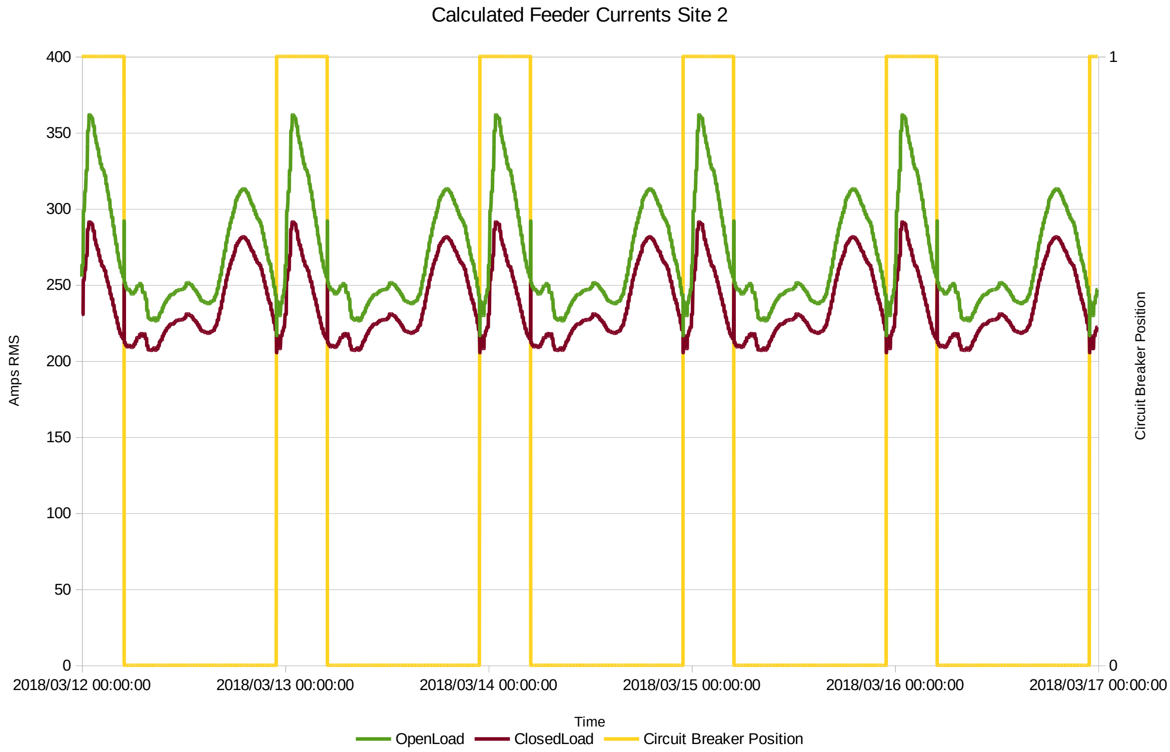


**Figure 39: Calculated Feeder Currents – Site 2**

The prediction of the future open and closed load currents from this data goes exactly as before, with the graphs looking just the same because they are based on the same open and closed currents.

## 3.5 Present Transformer State

To make any prediction about the future temperature of the transformer, we must first know what state it is in now. This is done by tracking the transformer's thermal state, calculated from the actual (measured) load current and actual (measured) ambient temperature using the Weathersense application. This does not require any predictions to be made, because it relates only to matters of historical fact.

For these tests the ambient temperature is held constant at 17$^{o}$C, so is not shown on the graphs.

### 3.5.1 Site 1

#### 3.5.1.1 Circuit Breaker Open

As before the blue trace is the total transformer load (Figure 40), in this case with the Site 1 Circuit Breaker (held) open. The load scale is shown on the left-hand y-axis. The purple trace shows the transformer top oil temperature, and the red the winding hot spot temperature. Both are plotted with reference to the right-hand y-axis. We can see the temperatures substantially lag the load current, both in heating and cooling.

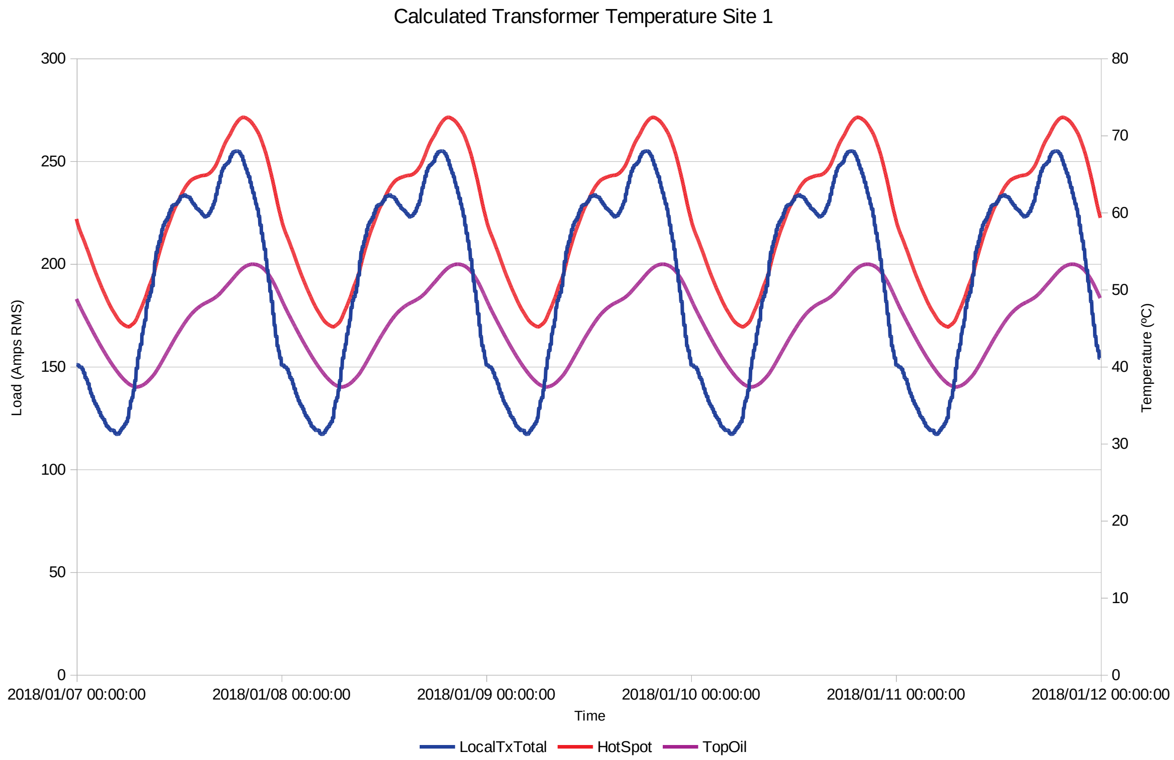


Figure 40: Calculated Transformer Temperature– Circuit Breaker Open – Site 1 (Multiple Days)

Looking at one day's cycle in more detail (Figure 41) whilst the load current peaks at 18:00 (UTC), the winding hotspot temperature peaks at 19:00 and the top oil temperature at 21:00.

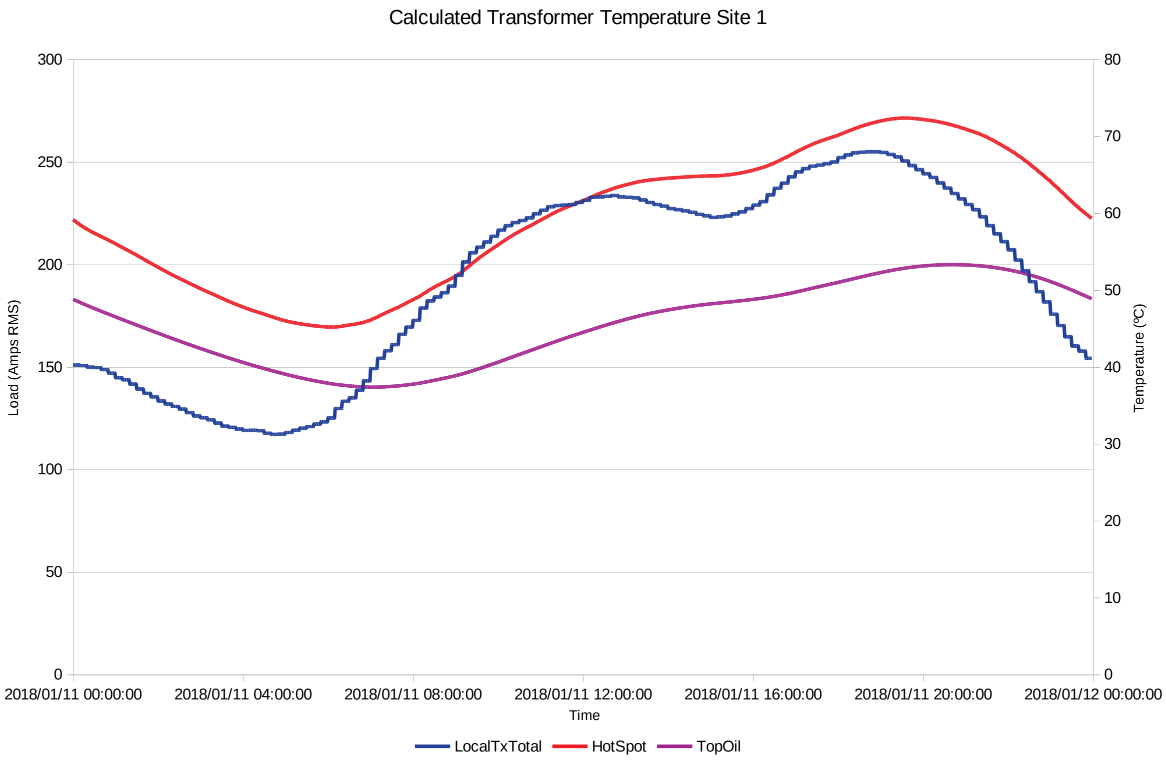


**Figure 41: Calculated Transformer Temperature– Circuit Breaker Open – Site 1 (Single Day)**

### 3.5.1.2 Circuit Breaker always Closed

If we were to operate the feeder in meshed configuration then we would observe a higher transformer operating temperature, with a second peak in the hotspot where the overnight economy 7 load comes in (Figure 42).

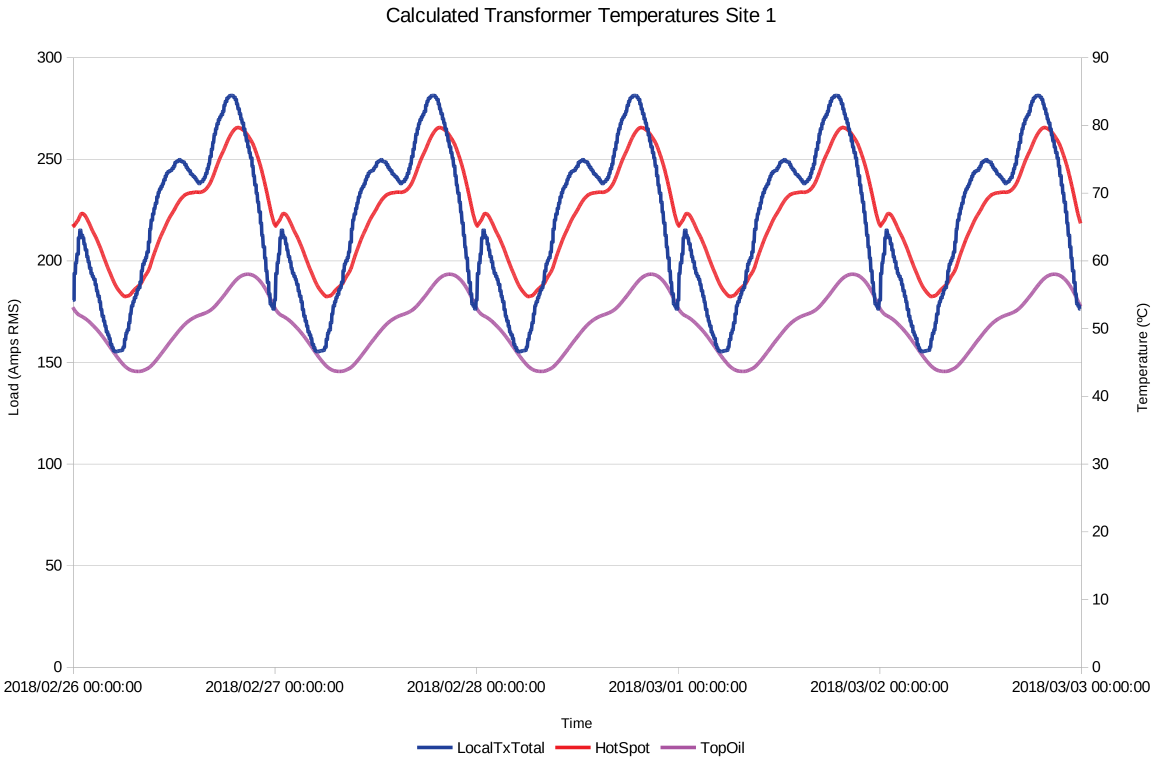


**Figure 42: Calculated Transformer Temperature – Circuit Breaker Closed – Site 1 (Multiple Days)**

Because the Economy 7 peak is relatively short it does not produce a peak in the top oil temperature, just a slowing in the rate of cooling after the main evening peak (Figure 43).

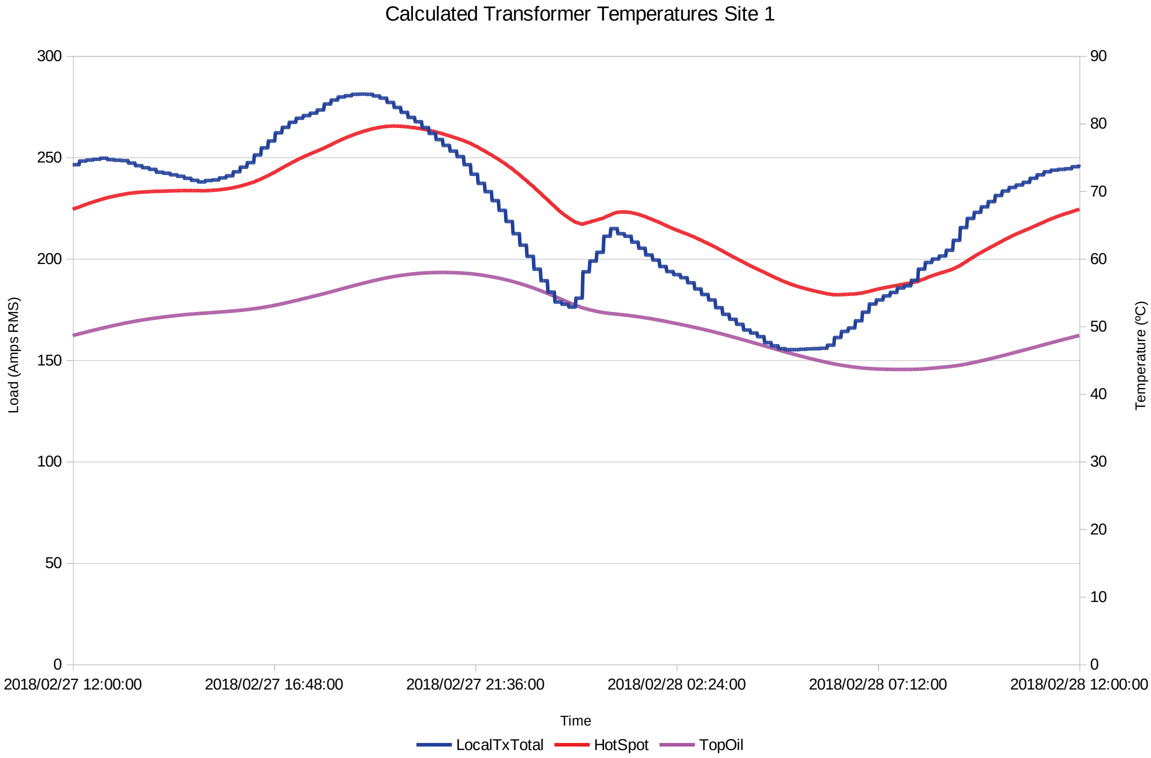


**Figure 43: Calculated Transformer Temperature – Circuit Breaker Closed – Site 1 (Single Day)**

### 3.5.1.3 Circuit Breaker switching

With the automated meshing operating to mesh the network only during the Economy 7 peak, we get an intermediate set of temperatures. There is a second peak during Economy 7, but it is less than with the network permanently meshed (Figure 44).

