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OPENLV

OPENING UP THE SMART GRID

SDRC 4

Learning Generated from the OpenLV Project trials by Method 1.

ea technology

RIIO NIC NETWORK INNOVATION COMPETITION

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Contents

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Glossary

Term	Definition
API	Application Programming Interface
BWCE	Bath and West Community Energy
CSE	Centre for Sustainable Energy
DNO	Distribution Network Operator
DSO	Distribution System Operator
DTR	Dynamic Thermal Rating
ECOE	Exeter Community Energy
FAT	Factory Acceptance Testing
LCT	Low Carbon Technology
LV	Low Voltage
LV-CAP™	Low Voltage Common Application Platform
NIC	Network Innovation Competition
NOP	Normally Open Point
OSCE	Owen Square Community Energy
PV	Photovoltaics
RTTR	Real Time Thermal Rating
SAVE	Solent Achieving Value from Energy Efficiency [project]
SDRC	Successful Delivery Reward Criterion
TEC	Tamar Energy Community
Tx	Transformer
UPS	Uninterruptible Power Supply
WPD	Western Power Distribution
YCE	Yealm Community Energy

Executive Summary

Background

The OpenLV Project trials an innovative new open access platform that was developed by EA Technology.

The OpenLV platform

- **Enables Open Data**
- **Hardware and Software agnostic**
- **Decentralised analysis and control**

Uniquely, the OpenLV platform provides a substation monitoring and operating system (EA Technology's LV-CAP™) that has been designed to be hardware agnostic and, in a Method analogous to a smartphone, to be able to host multiple apps. The trial system allows hosted apps to share monitored data and each other's outputs. LV-CAP™ was designed so that calculations and decisions can be made locally, speeding up reaction times and reducing the amount of data that needs to be sent to central aggregation servers. It provides a secure environment for the maintenance and management of apps, while continuing to ensure the security of the electricity network.

The OpenLV trial

This trial opened access to 100 Million data points from 80 substations.

The OpenLV Project is seeking to prove the technology and assess how it enables benefits to the DNO (Distribution Network Operator), community groups, business's and academia.

The trial was organised to:

- Investigate the benefits of decentralised analysis and LV network automation through **Method** 1 of the trial
- Investigate how OpenLV enables community action through **Method 2** of the trial
- Investigate how OpenLV creates new opportunities for business and Academia through **Method 3** of the trial

Further information on the overall project can be found in the Full Bid Submission, which is available on the OpenLV Project website [1].

Report Purpose

In this report we present the results and learning from Method 1, with the learning associated with Method 2 and Method 3 detailed in linked reports as part of SDRC 4.

Subsequent reports will analyse the opportunities and benefits of implementing the platform into business as usual.

Key Findings

Within this report we outline the following key findings from Method 1 that investigated the capability of the LV-CAP™ platform to provide direct network benefits.

- The OpenLV trial demonstrated that decentralised analysis and control was able to present a robust Method of automation for the Low Voltage network. This output was evidenced by the fact that OpenLV enabled the trial low voltage networks to be physically reconfigured at times of simulated network stress.
- To enable this trial of network automation, the trial LV networks were configured to enable LV substations to be meshed together by closing a smart LV network device that was located at one of the substation pairs, in effect joining them together via an LV feeder. This was a slightly artificial arrangement as, in Business as Usual (BAU), LV networks are normally sectionalised at link boxes located between the two substations.

  This trial demonstrated that temporarily meshing together two substations in this manner, was an ineffective Method to de-load substation transformers. However, the trial also presents evidence that had OpenLV been able to implement load sharing capability through alternative configuration of the automated switches there was the potential for more network uplift. Smart link boxes were not available cost-effectively for the OpenLV Project at the time of project initiation, and this may be a significant follow up point from the project, partly as it would enable great capacity uplift and also because it would allow novel use cases to be implemented by the LV-CAP™ platform such as automatically restoring customers after an LV fault.
- The Method 1 trial also investigated decentralised computation of the amount of capacity headroom available at LV transformers. This was investigated by trialling a real time rating calculation that constantly forecasting the capacity available on the transformer based on real time measurements of transformer temperature and load duration. This calculation was subsequently made available to other apps that served the interests of Method 3 participants.

  Having a decentralised computation capacity could enable 6350 MVA of capacity uplift across WPD's four license areas.

  This part of the trial demonstrated that there could be a significant capacity benefit from applying real time rating analysis to LV transformers rather than assigning a rating based on fixed or less periodic updates to rating assumptions. This benefit was estimated at 6350MVA of capacity uplift across 39,500 of WPD's 140,000 LV substations.

  Whilst it is possible in theory to implement this analysis using centralised computation, establishing sufficiently robust communications between central locations and large quantities of LV substations is an expensive undertaking, prone to potentially harmful communications faults.

1 Introduction

1.1 Project Background

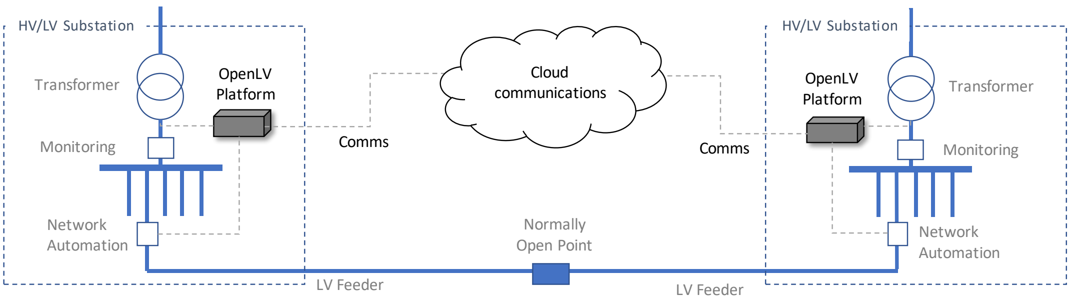
Great Britain has about 1,000,000 Low Voltage (LV) feeders; these have largely been designed and operated on a fit-and-forget basis for the last 100 years, but things are set to change. LV networks are expected to see radical change as we, as customers, alter our behaviour and requirements, stemming from the vehicles we drive, to the generation and storage devices we put onto and into our homes.

The technology to be trialled as part of the OpenLV Project provides a new, open and flexible solution that will not only provide the DNO, community groups and the wider industry with data from the LV network, but will also enable these groups to develop and deploy apps within LV substations through a common hardware platform. The OpenLV Project is seeking to prove the technology and assess how the provision of LV network data and the ability to develop and deploy apps can provide benefits to the DNO, community groups and the wider industry. These Methods used to achieve this objective are outlined below.

1.1.1 Method 1: Network Capacity Uplift

Figure 1 provides an overview of the systems architecture that will be deployed to complete Project trials for Method 1 – Network Capacity Uplift.

As part of the Project trials for Method 1, apps will be used to increase the capacity of existing LV assets through the application and implementation of Dynamic Thermal Rating of the LV Transformer and through meshing LV feeder(s) on the LV network.



What

- Check network capacity against thermal rating of transformer; when breached, close two radial circuits to mesh the LV network
- Deploy two proven techniques
  - ‘Dynamic Thermal Ratings App’ and
  - ‘Network Meshing App’.
- Together with a ‘Network Control App’ to operate/configure the network

How

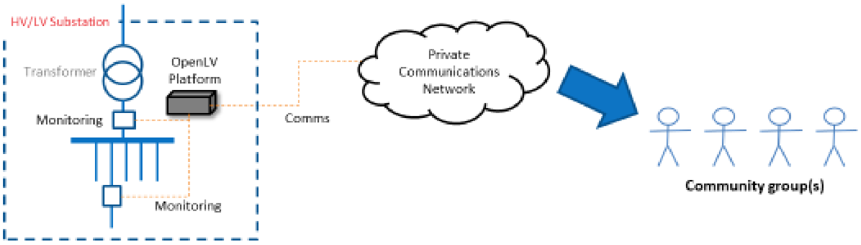
- Assess WPD’s network to identify candidate circuits
- Deploy LV-CAP™ to 60 substations
- Monitor how the solution would operate over several months
- Install actuators on 5 circuits (2 ends each) to prove end-to-end control
- Assess and report on performance

Figure 1: Method 1 – Network Capacity Uplift

1.1.2 Method 2: Community Engagement

Figure 2 provides an overview of the systems architecture that will be deployed to complete Project trials for Method 2 – Community Engagement.

As part of the Project trials for Method 2, Community Groups will make use of the LV network data provided by the OpenLV Platform to provide benefits to Communities.



What
- To work with key community groups to understand whether Apps can be developed and installed on the platform
- Identify funding sources that customers / communities can use to develop specific Apps

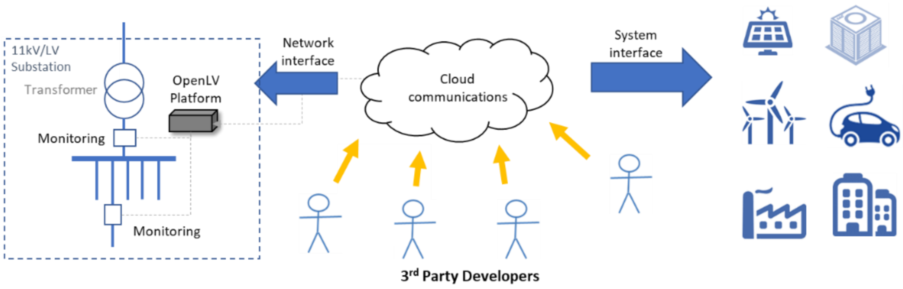
How
- Community engagement to promote availability of platform / LV network data
- Make available 10 LV-CAP™ units for deployment
- Provide communities access to relevant data

Figure 2: Method 2 – Community Engagement

1.1.3 Method 3: OpenLV Extensibility

Figure 3 provides an overview of the systems architecture that will be deployed to complete Project trials for Method 3 – OpenLV Extensibility.

As part of the Project trials for Method 3, the Wider Industry will either, make use of the LV network data provided by the OpenLV Platform, and/or develop and deploy 'apps' to provide benefits to: DSOs (Distribution System Operator), Platform Providers, 3rd Party Developers and Customers.



What
- To enable companies to develop innovative algorithms and applications for either the DNO, or it's customers

How
- Publicise the opportunity to 3rd parties
- Make available standard App 'container' for third parties to use for their development
- Make available 10 LV-CAP™ devices for substation deployment
- Funding to develop specific Apps to be raised outside of the project budget, e.g. private sector

Figure 3: Method 3 – OpenLV Extensibility

1.2 Document Purpose

The OpenLV Project Successful Delivery Reward Criteria 4(SDRC) report 4 was structured to meet the evidence requirements outlined in the OpenLV Project Direction [2].

The primary SDRC 4 report was issued to Ofgem as a single document, detailing the evidence relating to Methods 1, 2 and 3 of the OpenLV project.

1. Sharing the level of capacity uplift achieved through Method 1
2. Sharing which LV networks can benefit from OpenLV and why
3. Establishing the level of capacity uplift that could be achieved in WPDs licence area
4. Sharing how DNOs can engage with communities who want to become part of a smarter grid to exploit the open and flexible nature of OpenLV
5. Sharing how community engagement supports the uptake of LCTs (Low Carbon Technologies)
6. Outlining the routes communities can take to raise funding
7. Sharing the network benefits provided by community engagement
8. Sharing how DNOs can engage with academics, companies (including non-energy companies) to exploit the open and flexible nature of OpenLV
9. Sharing the network benefits provided through Method 3
10. Sharing how the Method facilitates non-traditional business models

In this document we present the results and learning relating to Method 1, with matching documents available for Methods 2 and 3.

1.3 Report Structure

The structure of this report is as follows:

- **Section 2: Method 1: Capacity Uplift –** demonstrates the ability of EA Technology's LV-CAP™ platform to deliver network benefits
- **Section 3: Conclusions -** outlines how the project has met the Successful Delivery Reward Criteria as set out in Section 1.2

2 Method 1 – Capacity Uplift

2.1 Principles of the Method 1 Trials

Fundamentally, the purpose of the OpenLV Project was to test and verify the ability of a distributed intelligence platform to provide network benefits. Method 1 focussed on the potential for direct benefits and deployed two use cases intended to improve transformer utilisation.

The use of locally calculated Dynamic Thermal Rating (DTR) of Network Assets in combination with autonomous network switching to adjust load balancing and release capacity, demonstrated the ability of LV-CAP™ to

- Monitor the local network assets
- Store the data relating to the system operation
- Process this data, deriving meaningful information
- Make decisions in response to this processed data
- Enact the result of these decisions, providing measurable changes to the local network

2.1.1 Thermal Rating of the Transformer

Existing equipment ratings are based on the conservative assumption that the peak load is continuously delivered over a prolonged period, thus allowing time for the transformer to heat up to its maximum recommended operating temperature. This approach is used to determine the 'nameplate' rating for the Transformer. This rating being the amount of load (in kVA) the transformer can continuously provide in an Ambient Temperature of 20°C.

In reality, particularly on networks supplying predominantly domestic customers, the load is at its peak only for a relatively short period each day whilst also experiencing a continually varying Ambient Temperature. Utilising actual loading and thermal data can allow for increased loading of the transformer without exceeding acceptable operating temperatures, often allowing loads significantly above the nameplate rating of the transformer to be achieved at times of peak loading.

The Transformer Thermal Rating application utilised in the OpenLV Project uses knowledge of the previous loading conditions, coupled with the heating and cooling characteristic of the equipment, to determine a new dynamic load (rating) that the equipment can safely supply without overheating.

2.1.2 Meshing the network

Meshing (joining together or interconnecting) LV substations originally designed to be run separately (with open points on feeders between them) has been demonstrated in previous Projects to be an effective Method of supporting network assets where an imbalance in loading exists in close proximity on the network. Automating meshed operation of the LV network, to operate only when required, has the potential to increase capability to support higher penetrations of LCTs.

It is noted that implementation of meshing between LV substations, whether at the NOP (Normally Open Point) or at the substation requires consideration of network fault conditions to ensure protection systems will operate when required.

2.1.3 Combining the two

The implementation of DTR and automated meshing by LV-CAP™, using DTR calculations as the control signal for meshing automation, demonstrates the ability of the platform to deliver the five points detailed above, as the end-to-end process would otherwise not be possible.

2.2 Methodology

The purpose of Method 1 within the OpenLV Project was to demonstrate the ability of LV-CAP™ to autonomously provide network benefits, without the need for system controllers to implement or authorise system actions.

Further learning from Method 1 comprises an assessment of how much additional capacity can be delivered by:

1. Dynamic Thermal Rating of the transformer
2. Implementing LV network meshing at the Normally Open Point
3. Combining both techniques

This was achieved through gathering data, and demonstrating the implementation of control actions through the use of distributed intelligence in a two-stage process:

1. Deployment of LV-CAP™ enabled platforms in ‘passive pairs’ with monitoring equipment and analysis applications, but no ability to control the LV network
2. Deployment of LV-CAP™ enabled platforms in ‘active pairs’ including enhanced decision-making applications and EA Technology’s Alvin Reclose™ devices to enact LV network actuation

2.2.1 Testing & Data Gathering

Trial equipment was deployed under Method 1 in two phases; passive monitoring pairs, intended for network monitoring and providing data for simulation and analysis, and active pairs where the network automation would be implemented as well.

Phase 1 pairs were considered candidates for subsequent upgrades to becoming an active, Phase 2 pair, but during the initial roll-out of equipment sufficient hardware was retained to enable additional substations to be utilised if those initially selected proved unsuitable for active control.

The overall process was:

1. Undertake desktop and site surveys to identify potential trial pair locations
2. Deploy equipment to 25 pairs for Phase 1 (passive) operation
3. Evaluate data from these pairs, with a view to upgrading pairs to Phase 2 (active) operation if possible
4. Upgrade sites where possible
5. Deploy equipment to the remaining 5 pairs, in either Phase 1 or Phase 2 configuration such that overall, there were 25 Phase 1 pairs and 5 Phase 2

2.2.2 Phase 1 – Passive Pairs

Network Arrangement

All trial substations were outfitted with LV-CAP™ enabled distributed intelligence devices, LV network monitoring equipment and temperature sensors, but not all were provided with the necessary hardware or control software for network automation.

The LV network arrangement was unchanged, with the NOP between the two substations providing separation between the two feeders. The data gathered from the passive sites matched that gathered from the active deployments, with the only variation occurring from the network layout.

The substations were assigned Site 1 or Site 2 on the basis of transformer rating and proportional loading where the substation with the lowest loading was assigned to be Site 1 for the purposes of simulating the system operation. See Figure 4.

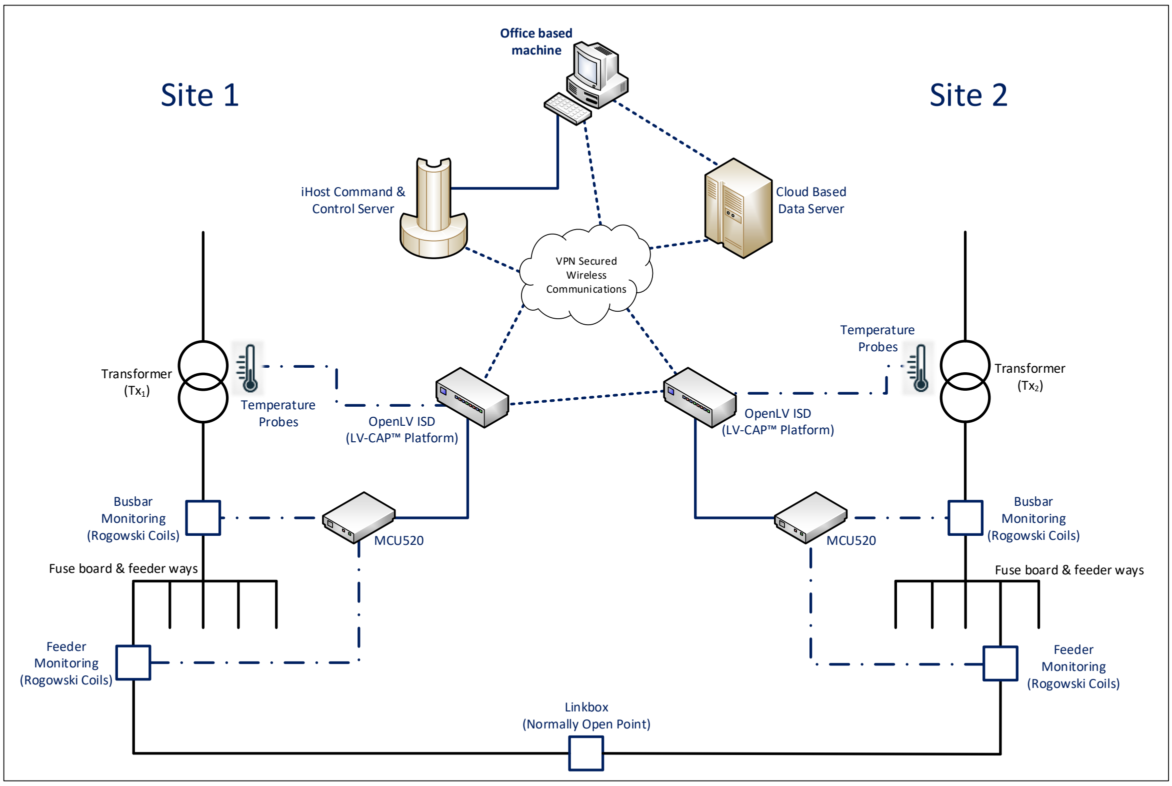


Figure 4: LV network arrangement and LV-CAP deployment

In total, 50 units were deployed in 25 paired locations in this configuration, across WPD's licence areas, as shown in Figure 5.

Figure 5: Map of units deployed across WPD's licence areas

2.2.3 Phase 2 – Active Pairs

Network Arrangement

In the trials, substation pairs selected for the Phase 2 trials were confirmed to be suitable for use through evaluation of the network loading, configuration, and detailed fault study analysis, with particular emphasis on the impact of required changes to the network's normal operating conditions.

Neither of the substations in a pair was at risk of overload relative to the transformer's kVA rating, nor was it in danger of overheating whether supplying full load to the interconnecting feeder, or sharing the load between both transformers in the pair. As such, it was necessary to utilise 'trigger thresholds' optimised for ensuring system operation rather than asset protection.

The thresholds assigned in the trial were:

- Site 2 would 'request assistance' if, for the scenario of circuit breaker remaining open, the predicted Hot Spot Temperature of the transformer exceeded a defined threshold
- Site 1 would help if requested if, for the scenario of circuit breaker being closed, the predicted Hot Spot Temperature of the transformer remained below 65°C

At Site 1, EA Technology's Alvin Reclose™ units are controllable by the LV-CAP™ platform with the default configuration having the breaker 'open' unless otherwise instructed to close.

The Alvin Reclose™ units at Site 2 remains 'closed' except in the situation where a network fault is detected, in which case the breaker will automatically open to protect the network.

In all circumstances, the protection of the network is paramount, and the control logic of the system is designed to only operate 'active control' when doing so is to the overall benefit of the local network, and operational safety requirements (e.g. opening breakers in the event of a fault) override all other instructions.

Network fault studies

Full network analysis was undertaken for each network utilised in the Phase 2 trials, ensuring that network fault current levels, and fault response times remained within acceptable tolerances. The report detailing the network study for each Phase 2 pair is located in Annex 1.

Some pairs initially evaluated were found to be unsuitable for use as an active control pair as the network lengths, if being energised from just one substation were such that the network fault risked not clearing sufficiently quickly to meet WPD's operating requirements.

Operational process

The operational process for demonstrating automated control on the LV network is outlined below. Note that this process occurs simultaneously at both substations in the pair.

1. Network data is gathered by the monitoring hardware provided by Lucy Electric GridKey
2. Network data is passed to the LV-CAP™ platform
3. Asset data, (Transformer Top-Oil Temperature) and Ambient Temperature readings are gathered directly by the LV-CAP™ platform
4. A load forecast application takes the available historical information and predicts the load for the transformer, and connecting feeder, for the near future (configured as 4 hours)
    - This forecast is generated for two scenarios, the first where the circuit breaker at Site 1 is 'open' for the next 4-hours, the second where it is 'closed' for the same period
5. A Dynamic Thermal Ratings application developed by the University of Manchester calculates the temperature of the Transformer 'Hot Spot' for both scenarios
6. For the scenario where the Site 1 circuit breaker is 'open', if the maximum forecast temperature for the Transformer Hot Spot at Site 2 is predicted to exceed the threshold programmed in the system, Site 2 will 'request assistance' from Site 1
7. If such a request is received, and the predicted Hot Spot Temperature for Site 1 for the scenario of the circuit breaker being closed, does not exceed the threshold programmed in the system, then Site 1 closes the circuit breaker, meshing the LV network and reducing the load on the Site 2 Transformer

Full details of the control system operation utilised in the OpenLV Project trials was published as part of SDRC 2.2, (Annex 1 - "Loadsense Operational Logic").

Alvin Reclose™ control software testing

Prior to deployment of the Alvin Reclose™ hardware for the purpose of LV network switching, Factory Acceptance Tests (FAT) were undertaken in a laboratory at EA Technology offices to verify the capability of the trial platform to:

- Track the transformer's thermal state
- Take the output of the profile prediction application and predict the transformer's future thermal state
- Control the Alvin Reclose™ device to manage the network in response to that prediction

Five specific tests were witnessed by representatives from WPD, with a detailed explanation of system operation provided following testing completion.

Both the FAT documentation, and following explanatory report are provided in Annex 2 and Annex 3.

Following receipt of the detailed explanation of the system operation, WPD approved the system for trial deployment.

2.2.4 Site Selection Process

The process for selecting substations for use in the project trials (fully detailed in SDRC 2.2) resulted in 30 pairs of substations being utilised in the project; 25 pairs were installed as Phase 1 (passive) sites, with the remainder being outfitted for Phase 2 (active) sites.

Wherever possible, network pairs were selected to avoid the potential of interlinking different higher voltage circuits. In some instances such potential was unavoidable due to the requirement for a minimum number of each LV network Template Type, these pairs were removed from consideration for the active switching part of the trials and only operated as a Phase 1 pair.

