INNOVATION PROJECT CLOSE-OUT REPORT

USE OF TEMPERATURE SENSORS WITH SIGFOX TO ASSESS SUBSTATION LOADING #171

PROJECT OWNER: JOHN FITZGERALD

DATE OF REPORT: 14th January 2022

DOCUMENT NO.: DOC-091121-HFG Ver: 1.0

Project Start date: (e.g. Q3, 2020)
Project End date: (e.g. Q4, 2021)

Contributors:
Clem Power, Jack Herring, Dan Catanase, Laura McCartney, Robert Arthur, Con Moloney, Kevin Gleeson (ESB Networks)

Mark Bannon, Will Ferguson (VT IoT)

Gokhan Kalkan (Kyte Powertech)

Contents

1. PROJECT SCOPE AND DESCRIPTION

The Climate Action Plan (CAP) calls for 945,000 electric vehicles (EV's) and 600,000 heat pumps to be adopted by 2030. Combined with the decarbonisation of the electricity network, currently targeted to operate at 80% renewable generation by 2030, this electrification of heat and transport will greatly reduce Irelands emissions of carbon dioxide.

To date, ESB Networks have not required visibility/sensors on the low voltage (LV) network as the design standards and consumer loads have not greatly varied over the last few decades. For the exceptional problem which would arise; a consumer would contact ESB Networks to report a power quality issue and ESB Networks would mobilise a Technician to investigate individual cases, some of which would result in reinforcement of the LV network in the vicinity of the complainant. In the coming years, as more and more customers adopt low carbon technology (LCT), the loading on the LV network will increase dramatically and will challenge the design limits and could cause a large rise in customer complaints on issues such as not being able to charge their car or heat their home. Such a situation would be untenable.

To mitigate this scenario, ESB Networks instigated a project to ascertain the viability of deploying appropriate monitoring on the LV network so that assessments can be made as to which transformers are likely to become overloaded, and hence require to be uprated. As part of this innovation initiative, over 1,000 MV/LV transformer monitors were deployed.

It is expected that in time, with full Smart Meter rollout, development of appropriate IT (compliant with all GDPR requirements) could allow for a 'bottom up' assessment of transformer loadings. However, in the interim period, it is important to obtain vision of the capacity of the LV network, in particular the capacity of transformers, so that any reinforcement which might be required can be programmed in advance of overloads taking place.

In advance of obtaining smart meter data, an interim solution which provides vision of the capacity of transformers needs to be low-cost, and easy to install safely with minimum interruption of supply to customers, to ensure that the cost-benefit is maximised. This meant that installation of traditional load monitoring devices could not be entertained. To this end, the project sought to assess the viability of LPWAN (Low Power Wide Area Network) IoT Temperature sensors to provide an indication of transformer overload. It was expected that temperature sensors would provide early warning of loading levels and hence allow the pre-emptive uprating of the Substation capacity. It was decided to build upon a previous innovation project which used the Sigfox network to develop a proof of concept for low-cost harvesting of data.

2. MEASURES OF SUCCESS AND EXPECTED BENEFITS

The success criteria were defined as follows;

1. That temperature data will correctly indicate the loading levels at which a transformer should be uprated
2. That the solution is low-cost when compared to traditional load monitoring solutions

The expected benefits are;

1. Low-cost data can be used to identify transformers with capacity constraints and allow ESB Networks time to programme a planned uprate, in advance of the transformer failing.
2. Transformer capacity can be increased in areas where customer adoption of LCT is increasing before the transformer becomes overloaded.

3. CHANGES TO PROJECT (SCOPE / TIMELINES / DELIVERABLES / BUDGET / RESOURCES)

It was originally envisaged that temperature-only sensors could be used to identify overloaded transformers. However, the project team believed that a scope change to include phase current measurements would be prudent as;

1. It was a low incremental increase in cost of solution.
2. Would allow analysis of correlation between current and transformer temperature at different ambient temperatures, and at different loadings, of transformers in the field. Such an approach would provide further data before deciding to adopt temperature-only sensors on a wider scale.
3. Would allow analysis of actual ADMD (After Diversity Maximum Demand), which was required as part of a separate innovation project.