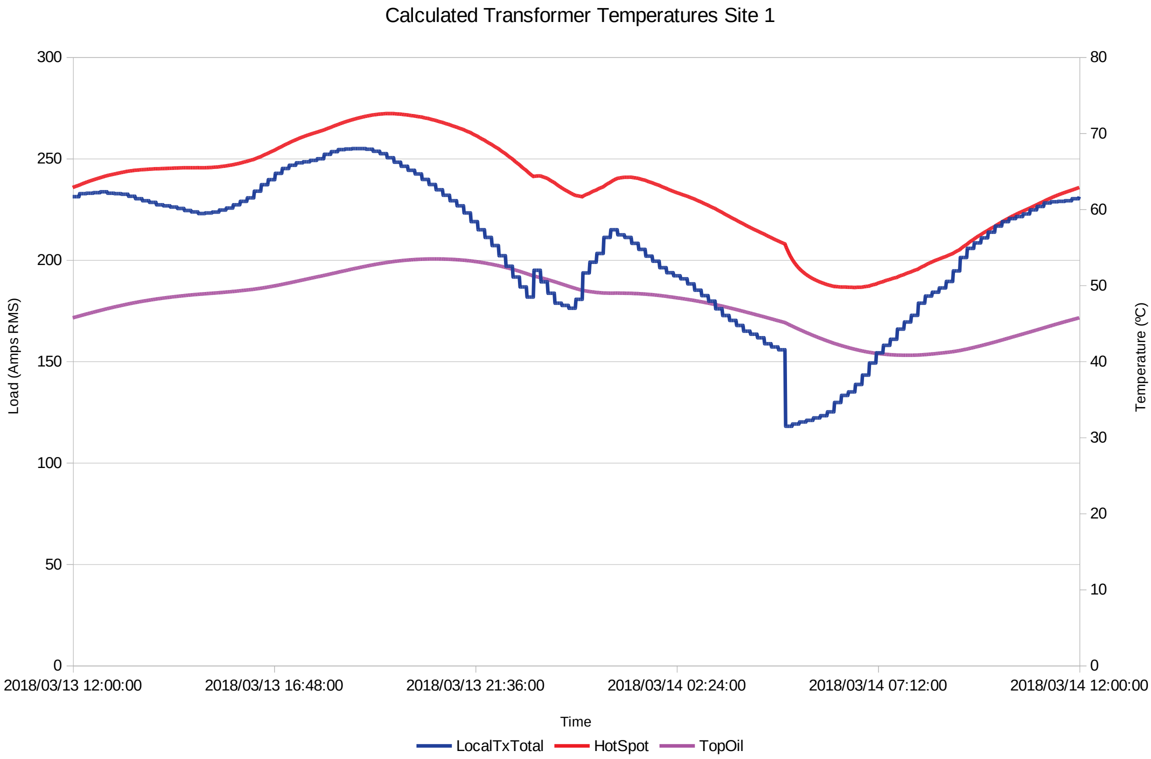


Figure 44: Calculated Transformer Temperature – Circuit Breaker Switching – Site 1 (Single Day)

This is clearer if we plot the hotspot under all three circumstances on one graph (Figure 45) – with the Site 1 Alvin Reclose™ Circuit Breaker always open, with it always closed, and with it switched automatically.

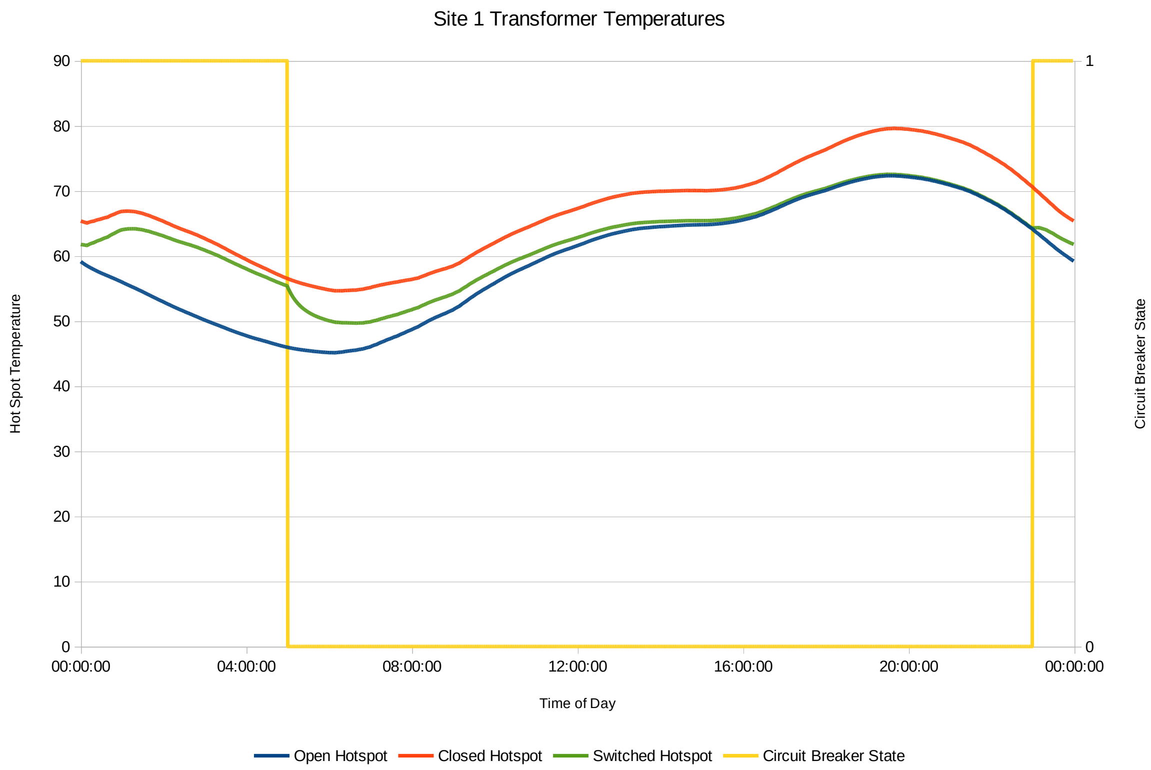


**Figure 45: Transformer Temperatures – Circuit Breaker Switching – Site 1**

Although the effects of the oil temperature mean it does not align exactly, we have the Switched trace following the Open trace most of the day but swinging off to follow the Closed trace when the Circuit Breaker is closed.

### 3.5.2 Site 2

#### 3.5.2.1 Circuit Breaker always Open

In Figure 46, the blue trace is the total transformer load, in this case with the Site 1 Alvin Reclose™ Circuit Breaker (held) open. The load scale is on the left-hand y-axis. The purple trace shows the transformer top oil temperature, and the red the winding hot spot temperature. Both are plotted with reference to the right-hand y-axis. We can see the temperatures substantially lag the load current, both in heating and cooling.

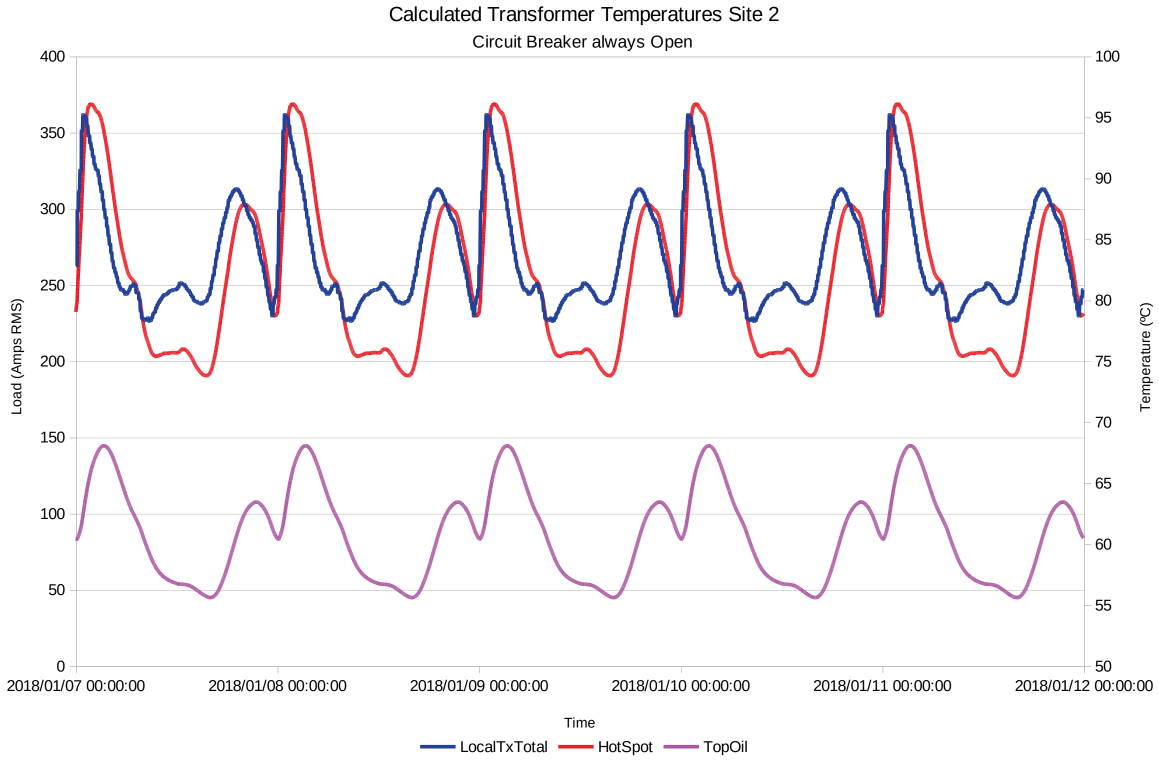


**Figure 46: Calculated Transformer Temperatures – Circuit Breaker Open –Site 2 (Multiple Days)**

### 3.5.2.2 Circuit Breaker always Closed

In this instance, (Figure 47), the load with the Site 1 Alvin Reclose™ Circuit Breaker closed is lower, and so are the temperatures, particularly during the Economy 7 peak due to the load being shared across Site 1 and Site 2 transformers.

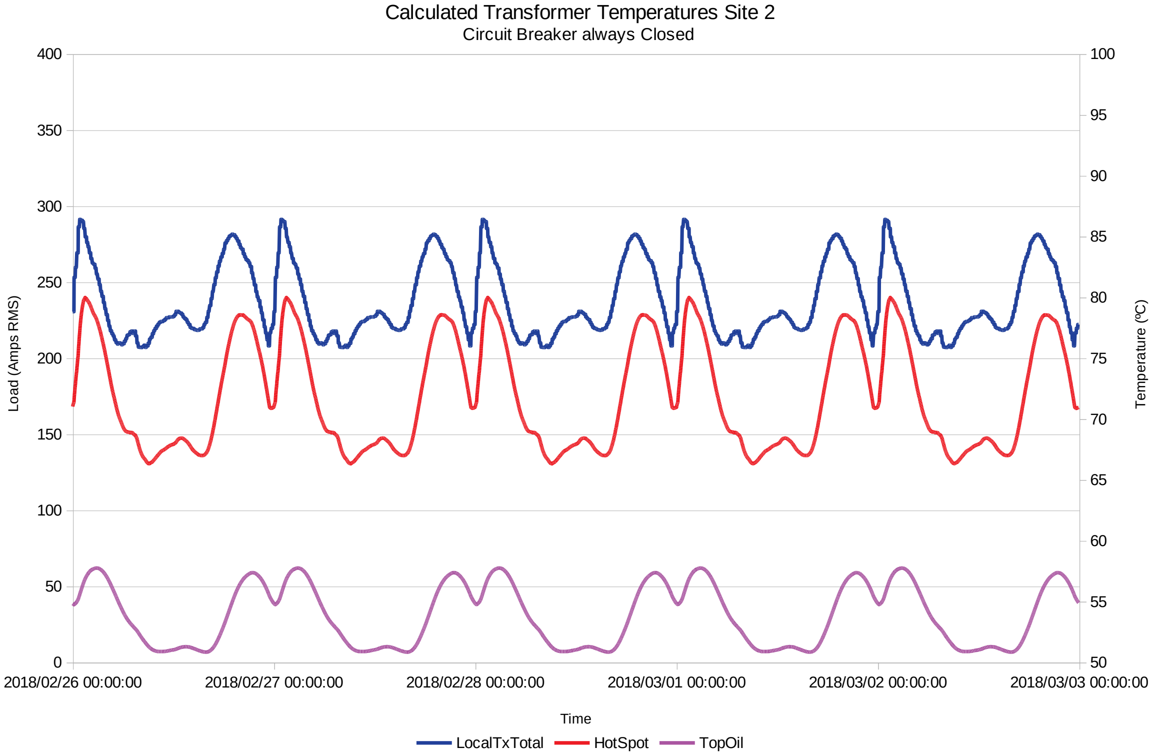


Figure 47: Calculated Transformer Temperatures – Circuit Breaker Closed –Site 2 (Multiple Days)

## 3.6 Predicted Transformer Temperature

To make the decisions for LoadSense it is necessary to make predictions for two scenarios: with the Site 1 Alvin Reclose™ Circuit Breaker open for the next four hours, and with the Site 1 Alvin Reclose™ Circuit Breaker closed for the next four hours. In both cases the starting point of the predictions is the present thermal state of the transformer, whether the Circuit Breaker is open or not. If the prediction is for a different circuit breaker state to what is presently the case, this may result in an abrupt change of load current for the transformer between the historic loading and the prediction. This is correct, because the prediction is assessing the consequences of operating the Circuit Breaker and causing this load change.

### 3.6.1 Site 1

#### 3.6.1.1 Circuit Breaker (always) Open

First, consider that the system has been running with the Site 1 Alvin Reclose™ Circuit Breaker open (so full load on Site 2, none transferred to Site 1), and we want to make a prediction for both Site 1 and Site 2 in the scenario where this Circuit Breaker remains open.