It was also identified in some locations that whilst the two substations were connected to the same 11kV circuit at the time of the network selection process, it was possible, in the event of a network fault, for some automated restoration procedures to connect them to different 11kV circuits.

Where this was identified, the networks were not utilised for active switching trials, and the data gathered was used to inform the thermal modelling work.

LV network Templates Analysis

WPD provided EA Technology with the necessary information relating to the LV network across their licence areas, allowing the evaluation of every substation using the LV network Templates tool, created by WPD's previous Network Templates research project [3].

A relatively small number of substations across each licence are were unable to be evaluated due to gaps in the data, but in total, the data for more than 146,000 substations was processed, with the LV network Template Type being determined for each.

Full details on the distribution of different LV network Template Types across WPD Licence Areas are detailed in Appendix 1.

Trial Substations

It was stated in the OpenLV Bid Documentation that of the eight LV network Templates to be used in the trials, at least three of each type would be utilised within the project except for network types 8 and 10. These were excluded from the desired trial networks due to the load type and general lack of variability within the load profiles.

Table 1: LV network Types

LV network Type	Template Description	No. of Networks (Method 1)
1	High I&C Dominance	7
2	Modest Domestic Dominance (~60%) (Suburban)	11
3	Modest Domestic Dominance (~60%) (Urban)	7
4	High Domestic Dominance (~90%) (Modest Customer Size ~170)	14
5	High Domestic Dominance (~90%) (Low Customer Size ~70)	3
6	Very High I&C Dominance	10
7	Modest Domestic Dominance (~60%) (Rural)	3
8	Industrial Flats	N/A
9	Domestic Economy 7 Dominance (~65%)	5
10	Lighting	N/A

Appendix 2 provides details on which LV network Template type each substation used in the project trials was determined to be.

It is noted however that due to changing load across seasons, a substation's network type can change over the course of the year; for the purposes of the project, Winter was selected as the season for assigning the network type, as traditionally this is the period of peak loading on the distribution network.

2.2.5 Data Collected

The LV-CAP™ platform deployed as part of the OpenLV trials utilised Lucy Electric GridKey (MCU520) platforms to directly monitor the LV network, passing the data gathered to the LV-CAP™ platform for storage and access by other application containers running on the platform.

Full details of the measurements recorded by the trial equipment are detailed in Annex 4.

Across the 80 substations deployed as part of the OpenLV trials, accounting for the different configurations of network feeders at each location, in every 24-hour period where all units were operational, over 15 million individual data points were collected.

There were a number of instances over the 2018 – 2019 period where transient faults on the local network caused the trial hardware to be switched off by local protection systems, causing a data gap until the local network team were able to visit the site to manually restart the system.

It is noted that the requirement for a manual intervention in these circumstances is due to the specific Method of powering the trial hardware and would not affect BAU deployments of distributed intelligence hardware.

2.3 Analysis and Results

2.3.1 LV-CAP™ platform

The OpenLV trials have successfully demonstrated the ability of the LV-CAP™ platform to deliver on the system requirements outlined in Section 2.1, through the use of measured data to make predictions about future behaviour on the network and implement actions as a result.

The LV-CAP™ platform was designed so each calculation container would be capable of interchangeability with another. The intention being for bespoke combinations of applications being configurable for individual substations, or areas, utilising the best 'product' for each location.

In line with this approach, the applications deployed to the LV-CAP™ platforms as part of the OpenLV Project each perform a single discrete task, and are capable of being replaced by another application in the future; as long as the published outputs are replicated the system would continue to operate with no loss of service.

The specific calculations undertaken for the autonomous Method 1 deployments are detailed below.

1. A **Load Profile Prediction** application; every 30 minutes, this application utilised the historical load on the transformer and feeder to make a broad prediction of the load for the next 4 hours, in the two scenarios defined above, publishing a load profile for each scenario
2. No external information such as weather forecast, or anticipated date specific load variations was utilised to inform the predictions
3. The predicted load profiles served as the input data for the **Dynamic Thermal Rating** application, originally created by the University of Manchester prior to the OpenLV Project. This utilised a combination of historical loading and Ambient Temperature data to calculate the Transformer Hot Spot, and Top Oil Temperatures
4. The Dynamic Thermal Rating application then takes the profile predictions for the next four hours and calculates the temperatures the Transformer publishing the highest temperature it is anticipated to reach within that period for both scenarios

5. Finally, an application called **Loadsense** monitors the outputs, and at the Site 2 location if, for the scenario forecast for the circuit breaker remaining open, a temperature that exceeds the operation threshold programmed into the system is predicted, a 'request' for Site 1 to provide assistance is transmitted
6. The **Loadsense** application at Site 1, on receipt of an assistance request from Site 2, will check whether in the 'circuit breaker closed' scenario, it has capacity to provide support. If it does, then the circuit breaker is closed and the transformer at Site 1 takes on some of the load from the connecting feeder, reducing the load at Site 2

It is noted that the LV network system arrangement for these active trials is shown in Figure 4, where the full feeder length is initially energised from the Site 2 substation, with support from Site 1 when required.

The LV-CAP™ platform ably demonstrated the capabilities of Distributed Intelligence, undertaking active control of the LV network, without the intervention of operators from WPD or EA Technology, and retrospective analysis of the data showed it had operated exactly as had been intended.

Overview of switching data plots

In the below series of plots, Pair 22 is used as the exemplar location, demonstrating the measurable effect of active trial operation on the LV network.

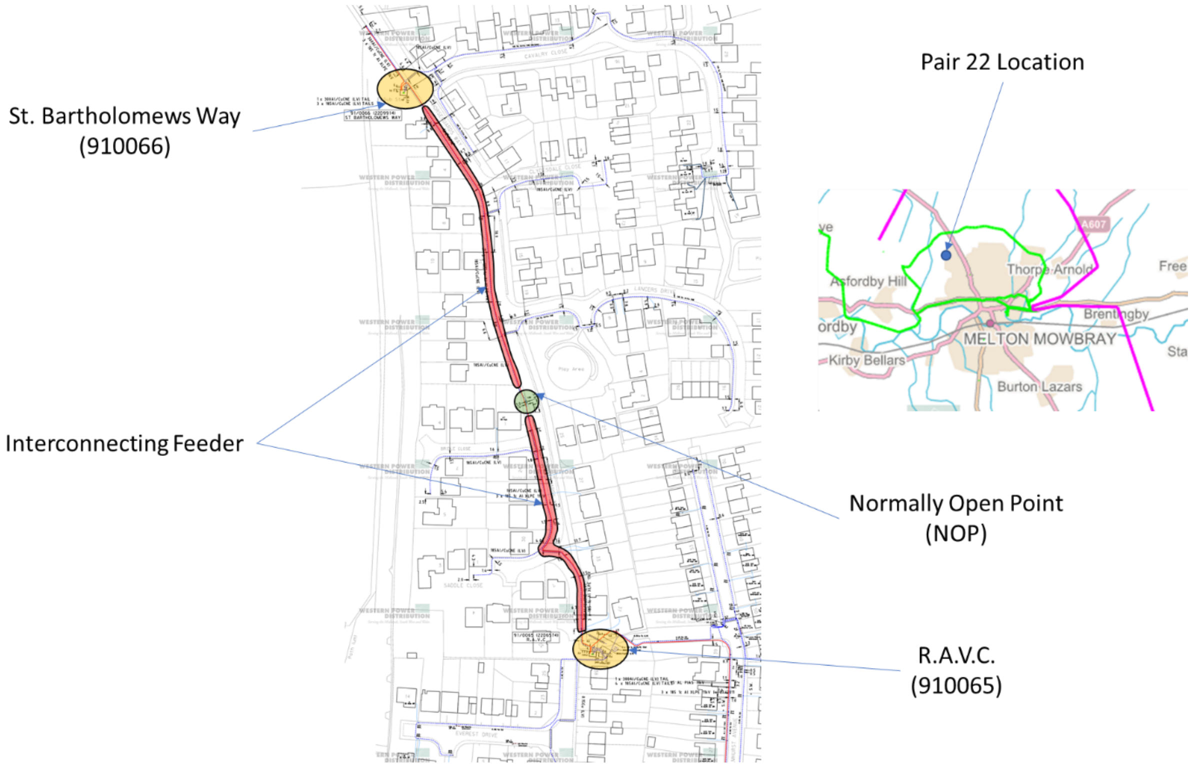


Figure 6: Pair 22 - Location and Network Layout Details

In this network, the substation designated RAVC is operating as Site 1, (the Control Site), responding to Site 2, located at St. Batholomews (the Supported Site) when assistance is requested.

Figure 7 below shows the total loading on each transformer across the week commencing July 15th, 2019. The RAVC transformer is rated at 800kVA with St. Bartholomews being rated at 315kVA and it is clear that neither are approaching their capacity limits.

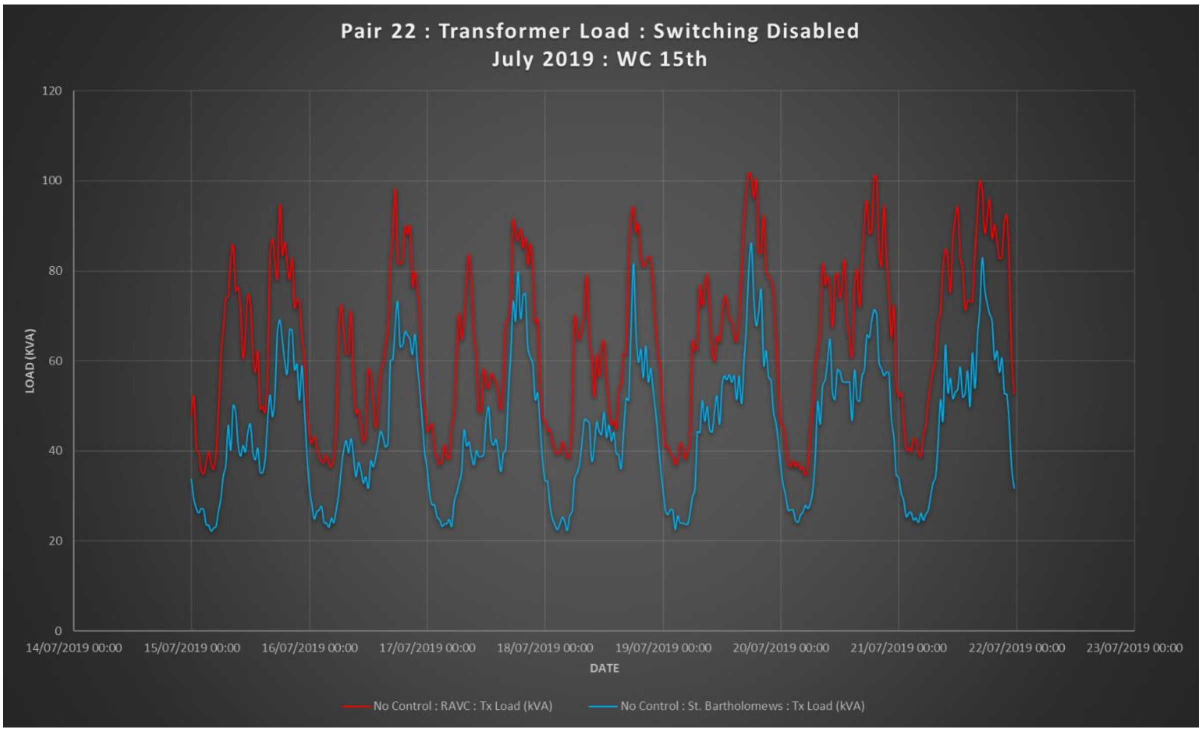


Figure 7: Pair 22 - Transformer Loading

The algorithm developed by the University of Manchester is used to undertake a number of calculations every 30 minutes:

- The instantaneous Hot Spot Temperature based on the data recorded by the system and information on the transformer
- The Top Oil Temperature, based on the Hot Spot Temperature and information on the transformer
- Utilising predicted load profiles to predict the highest Hot Spot Temperature to occur in the Site 1 transformer if the circuit breaker is closed
- Utilising predicted load profiles to predict the highest Hot Spot Temperature to occur in the Site 2 transformer if the circuit breaker remains open

As it is impossible to measure the Hot Spot Temperature of an operational transformer, the calculated Top Oil Temperature is used as a proxy to determine whether the calculations can be relied upon for the trial's control system.

It can be seen below in Figure 8 that for both transformers, the measured and calculated temperature for the Top Oil are following near identical tracks, but offset by approximately 3°C. The process for calculating the Top Oil Temperature is linked to the Hot Spot Temperature, giving assurance that the calculated Hot Spot Temperature is also following a similarly accurate trace to the actual temperature, whilst also being offset in the same way.

This offset, calculating a slightly higher temperature than was actually recorded, served to provide an additional safety margin for the system being trialled.

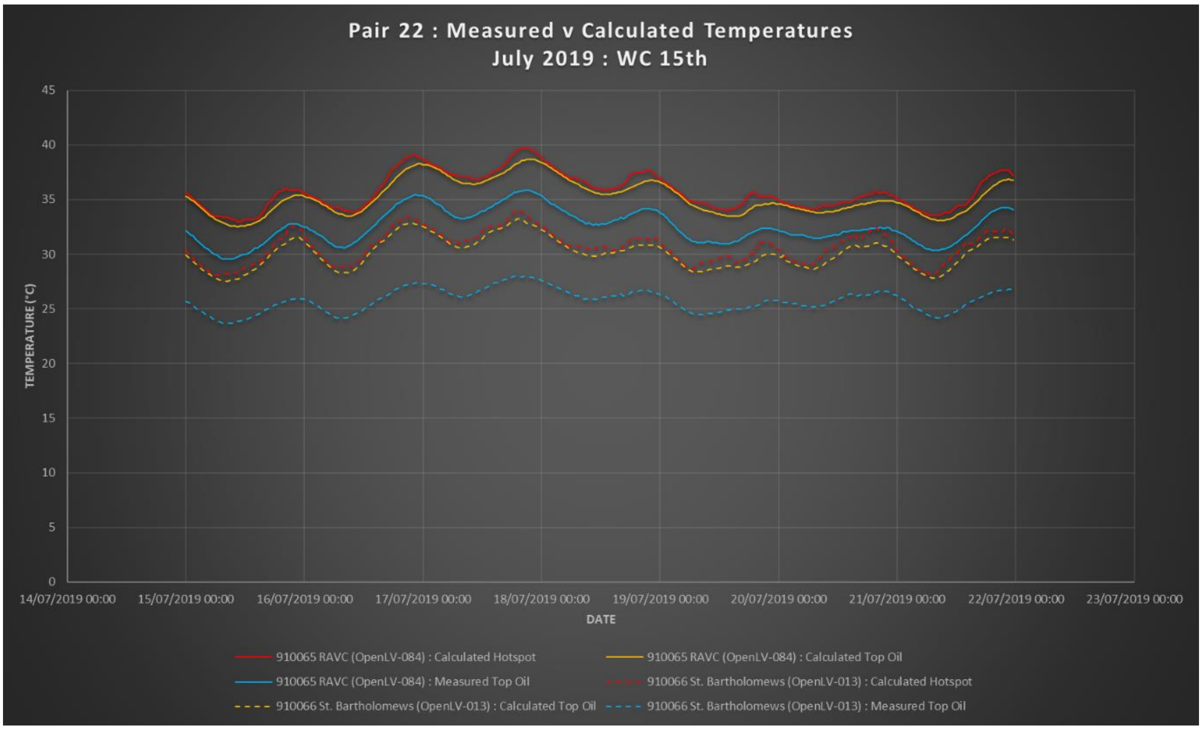


Figure 8: Pair 22 - Measured vs Calculated Temperatures

Using forecasted load profiles allows the thermal rating application to predict the Hot Spot Temperature for the worst-case scenario for each transformer as defined above.

In a business as usual scenario, it is anticipated that the thresholds would be set for the protection of each transformer using values defined to avoid accelerated asset ageing, refer to Table 2, but in order to ensure system operation within the trials, thresholds were set at significantly lower values to demonstrate platform functionality.

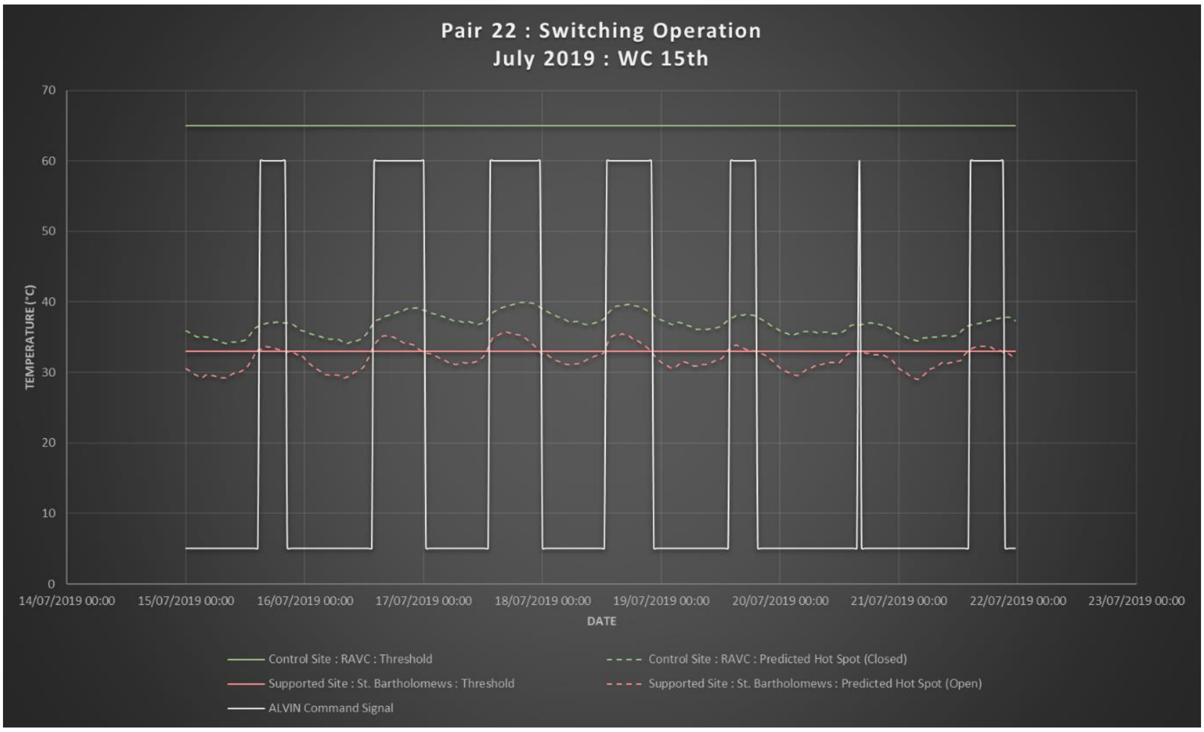


Figure 9: Pair 22 - Switching Operation

Figure 9 shows that at all times, the forecast Hot Spot Temperature for the RAVC transformer remains well below the safety threshold, where the system would abort any requested meshing operation.

Consequently, the switching operation is triggered only in response to the Hot Spot Temperature for the St. Bartholomews and it can be seen that the switching operation occurs whenever the forecast temperature exceeds the threshold.

The system operation had a measurable impact on the total transformer and connected feeder load, as shown in the below plots, comparing the load that would have occurred without switching being implemented, with the actual load as a result of the control system operation.

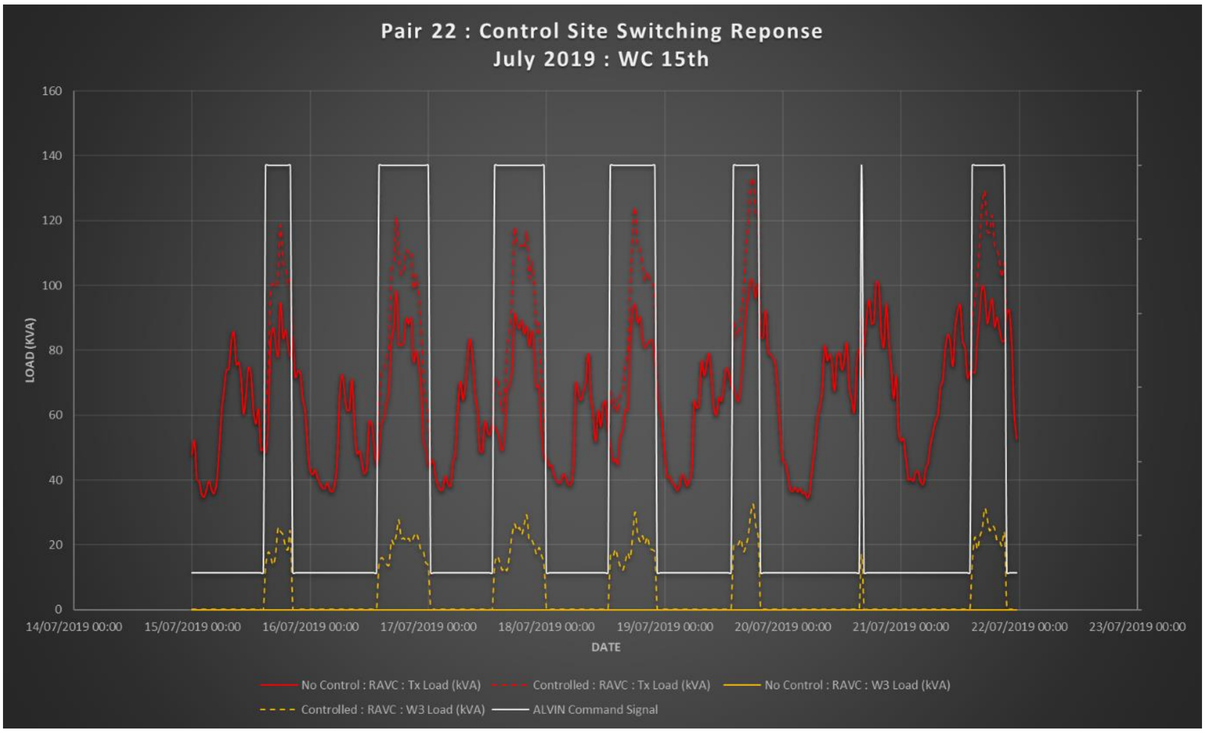


Figure 10: Pair 22 - Control Site Switching Response

Figure 10 (above) and Figure 11 (below) show an increase in load on the feeder and transformer at the RAVC substation, with equivalent decreases at St. Bartholomews when the circuit breaker is closed.

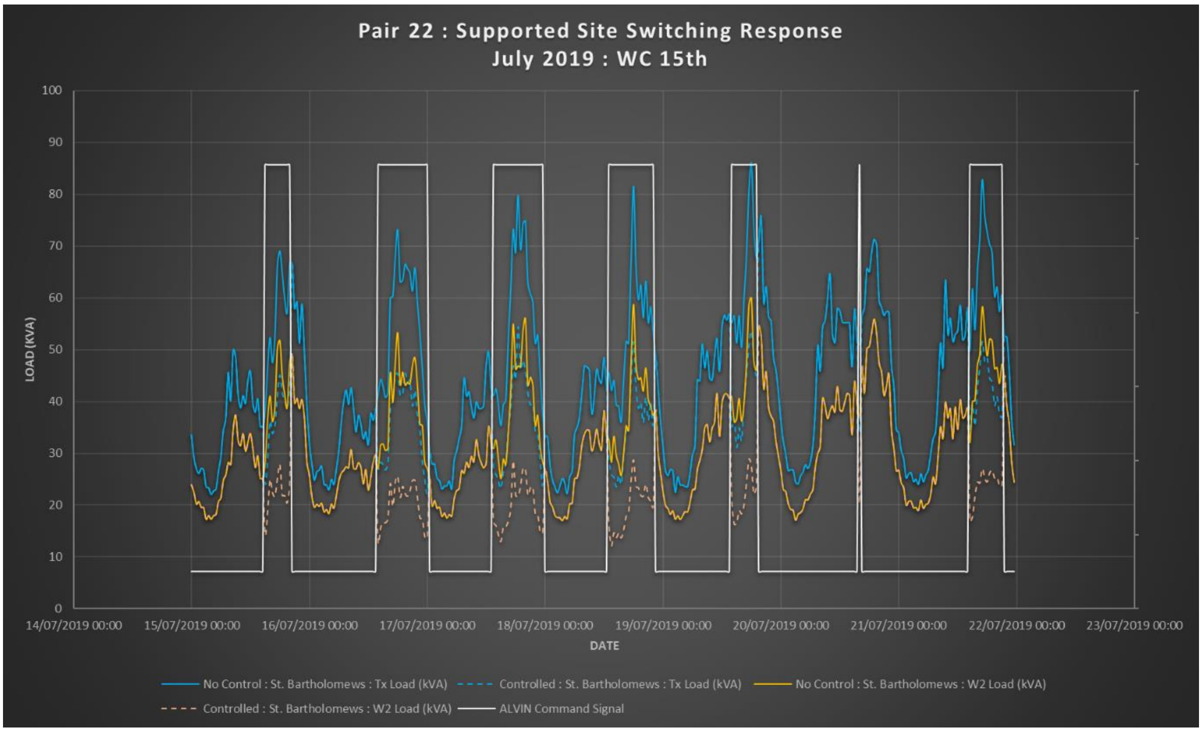


Figure 11: Pair 22 - Supported Site Switching Response

Figure 12 below shows the effect of the switching control on the network assets, comparing the predicted Hot Spot Temperatures against the instantaneously calculated value for each 30-minute period.