4. RESULTS

4.1. Overview of approach

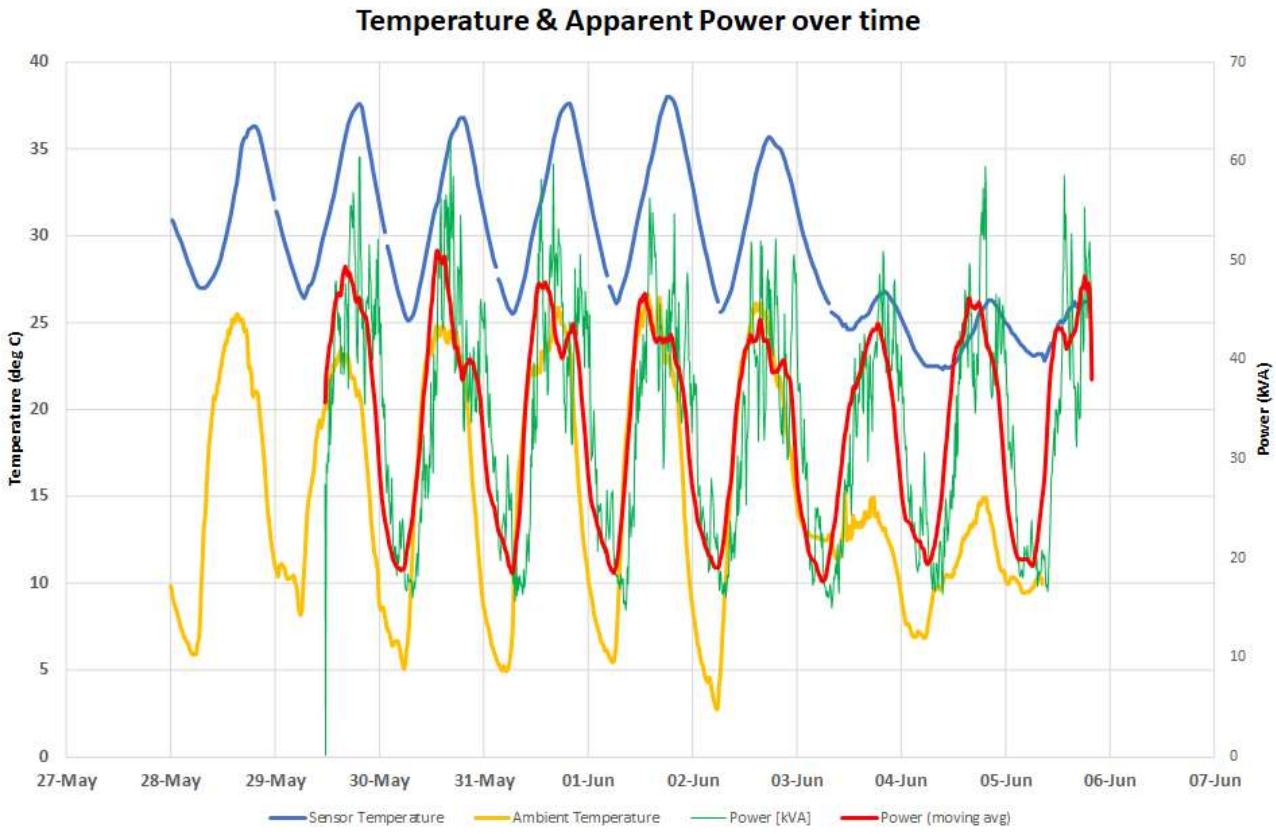
Given that the transformer overloading use-case for this technology was new, the project team decided to implement the solution using an agile methodology, whereby parts of the solution were developed and tested in stages.

4.2. Proof of concept

ESB Networks first engaged with the Sigfox Network Operator in Ireland and IoT innovation Company, VT IoT to implement a proof of concept, whereby we obtained several different models of IoT enabled temperature sensors and VT’s Octopus Asset Management Platform.