Looking at 2018/01/14 at 13:00 UTC, (Figure 48), we get a prediction for load over the next four hours (brown), and from that obtain a transformer hot-spot temperature prediction for the next four hours (green), which overlays exactly on the actual HotSpot temperature which occurred. (It is noted that the actual temperature would not be known at the time of the calculation, but the prediction and actual values are shown below to demonstrate the accuracy of the prediction.)

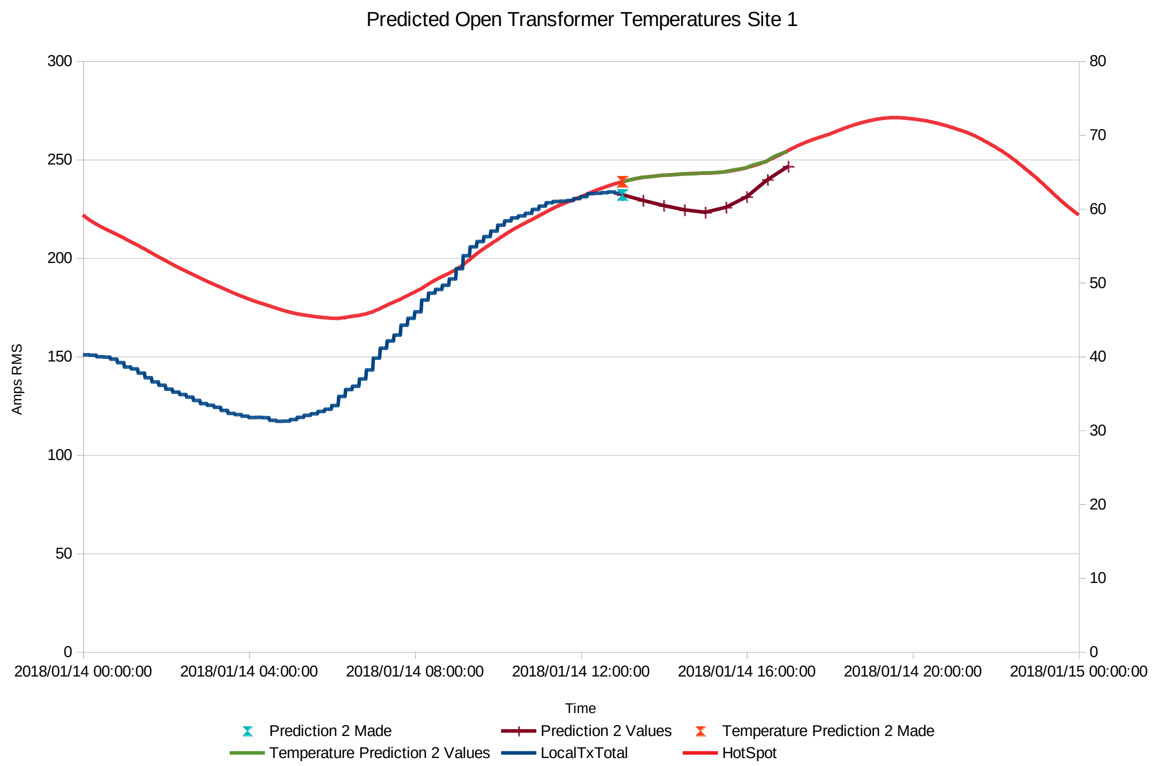


Figure 48: Predicted Open Transformer Temperatures – Site 1

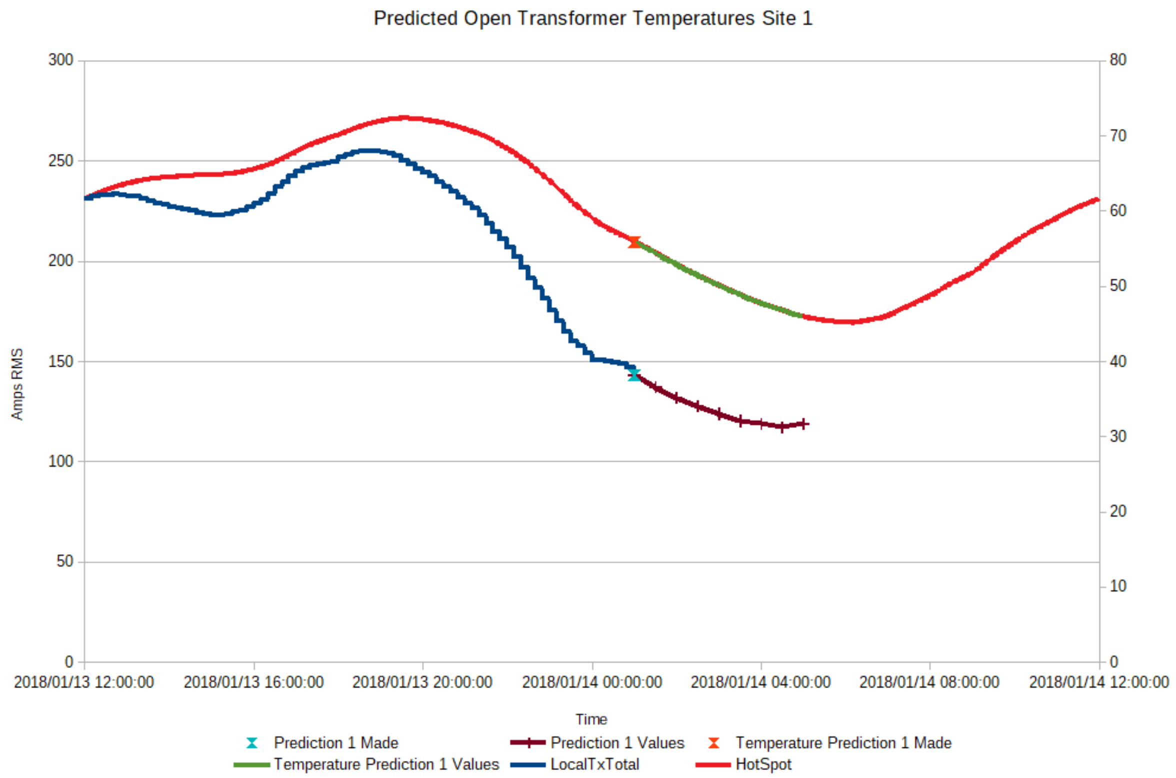


**Figure 49: Predicted Transformer Temperatures – Site 1**

Figure 49 shows another snapshot at 01:00 UTC, with the same matching of prediction and outcome.

The final step is to take the maximum temperature during the prediction period of 4 hours, because this is the value which the LoadSense algorithm depends upon. In Figure 48 the maximum is the last temperature in the prediction (because the load is forecast to rise steeply), where as in Figure 49 the maximum predicted temperature is the first temperature in the prediction, because a steadily falling load is forecast.

This is shown if we plot the maximum temperature from each forecast on the same graph as the out-turn HotSpot temperature (Figure 50).

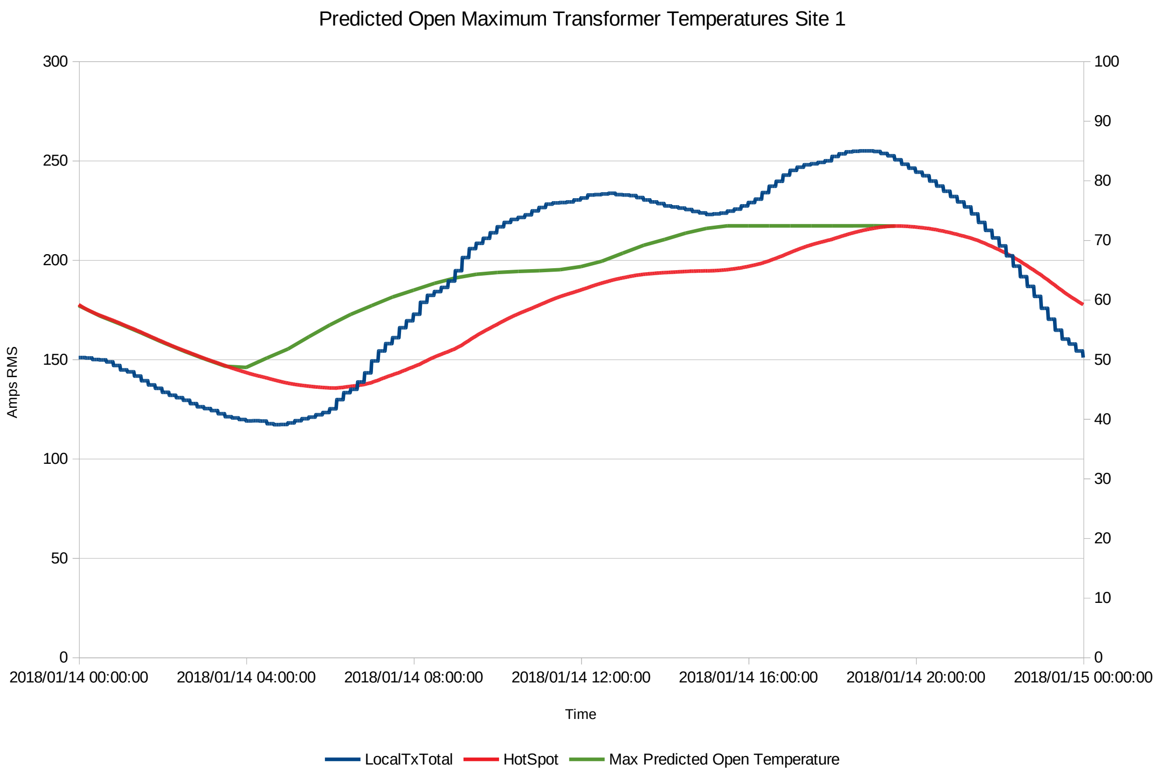


**Figure 50: Predicted Open Maximum Transformer Temperature – Site 1**

In the first part of the graph, the 4-hours-ahead maximum (calculated every 30 minutes) follows the cooling transformer down, but once the morning load rise comes into the 4-hour window, the maximum predicted transformer hotspot curve (in green) rises ahead of the actual transformer temperature (in red), with a 4-hour flat top (starting at 16:00) before it begins to fall again overnight.

Next consider that the system has been running with the Site 1 Alvin Reclose™ Circuit Breaker open (so no load transferred to Site 1), and we want to make a prediction for the scenario where the Circuit Breaker is closed, and load is transferred to Site 1.

Looking at 2018/01/08 at 13:00 UTC, (Figure 51), we start with the Site 1 Alvin Reclose™ Circuit Breaker open, and so the transformer load is as in the blue trace "LocalTxTotal". The prediction for load over the next four hours in brown shows the sudden rise when the Circuit Breaker is closed, which continues to rise with the system load. For comparison, the closed load calculation is plotted in red, so we can see how the prediction matches it.

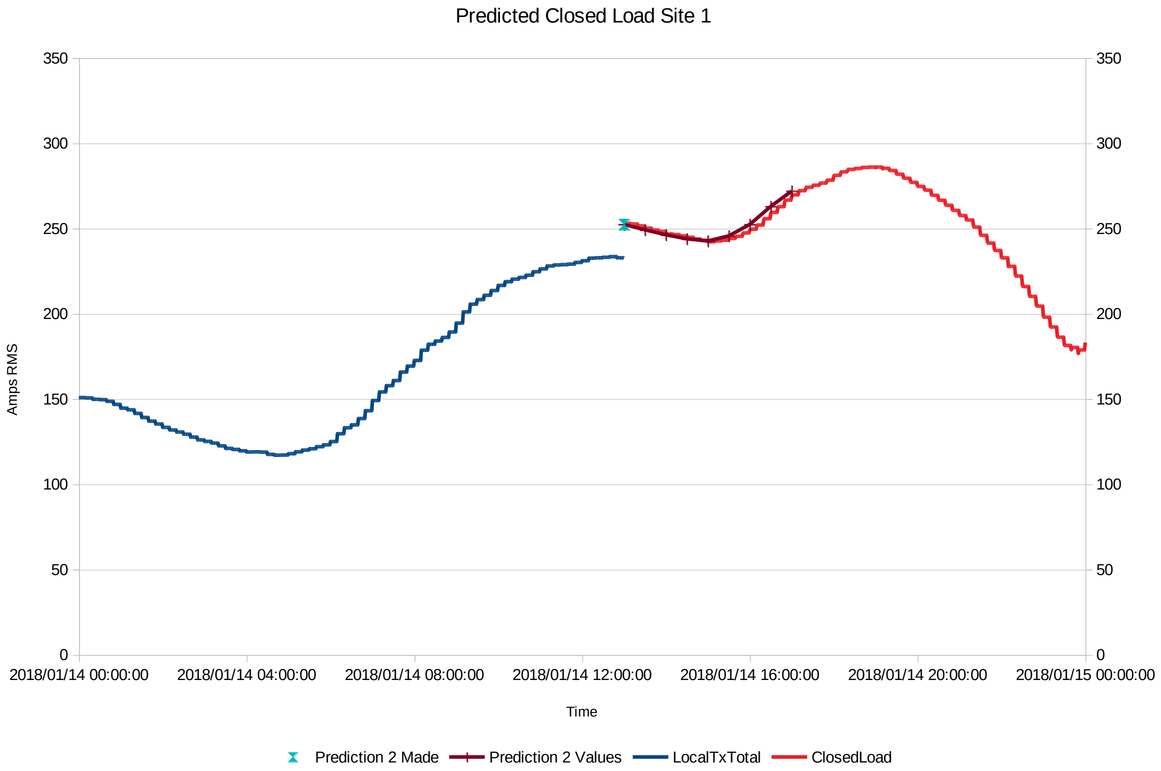


**Figure 51: Predicted Closed Load – Site 1**

From the load prediction a transformer hot-spot temperature prediction for the next four hours (green) is produced (Figure 52). The load initially rises when the Circuit Breaker operates (because load is transferred from Site 2 to Site 1), which causes the winding temperature to rise steeply. The overall load is falling however, so the rate of rise slows down (without ever quite cooling). Later the load rises again, and we see the predicted hotspot temperature rising again. This means the maximum temperature for the 4-hour period is the temperature at the end of the prediction period.