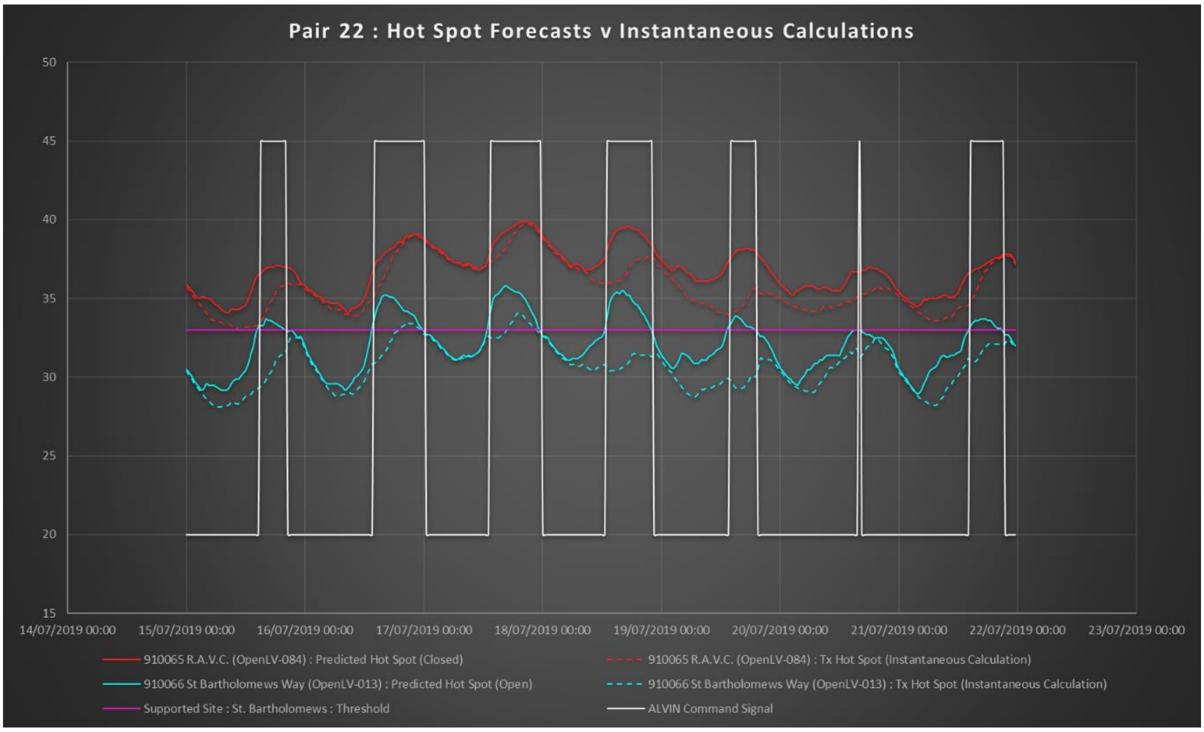


Figure 12: Pair 22 - Effect of Switching on Tx Temperatures

When the switching is not enacted, the instantaneous and forecast values match, or trend towards each other. Where this doesn't occur (July 18th – 19th) it can be seen that both transformers experienced lower than anticipated temperatures. This was due to a lower than anticipated demand on the local network, contributing to the lower actual temperatures and the subsequently shorter switching periods experienced on those two days.

It is emphasised that for Site 2 locations, implementation of such a control system will result in asset load being lower than the worst-case prediction, and subsequently a lower than predicted Hot Spot Temperature if the switching mechanism is enacted.

Inversely, for Site 1 locations the worst-case prediction will be tended towards where switching is enacted and once the network load begins to reduce, will track the current temperature until load forecasts begin to increase again.

It is clear from the above plots that the load experienced by each substation was different to that being forecast, prior to operation of the system. The LV-CAP™ platform enacted measurable changes to the LV network, demonstrated by the forecast temperatures being different to those that occurred during the period of active control.

Considering such a response in a business as usual scenario, where the system would only operate when protection of the network assets were required, rather than for artificially low thresholds as used in the trials, the approach of 'operate ahead of need' has been demonstrated to benefit the asset.

A system configured in this way and reporting such operations to the asset manager could provide additional capacity / extend usable life of the asset whilst assessment was undertaken and a longer-term solution, if necessary, prepared.

2.3.2 Dynamic Thermal Ratings (DTR)

When considering the utilisation of network assets, existing equipment ratings are based on assumptions about the cyclic nature of the connected load. These are conservative, and often mean that the ‘nameplate rating’ of a transformer may be significantly below what it can actually deliver.

Previous projects have demonstrated the benefits of DTR or RTTR (Real Time Thermal Rating) of assets and as such, the OpenLV Project did not intend to evaluate the effectiveness of such an approach in general terms.

The specific application developed by the University of Manchester for calculating the Hot Spot Temperature of a transformer will be evaluated however, to determine the potential benefits from deployment in a BAU context using a distributed intelligence platform.

The application deployed in the trials, utilised algorithms developed as part of a study of “Thermal Monitoring and Thermodynamic Modelling of Distribution Transformers” undertaken by the University of Manchester with Electricity North West, included in Annex 5.

The pertinent element of this research, from the OpenLV Project perspective, was work to “refine thermal parameters for individual transformers to reflect their differences in thermal characteristics based on the IEC 60076-7 thermal model.”

As such, the algorithm developed by the University of Manchester was ideally suited to be deployed in a self-contained application on the LV-CAP™ platform and provide the project with a calculation for the Hot Spot Temperature that could be considered reasonably accurate. This allowed for control operations to be initiated based on value that was previously impossible to use directly.

Business as Usual Considerations

The nameplate value on a transformer is the static kVA rating for the asset whereas the use of cyclic ratings can provide additional ‘peak capacity’, leveraging the variability in network loading and that asset temperatures vary far slower than load.

Cyclic ratings are higher than a static rating because under normal operating conditions, the temperature of the transformer is the principle factor when considering the ageing rate of the asset.

The Hot Spot Temperature is primarily affected by two factors: the Ambient Temperature affecting the rate at which the transformer can radiate heat to the environment and the network load, with higher energy draws by connected customers increasing the heat generated within the transformer.

SP Energy Networks' Flexible Networks for a Low Carbon Future report titled 'Enhanced Transformer Ratings Tool' confirms a continuous, or static rating of a transformer is calculated on an Ambient Temperature of 20°C and a Hot Spot Temperature of 98°C. Whilst this report was written with respect to Primary Transformers, the industry standard thermal model utilised as the primary reference (IEC 60076-7) was also the source for the work undertaken by Electricity North West and the University of Manchester when developing the algorithm utilised in the OpenLV Project for Dynamic Thermal Rating calculations. IEC 60076-7 provides an indication of the effects of Hot Spot Temperature on the aging rate of the asset, and therefore confirms that operating a transformer below a temperature of 98°C is preferred.

Table 2: IEC 60076-7 Hot Spot Temperature vs Age Rate

Hot Spot Temperature (°C)	Non-Thermally Upgraded Insulation Age Rate
80	0.125
86	0.25
92	0.5
98	1
104	2
110	4
116	8
122	16
128	32
134	64
140	128

Calibration & Accuracy

The application deployed in the project utilised historical network loading and Ambient Temperature data to calculate the instantaneous temperatures of both the Hot Spot and the Top Oil.

Each application was initially calibrated based on the transformer's power rating (kVA) and the voltage level, with further adjustment proving essential dependent on the environment of the substation assets.

These adjustments were undertaken over a period of several weeks for each transformer, eventually provided a good calculated value for the Top Oil Temperature when compared directly with the measured temperature. of calibration to ensure a good fit between the calculated and actual Top Oil Temperatures.

The below figures show the improvement in calculated accuracy as a result of calibration updates to the LV-CAP™ platform installed at unit OpenLV-064.

On first deployment of the dynamic rating application to OpenLV-064, the calculated Top Oil Temperature varied from the measured reading by approximately 5.5°C, a difference that reduced to approximately 4°C after the configuration was adjusted for the specific asset characteristics. detailed in Annex 5, Appendix: Thermal parameters derived by heat run test data of 20 distribution transformers representing population.

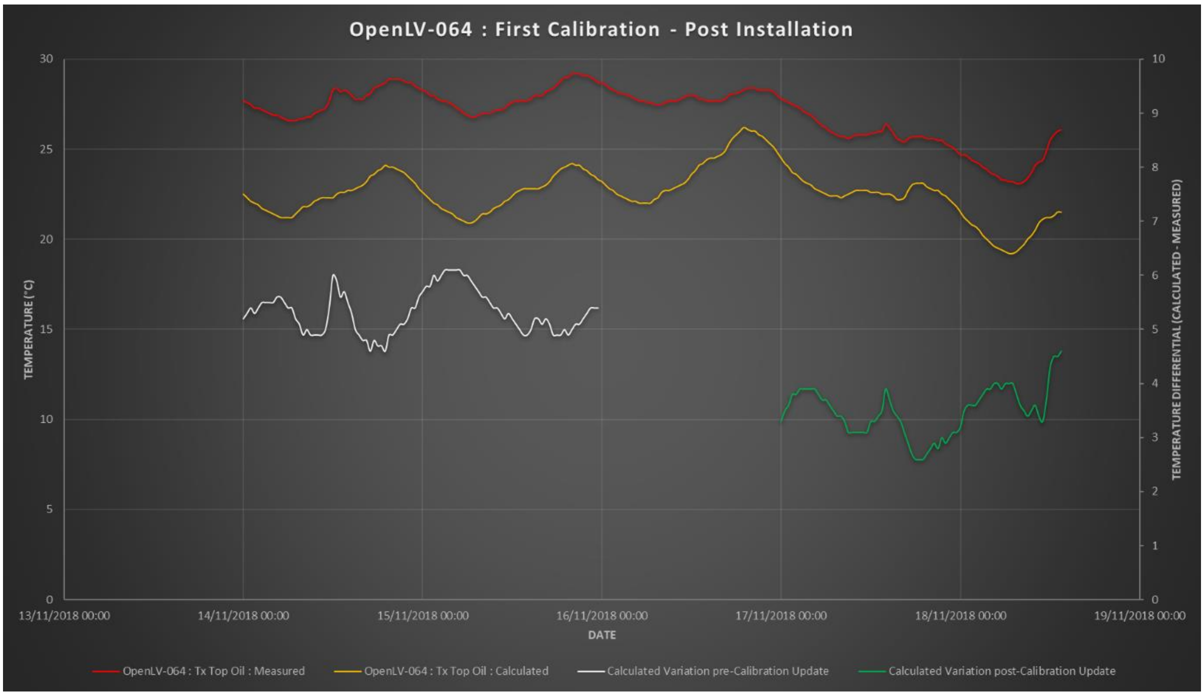


Figure 13: DTR Application Calibration - First Stage

A further adjustment to the configuration of the algorithm reduced the differential between calculated and measured Top Oil values to an average of less than 1°C.

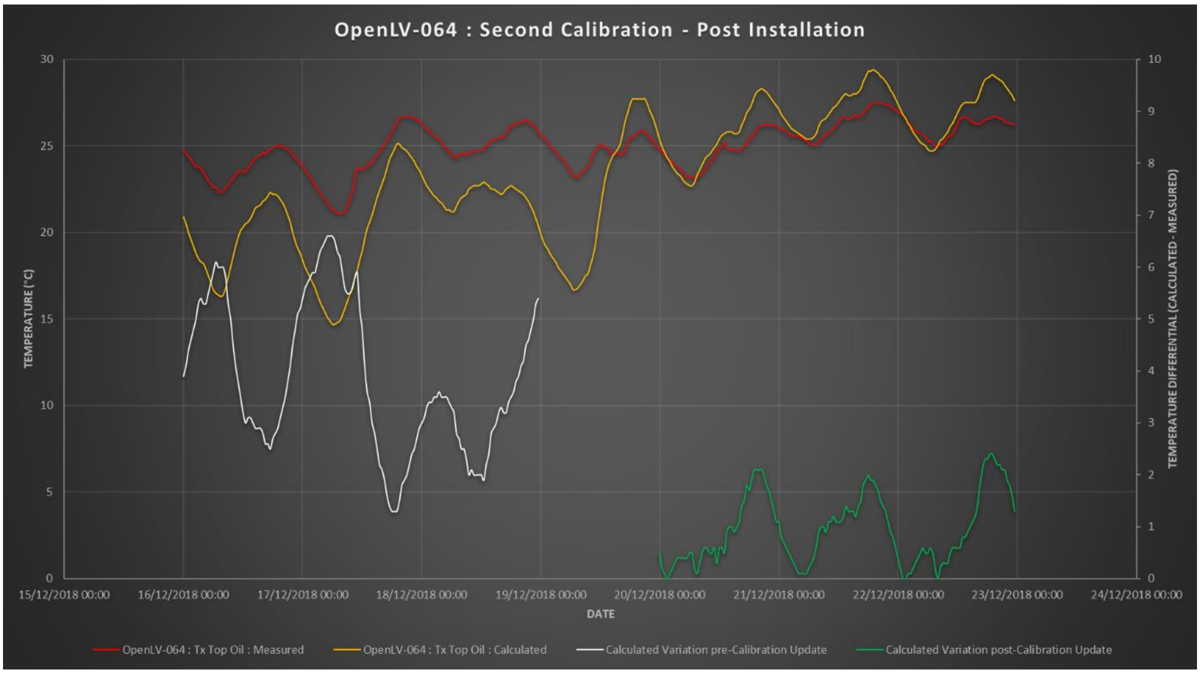


Figure 14: DTR Application Calibration - Second Stage

The final settings utilized for the trial did not fully account for the thermal mass of the transformer, as the calculated value tended to overshoot the measured readings but on average the temperature value was approximately 0.75°C away from the measured reading, an accuracy considered to be 'close enough' for the purposes of the project.

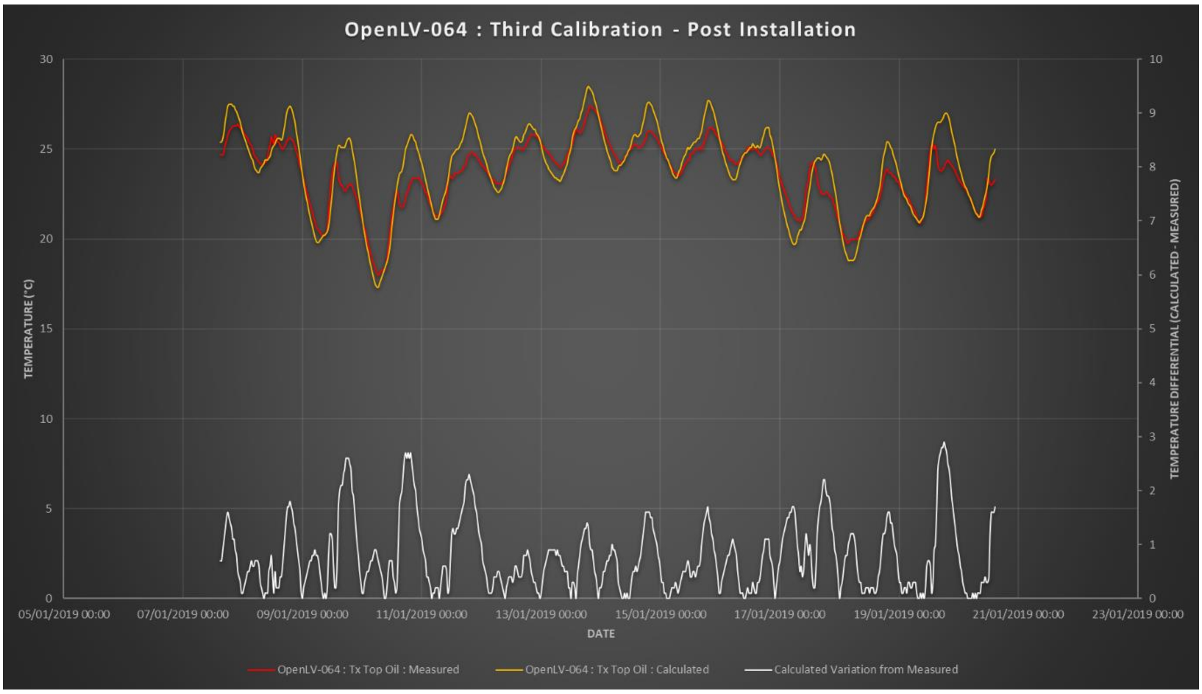


Figure 15: DTR Application Calibration - Third Stage

This process was followed for each of the network pairs utilized in the active control trials, and whilst a reasonably high level of accuracy was achieved, the necessary configuration process would be unsustainable for deployment across the GB network.

For any application requiring similar levels of calibration, it is recommended that a Method of automatic tuning should be incorporated. An accuracy rating would also be beneficial if included in such an application's outputs, (where a measured value can be directly compared with a calculation), allowing for a 'trust level' to be applied to system outputs.

It is clearly not possible to measure the Hot Spot Temperature of a transformer during normal operation, preventing a direct comparison between the actual Hot Spot Temperature and that calculated by the application.

However, as the same process of temperature calculation is used for both the Top Oil and Hot Spot Temperatures, ensuring the calculated Top Oil Temperature was practicably close to the measured value, provided assurance that the Hot Spot Temperature could be assumed to also be reasonably close.

After calibration, it was found that it was possible to achieve a high level of accuracy with an average difference of 2°C across all ten substations.

The table below shows the maximum, average and minimum differences between the actual and calculated Top Oil Temperatures for all Method 1, Phase 2 substations in March 2019.

Table 3: Method 1 Phase 2 - Calculated Top Oil Accuracy

Pair ID	Pair 22		Pair 26		Pair 27		Pair 28		Pair 29	
OpenLV ID	OpenLV-084	OpenLV-013	OpenLV-016	OpenLV-042	OpenLV-041	OpenLV-064	OpenLV-067	OpenLV-082	OpenLV-075	OpenLV-050
Tx Rating (kVA)	800	315	500	500	500	315	500	500	315	500
Substation Type	Indoor	Indoor	Indoor	Indoor	Indoor	GRP	GRP	GRP	Indoor	Indoor
Max Variation	3.70	6.10	6.30	1.90	4.80	5.20	2.60	4.70	4.60	2.40
Average Variation	2.53	3.75	4.57	0.83	2.90	1.15	0.61	1.98	1.44	0.79
Min Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The process encoded within the application to calculate the Top Oil Temperature is also used to predict the transformer Hot Spot Temperature and as such, whilst it is not possible to directly measure the Hot Spot Temperature, it is assumed that the calculated Hot Spot Temperature will not be significantly less accurate than the calculated top oil value.

Assessment of relationship between the Tx Load and Hot Spot and Top Oil Temperatures

Statistical analysis (detailed in Appendix 1) was utilised to determine the relationship between the Transformer Load and the calculated Hot Spot Temperature, such that it could be deployed more widely and cost effectively.

This analysis determined that where real-time monitoring was available for the Temperature of both the Transformer Top Oil, and the environment surrounding the Transformer, and the total % Loading of the Transformer, then the Hot Spot could be calculated with a high level of accuracy through the derives equation.

Equation 1 : Three variable equation for calculating Tx Hot Spot

$$Temp.TxHotSpot_E = 2.96 + (0.627 \times Temp.TopOil_M) + (21.5 \times Tx\ \%Load_M) + (0.349 \times Temp.Ambient_M)$$

Calculated Hot Spot Temperatures

Evaluation of the calculated Hot Spot Temperatures in relation to the % Loading of the OpenLV trial transformers revealed that the 98°C threshold was only exceeded on two occasions (see Figure 16).

Transformers of different ratings were found to operate in a similar manner at lower ratings, but begin to slightly diverge as the loading increases. As such, transformers were split into three groupings for consideration: <500kVA, 500kVA, and >500kVA as shown in the figure.

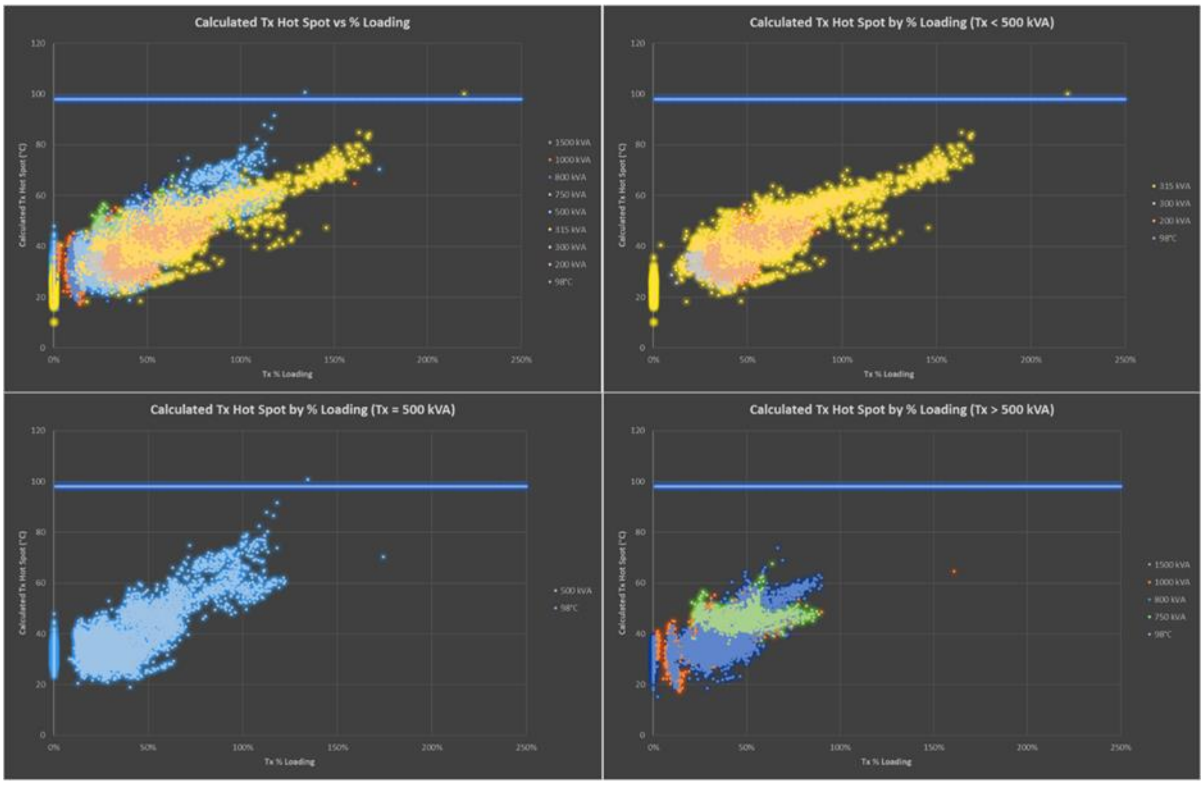


Figure 16: Calculated Hot Spot vs % Loading (Tx Groupings)

Utilising this data to derive formulae for predicting LV transformer Hot Spot Temperatures as loading increases allowed calculation of the theoretical limit to which LV transformers can be loaded to, when Ambient Temperature conditions are suitable. This was achieved through determining trend line for the three transformer groupings evaluated, as seen in Figure 17.