These sensors were inspected by the project team and installed in a 400 kVA unit substation called ‘Browneshill Rise’ for several days. A load monitor was also installed so that the temperature could be compared with the load on the transformer. Weather data was also downloaded from a nearby weather station to compare the ambient air temperature with the temperature from the monitor inside the unit substation. The data was analysed and is shown in **Error! Reference source not found.**.

Figure 1: Browneshill Rise 400 kVA unit Substation, Transformer Lid temperature, Power, and Ambient Temperature



A number of observations are evident;

1. The 400 kVA transformer was not heavily loaded, peaking at 60 kVA (15% of rated load)
2. The temperature at the transformer lid as measured by the sensor was more influenced by the ambient temperature, rather than the electrical load on the transformer

Note: Observation no. 2 above is a typical characteristic of lowly loaded transformers. Following further trials in the field, detailed later in the report, it is evident that the temperature on the transformer lid only begins to correlate with transformer load once the transformer is greater than 50% loaded.

At this phase of the trial, it was not possible to establish the correlation between sensor temperature and phase current in the field on a heavily loaded transformer. This is because no dataset existed which would categorically identify a heavily loaded transformer. The latter was the essence of the problem statement driving the execution of the project. Therefore it was decided to undertake a standard heat rise test in a factory setting as a next step.

The project team worked with VT IoT to configure the sensors for ESB Networks’ use case. As Sigfox is a low power communication protocol, it was important to minimise the data needed to accommodate the intended use case, due to the bandwidth allowed of the protocol. I.e. Each Sigfox message has a maximum 12-byte payload. VT IoT carried out the data decoding and token management for the sensors, so that the data delivered on ESB Networks’ requirements as follows;

1. Current measured on a scale between 0 – 4096 Amps (word length of 12 bits giving a resolution of 1 Amp)

2. Temperature measured on a scale of 0 – 150°C
3. The sensor samples every 1 minute, and calculates the median, maximum, and minimum value for the 60 samples taken in the previous hour. It then transmits those three values over the Sigfox network as a single data packet every hour. I.e. 24 data packets/day.
4. To cater for a last resort scenario, the sensor stores the last 166 days of data on-chip, which can be downloaded using a laptop with a near field communications interface.
5. The device is self-powered with battery life expected to last 9 years with the above data sampling and communication interval specification.
6. A downlink message can be issued to the devices (on a device level or on a fleet wide basis) over the Sigfox network to change the data sampling rate as well as the data transmission rate, with a corresponding trade-off on battery lifetime.
7. VT's database would process, decode, and store the measurement data from Sigfox and/or Cellular sources before sending a clean processed data stream to ESB Network servers via API
8. VT's Octopus platform would separately store and display the transformer data for consumption by ESB Networks users on the Octopus front-end.
9. VT's Octopus analytics engine would perform analytical insights on the Transformer data to model, predict, and alert on transformer operation, performance and capacity during the deployment including current, temperature, total power, imbalance, and capacity.
10. VT would provide an installation web application to aide installation confirming site coverage.

4.3. Heat Rise Test in Factory Controlled Environment

The project team requested Kyte Powertech to undertake a standard heat rise test of a 400kVA transformer in a unit sub enclosure in their factory. The purpose of this test was to compare current & temperature values measured by Kyte Powertech with the values measured by the prototype VT IoT Transformer-Scope current + temperature sensors. A comparison was also performed with a Comet Sigfox-enabled temperature sensor. The apparatus was set up as shown in Figure 2 and Figure 3 below.