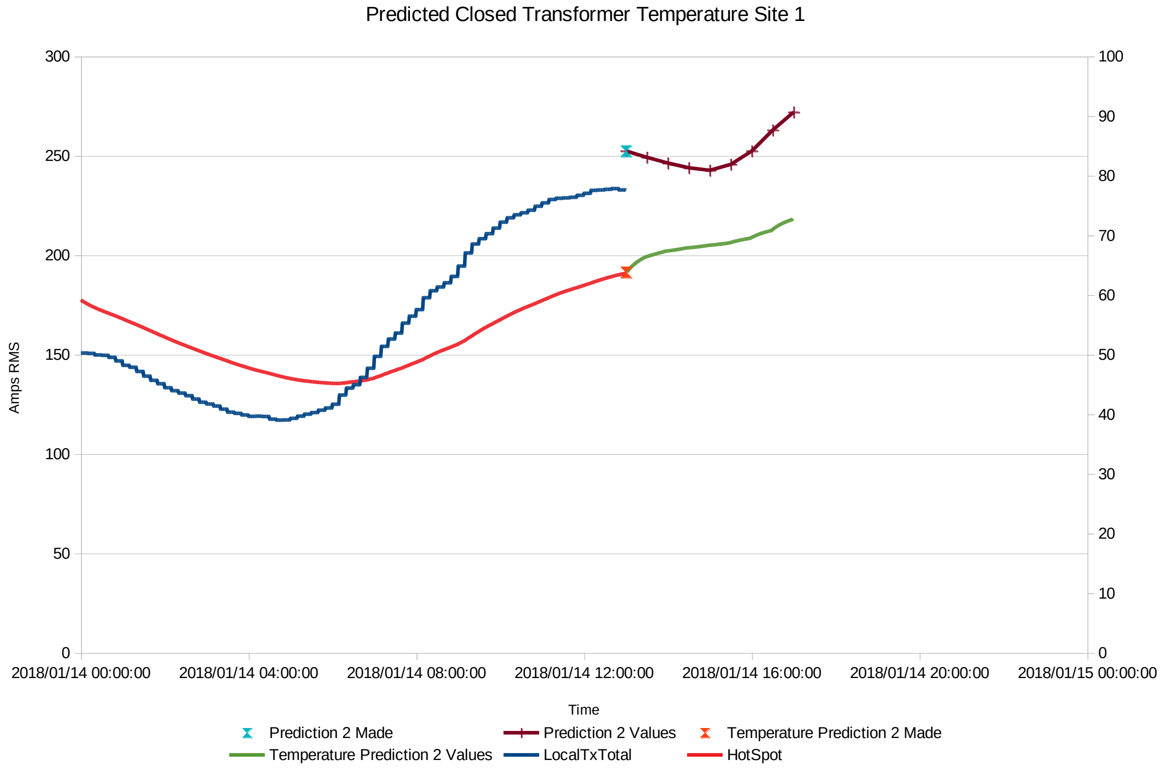


**Figure 52: Predicted Closed Transformer Temperature – Site 1**

The plot of the predicted maximum closed temperatures over the day (Figure 53), each time starting from the open load conditions, is not obvious.

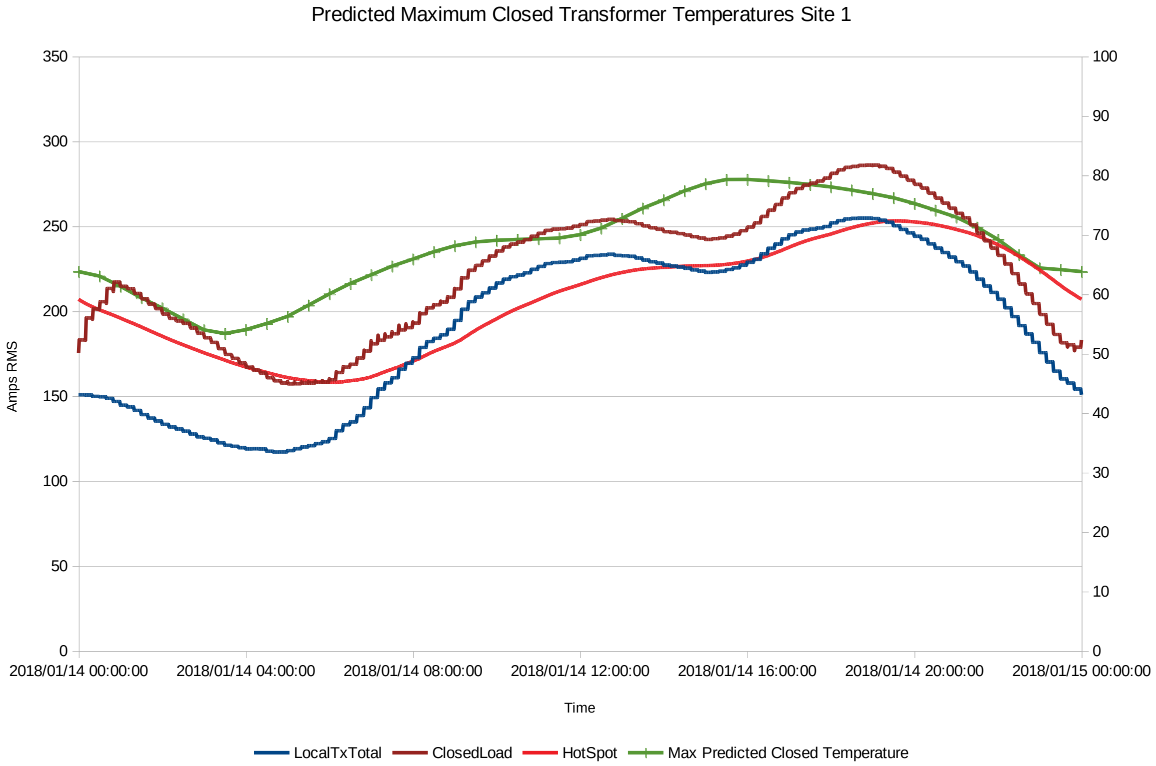


**Figure 53: Predicted Maximum Closed Transformer Temperature – Site 1**

Each point on the green trace reflects the outcome of a scenario evaluation in which:

- The Circuit Breaker is closed at the time the scenario starts (which is the present time).
- The Circuit Breaker remains closed for the next 4 hours.
- The maximum hotspot temperature experienced is evaluated.

The red trace shows the present transformer hot spot temperature under the present operating conditions, which for this graph is with the Circuit Breaker open.

The green curve is hotter than the red curve (as would be expected for increased load) almost all the time, except for a point at 23:00 where the two curves touch (but do not cross). This last point seems surprising.

Referring to the load graph (Figure 54), we can see that the load prediction for closing the Circuit Breaker at 23:00 jumps up for just one half-hour point, then drops back before rising again, following the closed load curve (Figure 54). This reflects the fact the prediction window starts on the falling shoulder of the evening load peak, but then extends to include the crest of the Economy 7 load peak.

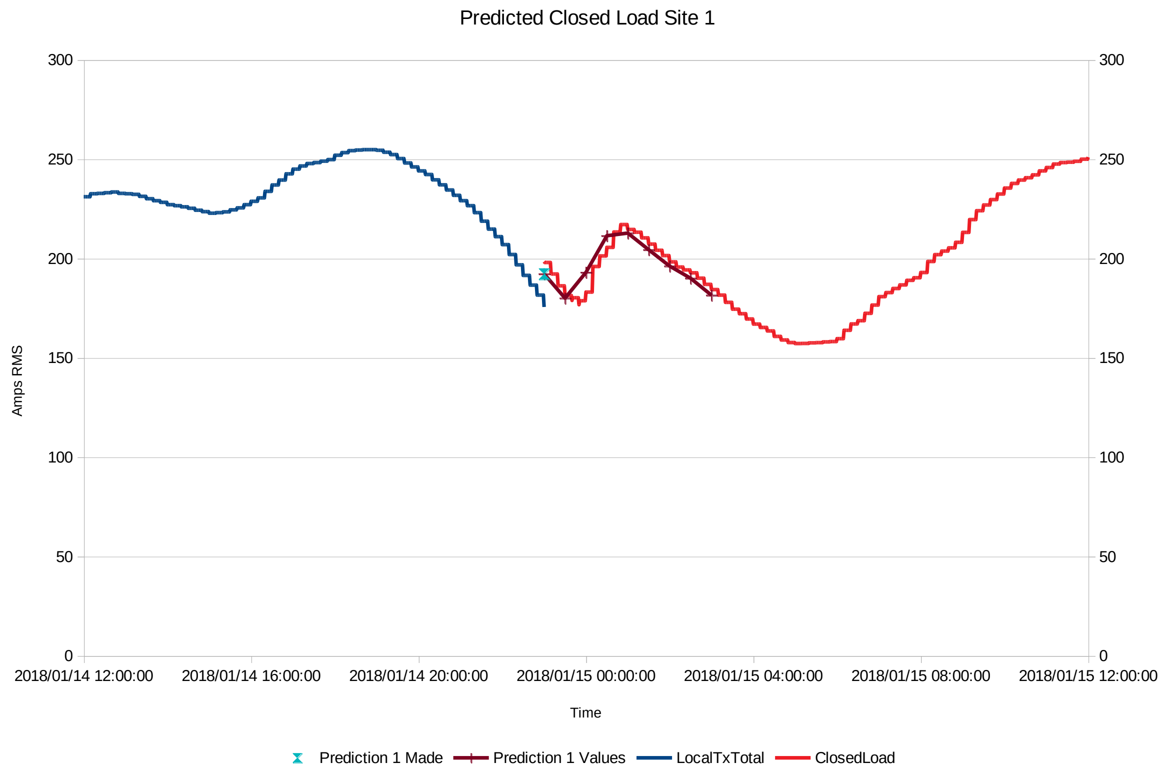


**Figure 54: Predicted Closed Load – Site 1**

Figure 55 plots the same data to show (blue then brown traces) the loading which is predicted for the following scenario:

- The Circuit Breaker is closed at the time the scenario starts (which is the present time).
- The Circuit Breaker remains closed for the next 4 hours.

That is the same as that used to calculate the green trace in Figure 53.

What we see is that when the Site 1 Alvin Reclose™ Circuit Breaker is closed, the actual load (blue trace) is predicted to immediately increase (jump to brown trace), then drop for a short period before increasing then falling again (following brown trace).

At the time this scenario is being evaluated, the transformer is steadily cooling. As the blue trace shows, the load peaked at 18:50 UTC, with a subsequent peak hot-spot temperature occurring a short while afterwards at 19:30 UTC.

Figure 55 shows the hot spot temperature prediction made for this scenario (in green) as well as the hot spot temperature if the Circuit Breaker remains open. The effect of the additional load in the closed scenario is to make the predicted transformer temperature (green trace) hotter than it would have otherwise been (red trace). However, this is against a background of a steadily cooling system, so even the higher load scenario does not cause a rise in absolute temperature, just a reduction in the rate of cooling.

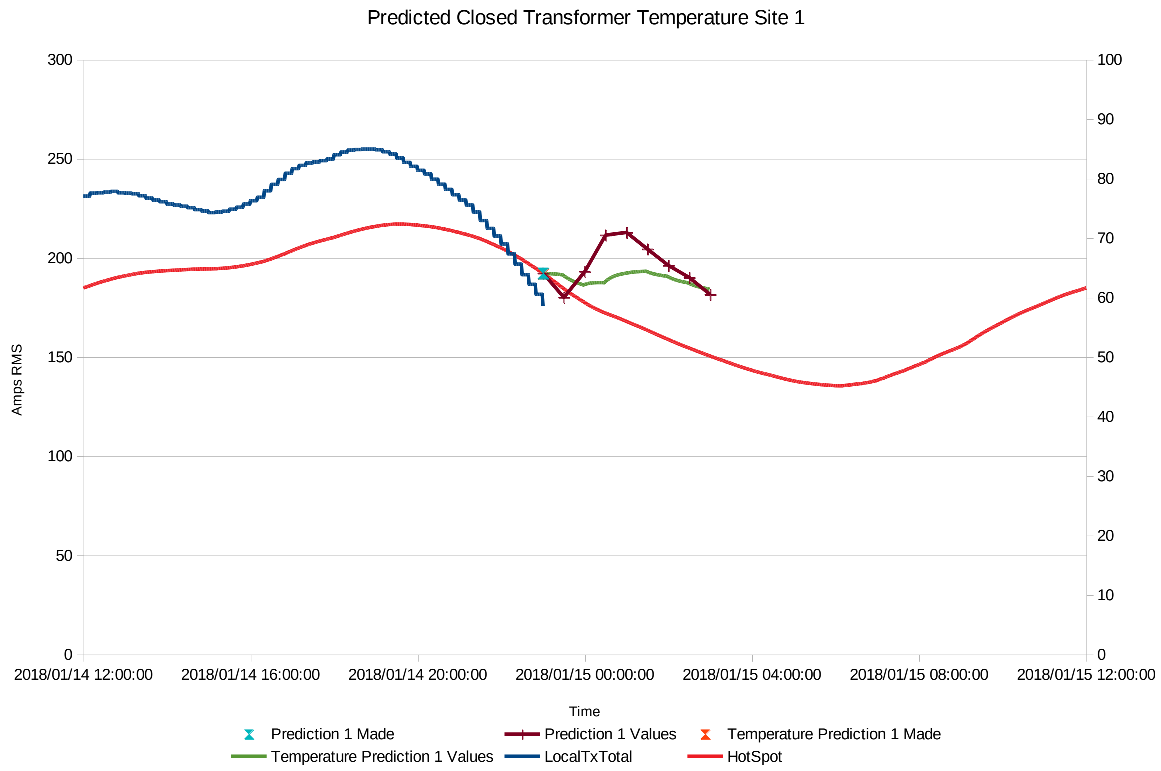


**Figure 55: Predicted Closed Transformer Temperature – Site 1**

The full prediction (green trace in Figure 55) is for a rise of 0.02 degrees, then a dip followed by a second peak which is 0.4 degrees above the starting temperature, and a further fall. The result for the scenario (which evaluates the maximum hot spot temperature over the four hours) is therefore 0.4 degrees above the starting temperature, which is indistinguishable on this graph scale. This explains why the two curves (red and green traces in Figure 53 and Figure 56) seem to meet at this point.

Figure 56 is the same data as Figure 53 but with the X axis rotated through 12 hours to change the break point from 00:00 UTC to 12:00 UTC for clarity.