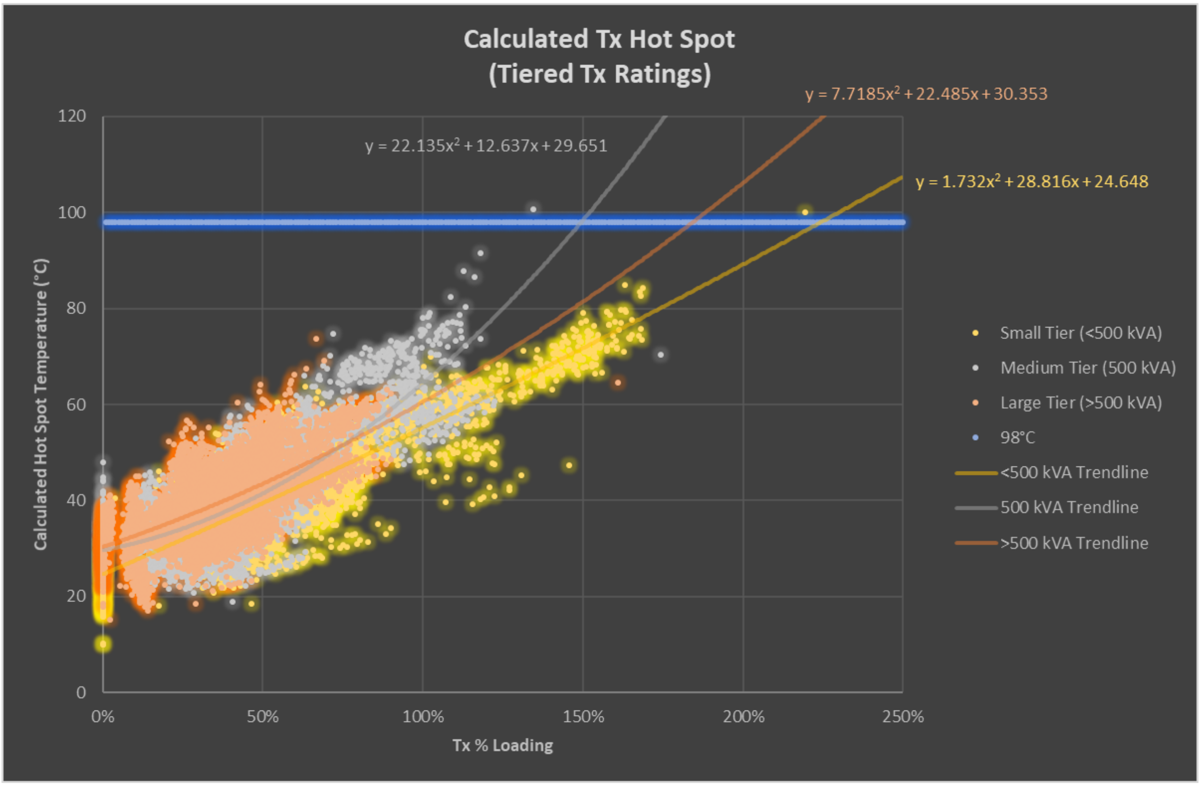


Figure 17: Forecasting Tx Hot Spot Temperatures

Solving the derived formulae for a Hot Spot value of 98°C, provides a theoretical peak loading for each grouping or tier of transformers, if utilising the algorithm developed by the University of Manchester in comparable environmental conditions to the original data set.

Table 4: Instantaneous DTR Rating

Tx Tier	Instantaneous DTR Rating
Small (<500 kVA)	224%
Medium (500 kVA)	149%
Large (>500 kVA)	184%

Determination of the potential headroom increase achievable from the DTR application up to the levels determined in Table 4 of requires consideration of the existing policies, viability of installation of the necessary distributed intelligence hardware, and whether surrounding hardware is capable of such increase.

Effect of Ambient Temperature on Calculated Hot Spot Temperatures

The wide range of Hot Spot Temperatures measured for any given level of proportional loading is an effect of the Ambient Temperatures. This is evidenced by the below plots showing the range of calculated Hot Spots relative to proportional loading, grouped by Ambient Temperature ranges.

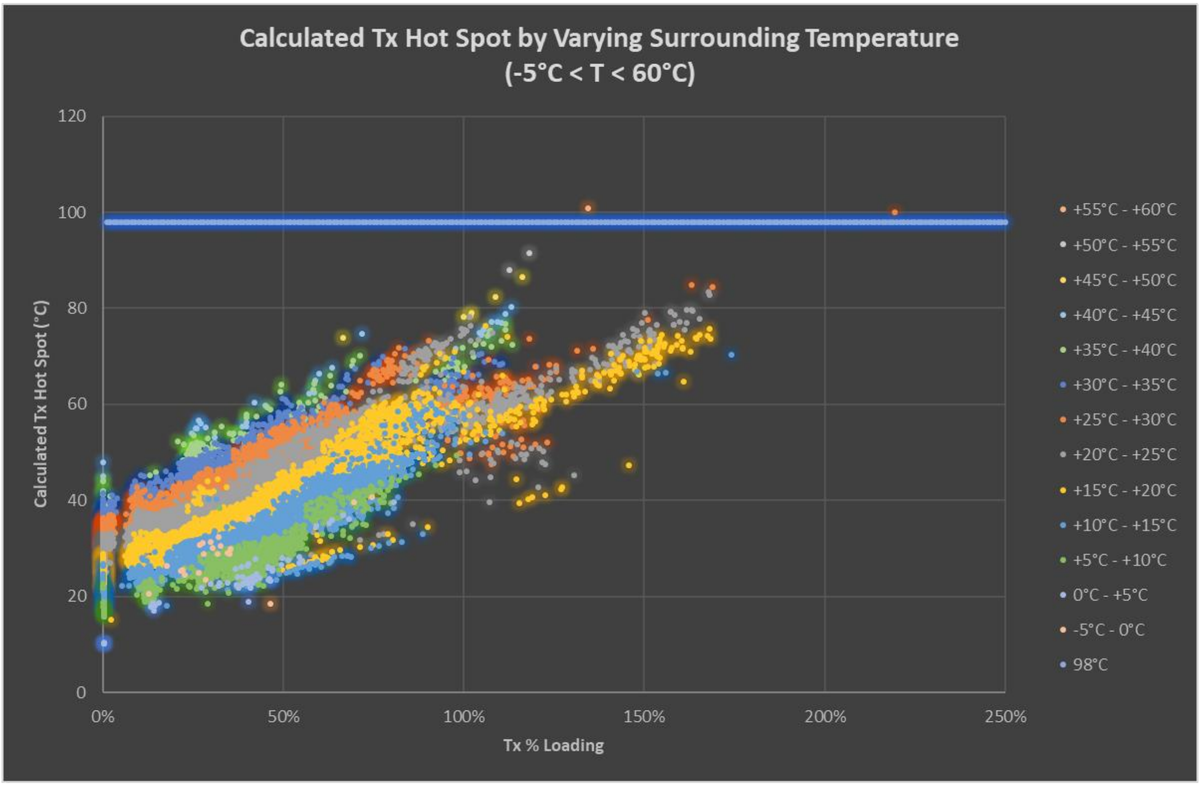


Figure 18: Calculated Tx Hot Spot in relation to surrounding temperature

Figure 18 shows clear bands of calculated Hot Spot Temperatures, all following broadly the same pattern of increasing in line with the proportional loading experienced by the transformers, but consistently increasing as the temperature of the surrounding environment increases (whether an indoor or outdoor site transformer).

Further analysis of calculated Hot Spot Temperatures is available in Appendix 4. Figures detailing the banding in separate plots are provided in Appendix 5.

2.3.3 LV Switching

Within the active trials' element of the OpenLV Project, the controllable circuit breaker was located at one substation of the pair, principally to reduce the cost of project deployment, whilst maintaining the ability to demonstrate active control of the network by the LV-CAP™ platform.

Were automated network meshing to be utilised for business as usual deployments, it would be preferable to 'mesh' the networks at the Normally Open Point, leaving the LV network in a standard radial configuration when meshing is not required.

Consequently, rather than simulating the meshing of LV networks at one substation or the other, the below analysis has been undertaken as if the meshing were to occur at the NOP.

Analytical Process

The potential benefits from this load switching solution rely on the linking of two feeders via the NOP enabling a proportionally less loaded transformer to 'pick up' load from another transformer that has a higher proportional load.

Note that it is not necessary for either transformer to be under excessive strain for benefits to be achieved, but it requires the connecting feeder to be imbalanced on either side of the NOP, otherwise the load transfer from one side to the other will be minimal. It is also possible that when meshing is initiated at the NOP, any load transfer is low enough, in proportion to the overall transformer load, that any benefit is negligible.

For the purposes of determining the maximum potential benefit achievable from this solution, simulation of the network benefit in each substation pair was done by calculating the effect of linking the feeders at the NOP with the assumption that the load share between the feeders will be 50% to each substation.

Pair 2 is used to demonstrate this approach in the figures below.

Substation OpenLV-005 has a transformer with a nameplate rating of 500kVA, with an average loading through January 2019 of 37%. The connected substation, OpenLV-008, is an 800kVA nameplate rated transformer that experienced an average loading of 12% in the same period.

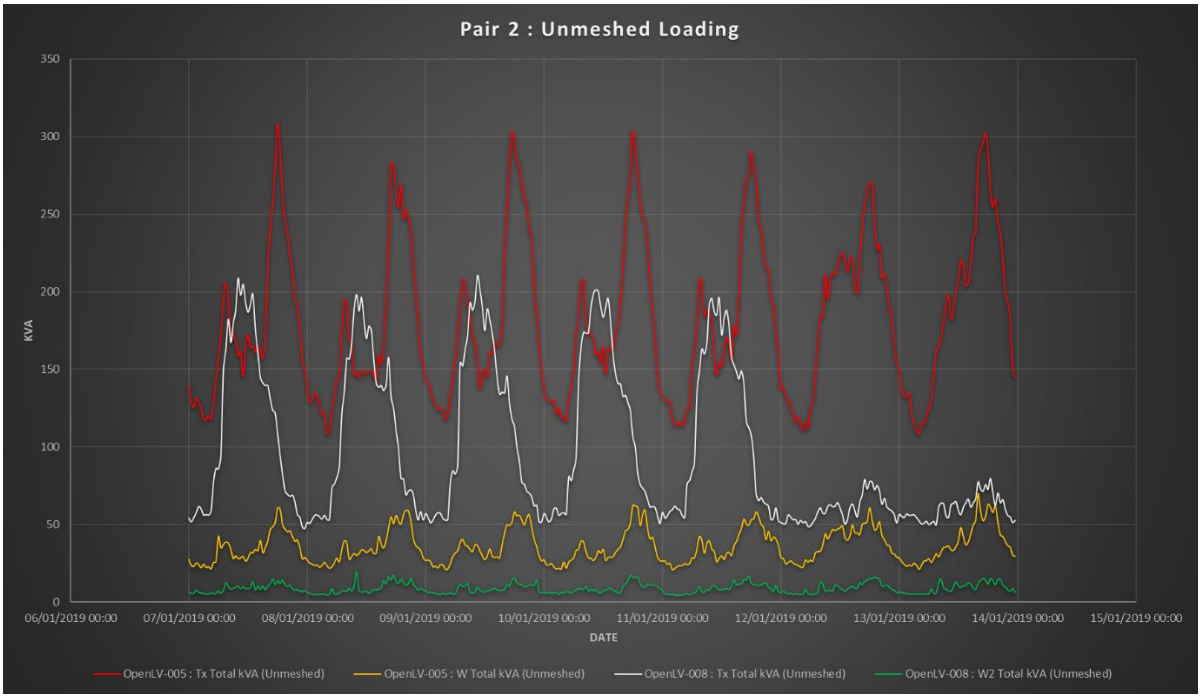


Figure 19: Pair 2 - Unmeshed Loading

It can be seen from the above figure that there are relatively substantial differences in the load on each transformer, and on the connecting feeder from each substation. It would appear that if either transformer were approaching its operational limit, benefit could be gained from meshing the LV network.

OpenLV-005 has the highest actual load, both at the transformer and along the feeder, and hence will benefit from the implementation of a load sharing scheme. Simulating this solution for the feeder provides the result shown below, with the highest load peaks on the feeder from OpenLV-005 dropping to approximately 60% of the pre-mesh figure, with the load on the OpenLV-008 feeder increasing accordingly.

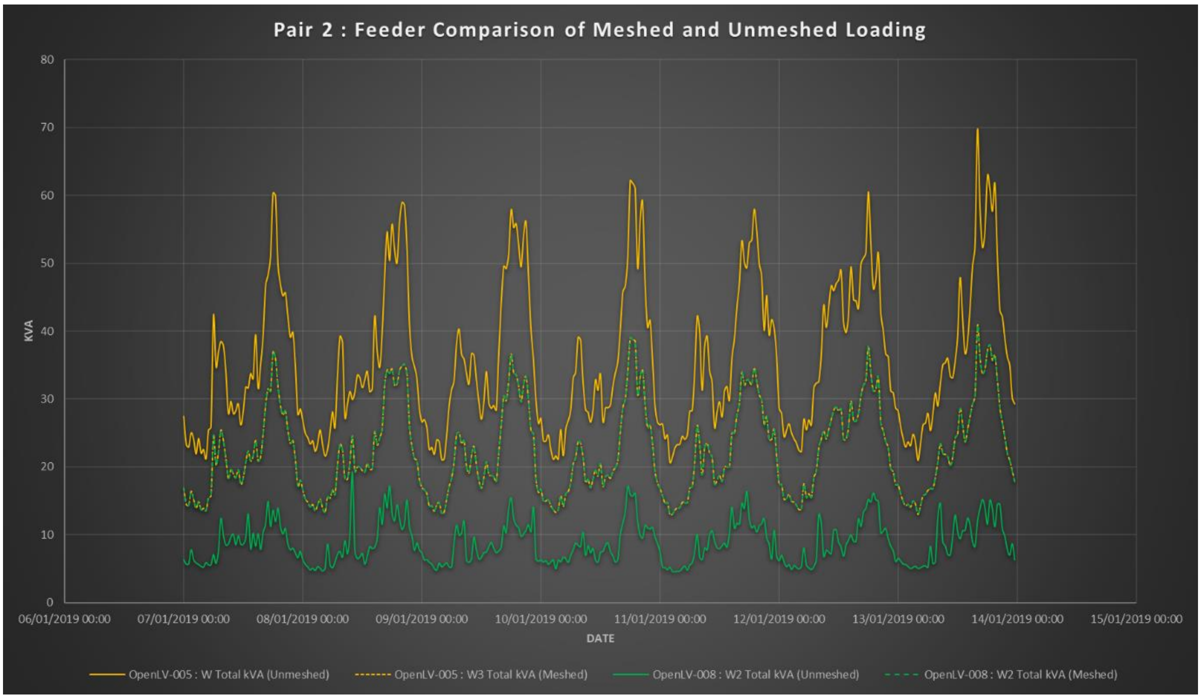


Figure 20: Pair 2 – Feeder Comparison – Meshed & Unmeshed Loading

This solution smooths the variability of load on the feeder whilst lowering the peak and average feeder load for -005 and raising it for -008, an effect also repeated at the Transformer level.

In contrast however, it is clear that the relatively high benefits achieved at the feeder level, do not translate to equivalent, proportional benefits at the transformer level (see Figure 21) due to overall loading differential.

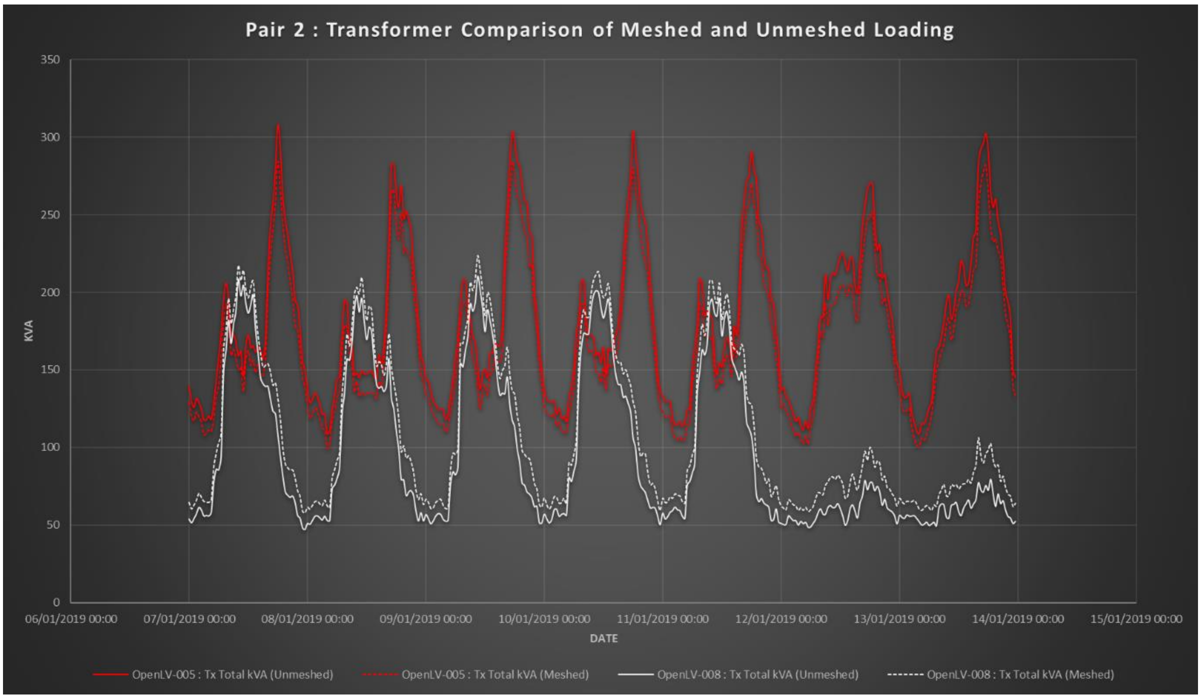


Figure 21: Pair 2 – Transformer Comparison – Meshed & Unmeshed Loading

In circumstances where there is a load imbalance between two substations at either end of the feeder, linking the feeders together benefits one substation through load reduction, but negatively affects the other by the same amount in real terms.

The implementation of automated load transfer schemes, either through the use of Smart Link Boxes or configuring the Alvin Reclose™ style switches to implement such services has the potential to provide localised headroom increases, depending entirely on the Tx ratings and load on the interconnected feeders.

Outcomes

This solution is viable however in certain circumstances:

1. If the transformer experiencing a load increase has a larger nameplate capacity than the other, then additional capacity has been released through better balancing of the network assets
2. Similarly, if the transformer to experience a load reduction is near its operating limit then any reduction that can be achieved is of benefit, so long as the load transfer does not push the other transformer into a similar state
3. Where the load types are significantly different on the two feeders, (i.e. industrial load versus domestic), where there is minimal overlap in load requirements and both transformers can benefit from reduced feeder loads
4. Where Alvin Reclose™ type have already been deployed for the purpose of automated fault restoration as the marginal cost for implementing automated load sharing / LV switching could be a worthwhile investment

This particular combination of circumstances is not common across the LV network and unless significant load imbalances are in effect, are unlikely to provide any material benefit.

Recalculating the average loading for Pair 2 in January 2019, assuming the load transfer were in place throughout the period, results in a minor capacity release of 1.55kVA, achieved through the reducing the load experienced by OpenLV-005 by a greater proportional amount than the increase experienced by OpenLV-008.

Across the substation pair, this equates to a 0.12% increase in capacity, and is the highest identified gain of any pair in the OpenLV Project.

The full table of potential benefits from this Method across the 30 pairs deployed in Method 1 is provided in Appendix 5.

It is therefore concluded that whilst the LV-CAP™ platform demonstrated the ability to automate network switching, to deploy such a solution in isolation, for the purposes of releasing additional network capacity is unlikely to achieve any widescale network benefits, although it remains a possibility in isolated instances.

For the purposes of this report however, the level of practicable capacity uplift that can be achieved as a result of deploying such a solution are determined to be zero.

2.3.4 Combining DTR with LV Switching

The net benefit achievable from implementing LV switching is unchanged when combined with the use of Dynamic Thermal Ratings.

Consequently, the level of capacity uplift that can be achieved from deploying both solutions, as configured in the OpenLV Project, is the same as for the implementation of DTR alone.

2.3.5 Extrapolation to BAU

Analysis of the data gathered throughout the OpenLV Project has not demonstrated any measurable difference between the potential benefits for different network types. The measurable variations relate to the transformer capacities and the changing temperature of the transformer's surroundings.

Consequently, on a theoretical basis, the realisable benefits from the Method 1 trials can be applied to all substations in the GB network, if deemed cost effective to do so.

WPD Licence Areas

WPD's Company Directives and Policies reference multiple industry standards, and when considering the extent to which transformers can be loaded beyond the nameplate rating, define the following principles:

- Policy Document SD4/8 [4]: when discussing the implementation of Active Network Management (ANM) schemes then "the maximum load on any item of plant or equipment, excluding overhead lines, shall not exceed 125% of its rating" when the effect of the implemented ANM scheme is disregarded. This is intended to mitigate the impact of the ANM scheme failing for any reason
- Standard Technique TP4B/2 [5]: states that when selecting fuses for 11kV and 6.6 kV transformers, "Transformer overloads up to 150% of nameplate rating shall be possible". This is taken to mean that even with active network management monitoring the hot spot of these units, 11 kV and 6.6 kV transformers will not be able to be loaded above 150%

Analysis of WPD's licence areas provides the detail available in Appendix 1 from which is can be seen that the total capacity of WPD's LV network Transformers is approximately 25,400 MVA.

This is comprised of:

Table 5: WPD Licence Area Network Capacity

Transformer Ratings	LV network Capacity (Nameplate Ratings)
< 500 kVA	10,300 MVA
500 kVA	8,400 MVA
> 500 kVA	6,700 MVA
Total	**25,400 MVA**

When considering the potential head room increase possible from the OpenLV Project's DTR trials, WPD's operational policies and procedures, the following points are key:

1. That without the presence of an Active Network Management scheme, the maximum capacity of the network is 125% the nameplate rating of the connected transformers
2. That deployment of a Distributed Intelligence Device enables implementation of ANM schemes that will maintain operational effectiveness even in the event of poor communications, and therefore will continue to operate whilst the connected LV network is energised
3. That short-term overloads of assets are possible, and shall remain restricted to 150% of the nameplate rating. This restriction stems from fuse limitations rather than those of the transformers

As the DTR formula calculations restrict 500 kVA transformers, on average, to 149% of the nameplate rating (as demonstrated in in Section 2.3.2) which is less than the currently permissible short-term overload, the potential for further capacity release lies with the transformers above and below this 500kVA rating (see Table 4 in Section 2.3.2).

However, it is also considered unlikely that transformers of a capacity below 300 kVA would be outfitted with distributed intelligence platforms for solely network capacity uplift benefits[1], (at least within the foreseeable future), as the achievable benefits would be outweighed by the deployment and maintenance costs.

Therefore, determining the potential increase in WPD's network capacity based on transformers of a rating 300 kVA and greater, provides:

Table 6: Implementing OpenLV DTR in comparison to WPD's current operational practices

Tx Rating	No. of Tx	Static Capacity (100% Rating)	Cyclic Capacity (125% Rating)	Cyclic Capacity (Fuse Limited) (150% Rating)	Theoretical Thermal Capacity[2] (DTR Rating)
< 300 kVA	106, 705	5,700 MVA	7,150 MVA	8,600 MVA	8,600 MVA
300 kVA	6,384	1,900 MVA	2,400 MVA	2,900 MVA	4,290 MVA
315 kVA	8,534	2,700 MVA	3,400 MVA	4,000 MVA	5,900 MVA
500 kVA	16,805	8,400 MVA	10,500 MVA	12,600 MVA	12,500 MVA
750 kVA	1,625	1,200 MVA	1,500 MVA	1,800 MVA	2,240 MVA
800 kVA	3,995	3,200 MVA	4,000 MVA	4,800 MVA	5,900 MVA
815 kVA	1	815 kVA	1 MVA	1.2 MVA	1.5 MVA
1000 kVA	2,238	2,200 MVA	2,8000 MVA	3,400 MVA	4,100 MVA
1500 kVA	9	13.5 MVA	16.9 MVA	20,250 MVA	24,800 MVA
1600 kVA	1	1.6 MVA	2 MVA	2.4 MVA	2.9 MVA
Total Capacity		25,400 MVA	31,750 MVA	38,100 MVA	43,700 MVA
Rating Increase (Relative to Previous Level)			6,350 MVA	6,350 MVA	5,600 MVA
Total Capacity (Relative to Previous Level)		100%	125%	150%	172%

[1] It is acknowledged that deployment to smaller transformers for the purposes of supporting community groups or third party requirements may occur, but for the purposes of only seeking to increase network capacity in such a situation, upgrading of the asset is considered to be a more viable solution.