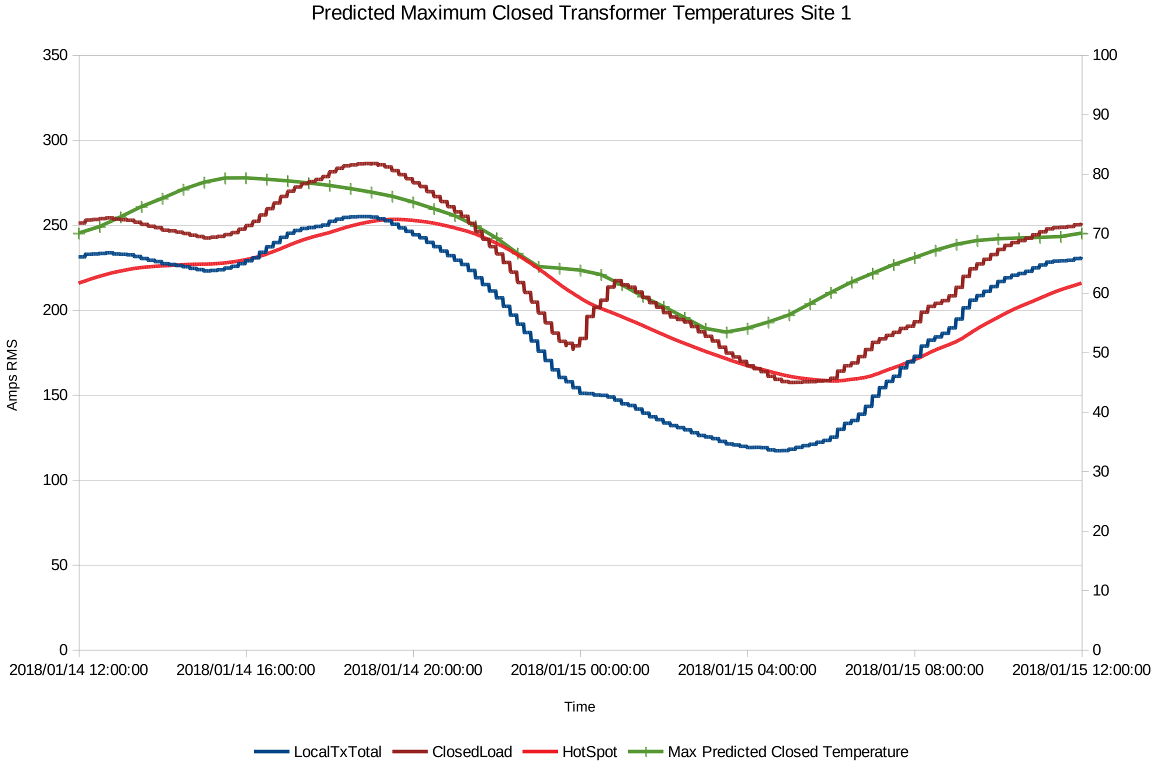


**Figure 56: Predicted Maximum Closed Transformer Temperature – Site 1**

### 3.6.1.2 Site 1 Alvin Reclose™ Circuit Breaker (always) Closed

Turning now to the cases when the Site 1 Alvin Reclose™ Circuit Breaker starts off closed (we have meshed the network), a prediction is generated for keeping the network meshed. At Site 1, where meshing causes an increase in load, this is an important prediction because if this is predicted to overheat the Site 1 transformer then the system will be blocked from meshing or if already meshed, may be forced to open the circuit breaker.

As we would hope, the load prediction carries on with the status quo, and the temperature prediction carries on smoothly from the calculated temperature.

Taking the maximum of each prediction, we get a curve (Figure 57) for the forecast transformer temperature if the Circuit Breaker remains closed, for the next four hours ahead.

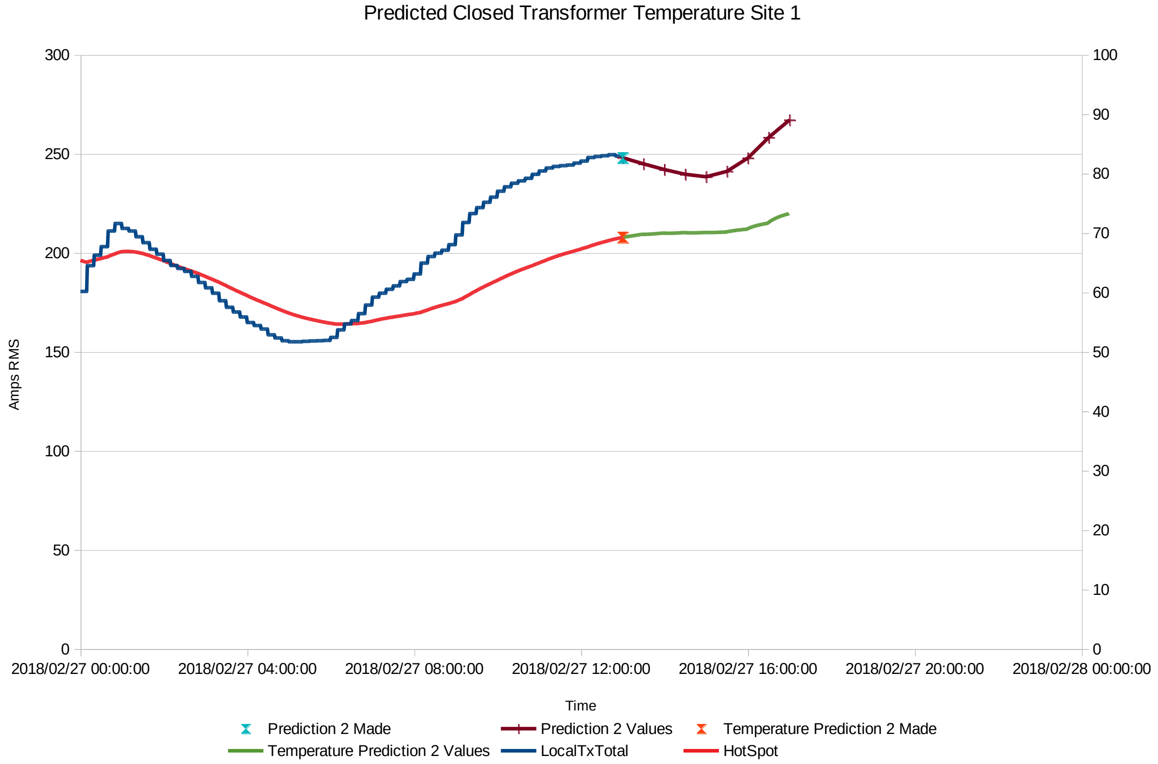


**Figure 57: Predicted Closed Transformer Temperature – Site 1**

As would be expected, the 4-hour ahead temperature forecast (green plot) follows the transformer temperature (red plot) when load is falling, and the transformer is cooling, until the temperature is predicted to rise within the next four hours. This results in an increase ahead of rising load to give a flat-topped curve overall (Figure 58).

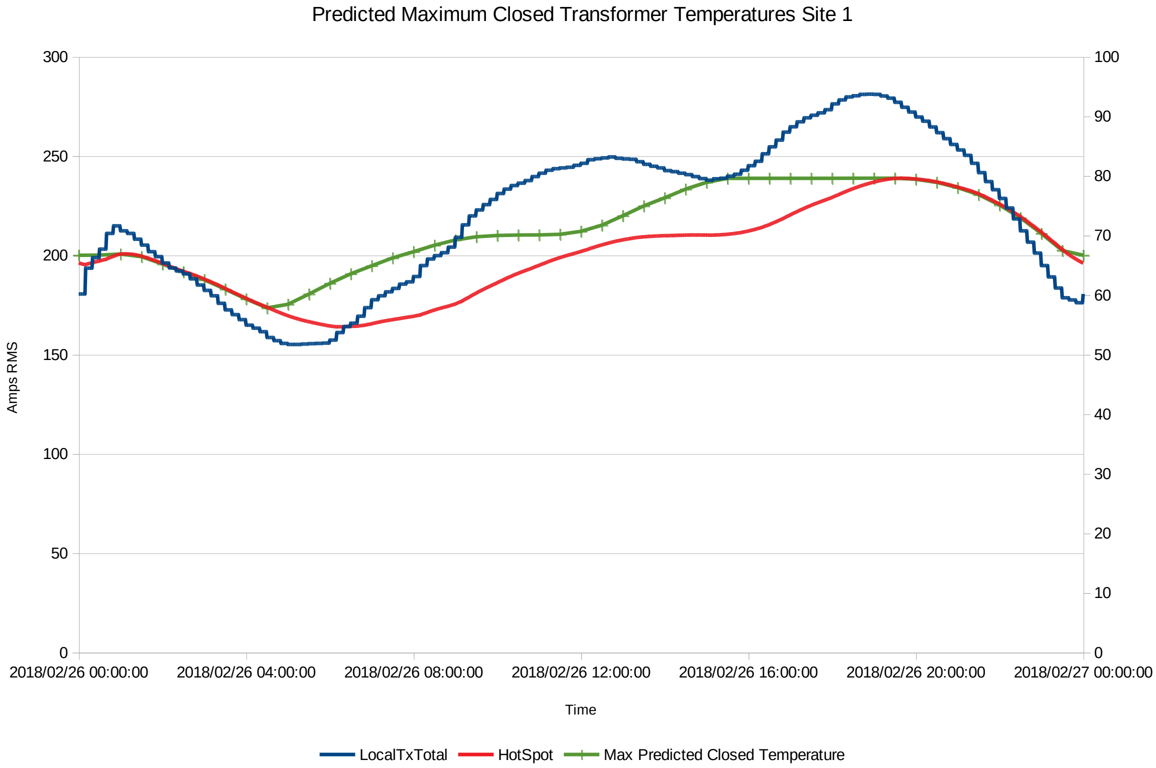


**Figure 58: Predicted Maximum Closed Transformer Temperature – Site 1**

### 3.6.2 Site 2

#### 3.6.2.1 Site 1 Alvin Reclose™ Circuit Breaker always Open

Taking an easy case first, consider that the system has been running with the Circuit Breaker open (so full load on Site 2), and we want to make a prediction for the scenario where this Circuit Breaker remains open.

Looking at 2018/01/08 at 13:00 UTC, we get a prediction for load over the next four hours (brown), and from that obtain a transformer hot-spot temperature prediction for the next four hours (green), which overlays exactly on the actual HotSpot temperature which occurred (Figure 59)[3].

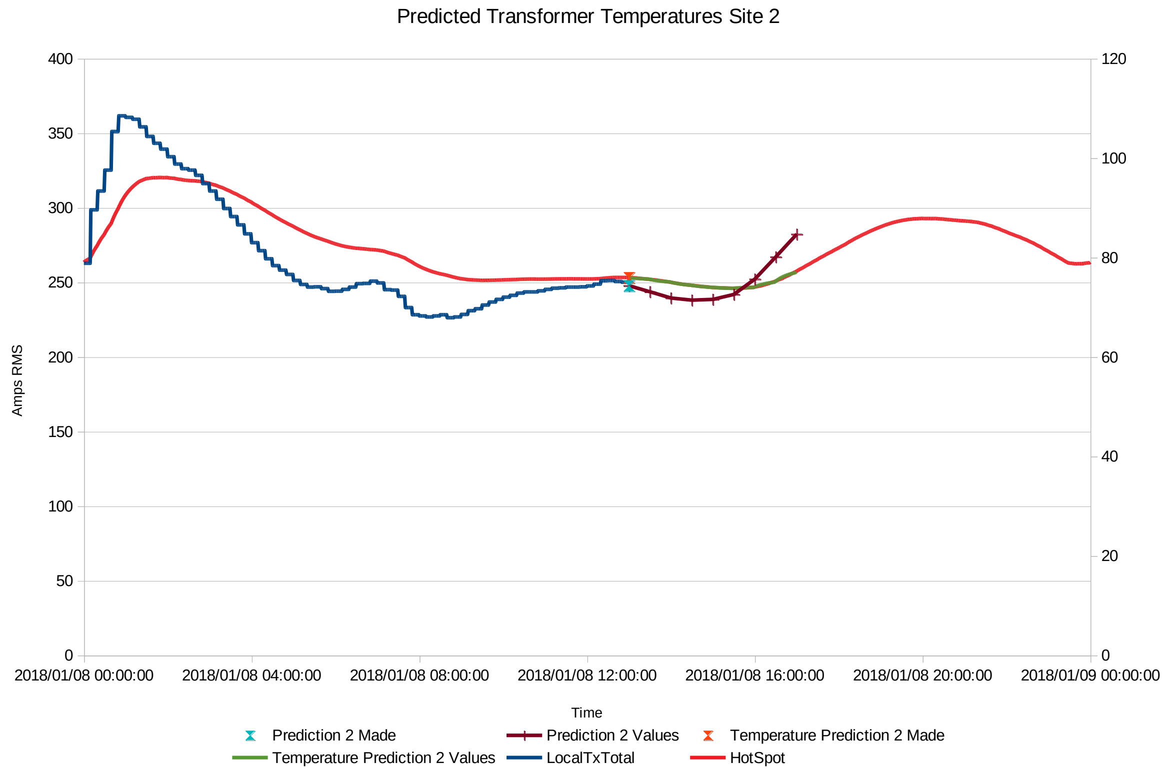


**Figure 59: Predicted Transformer Temperature –Site 2**

[3] It is noted that as the load profiles are identical from day to day in this simulation, and the ambient temperature remains constant, the HotSpot temperature follows the same predictable pattern, allowing comparison with the temperature prediction.

The final step is to take the maximum temperature during the prediction period of 4 hours, because this is the value which the LoadSense algorithm depends upon. In this case the maximum is the last temperature in the prediction (because the load is forecast to rise steeply), but it equally well could have been the first temperature in the prediction at a point where falling load is forecast.

This is shown (Figure 60) if we plot the maximum temperature from each 30-minute forecast on the same graph as the out-turn HotSpot temperature.

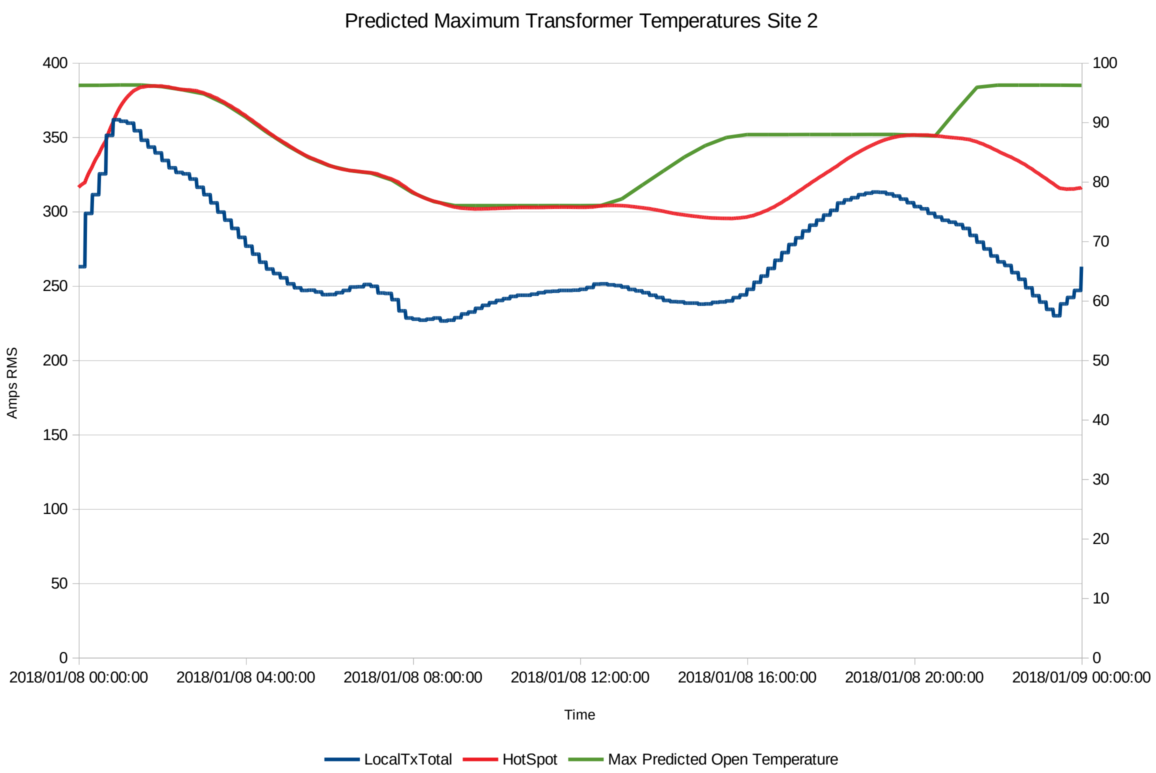


**Figure 60: Predicted Maximum Transformer Temperature –Site 2**

In the first part of the graph, the 4-hours-ahead maximum follows the cooling transformer down, but once the evening and overnight load peaks are within the 4-hour window looking ‘forward’, the maximum predicted transformer hotspot curve (in green) rises ahead of the actual transformer temperature (in red), with a 4-hour flat top before it begins to fall again as the daily cycle repeats.