[2] Due to protection setting policy, this level of uplift is purely theoretical.

Whilst utilising the DTR calculations on all transformers considered eligible for active management of this nature results in a slight reduction in available capacity from 500 kVA transformers, across WPD's licence areas a net increase of 5,600 MVA is theoretically possible, if all transformers were outfitted with a distributed intelligence platform.

Such an approach would however require alternative solutions to managing the protection requirements as exceeding 150% rating risks burning out fuses.

It can clearly be seen from Figure 22 that pushing transformer loading to 150%, and using distributed intelligence to provide support systems for the reporting of outlier substations, can allow greater confidence in the management of the LV network.

Allowing additional benefits from the deployment of distributed intelligence devices for the purpose of real-time asset monitoring, providing confidence the network is operating within acceptable tolerances, with the capability to trigger alerts where needed.

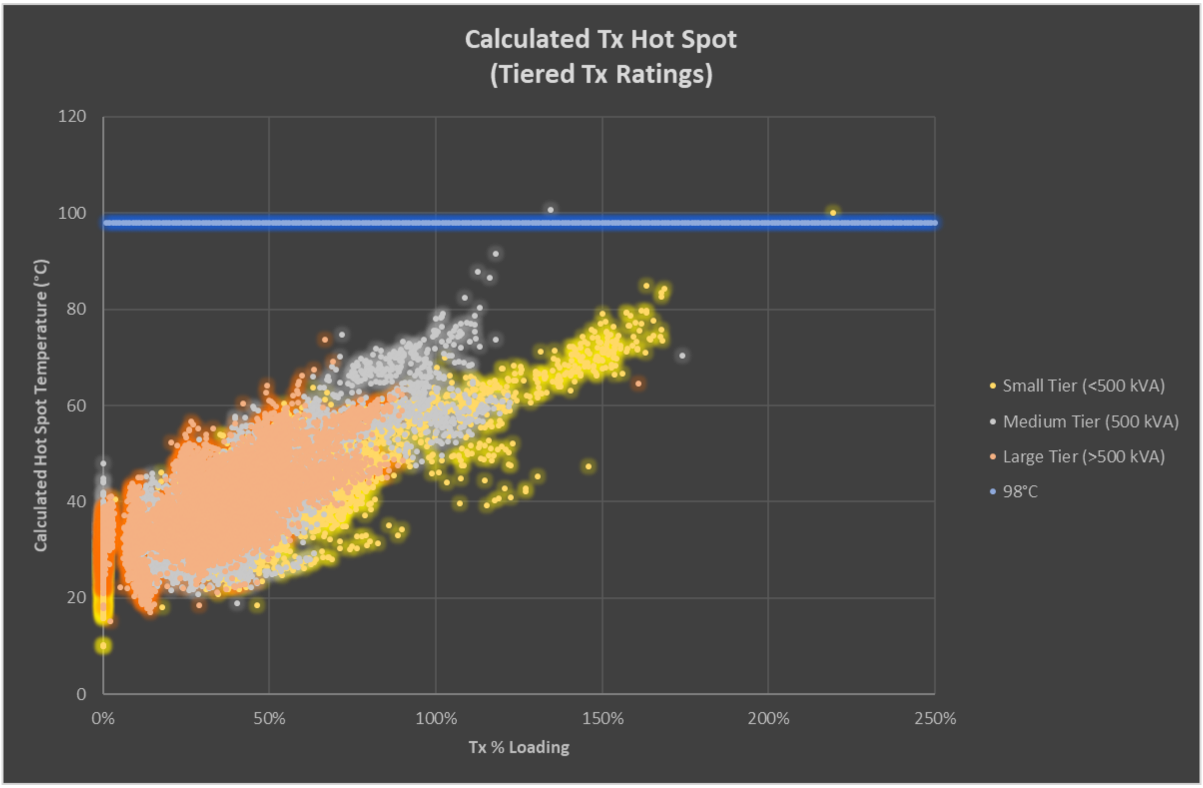


Figure 22: Calculated Tx Hot Spots by % Loading

GB LV networks

EA Technology's Transform Model™ (detailed in Appendix 7) is a mathematical model of the GB LV Distribution Network.

The model mathematically defines 966,700 transformers with varying customer types (both load and generation) to forecast future scenarios for the network.

Utilising the variety of transformer nameplate ratings across WPD's four licence areas as a baseline, the following figures were determined as a reasonable estimate for transformer rating variation across the GB network.

Table 7: Implementing OpenLV DTR on GB LV networks, utilising the same operational practices as WPD

Tx Rating	No. of Tx	Static Capacity (100% Rating)	Cyclic Capacity (125% Rating)	Cyclic Capacity (Fuse Limited) (150% Rating)	Theoretical [3]Thermal Capacity (DTR Rating)
< 300 kVA	705,084	37,820 MVA	47,270 MVA	56,725 MVA	56,725 MVA
300 kVA	42,184	12,655 MVA	15,820 MVA	19,000 MVA	28,350 MVA
315 kVA	56,391	17,760 MVA	22,200 MVA	26,600 MVA	39,800 MVA
500 kVA	111,044	55,520 MVA	69,400 MVA	69,400 MVA	82,700 MVA
> 500 kVA	51,997	44,000 MVA	55,100 MVA	66,100 MVA	81,079 MVA
Total Capacity		167,800 MVA	209,800 MVA	251,730 MVA	288,670 MVA
Rating Increase (Relative to Previous Level)			42,000 MVA	83,900 MVA	120,850 MVA
Total Capacity (Relative to Previous Level)		100%	125%	150%	172%

The above calculations in Table 7 assume the same operational limitations and restrictions apply equally across the GB LV network.

This provides a theoretical headroom increase of 120,850 MVA for the GB network, subject to alternative arrangements being available to mitigate the risks associated with overloading fuses.

[3] Due to protection setting policies, this level of uplift is purely theoretical.

2.3.6 Overall Results

Benefits of Distributed Intelligence

The benefits available from the deployment of a distributed intelligence platform like LV-CAP™ can be considered in multiple categories:

- Where gathering network data is necessary, processing it locally and only transmitting the required information provides a significant reduction in operating costs
- Implementation of network automation, with the system reporting by exception, allows for quicker network responses than would be possible if operations were required to be initiated by control room staff
- Operating the network on the basis of 'known, real-time data' allows for greater capacity to be utilised, with different applications deployed to respond to specific network conditions
- Significant volumes of data can be gathered, leveraging the ability of the platform to process and analyse it locally and report back findings by exception. It is not practical to transmit all the available data from every LV substation on the GB network, but deployment of local monitoring allows for a greater confidence in assets that would otherwise be considered to be in an 'unknown state'

Dynamic Thermal Ratings

The Dynamic Thermal Rating application deployed within the project has the potential to provide network benefits, particularly when combined with distributed intelligence platforms and local, real time data.

Within WPD's licence areas, the potential headroom benefit from the implementation of such an app is up to 5,600 MVA.

Automated Network Switching

Automated Network Switching on the LV network is considered to have the potential for providing network benefit, but the viable use cases are highly specific, and were not experienced within the range of substations trialled in the OpenLV Project.

Where loads on the connecting feeder are significantly imbalanced allowing for load transfer to be implemented there is of potential benefit to the network. This will only apply however in situations where the Normally Open Point is not located at or near the loading mid-point on the network.

Additionally, where feeders on either side of a Normally Open Point experience peak loading at different times of day, such as there being a high proportion of industry & commercial loading on one side of the NOP with a high proportion of a domestic load on the other provides a potential for network benefits.

In both cases, reducing the peak loading of transformers combines with the real-time thermal rating to reduce transformer peak temperatures and hence increase headroom.

However, as the potential benefit is determined by the difference between the load on either side of the feeder, it is minor when compared to the rating of transformers.

Whilst the project team find it conceivable that there are a number of locations in the GB LV network where an approach to automated network switching may be a viable solution, the cost of deploying the necessary hardware means it is considered to be a niche solution for specific network issues that by default tend not to occur in a well-designed and balanced network.

Beneficial Applications

Within the OpenLV Method 1 trials, the key benefit from the perspective of increased headroom was produced by the DTR application, however this remains a single, highly specific, albeit widely deployable, use case.

Previous studies into the use of Dynamic Thermal Ratings on the distribution network have proved the significant potential such an approach can provide. Implementing DTR in combination with a distributed intelligence platform allows the real-time loading to be compared with the varying headroom based on the actual network conditions, and alert control staff if required.

This allows focus to be directed where the most benefit can be realised whilst reducing risks inherent with operating the network through greater available knowledge of the state of the network at any time.

Similarly, implementation of the Alvin Reclose™ units demonstrated the ability of an LV-CAP™ platform to autonomously control the LV network, without the direct intervention of control room staff. Such a system could be configured to notify the control room whenever operation was required, or only when operation was required a specified number of times within an assigned period, allowing flexibility to monitor the network as lightly, or detailed, as appropriate.

Additionally, the commissioning process for the network automation hardware also demonstrated the ability for manual control of the automated switching devices through the LV-CAP™ platform. An appropriately secured distributed intelligence platform can provide automation, and remote-control capability for any asset with a suitable connection to the platform.

2.4 Recommendations

2.4.1 Distributed Intelligence

Within the OpenLV Project the LV-CAP™ platform has demonstrated the utilisation of local, real-time and historical data, enables a distributed intelligence platform to implement changes to the local network to greater capabilities than has been previously possible.

The value to be gained from such an approach is greater than is realised from just the applications deployed within the project trials.

As the distribution network transitions further to a low carbon focus, the Distribution System Operator will require exponentially greater levels of information regarding the status of the network. Widespread deployment of distributed intelligence platforms is recommended as a valuable asset in both the gathering, and management of this data.

By utilising trusted distributed intelligence platforms, running applications configured in line with the DSO operational requirements, significant volumes of data transmission can be avoided through local processing, and decision making, with reporting by exception allowing the focus of control engineers to be prioritised where it is most beneficial.

The OpenLV Project has demonstrated that Distributed Intelligence devices can provide a significant benefit to the network, the limits being the applications available and the extent to which responsibility will be delegated to autonomous platforms by the DSOs.

It is therefore recommended that the deployment of Distributed Intelligence Devices be considered by DSO's as a key tool in their future plans to effectively manage changing loads on the LV network as the GB network transitions further towards a Low Carbon Economy.

2.4.2 Dynamic Thermal Rating Applications

Deployment of applications

The LV-CAP™ platform's ability to have software packages updated and reconfigured as and when required is a key consideration to the approach taken to determining the potential benefit that can be derived from a Dynamic Thermal Rating application deployed in wide scale to the platform.

Whilst the application deployed within the trials demonstrated the ability for accurate predictions of asset temperatures, the project team found that the level of calibration required to achieve this was unsustainable for deployment to more substations than required within a limited series of trials.

As such, there are two primary recommendations relating to the deployment of such a DTR application.

1. Deploy Dynamic Thermal Rating Applications in two stages.

   Where a DTR application is being deployed to provide general monitoring purposes, for example as a default monitoring application to all standard deployments of a distributed intelligence platform, an application container utilising the general formula detailed as Equation 1 in Section 2.3.2should be installed.

This application will utilise the data gathered on the transformer's load, and temperatures of both the top oil and ambient environment to calculate the instantaneous Hot Spot Temperature of the transformer. The application should be configured with a standard set of alert triggers, defined by the DSO, where an alert will be raised once the Hot Spot exceeds a particular level, or for an extended period. Once this alert is triggered, deployment of an application similar to that utilised within the OpenLV trials can be deployed, providing a more accurate Hot Spot calculation value, at the expense of requiring calibration on the initial deployment.
This approach allows for the implementation of a Dynamic Thermal Rating 'early warning' system where distributed intelligence platforms are deployed, with minimal requirements to configure the platform before there is a defined need.
If this approach were utilised, the OpenLV Project team recommend a simple trigger be considered in the first instance, such as the calculated Hot Spot temperature exceeding 90°C.

2. Automate the configuration requirements of Dynamic Thermal Rating Applications.

   The DTR software container (or any other similar application) deployed in the OpenLV could be refined with a self-calibration layer to enable automated configuration.
   As the OpenLV trial hardware directly monitored the Transformer Top Oil Temperature, a value calculated by the DTR application developed by the University of Manchester, this could be utilised by the application to 'learn' the ideal characteristics of the transformer being monitored.
   This would enable greater accuracy in calculated Hot Spot values, at the expense of an application likely to be more expensive, a delay before usable readings were generated and the need for additional thermal monitoring hardware being installed at each substation.
   Such an approach, if utilised, should include an 'estimated accuracy' value with any calculated outputs, based on the difference between the calculated and measured Top Oil values.

Realisation of DTR benefits

The use of a simplified application, utilising key data available within a substation to calculate the transformer Hot Spot Temperature can provide immediate benefits to the potential headroom available within the LV network.

Based on the data gathered, it is recommended that where distributed intelligence capable platforms are deployed, the simplified algorithm detailed in Section 2.3.2 is installed as standard, with automated alerts triggered when the Hot Spot Temperature is calculated to be approaching 98°C (a 90°C threshold for example).

This is expected to provide up to 30% additional capacity in each location where the substation has been fitted with distributed intelligence capability.

It is also recommended however that additional monitoring applications are developed, as whilst the data gathered by the OpenLV Project shows that the combination of Ambient Temperature conditions and loading profiles allows for transformers to be utilised to a greater extent than the Nameplate rating would otherwise suggest, it would be unwise to rely on only transformer DTR.

2.4.3 Automated LV Switching

The principle of automated LV switching based on the real time requirements of the local network has been clearly demonstrated as a functionally useful tool for the management and operation of the network.

Due to the cost associated with the required hardware in comparison to the realisable benefits in most network locations, it is not recommended that this approach is considered as a default solution.

However, where other benefits can also be realised from the use of the switching hardware and distributed intelligence platform, this solution provides a reliable Method of automating the LV network.

It is the recommendation of the OpenLV Project team that the use of automated LV switching be deployed as part of a wider solution where the realisable benefits make it cost effective, a calculation that will be required on a site-by-site basis where the specific conditions make it viable to be considered.

3 Conclusions

3.1 Method 1 – Capacity uplift

3.1.1 Sharing the level of capacity uplift achieved through Method 1

Method 1 sought to test the hypothesis that having distributed intelligence available within distribution substations would enable capacity uplift through automated analysis and decision making based on observations of local conditions. Although the distributed intelligence does not in itself create capacity uplift, it does instead enable opportunities for capacity uplift.

Network Meshing

Method 1 also sought to demonstrate the ability of the OpenLV platform in instructing the operation of physical devices through a network meshing trial. The network meshing trial sought to allow two substations to run in parallel for a period of network requirement.

To implement network meshing, it should be noted that the OpenLV trial installed intelligent LV devices at the 11kV/LV substations as a means to form NOPs that could be automated. This was an artificial approach as under business as usual conditions NOP's would be found in link boxes in the public highway at a location typically midway between substations rather than on the bus bars at one of the substation pair. This artificial approach had to be taken as link boxes that could be automated were not commercially or technically mature at the time of project conception.

The Method 1 network meshing trial demonstrated that it is practical to automate low voltage switching devices through the use of the OpenLV distributed intelligence platform.

The sequence of calculation and switching detailed in Section 2.3.1 was found to operate as expected, based on the control logic programmed into the system. The trigger thresholds were adjusted through the period of active trials to allow for changing Ambient Temperatures and network loading, whilst ensuring the system would continue to operate.

The network meshing trial also provided evidence that joining together of LV substations as demonstrated in the trial was unlikely to lead to significant capacity uplift between transformers. But it has already been acknowledged that this was an artificial trial approach.

This trial also provided analytical evidence that points to a greater benefit of being able to control NOP's located within link boxes, than having automated NOP on the LV bus bars. By investigating the effect of meshing at the feeder link box level, it was shown that there would be viable cases where meshing helped the feeder pairs share load much more effectively, but this approach was unlikely to help create transformer uplift.

It should also be stressed, because of the maturity of automated link boxes at the time of project initiation, that this trial did not demonstrate the effect of transferring customers between substations by reassigning NOPs from the feeder mid-point to one of the feeding substations.

By definition, moving NOP's in this manner will always be effective in reallocating 50%-100% of a feeder's load between substations. Having a capability to move NOP's in this manner will also create additional use cases not considered in this trial, an example being the capability to automate LV customer restoration after unplanned outages.

Dynamic equipment ratings

DNO's do allow a cyclic rating to be applied to their distribution transformers for limited emergency conditions, during a period of additional backfeed load for example. But these are based upon fixed and worst-case assumptions and typically only allow a fixed uplift beyond the continuous nameplate rating.

Method 1 clearly demonstrated that having the ability to be able to apply real-time thermal ratings, based on site-specific measurements of Ambient Temperature and loading was capable of creating dynamic rating beyond the transformer's nameplate rating. Because this process was continuous and undertaken locally, operating whilst power was available to energise the OpenLV equipment, if deployed in a BAU scenario, the rating uplift would be available, in effect on an ad-infinitum basis, rather than under emergency conditions.

For such dynamic ratings to be taken advantage of there would need to be the ability to plan the network to remain with the expected dynamic ratings. Because the OpenLV trial gathered site-specific Ambient Temperature, hot spot forecast and loading cycles, this requirement would be satisfied.

This capacity uplift would be leveraged further when and if distributed intelligence devices are able to instruct smart devices to respond to periods where the transformer was forecast to exceed temperatures without additional intervention.

Such smart devices might include customer flexibility that was demonstrated through some of the Method 3 trials or alternatively some form of network reconfiguration such as changing the network open points. (It is acknowledged that the network meshing trial was inconclusive, but a next development step may be to prove the concept of LV network load transfers using smart link boxes. Smart link boxes were not technologically available at the time of the project initiation but progress in this field is ongoing.)

Network meshing and Dynamic Thermal Ratings

To implement Dynamic Thermal Ratings and network meshing, this trial had to implement three different applications running of the OpenLV platform within the substations. These applications were:

- A load forecasting application
- A transformer Dynamic Thermal Ratings application
- The Loadsense application. This application would review data from the load forecasting application and the Dynamic Thermal Rating application and when the forecast load exceeded the forecast thermal rating, it would instruct the network to mesh

3.1.2 Establishing the level of capacity uplift that can be achieved in WPD's licence area and across GB

Section 2.3.5 describes how Method 1 has provided evidence regarding the amount of capacity uplift that could be experienced across WPD's licence areas and also across the UK.

This analysis makes a conservative assumption that if dynamic transformer ratings were only applied to transformers of a size 300kVA or greater (which is less than 27% of WPD's total population of LV transformers) then 6350 MVA of total additional capacity would be created across 39,500 WPD substations. Extrapolation of this analysis across the total LV substation demographic of Great Britain would see a total uplift of 120,850MVA in transformer headroom.

It should be remembered thought that the purpose of Open data platforms is that they have multiple roles and capabilities.

For example, if a community wished to have an OpenLV platform monitor their community, then the incremental cost to deploy Dynamic Thermal Ratings would be minimal as it would simply require the analysis package to be loaded onto the platform. Conversely, in cases where an OpenLV data platform has been loaded into a substation to enable Dynamic Thermal Ratings, then additional applications can be loaded on to create even more value. Examples of these additional use cases may be pre-fault detection of LV faults or apps to track the amount of low carbon technology that has been installed in a LV network. For these reasons, it would be misleading to decide that installation of the OpenLV platform should be justified on solely based on the value created by Dynamic Thermal Ratings.

3.2 Which LV networks can benefit from OpenLV and why?

The OpenLV network has shown distributed intelligence within 11kV/LV substations enables a diverse set of benefits cases. The specific benefits are dependent on either the structure of the network or alternatively the needs of customers connected to those networks.

Evidence from Method 1 shows that use of real-time asset monitoring can provide two clear routes to aiding network operations. Use of the data available within the substation to calculate the state of assets in real-time, removing uncertainty inherent in the existing passive network, allows Operators to push assets harder than they can at present, with the knowledge that the asset is able to withstand the additional load. Removal of uncertainty with regard to network assets, reduces the risks associated with that uncertainty.

Additionally, the ability of distributed intelligence platforms to automate decision making, in accordance with logic agreed by the Control Team can provide the benefits of LV Automation to the DNO / DSO without introducing further data transmission costs, and the risk of information overload in Control Rooms were there a requirement to manually initiate or authorise every LV operation. 'Reporting by exception', where the system has identified a situation occurring that is outside of expected operational parameters allows attention to be focussed where it is most effective.

The next SDRC (SDRC 5) will investigate the costs and benefits of fitting OpenLV into substations onto the quantitative basis.

3.3 Next Steps

The next project deliverable will be SDRC 5 which considers the overall cost-benefit case of OpenLV and how it might be best employed to create industry value.

In addition to this next step, WPD has already announced that they are committed to maintaining the offer of community data by installing a number of EA Technology VisNet units that will be installed into substations.

3.4 Criterion Compliance

Table 8 provides a summary of the SDRC criterion that is expected for this milestone and where evidence is provided for its completion.

Table 8: SDRC Criterion & Evidence Compliance Matrix

Successful Delivery Reward Criterion	Section(s)
Sharing the level of capacity uplift achieved through Method 1	Section 2.3.5
Sharing which LV networks can benefit from OpenLV and why	Section 2.3.5
Establishing the level of capacity uplift that can be achieved in WPD's licence area and across GB	Section 2.3.5
Sharing how DNO's can engage with communities who want to become part of a smarter grid to exploit the open and flexible nature of OpenLV	SDRC 4 – Method 2
Sharing how community engagement supports the uptake of LCT	SDRC 4 – Method 2
Outlining the routes communities can take to raise funding	SDRC 4 – Method 2
Sharing the network benefits provided by community engagement	SDRC 4 – Method 2
Sharing how DNOs can engage with companies (including non-energy companies) and academics to exploit the open and flexible nature of OpenLV	SDRC 4 – Method 3
Sharing how the Method facilitates non-traditional business models	SDRC 4 – Method 3

4 List of Annexes

1. Annex SDRC 4.A1: Fault Current and Protection Studies for Alvin Installation
   This document details the analysis undertaken on the Method 1 Phase 2 trial networks to verify the proposed network meshing was acceptable from network safety and operational perspectives.
2. Annex SDRC 4.A2: OpenLV Solution Factory Acceptance Test Stage 2 Documentation
   The document details the tests undertaken on the OpenLV trial hardware, operational logic and control software prior to deployment as part of the project.
3. Annex SDRC 4.A3: Post-FAT Loadsense Analysis
   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 LVCAP™ platform but it was not practicable to provide the detail necessary to explain the operation of the Loadsense application.
   The report 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.
4. Annex SDRC 4.A4: OpenLV Measurement Points
   This document lists the measurements which are made by the OpenLV hardware and published on the LV-CAP Data Marketplace so that Applications running in the substation can make use of them.
5. Annex SDRC 4.A5: Thermal Monitoring & Thermodynamic Modelling of Distribution Transformers
   This report assesses a strategy for the future adaptability of distribution transformers under scenarios where EVs are introduced. As part of the investigation, modelling of distribution transformers is undertaken and a configurable algorithm developed allowing calculation of Distribution Transformer Hot Spot Temperature from measurable readings.
   This algorithm was utilised in the OpenLV Project Trials.

5 References

[1] "OpenLV Project Website," [Online]. Available: https://openlv.net/.

[2] Ofgem, "OpenLV - WPD's Project Directory," [Online]. Available: https://www.westernpower.co.uk/downloads/2311.