Next consider that the system has been running with the Site 1 Alvin Reclose™ Circuit Breaker open (resulting in full feeder load supplied by Site 2), and we want to make a prediction for the scenario where the Circuit Breaker is closed, and the load is shared between Site 1 and Site 2.

Looking at 2018/01/08 at 13:00 UTC, we start with the Site 1 Alvin Reclose™ Circuit Breaker open, and so the transformer load is as in the blue trace "LocalTxTotal" (Figure 61). The prediction for load over the next four hours in brown shows the sudden drop when the Circuit Breaker is closed, then the rise. For comparison, the closed load calculation is plotted in red, so we can see how the prediction matches it.

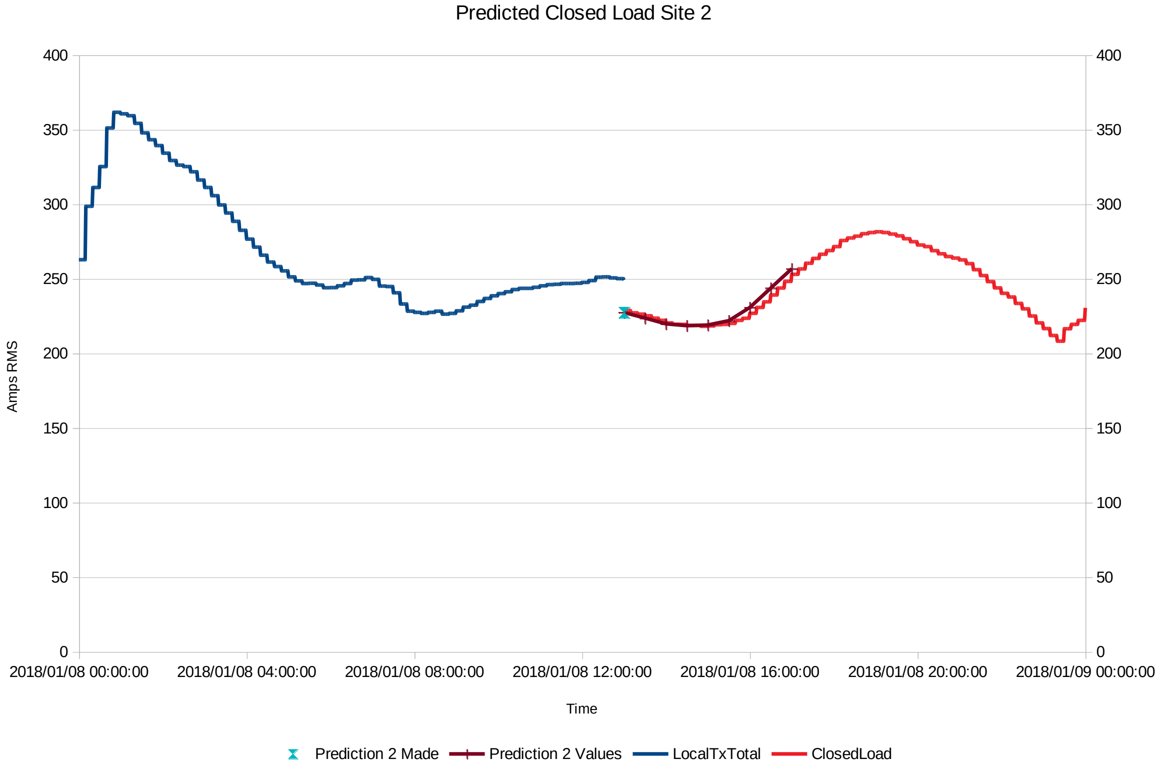


**Figure 61: Predicted Closed Load – Site 2**

From the load prediction a transformer hot-spot temperature prediction for the next four hours (green) is produced (Figure 62). Because the load initially falls when the Circuit Breaker operates, the transformer initially cools. Later the load rises again, and so we see the predicted hotspot temperature rise, but it does not rise far enough to take it past the starting temperature. This means the maximum temperature for the four-hour period is the temperature at the start of the prediction period.

This is obvious in the plot of the predicted maximum closed temperatures over the day, each time starting from the open load (in blue). We can see that the predicted temperature 4 hours ahead with the Circuit Breaker closed (in green) is only hotter than the current temperature with the Circuit Breaker open (in red) when there is a large increase in closed load (in brown) within the four hours ahead window. The result of this is that the predicted maximum temperature curve under these conditions does not have the four-hour flats on transition from rising to falling temperatures seen previously.

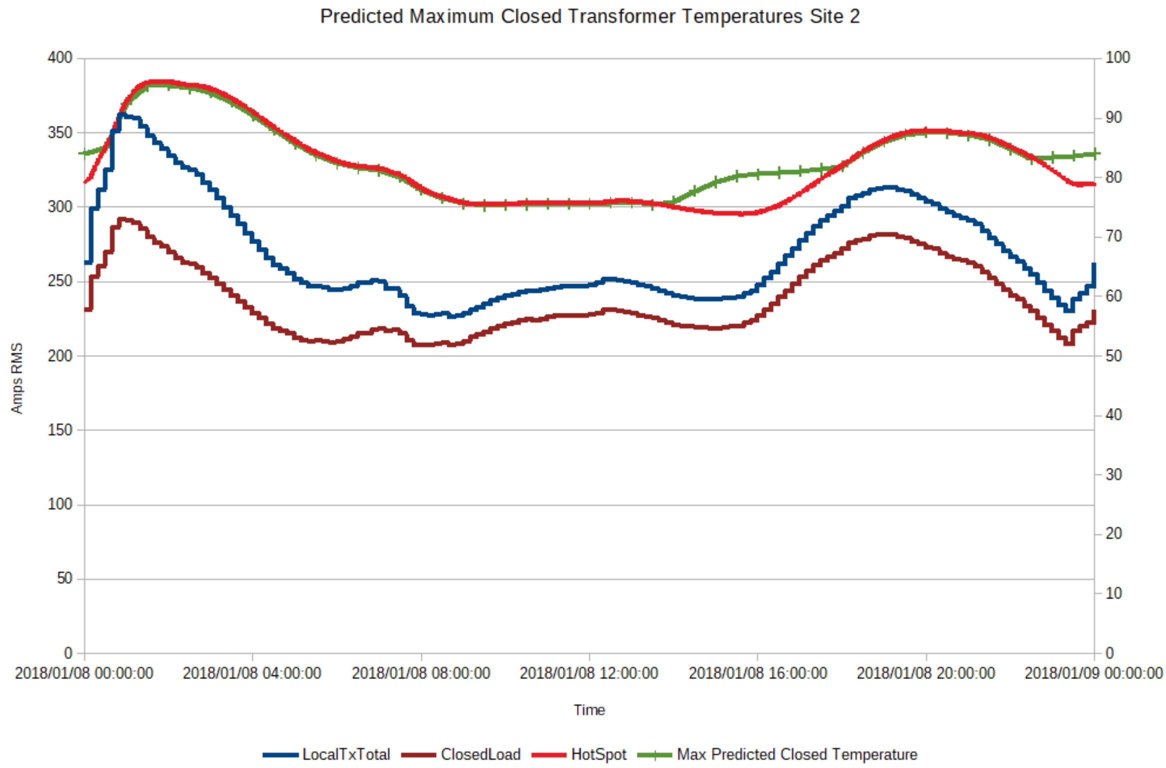


**Figure 62: Predicted Maximum Closed Transformer Temperature – Site 2**

### 3.6.2.2 Site 1 Alvin Reclose™ Circuit Breaker always Closed

When the Circuit Breaker is closed, we still make two predictions (Figure 63), but they are reversed, relative to those made previously:

1. the prediction with the Circuit Breaker closed is the continuation of the status quo (and so a very simple graph); and
2. the prediction with the Circuit Breaker open involves changing the network configuration state to increase the transformer load.

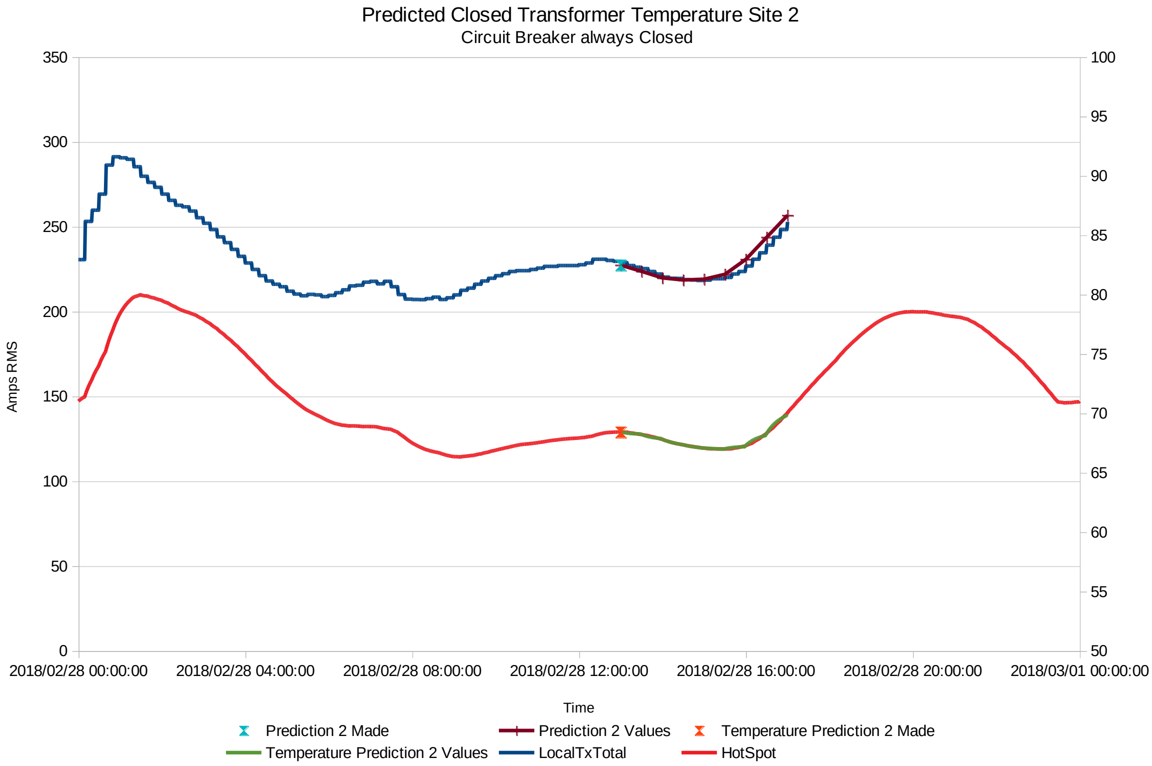


**Figure 63: Predicted Closed Transformer Temperature– Circuit Breaker Closed –Site 2**

The second graph (Figure 64) shows the predicted load (in brown) jumping upwards (from the blue trace) if the Circuit Breaker is opened. The transformer temperature responds by rising steeply in response to the initial extra step load, then more slowly as the network load rises.

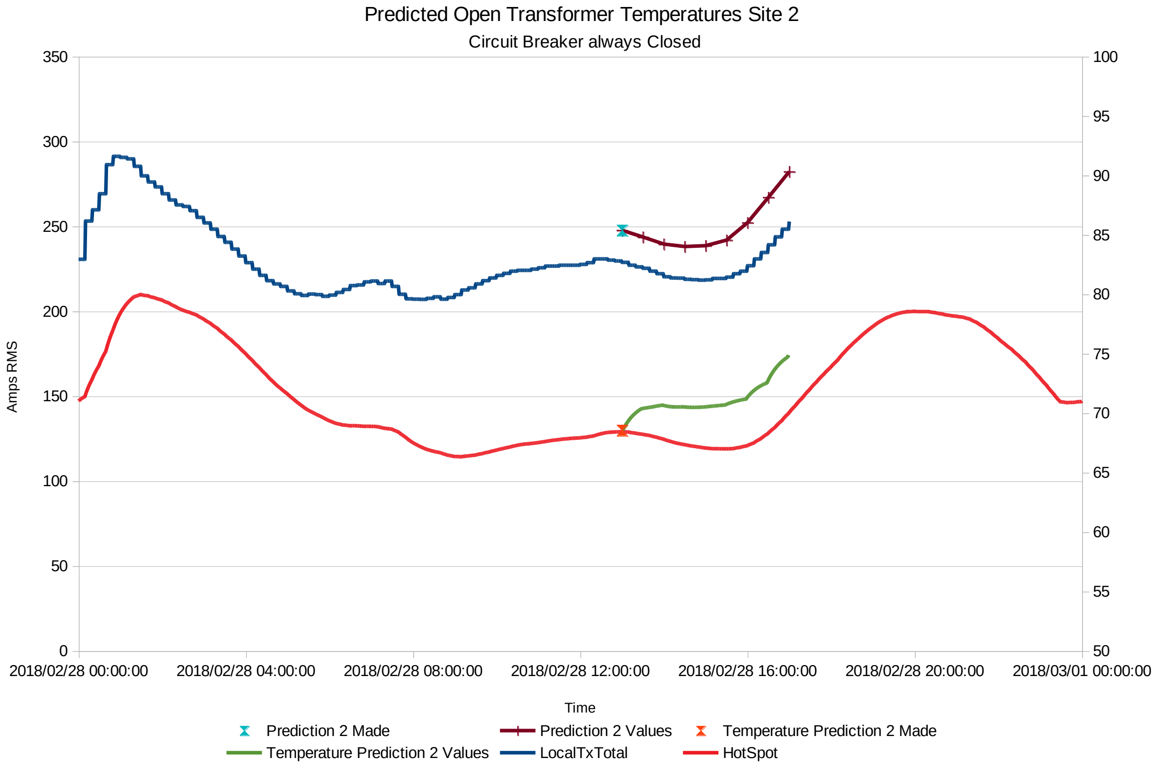


**Figure 64: Predicted Open Transformer Temperature– Circuit Breaker Closed –Site 2**

Plotting the maximum of each transformer temperature prediction (in the last case the end of the prediction) gives the graph of how predicted maximum transformer temperature varies over the day, either with the Circuit Breaker remaining closed or opened at the time of the prediction.

With the Site 1 Alvin Reclose™ Circuit Breaker remaining closed and the network configuration therefore being unchanging throughout the period (Figure 65), the maximum graph is simply looking at the current hot-spot temperature four hours ahead.