[3] "WPD Network Templates," [Online]. Available: https://www.westernpower.co.uk/projects/network-templates.

[4] WPD, "Policy Document SD4/8".

[5] WPD, "Standard Technique TP4B/2".

Appendix 1. Distribution of LV Network Templates in WPD Licence Areas

In total, the network data for 146,297 substations was analysed covering all four licence areas operated by WPD, assigning each an LV network Template type.

Table 9: LV network Template Types in WPD

LVNT Types	Total	%	SWEB	SWAE	MIDE	EMEB
1	3365	2.30%	918	624	1518	305
2	35803	24.47%	8252	2306	9981	15264
3	61042	41.72%	18072	17316	20188	5466
4	935	0.64%	96	243	402	194
5	5799	3.96%	2049	1409	1670	671
6	2583	1.77%	777	47	1377	382
7	3491	2.39%	799	600	1129	963
8	4649	3.18%	693	684	1106	2166
9	5540	3.79%	672	61	387	4420
10	23090	15.78%	6080	5015	4687	7308
Total	146297		38408	28305	42445	37139
			26%	19%	29%	25%

There is a high dominance of Type 2 & 3 networks across the four licence areas, although they are not evenly distributed across the four licence areas, as shown more clearly in Figure 23.

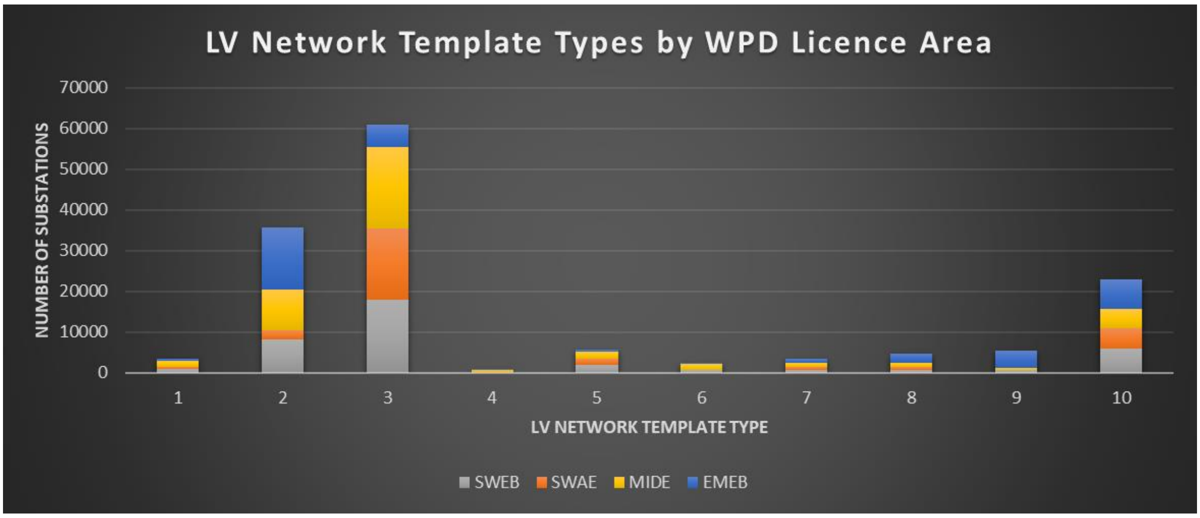


Figure 23: LV network Template Types by WPD Licence Area

Mapping the assigned LV network Templates against the transformer ratings across the four licence areas managed by WPD provides the following allocations.

Table 10: Allocation of LV network Template Type by Tx Rating

			Tx kVA Ratings in WPD												
LVNT Type	Total	% of LVNTs	1	4	4.5	5	10	15	16	20	25	45	50	75	100
1	3365	2.30%	0	0	0	0	0	0	0	0	1	3	16	0	325
2	35803	24.47%	0	1	0	53	194	1209	1059	733	3703	336	6835	16	7564
3	61042	41.72%	0	25	36	2085	1130	11546	12888	718	9907	142	7034	4	4310
4	935	0.64%	0	0	0	0	0	0	0	0	0	0	0	0	100
5	5799	3.96%	0	1	2	58	95	841	704	125	1128	8	1258	1	701
6	2583	1.77%	0	0	0	1	2	12	19	26	94	78	134	0	990
7	3491	2.39%	0	0	0	0	0	1	1	15	20	12	95	1	340
8	4649	3.18%	0	0	0	0	1	0	4	0	16	0	43	0	38
9	5540	3.79%	0	0	0	0	0	3	4	1	17	18	53	0	127
10	23090	15.78%	1	10	11	517	245	2455	3495	364	3176	92	4680	9	3433
Total	146297		1	37	49	2714	1667	16067	18174	1982	18062	689	20148	31	17928
			0.00%	0.03%	0.03%	1.86%	1.14%	10.98%	12.42%	1.35%	12.35%	0.47%	13.77%	0.02%	12.25%

LVNT Type	150	200	250	300	315	500	750	800	815	1000	1250	1500	1600	30000
1	0	31	18	496	419	1621	132	201	0	102	0	0	0	0
2	17	3969	38	2029	2582	4604	231	449	0	181	0	0	0	0
3	17	1993	41	2311	2403	3963	125	243	1	120	0	0	0	0
4	0	1	1	21	20	238	86	298	0	170	0	0	0	0
5	0	206	7	173	166	318	0	5	0	2	0	0	0	0
6	1	540	0	19	39	180	64	207	0	177	0	0	0	0
7	8	438	15	380	459	1036	84	376	0	203	0	6	1	0
8	0	12	10	249	960	1608	133	1024	0	549	0	2	0	0
9	1	239	7	465	1076	1826	542	767	0	393	0	1	0	0
10	1	1540	5	241	410	1411	228	425	0	341	0	0	0	0
Total	45	8969	142	6384	8534	16805	1625	3995	1	2238	0	9	1	0
	0.03%	6.13%	0.10%	4.36%	5.83%	11.49%	1.11%	2.73%	0.00%	1.53%	0.00%	0.01%	0.00%	0.00%

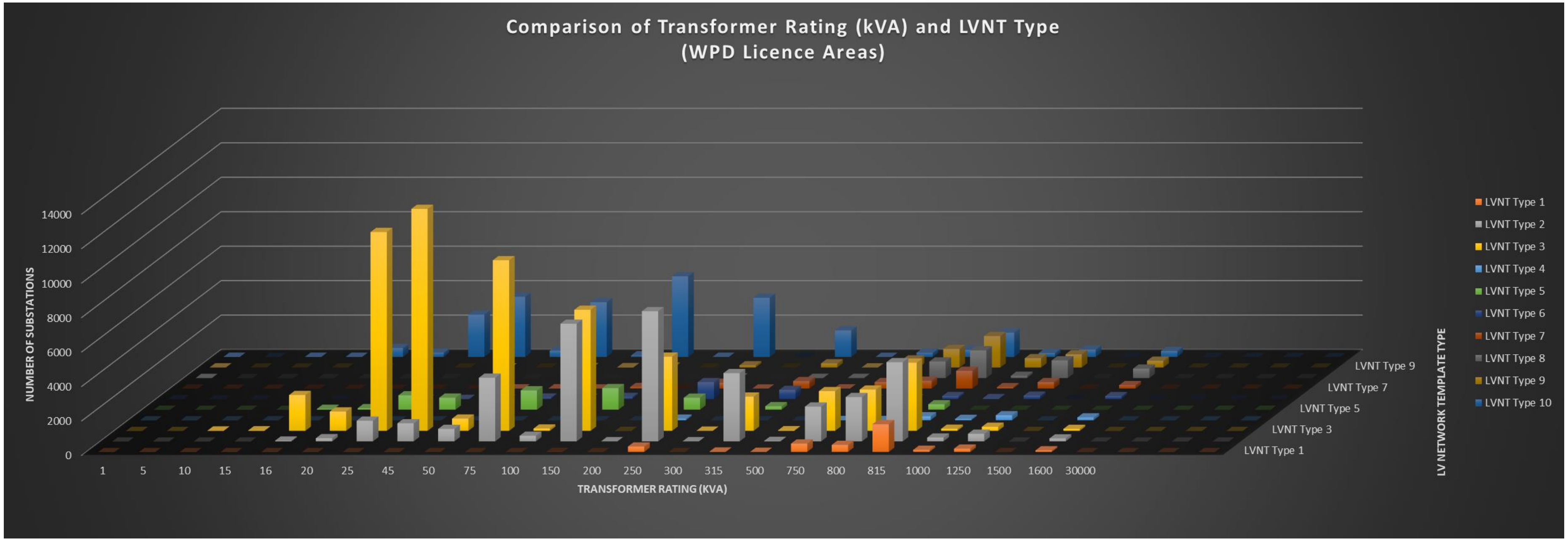


Figure 24: Allocation of LV network Template Type by Tx Rating

The total capacity (kVA) within each licence area provided by the various transformer capacities is detailed below, including the determination by Small, Medium and Large Tier transformers as outlined in Section 2.3.2.

Table 11: Tx capacities across WPD Licence Areas

Transformer Tier	Tx kVA Ratings	Total	%	Tx kVA Ratings in WPD				Tx kVA Capacity in WPD					
				SWEB	SWAE	MIDE	EMEB	SWEB	SWAE	MIDE	EMEB	Total	
Small	1	1	0.00%	0	1	0	0	0	1	0	0	1	10326578.5
	4	37	0.03%	0	37	0	0	0	148	0	0	148	
	4.5	49	0.03%	0	25	24	0	0	112.5	108	0	220.5	
	5	2714	1.86%	1048	1208	356	102	5240	6040	1780	510	13570	
	10	1667	1.14%	1053	11	520	83	10530	110	5200	830	16670	
	15	16067	10.98%	5299	4225	5874	669	79485	63375	88110	10035	241005	
	16	18174	12.42%	5751	8360	2997	1066	92016	133760	47952	17056	290784	
	20	1982	1.35%	1590	0	387	5	31800	0	7740	100	39640	
	25	18062	12.35%	5415	4122	6088	2437	135375	103050	152200	60925	451550	
	45	689	0.47%	569	1	119	0	25605	45	5355	0	31005	
	50	20148	13.77%	5206	2606	5456	6880	260300	130300	272800	344000	1007400	
	75	31	0.02%	5	0	2	24	375	0	150	1800	2325	
	100	17928	12.25%	2759	1552	7837	5780	275900	155200	783700	578000	1792800	
	150	45	0.03%	15	4	14	12	2250	600	2100	1800	6750	
	200	8969	6.13%	1572	1028	2475	3894	314400	205600	495000	778800	1793800	
	250	142	0.10%	88	4	21	29	22000	1000	5250	7250	35500	
	300	6384	4.36%	1535	1224	1792	1833	460500	367200	537600	549900	1915200	
	315	8534	5.83%	1664	1058	2175	3637	524160	333270	685125	1145655	2688210	
Medium	500	16805	11.49%	3530	2151	4790	6334	1765000	1075500	2395000	3167000	8402500	8402500
Large	750	1625	1.11%	465	44	111	1005	348750	33000	83250	753750	1218750	6668665
	800	3995	2.73%	570	455	767	2203	456000	364000	613600	1762400	3196000	
	815	1	0.00%	0	1	0	0	0	815	0	0	815	
	1000	2238	1.53%	270	188	639	1141	270000	188000	639000	1141000	2238000	
	1250	0	0.00%	0	0	0	0	0	0	0	0	0	
	1500	9	0.01%	3	0	1	5	4500	0	1500	7500	13500	
	1600	1	0.00%	1	0	0	0	1600	0	0	0	1600	
	30000	0	0.00%	0	0	0	0	0	0	0	0	0	
	Total	146297		38408	28305	42445	37139	5085786	3161126.5	6822520	10328311	25397743.5	kVA

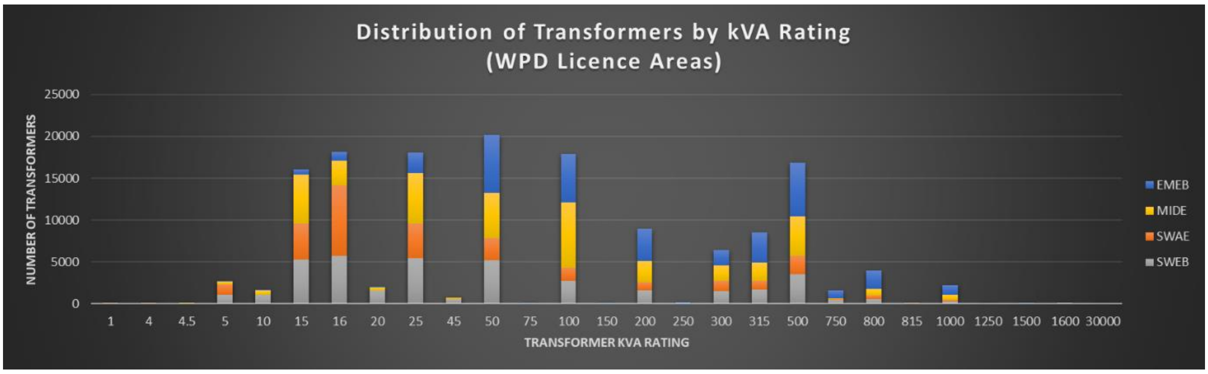


Figure 25: Distribution of Transformers by kVA Rating

Appendix 2. OpenLV Project Locations – LV network Template Types

LV-CAP™ ID	SSID	LV-CAP™ Method	LVNT Type	Tx Rating (kVA)	Substation Type
OpenLV-003	873105	Method 1 - Phase 1	9	500	Indoor
OpenLV-004	941991	Method 3	1	800	GRP
OpenLV-005	872983	Method 1 - Phase 1	6	500	Outdoor (Fenced)
OpenLV-006	432566	Method 3	7	1000	GRP
OpenLV-007	873070	Method 1 - Phase 1	3	1000	Indoor
OpenLV-008	872869	Method 1 - Phase 1	5	800	GRP
OpenLV-011	872523	Method 1 - Phase 1	2	500	GRP
OpenLV-012	872775	Method 1 - Phase 1	2	500	Outdoor (Walled)
OpenLV-013	910066	Method 1 - Phase 2	4	315	Indoor
OpenLV-014	872522	Method 1 - Phase 1	2	500	GRP
OpenLV-015	911800	Method 1 - Phase 1	1	800	Indoor
OpenLV-016	330326	Method 1 - Phase 2	2	500	Indoor
OpenLV-017	913081	Method 1 - Phase 1	2	300	Outdoor (Fenced)
OpenLV-018	881589	Method 1 - Phase 1	3	800	Indoor
OpenLV-019	943885	Method 1 - Phase 1	9	500	GRP
OpenLV-020	913075	Method 1 - Phase 1	2	315	Indoor
OpenLV-021	890921	Method 1 - Phase 1	4	200	GRP
OpenLV-022	890918	Method 1 - Phase 1	4	315	GRP
OpenLV-023	905799	Method 1 - Phase 1	2	315	GRP
OpenLV-024	873804	Method 1 - Phase 1	1	500	Outdoor (Walled)
OpenLV-025	911805	Method 1 - Phase 1	6	800	GRP
OpenLV-026	331255	Method 3	7	300	Indoor
OpenLV-027	525745	Method 3	5	315	Indoor
OpenLV-028	316896	Method 2 / 3	2	500	Indoor
OpenLV-029	511326	Method 1 - Phase 1	1	800	Indoor
OpenLV-030	944493	Method 1 - Phase 1	6	800	GRP
OpenLV-031	944114	Method 1 - Phase 1	4	315	GRP

LV-CAP™ ID	SSID	LV-CAP™ Method	LVNT Type	Tx Rating (kVA)	Substation Type
OpenLV-032	944751	Method 1 - Phase 1	6	500	GRP
OpenLV-033	110048	Method 2	3	750	Indoor
OpenLV-034	914721	Method 1 - Phase 1	4	315	GRP
OpenLV-035	881585	Method 1 - Phase 1	5	750	Indoor
OpenLV-036	330474	Method 2	2	500	Indoor
OpenLV-037	513257	Method 1 - Phase 1	9	1000	Indoor
OpenLV-038	941547	Method 1 - Phase 1	5	500	GRP
OpenLV-039	943886	Method 1 - Phase 1	3	1000	Indoor
OpenLV-040	512448	Method 1 - Phase 1	9	1000	Indoor
OpenLV-041	332770	Method 1 - Phase 2	3	500	Indoor
OpenLV-042	331615	Method 1 - Phase 2	2	500	Indoor
OpenLV-043	790327	Method 2	7	300	Outdoor (Fenced)
OpenLV-044	790518	Method 2	7	800	Outdoor (Fenced)
OpenLV-045	872111	Method 1 - Phase 1	3	300	Outdoor (Walled)
OpenLV-046	904298	Method 1 - Phase 1	6	500	GRP
OpenLV-047	870634	Method 1 - Phase 1	6	800	GRP
OpenLV-048	944301	Method 1 - Phase 1	4	315	GRP
OpenLV-049	870635	Method 1 - Phase 1	2	500	GRP
OpenLV-050	911748	Method 1 - Phase 2	4	500	Indoor
OpenLV-051	872236	Method 1 - Phase 1	6	1000	Indoor
OpenLV-052	942223	Method 3	9	500	Indoor
OpenLV-053	872109	Method 1 - Phase 1	3	500	Indoor
OpenLV-054	511209	Method 3	3	315	Outdoor (Walled)
OpenLV-055	896332	Method 1 - Phase 1	4	500	Indoor
OpenLV-056	941546	Method 1 - Phase 1	1	800	Outdoor (Walled)
OpenLV-057	512058	Method 1 - Phase 1	7	315	GRP
OpenLV-058	901498	Method 1 - Phase 1	4	200	Indoor
OpenLV-059	896127	Method 1 - Phase 1	2	315	GRP

LV-CAP™ ID	SSID	LV-CAP™ Method	LVNT Type	Tx Rating (kVA)	Substation Type
OpenLV-060	512019	Method 1 - Phase 1	7	300	Outdoor (Fenced)
OpenLV-061	902435	Method 1 - Phase 1	2	315	GRP
OpenLV-062	873803	Method 1 - Phase 1	1	500	Outdoor (Fenced)
OpenLV-063	901586	Method 1 - Phase 1	4	315	GRP
OpenLV-064	332853	Method 1 - Phase 2	3	315	GRP
OpenLV-065	942847	Method 1 - Phase 1	7	315	Indoor
OpenLV-066	791195	Method 2	2	300	Outdoor (Walled)
OpenLV-067	912548	Method 1 - Phase 2	6	500	GRP
OpenLV-068	942848	Method 1 - Phase 1	1	750	GRP
OpenLV-069	791859	Method 2	7	315	Outdoor (Walled)
OpenLV-070	894954	Method 2	7	500	Outdoor (Fenced)
OpenLV-071	872776	Method 1 - Phase 1	4	800	Indoor
OpenLV-072	513248	Method 1 - Phase 1	9	800	GRP
OpenLV-073	314811	Method 2 / 3	2	500	Outdoor (Fenced)
OpenLV-074	915800	Method 1 - Phase 1	4	315	Indoor
OpenLV-075	911747	Method 1 - Phase 2	4	315	Indoor
OpenLV-076	160025	Method 2 / 3	7	800	Indoor
OpenLV-077	881739	Method 3	3	800	GRP
OpenLV-078	904299	Method 1 - Phase 1	6	750	Indoor
OpenLV-079	160294	Method 2 / 3	7	500	Outdoor (Walled)
OpenLV-080	872071	Method 1 - Phase 1	6	1000	Indoor
OpenLV-081	732105	Method 2	8	1000	Indoor
OpenLV-082	912807	Method 1 - Phase 2	1	500	GRP
OpenLV-083	526762_A	Method 3	6	1500	Indoor
OpenLV-084	910065	Method 1 - Phase 2	4	800	Indoor

Appendix 3. Simple Predictor for Transformer Hot Spot Temperature

Relevant Data

The purpose of this analysis was to see how well the estimate of Transformer Hot Spot Temperature, THS(e), from the University of Manchester algorithm (see Annex 5), could be predicted using a simple regression formula derived from the measured data.

We began with separate datafiles for each of 10 transformers, each datafile comprising half-hourly measured data for the period February to October 2019 along with estimated values of the Transformer Hot Spot Temperatures THS(e). Table 12 lists the relevant input data.

Table 12: List of relevant input data

Input Data Code	Description	Source
Rating	Transformer rating	Known
ALVIN Command	Indicator of switched state (0 = unswitched, 1 = switched)	Controlled
Load	Transformer loading	Measured
RLoad	Relative loading (= Load/Rating)	Calculated
Tamb	Transformer Ambient Temperature	Measured
Tout	Tamb for outdoor transformer	Measured
Tin	Tamb for indoor transformer	Measured
Toil(m)	Transformer Top Oil Temperature	Measured
Toil(um)	Transformer Top Oil Temperature (estimated using UoM algorithm)	UoM
Toil(e)	Transformer Hot Spot Temperature (estimated using simple derived equation)	EA Technology
THS(um)	Transformer Hot Spot Temperature (estimated using UoM algorithm)	UoM
cos(dayno)	Day number	Known
cos(TOD)	Time off day	Known

The ALVIN Command is included in the table because it was used in the cleaning-up process for the data. Rows of data either side of a switching event were often corrupted, and this was dealt with by deleting all such “switching rows”. Rows around midnight were also often corrupted and these were similarly deleted from the cleansed data.

The cos(dayno) and cos(TOD) parameters were added to check whether the time of year or time of day affected the results in a way that was not already accounted for in the measured temperatures. They were found to have an insignificant effect.

All 10 of the transformers in the study were mounted indoors, so Tamb was always equal to Tin.

From the parameters listed in Table 12, a useful derived quantity was found to be the relative load on the transformer, Rload, defined as the transformer load divided by the transformer rating.

Regression Formula

A series of multiple linear regressions were carried out using Minitab and it was quickly ascertained that with many of the parameters being related to each other, there was little to be gained from using more than 2 or 3 parameters. The best 2-parameter fit was obtained using Toil(m) and Load as the “independent” parameters, giving the following regression equation:

THS(e) = **1.51**(±0.02) + **0.953**(±0.001**) x Toil(m)** + **0.0406**(±0.0001) **x Load**

This gave an R-squared value of 94% (i.e. 94% of the variation of THS(e) could be attributed to the regression).

Alternativel, Tamb (instead of Toil(m)) and Load as parameters gives:

THS(e) = **7.13** + **0.918 x Tamb** + **0.0752 x Load** (R-squared = 76.8%)

Adding a third parameter (i.e. using both Toil(m) and Tamb as well as Load) gives:

THS(e) = **1.38** + **0.122 x Tamb** + **0.862 x Toil(m)** + **0.0449 x Load** (R-squared = 94.3%)

The R-squared values suggest that the [Toil(m)+Load] fit is much better than the [Tamb+Load] fit, which is not surprising since Toil(m) is a much more direct measure of THS than Tamb is. However, it is not obvious from the R-squared values whether or not the 3-parameter [Tamb+Toil(m)+Load] fit is significantly better than the 2-parameter [Toil(m)+Load] fit.

In an attempt to determine this, we looked at how well each of these regressions predicts the THS(e) values in the original data from the University of Manchester. This was done by calculating the differences (or errors) between the values of THS(um) and the fitted values obtained from the regression equation. Adding the squares of all these errors and then taking the square root gives an RMS (root-mean-square) error, which is effectively the standard deviation (σ) of the errors. If the distribution of errors is approximately normal, we would expect two thirds of the errors to lie within ± σ of zero and 95% of the errors to lie within ±2σ.

Table 3 shows the RMS errors for the 3 fits discussed above.

These indicate that the 2-parameter fit using Toil(m) is again much better (RMS = 1.71°C) than the 2-parameter fit using Tamb (RMS = 3.36°C), but also suggest, as with the R-squared values, that adding Tamb as a third parameter makes relatively little difference to the fits, reducing the RMS error from 1.71°C to 1.66°C.

Table 13: R-squared values and RMS errors for the 3 Load-based fits discussed above

Parameters	R-squared	RMS error (°C)
Toil(m) + Load	94.0%	1.71
Tamb + Load	76.8%	3.36
Tamb + Toil(m) + Load	94.3%	1.66

One might expect transformer temperatures to depend on relative transformer loads (RLoad = Load/Rating) rather than actual loads, so regressions were also carried out with Rload replacing Load. In all cases, better fits were obtained, whilst adding Tamb as a third parameter gives a slightly greater improvement than it did with the Load fits. Table 14 shows the results.