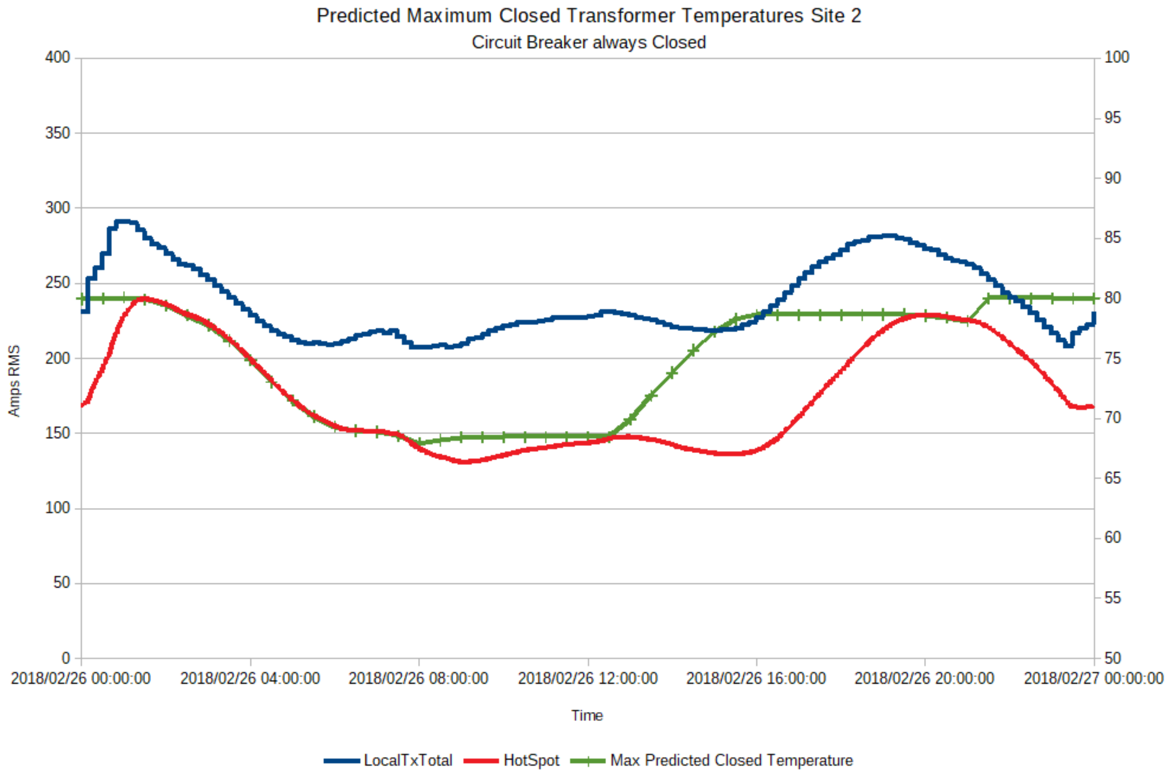


Figure 65: Predicted Maximum Closed Transformer Temperature– Circuit Breaker Closed –Site 2

Changing the network state (Figure 66) makes matters more complex. Each point on the green trace reflects the outcome of a scenario evaluation in which:

- The Circuit Breaker has previously been closed.
- The Circuit Breaker is opened at the time the scenario starts (which is the present time).
- The Circuit Breaker remains open for the next 4 hours.
- The maximum hotspot temperature experienced is evaluated.

The red trace shows the actual transformer hot spot temperature which occurs when the Circuit Breaker is kept closed, and thus is the starting point for each of the scenario evaluations.

The hot spot temperature with the Site 1 Alvin Reclose™ Circuit Breaker open will obviously be hotter than with it closed, because the load on site 2 is higher. This is reflected in the green trace lying above the red trace. Because each scenario is based on predicting four hours ahead, the prediction (green trace) is to the left of the actual hotspot (red trace).

What actually happens in each scenario evaluation is that transformer moves from the hot spot temperature with the Circuit Breaker always closed (red trace in Figure 66) towards the hot spot temperature with the Circuit Breaker always open (red trace in Figure 65).

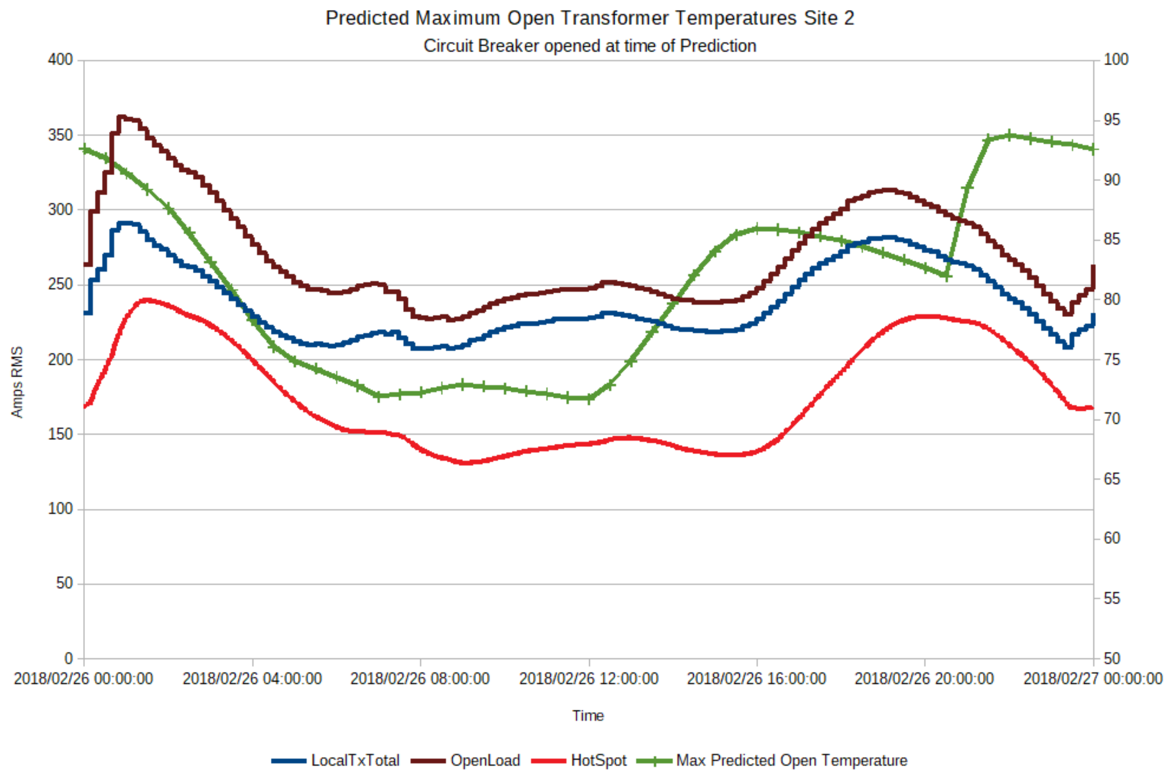


**Figure 66: Predicted Maximum Open Transformer Temperature– Circuit Breaker Opened at time of Prediction–Site 2**

Plotting the open and closed cases on the same graph (Figure 67) helps a little. The blue trace shows the transformer hot spot temperature with the Site 1 Alvin Reclose™ Circuit Breaker always open. The orange trace shows the transformer hot spot temperature with the Site 1 Alvin Reclose™ Circuit Breaker always closed. The blue trace is both always higher than the orange trace and has a proportionately bigger peak in the early hours of the morning.

The green trace is the result of a series of scenario evaluations in which:

- The Circuit Breaker has previously been closed.
- The Circuit Breaker is opened at the time the scenario starts (which is the present time).
- The Circuit Breaker remains open for the next 4 hours.
- The maximum hotspot temperature experienced is evaluated.

Because the model is in each case considering starting from the cooler (orange) curve and running with increased load for the next four hours, the flat tops seen on the other previous graph are not visible. Because the green trace is predicted four hour ahead, it is offset to the left of the blue trace in Figure 67.

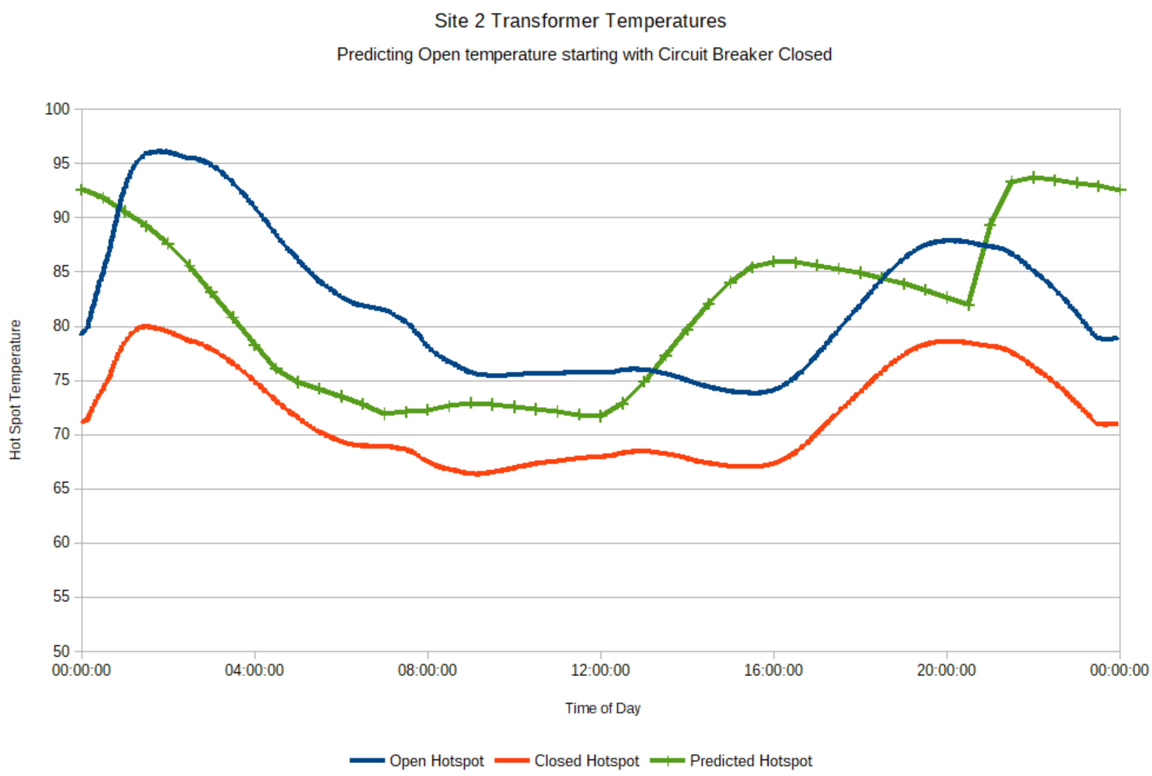


Figure 67: Transformer Temperature– Circuit Breaker Opened at start of each scenario –Site 2

Shifting the green trace four hours to the right in Figure 68 makes the correlation with the blue trace more obvious.

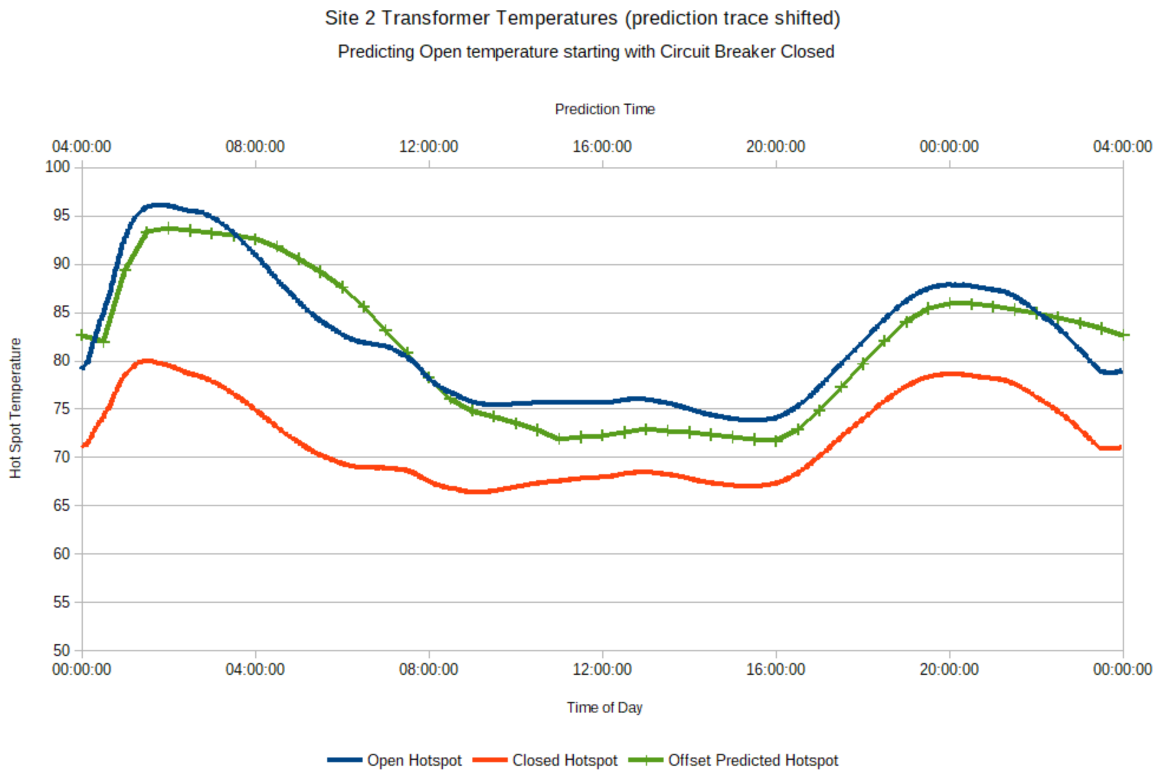


**Figure 68 Transformer Temperature with prediction shifted – Site 2**

Four hours is not long enough for the predicted transformer temperature to reach the blue trace in most cases, but it is close. The large, sudden, rise in the prediction (green trace) at 21:00 is now obviously caused by the 01:00 rise in load as Economy 7 load suddenly into the prediction time window.

Combining the data relating to the period when Loadsense is in control of the meshing (Figure 69), the switched hot spot temperature (green trace) is lowered towards (but not quite reaching) the always-meshed hot spot temperature (orange trace) through the Economy 7 peak. It does not reach the always-meshed temperature because it starts off with significantly hotter oil thanks to the previous evening peak. When the networks un-mesh, the hotspot begins to increase again towards the never-meshed hot spot temperature (blue trace), where it stays through the evening peak, until the whole cycle starts over again.

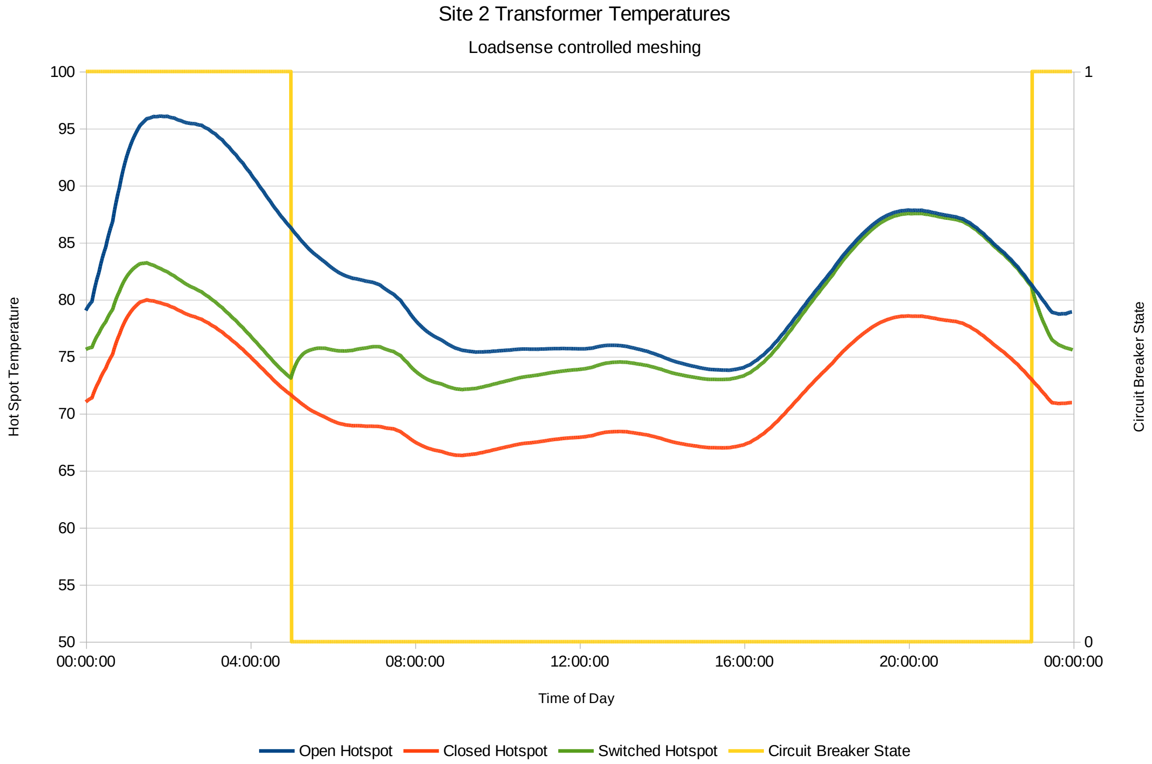


Figure 69: Transformer Temperature– Loadsense Controlled Meshing –Site 2

## 3.7 Control Outputs

Finally, we need to consider the control signals produced by the decision process shown in Figure 3.

This graph (Figure 70) shows that Site 1, even with the additional load from the network meshing, will not exceed its configured hotspot temperature threshold (85°C). This is helpful because it means that Site 1 is always available to assist Site 2. Site 2 needs this assistance, because it’s maximum hotspot temperature without meshing exceeds the configured threshold of 89°C. Putting these two conditions together, there is the opportunity to reduce high transformer temperatures at Site 2 without causing undesirably high temperatures at Site 1.

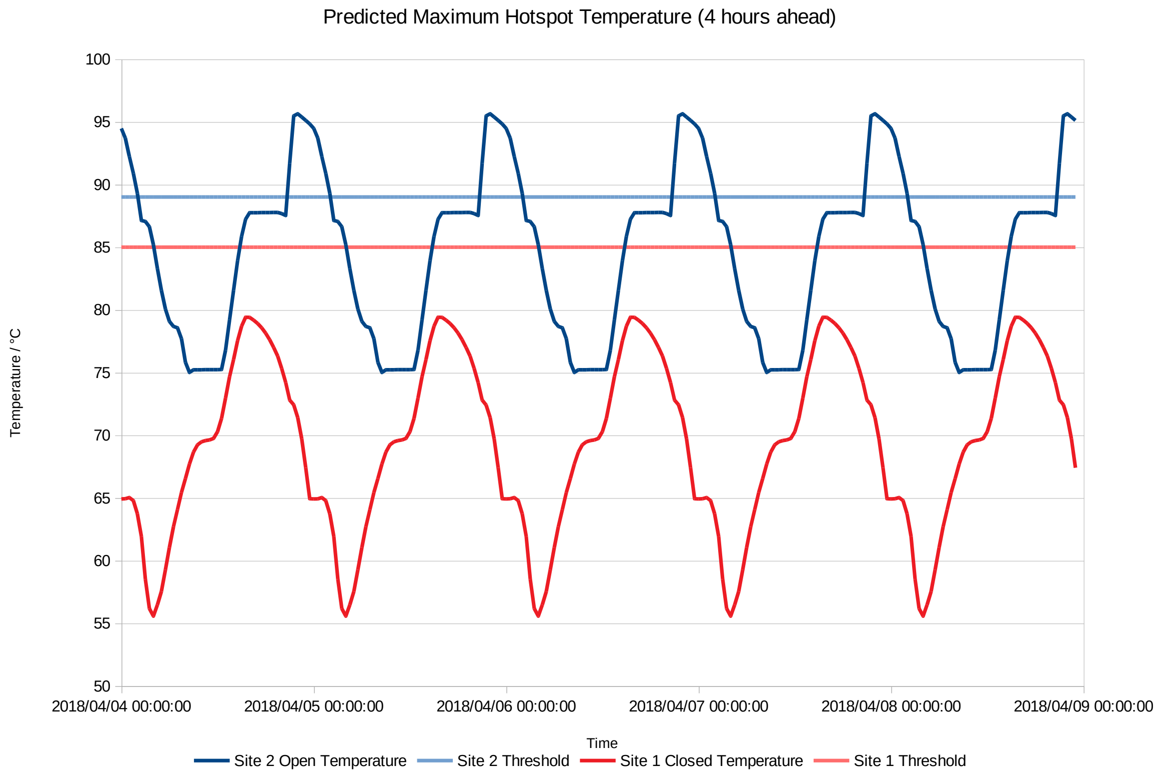


Figure 70: Predicted Maximum Hotspot Temperature– Site 2

This is shown in the next graph (Figure 71),which shows the Meshing Demand signal overlaid, i.e. when Loadsense determines that meshing the network would be desirable on thermal grounds. This is the output of the first two questions on the original flow chart. However, there is then a final question, the check for voltage to ensure there has not been a network fault.

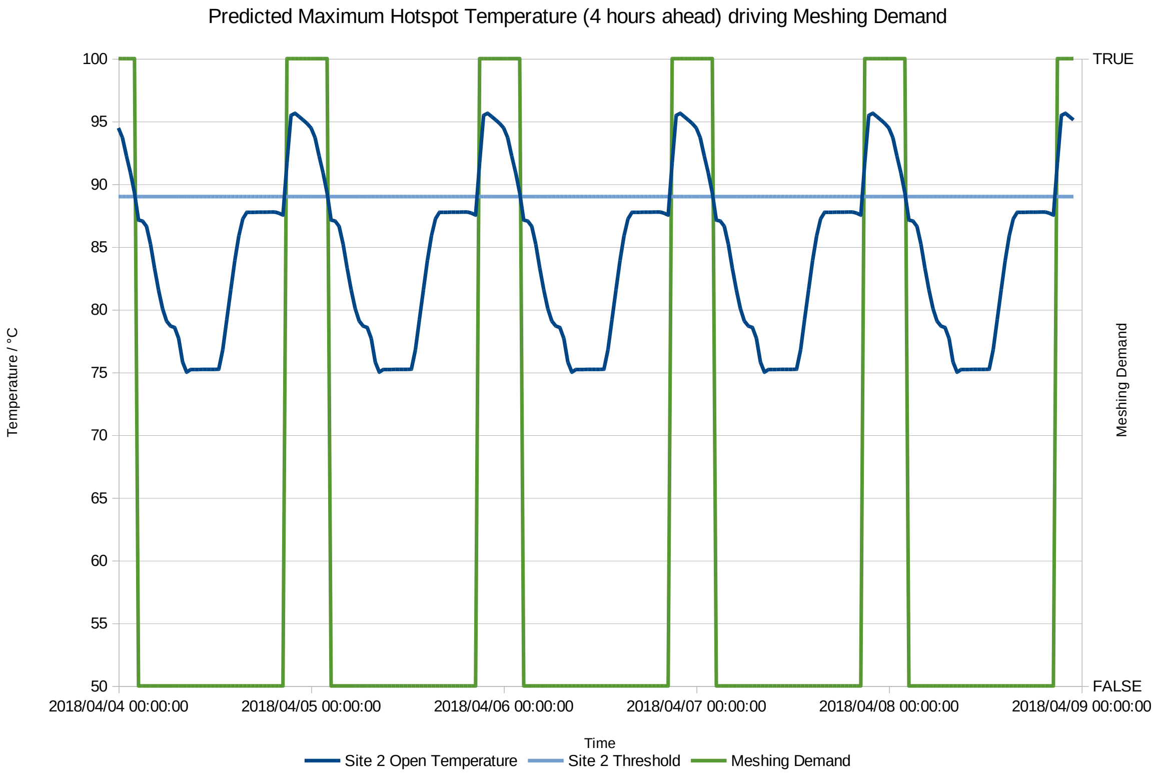


**Figure 71: Predicted Maximum Hotspot Temperature– Driving Meshing Demand**

In the test data presented, the cable voltages are all present, so the Loadsense demand is translated directly into Circuit Breaker control (Figure 72).

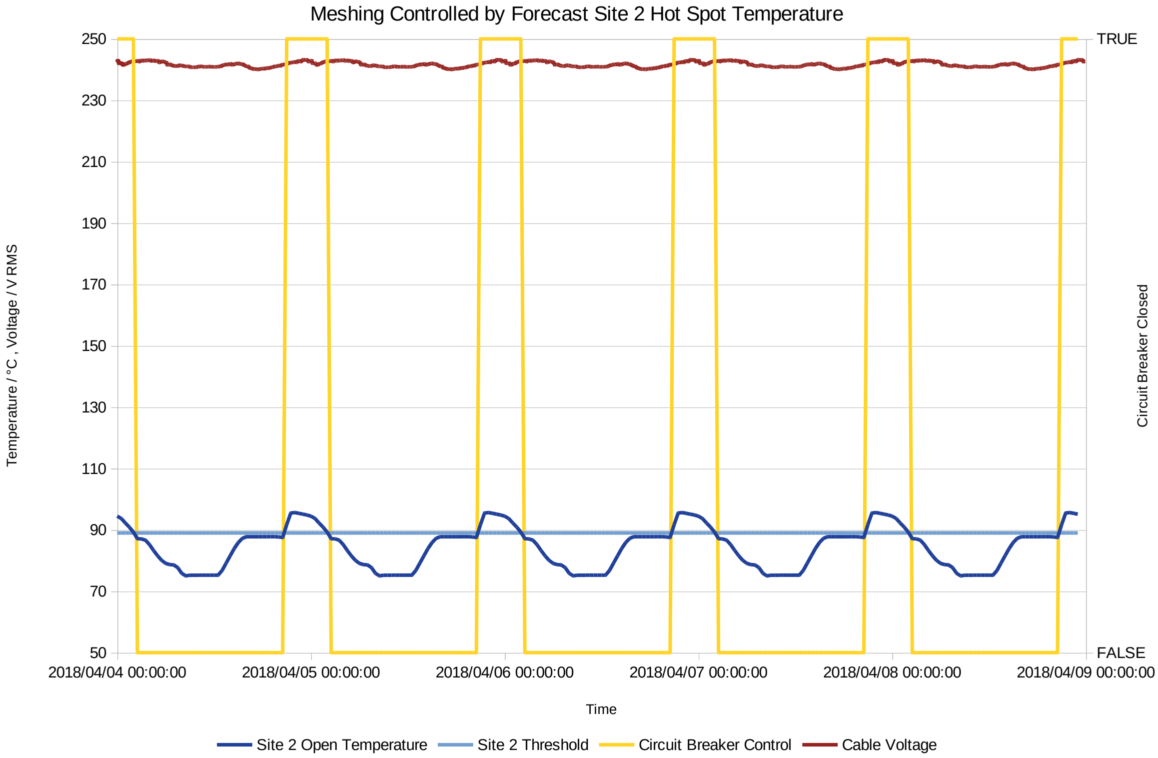


**Figure 72: Meshing Controlled by Forecast Hotspot Temperature –Site 2**

The Circuit Breaker is closed by Loadsense to mesh the network between 21:00 and 02:30 each day and opened outside of these times (Figure 73).

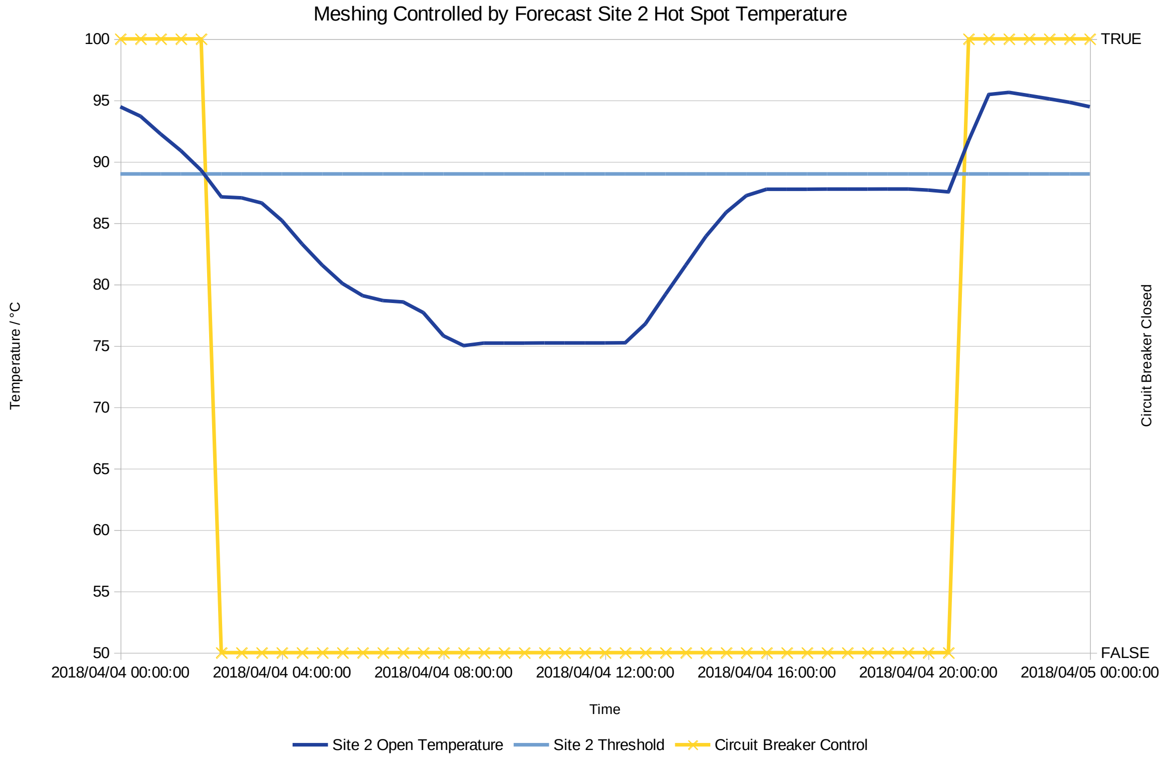


**Figure 73: Meshing Controlled by Forecast Hotspot Temperature –Site 2**