The 3-parameter Rload-based fit gives an R-squared value of 96.1% and an RMS error of 1.38°C compared with the 94.3% and 1.66°C for the 3-parameter Load-based fit in Table 13, whilst the 2-parameter Rload-based fit gave similar results to the 3-parameter Load-based fit.

Table 14: R-squared values and RMS errors for the 3 Rload-based fits.

Parameters	R-squared	RMS error (°C)
Toil(m) + RLoad	94.3%	1.66
Tamb + RLoad	89.6%	2.25
Tamb + Toil(m) + RLoad	96.1%	1.38

The corresponding Rload-based regressions are:

THS(e) = 2.92+ 15.80 x Rload + 0.913 x Toil(m) (R-squared = 94.3%)

THS(e) = 6.65 + 34.02 x Rload + 0.933 x Tamb (R-squared = 89.6%)

THS(e) = 2.96 + 21.50 x Rload + 0.627 x Toil(m) + 0.349 x Tamb (R-squared = 96.1%)

Thus, the best 2-parameter fit is [Rload + Toil(m)] and the best 3-parameter fit is [Rload + Toil(m) + Tamb]:

THS(e) = 2.96 (±0.02) **+ 21.50** (±0.04) **x Rload + 0.627** (±0.001) x **Toil(m) + 0.349** (±0.001) **x Tamb**

Appendix 4. Analysis of Calculated Hot Spot Temperatures

The formula derived in Appendix 1 above was then used to calculate the Hot Spot Temperatures for those transformers not part of the Method 1 Phase 2 trials.

Due to the volume of data available, (an average of 200,000 datum points per unit per day), a refinement of the data used was required.

For each day where the project has data available the highest recorded Top Oil Temperature was identified for each unit. For this timestamp, the Transformer Load, Top Oil and Ambient Temperatures were extracted.

This allowed for calculation of the Hot Spot Temperature for each transformer monitored in the trials, at the point of highest Top Oil Temperature, on each day. It therefore calculates the highest temperature the Hot Spot reaches on each day, based on the load drawn by the connected local network and the Ambient Temperature, representing the 'worst point' of each daily cycle during normal network operation.

Plotting these calculated Hot Spot Temperatures in relation to the % Loading, relative to the nameplate rating of each transformer produced the plot shown in Figure 26.

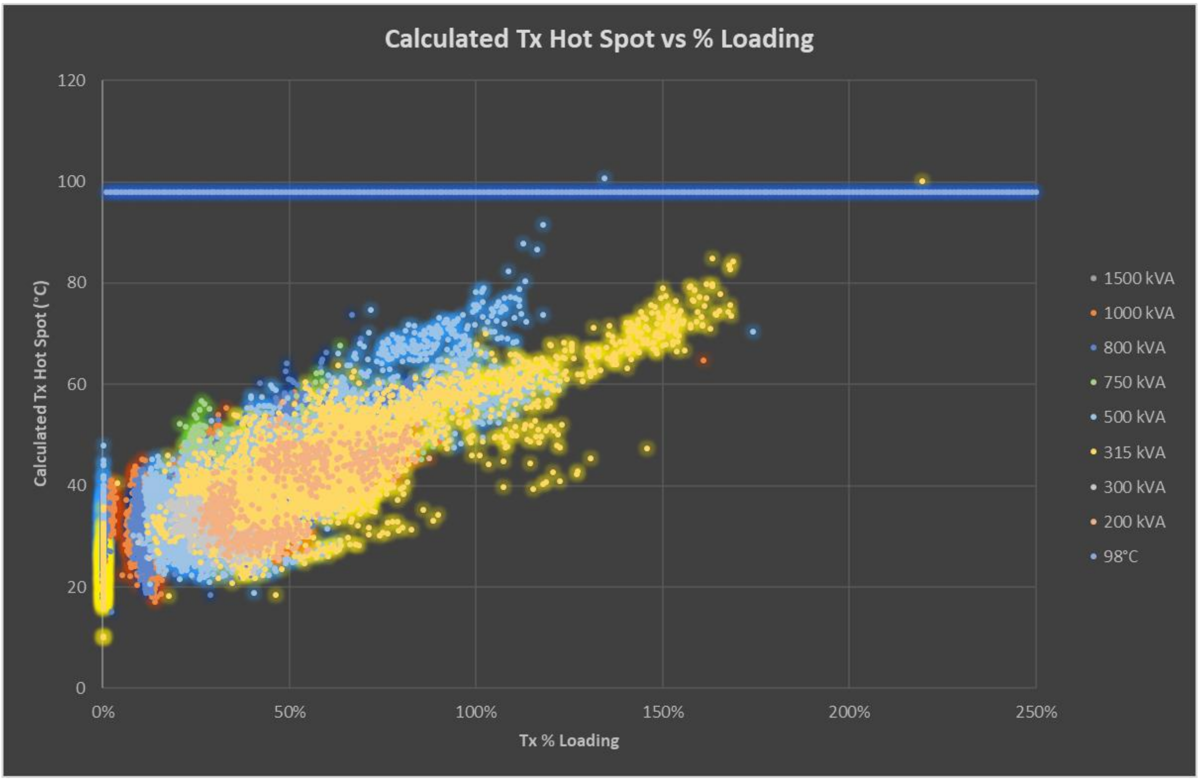


Figure 26: Calculated Hot Spot vs % Loading

It can be seen that whilst there are a significant number of points where the transformer loading exceeds the nameplate rating, there are only two points calculated where the Hot Spot is calculated to have exceeded the 98°C threshold.

Considering the specific transformer ratings reveals more specific trends.

Transformers experience a range of Hot Spot Temperatures for the same loading, a data artefact resulting from varying Ambient Temperatures between individual locations, and from separate days. However irrespective of the transformer rating, the calculated Hot Spot Temperature is reasonably tight at lower loading levels, with increased variation occurring as relative loading increases.

Evaluation of the distribution of points identified three groupings based on the transformer rating.

- Small Tier Transformers – <500 kVA
- Medium Tier Transformers – 500 kVA
- Large Tier Transformers – >500 kVA

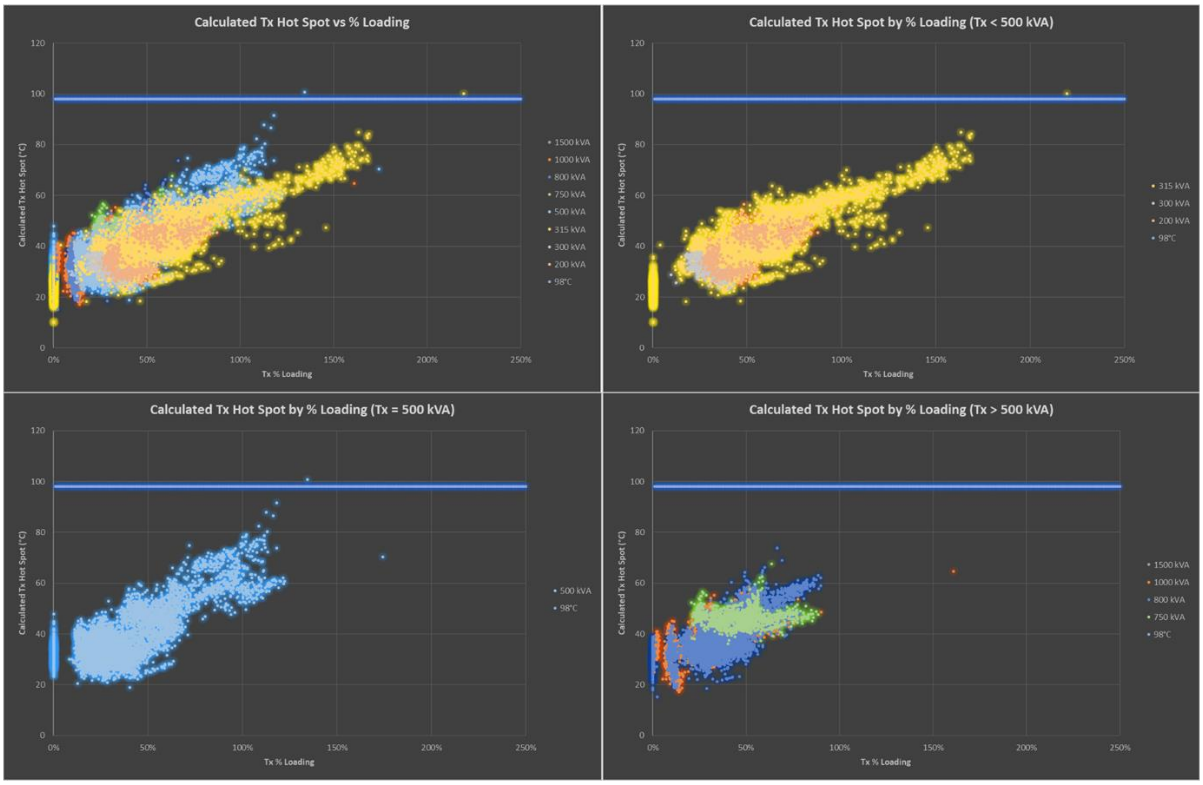


Figure 27: Calculated Hot Spot vs % Loading (Tx Groupings)

It can clearly be seen that the overall Hot Spot Temperature range is comparable across all transformer ratings but as the rating increases, the range of proportional loading within the dataset reduces.

For the smaller tier transformers it can be seen that despite peak loading exceeding 150% of the nameplate rating on a number of occasions, the calculated Hot Spot Temperature only exceeds 85°C once, requiring a peak proportional load of 219% to reach 100°C.

In contrast, however, a medium tier transformer in the medium tier range exceeds the 98°C threshold at 134% of the nameplate rating. This specific instance relates to July 2019, during the period where the highest temperature ever recorded in the UK occurred. The transformer is inside a GRP enclosure, the interior temperature of which reached 58°C at the same time.

None of the large tier transformers approached the 98°C threshold, although it is acknowledged that there was only one recorded instance where the transformer utilisation exceeded the nameplate rating.

The range of data points reduces as the transformer capacity increases, with both a reduced tendency for higher utilisations to occur at higher ratings, and a tighter range of resulting Hot Spot Temperatures.

This characteristic is due to the lower thermal mass of the lower rated transformers when compared to the higher rated units. Lower rating transformers gain and dissipate heat more easily than larger ones, but accordingly are more susceptible to the temperature of the surrounding environment.

Generating a best fit for the three tiers of transformer ratings allows for the extrapolation of an average capacity increase for the transformers monitored in the OpenLV Project through the use of DTR. This calculation provides an estimate of the instantaneous peak loading that could be achieved by the transformers utilised in the OpenLV Project when experiencing the same Ambient Temperatures as occurred in the duration of the project.

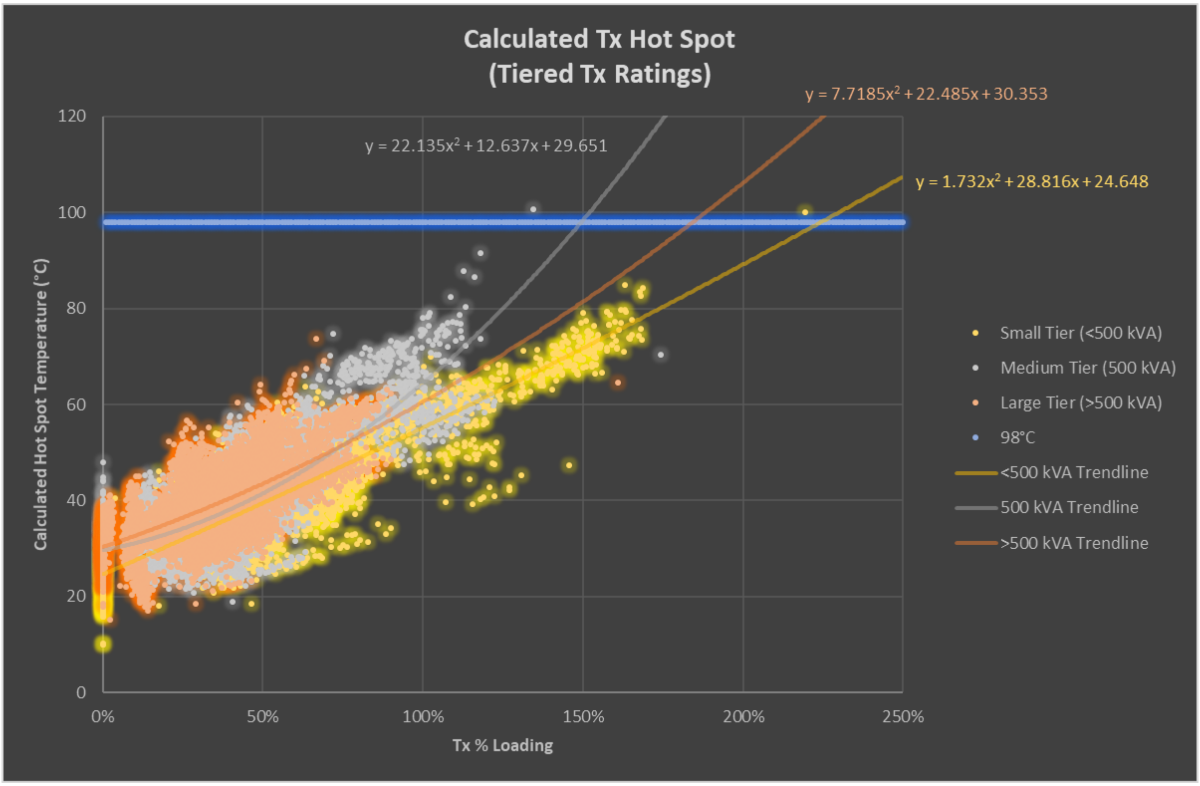


Figure 28: Forecasting Tx Hot Spot Temperatures

Solving the above formulae defined above for a Hot Spot value of 98°C, provides a theoretical peak loading for each tier of transformers, if utilising the algorithm developed by the University of Manchester in comparable environmental conditions to the original data set.

Table 15: Instantaneous DTR Rating

Tx Tier	Instantaneous DTR Rating
Small (<500 kVA)	224%
Medium (500 kVA)	149%
Large (>500 kVA)	184%

Appendix 5. Variation of Calculated Hot Spot Temperature with Surrounding Temperatures

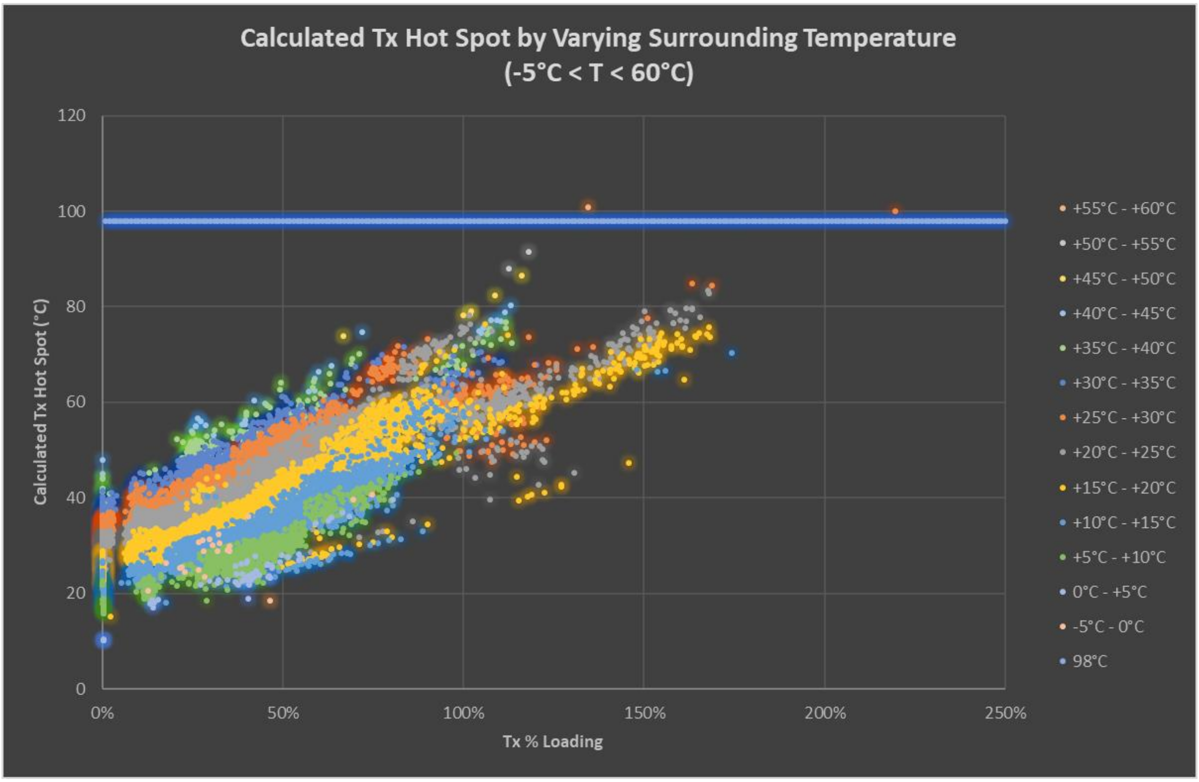


Figure 29: Calculated Tx Hot Spot by Surrounding Temperature (-5°C < T < 60°C)

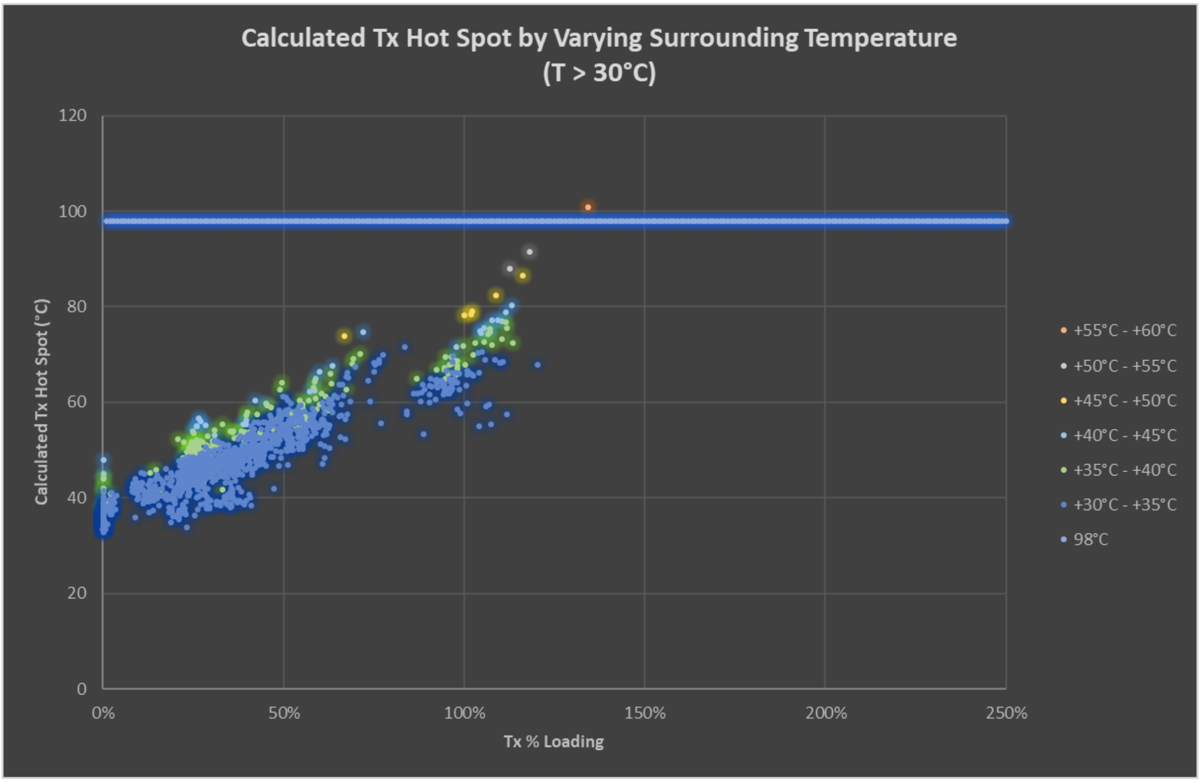


Figure 30: Calculated Tx Hot Spot by Surrounding Temperature (T > 60°C)

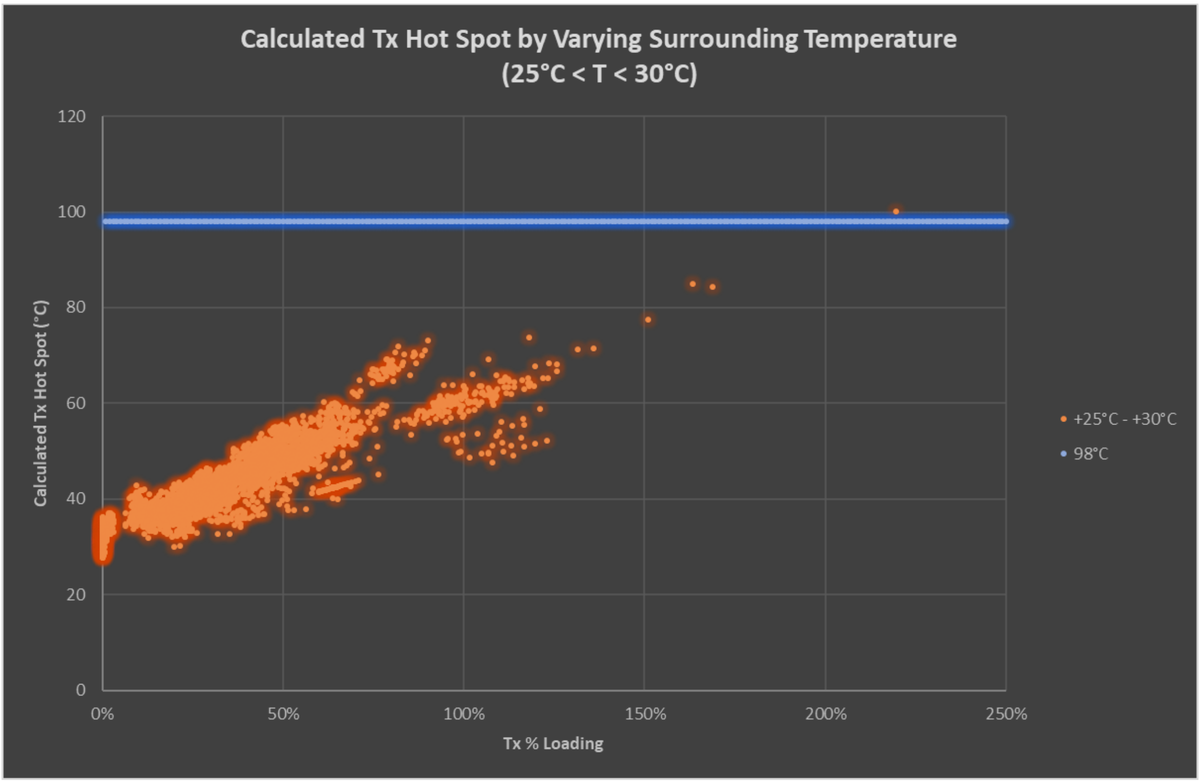


Figure 31: Calculated Tx Hot Spot by Surrounding Temperature (25°C < T < 30°C)

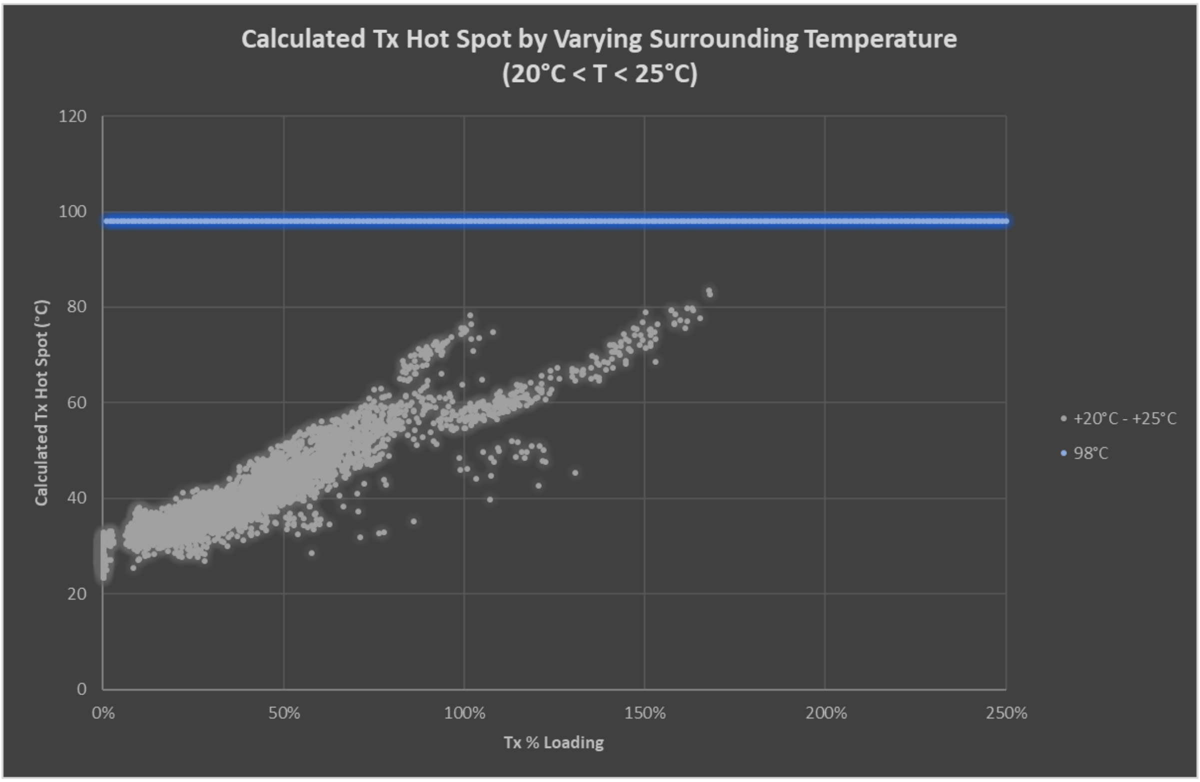


Figure 32: Calculated Tx Hot Spot by Surrounding Temperature (20°C < T < 25°C)

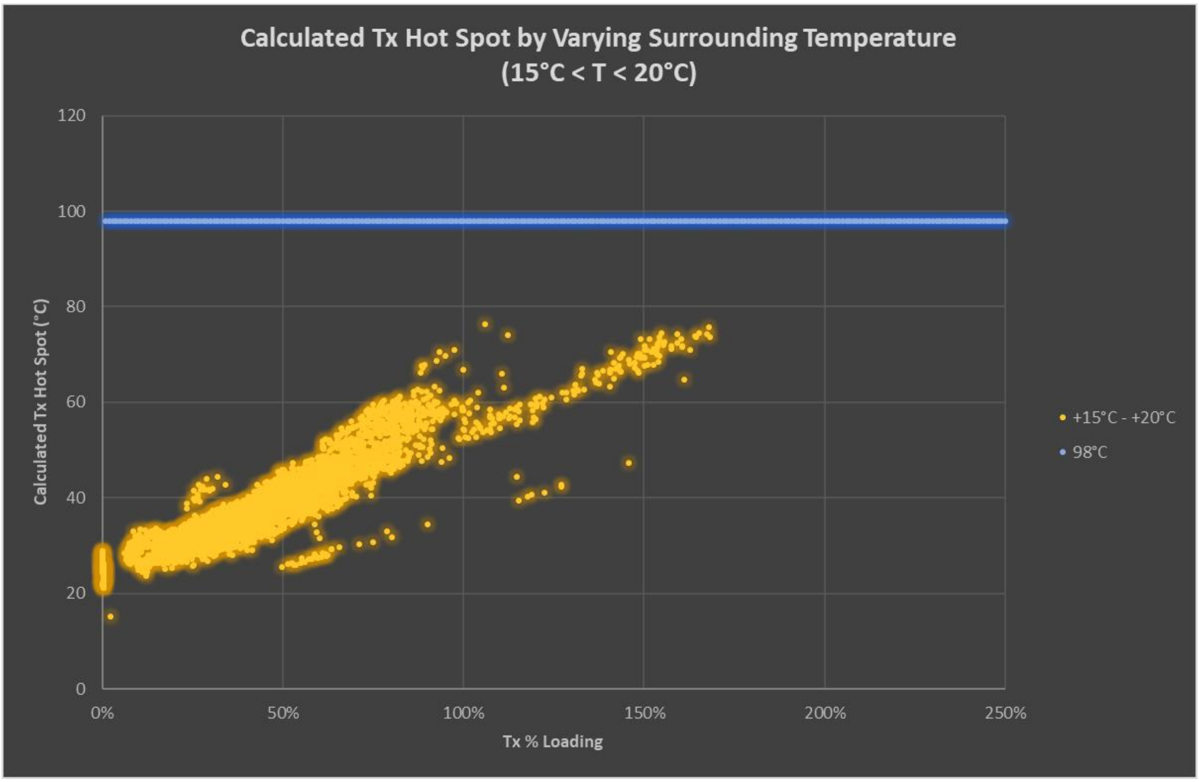


Figure 33: Calculated Tx Hot Spot by Surrounding Temperature (15°C < T < 20°C)

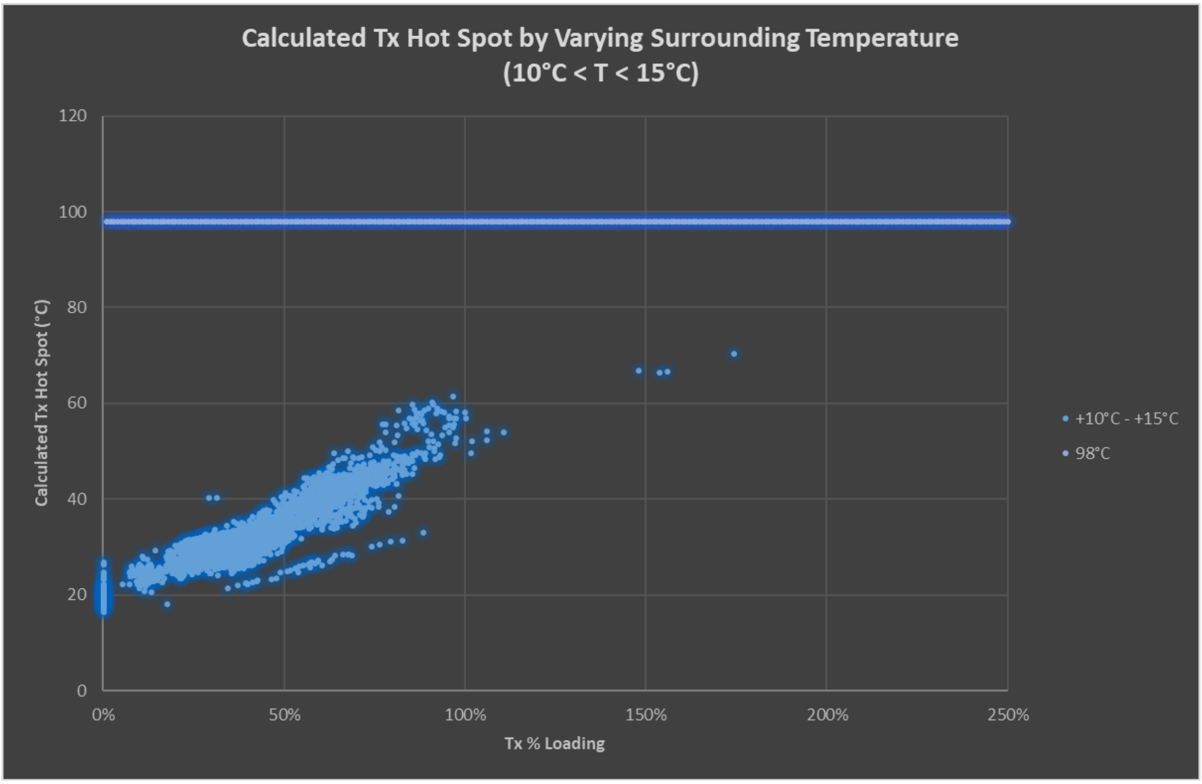


Figure 34: Calculated Tx Hot Spot by Surrounding Temperature (10°C < T < 15°C)

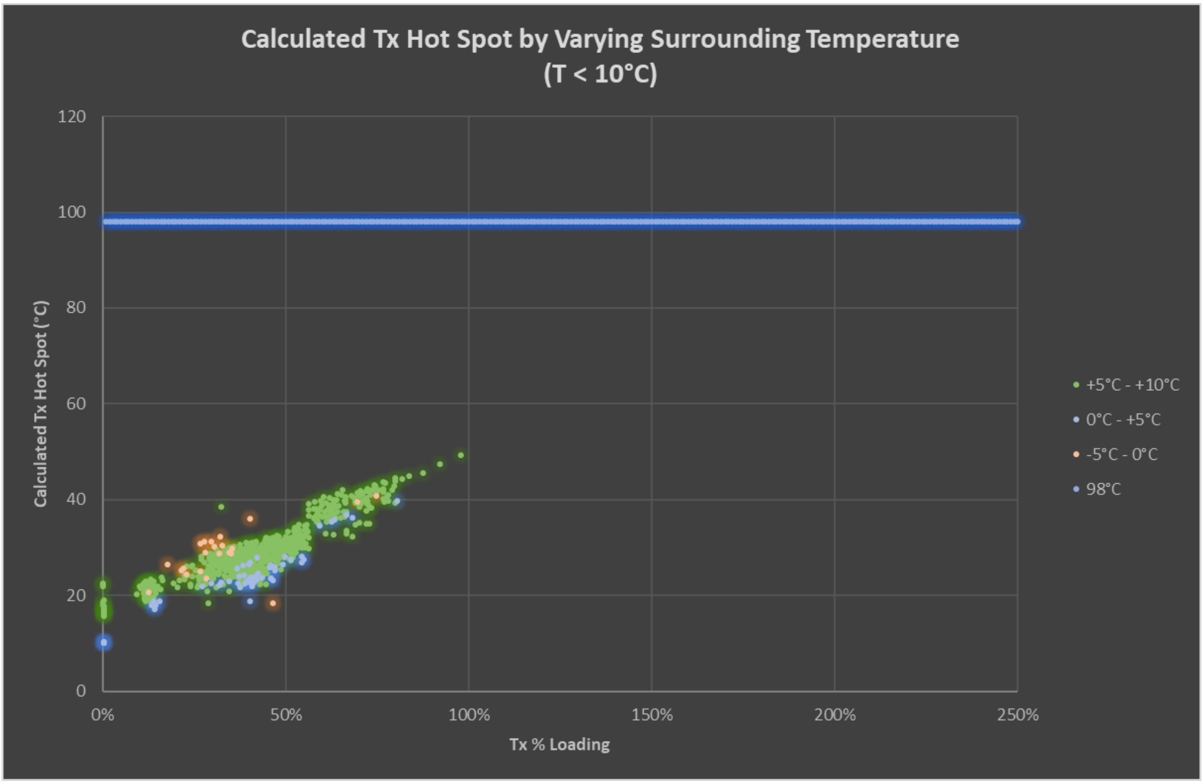


Figure 35: Calculated Tx Hot Spot by Surrounding Temperature (T < 10°C)

Appendix 6. Headroom Benefit of LV Switching

Pair ID	Site 1				Site 2				Original Capacity	Overall Variation	Revised Capacity	% of original
	Site ID	Rating (kVA)	Uplift (%)	Uplift (kVA)	Site ID	Rating (kVA)	Uplift (%)	Uplift (kVA)				
1	007	1000	-0.39%	-3.9	003	500	0.79%	3.9	1500.0	0.00	1500.00	100.00%
2	008	800	-0.017	-13.8	005	500	2.76%	15.4	1300.0	1.55	1301.55	100.12%
3	080	1000	0.026	26.0	051	1000	-2.60%	-26.0	2000.0	0.00	2000.00	100.00%
4	053	500	0.096	47.8	045	300	-15.94%	-47.8	800.0	0.00	800.00	100.00%
5	040	1000	-0.004	-4.5	029	800	0.56%	4.5	1800.0	0.00	1800.00	100.00%
6	037	1000	-0.010	-9.6	072	800	1.19%	9.6	1800.0	0.00	1800.00	100.00%
7	047	800	-0.055	-44.3	049	500	8.87%	44.3	1300.0	0.00	1300.00	100.00%
8	071	800	0.042	33.6	012	500	-6.73%	-33.6	1300.0	0.00	1300.00	100.00%
9	024	500	-0.027	-13.4	062	500	2.69%	13.4	1000.0	0.00	1000.00	100.00%
10	055	500	-0.035	-17.5	059	315	5.57%	17.5	815.0	0.00	815.00	100.00%
11	63	315	0.012	3.8	58	200	-2.43%	-4.9	515.0	-1.03	513.97	99.80%
12	015	800	0.009	7.2	025	800	-0.90%	-7.2	1600.0	0.00	1600.00	100.00%
13	023	315	-0.078	-24.5	061	315	7.77%	24.5	630.0	0.00	630.00	100.00%
14	068	750	-0.033	-24.6	065	315	7.81%	24.6	1065.0	0.00	1065.00	100.00%
15	056	800	0.004	3.1	038	500	-0.62%	-3.1	1300.0	0.00	1300.00	100.00%
16	018	800	0.047	37.6	035	750	-5.01%	-37.6	1550.0	0.00	1550.00	100.00%
17	022	315	-0.033	-10.5	021	200	5.27%	10.5	515.0	0.00	515.00	100.00%
18	020	315	-0.007	-2.1	017	300	0.69%	2.1	615.0	0.00	615.00	100.00%
19	031	315	-0.015	-4.8	048	315	1.53%	4.8	630.0	0.00	630.00	100.00%
20	39	1000	-0.010	-10.0	19	500	2.00%	10.0	1500.0	0.00	1500.00	100.00%
21	57	315	-0.013	-4.1	60	300	1.38%	4.1	615.0	0.00	615.00	100.00%
22	084	800	0.033	26.3	013	325	-8.08%	-26.3	1125.0	0.00	1125.00	100.00%
23	030	800	-0.029	-23.5	032	500	4.71%	23.5	1300.0	0.00	1300.00	100.00%
24	034	315	-0.211	-66.6	074	315	21.15%	66.6	630.0	0.00	630.00	100.00%
25	078	500	-0.007	-3.4	046	750	0.46%	3.4	1250.0	0.00	1250.00	100.00%
26	042	500	-0.016	-8.1	016	500	1.62%	8.1	1000.0	0.00	1000.00	100.00%
27	064	315	-0.083	-26.2	041	500	5.24%	26.2	815.0	0.00	815.00	100.00%
28	082	500	0.001	0.5	067	500	-0.10%	-0.5	1000.0	0.00	1000.00	100.00%
29	050	500	-0.064	-31.8	075	315	10.11%	31.8	815.0	0.00	815.00	100.00%
30	50	500	-0.030	-15.0	75	315	5.00%	15.8	815.0	0.75	815.75	100.09%

Appendix 7. Transform Model

The **Transform Model**®. tool was commissioned and built as a deliverable of the Smart Grid Forum, in consultation with the UK DNOs and other key UK industry stakeholders. The model offers an industry-recognised, robust, transparent and repeatable Methodology that has been tried and tested over the last 5 years by the GB regulator Ofgem and distribution companies across the world, including in Northern Ireland, New Zealand and Australia. In Great Britain, it was the sole driver of approximately £0.5bn of network investment in the latest regulatory price control period. Transform is:

- A parameter-based model, which considers network archetypes that can be characterised by a finite number of prototypical (or representative) network elements
- Based on real data from DNOs, government, academia, and a range of other sources
- Able to assess and optimise investment over a range of conventional, 'smart' network and non-network solutions
- Highly complex (48 moving parts), but consistent Methodology that can be repeated and validated.

The Transform Model creates an understanding of the year on year investment required to maintain network reliability, considering the forecasted demand and uptake of Distributed Energy Resources (DERs)and other Low Carbon Technologies (LCTs).

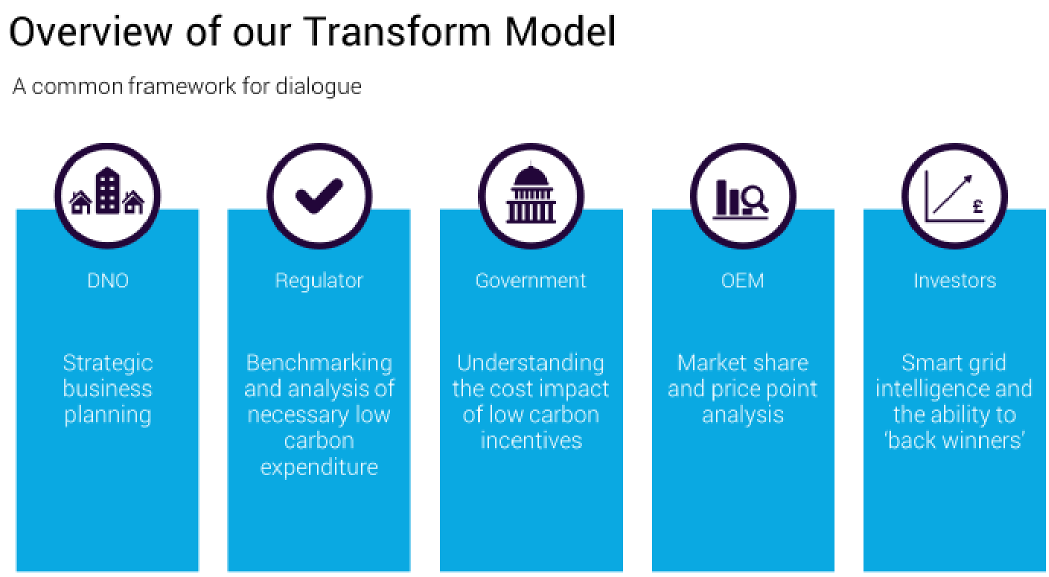


Figure 36: Transform Model Overview

Methodology

The figure below shows a high-level process diagram of the Transform Model Methodology. The following four subsections break this down, explaining in more detail the three stages of input configuration and the results that will come out of the model.

Once a network model is established with a baseline of capacity, scenarios describing future uptake of LCTs are added. When the network reaches a 'capacity' limit (which might be driven by overloading assets, voltage breaching statutory limits, or fault levels becoming too high), the model views its list of traditional network and smart non-network solutions, selecting the most economically efficient to relieve the particular constraint.

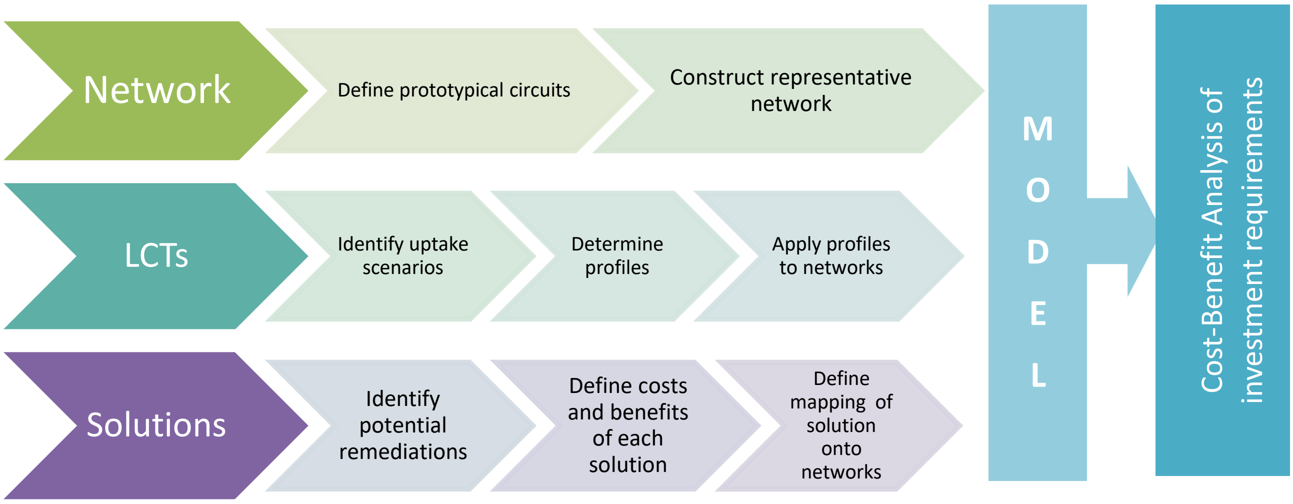


Figure 37: Process diagram showing the Transform Mode® Methodology.

Network

The prototypical circuits in the Transform Model are broadly defined by:

- Network topology (two possible types: radial or meshed);
- Network construction (three possible types: underground, overhead, or mixed);
- Location (urban/suburban/rural);
- The type of customer (by building types, age, terraced/semi-detached/apartments etc.)

For example, a representative circuit may be made up of rural, radial, overhead networks with a small number of farmsteads and detached homes. All these parameters will set the capacity of that archetype and also, its availability or potential to host low carbon heating and transport demand.

Solutions

The possible solutions for networks breaching their physical limits (whether thermal, voltage, fault level) range from traditional reinforcements - replacing the assets (cables or transformers) with new assets with larger ratings – or, more innovative solutions such as Demand Side Response, Active Network Management or Enhanced Automatic Voltage Control. The Transform Model® contains almost 100 pre-existing solutions. To populate new solutions, the information required includes:

- Cost curves, lead time, flexibility, cross network benefits;
- Which network limits they benefit (thermal, voltage, fault level);

- What types of network they can be applied on and if there are any other solutions which cannot co-exist?

A large number of the innovative ‘smart’ solutions require some enabling technologies such as monitoring (whether bespoke network asset monitoring or access to smart meter data) and advanced control systems which may be used for multiple purposes. These are populated in a similar fashion to the solutions with a matrix to illustrate the relationship between the enablers and the solutions.

Scenarios – LCT uptake

This part of the model examines the new demand and generation from the electrification of transport and heat and the uptake of distributed generation. There are two components to this:

- The daily demand profile
- The annual uptake of LCTs

There are currently 28 LCT profiles in the Transform Model - including 17 for EVs, 6 for heating and 5 for distributed generation. These profiles have been defined by looking at real-world data sets from the latest innovation projects such as Electric Nation, the world’s largest smart charging trial with almost 700 plug-in vehicle drivers providing charging data for an 18-month period.

Cost-benefit analysis results

The Transform Model will generate the annual capex and opex for each scenario entered. These figures will be based on the price of the solutions that will most cost-effectively ensure the networks do not exceed their limits in the forecasted time horizon. Hence, there will also be an output that describes the investment in each different technological solution. For the selected solutions the operational utilisation figures can also be obtained.

The below table utilises the distribution of transformer ratings in WPD’s licence areas as a baseline, and calculates the number across the GB LV network, assuming the proportional distribution remains the same.

Table 16: Extrapolation of Tx Distribution from WPD Licence Areas to GB

Tx kVA Ratings	Total (WPD)	% (WPD)	Total (GB)
1	1	0.00%	7
4	37	0.03%	244
4.5	49	0.03%	324
5	2,714	1.86%	17,934
10	1,667	1.14%	11,015
15	16,067	10.98%	106,167
16	18,174	12.42%	120,090
20	1,982	1.35%	13,097
25	18,062	12.35%	119,350

45	689	0.47%	4,553
50	20,148	13.77%	133,134
75	31	0.02%	205
100	17,928	12.25%	118,464
150	45	0.03%	297
200	8,969	6.13%	59,265
250	142	0.10%	938
300	6,384	4.36%	42,184
315	8,534	5.83%	56,391
500	16,805	11.49%	111,044
750	1,625	1.11%	10,738
800	3,995	2.73%	26,398
815	1	0.00%	7
1000	2,238	1.53%	14,788
1250	-	0.00%	-
1500	9	0.01%	59
1600	1	0.00%	7
30000	-	0.00%	-
Total	146,297.00		966,700.00