FIGURE 2: UNIT SUBSTATION. SUPPLY ON RMU AND LV PANEL SHORTED OUT

The Comet Sigfox-enabled temperature sensors were placed to measure temperature on:

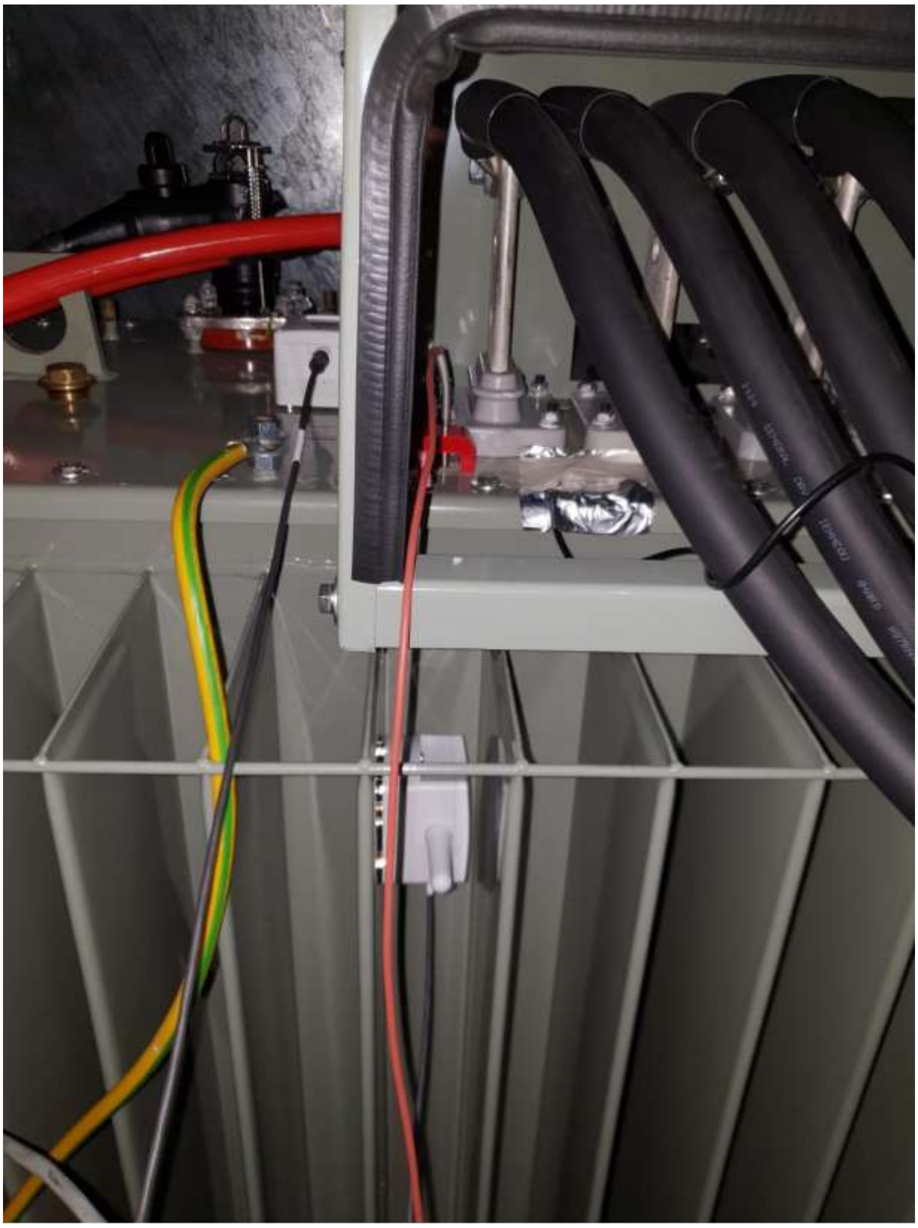
- the transformer lid near the LV bushings,
- transformer fin at the top oil level
- ambient air inside the substation
- ambient air outside the substation

The LV panel had the transformer phase connections shorted out using solid copper bars. The substation was fed from the MV RMU. Kyte Powertech also had temperature probes;

- on the transformer lid near the LV bushings,
- in the temperature pocket measuring the top oil temperature and,
- four ambient air temperature probes which were placed two meters away from each corner of the substation.

The substation doors were closed before the transformer was energised to simulate the working conditions of the substation.

FIGURE 3: PLACEMENT OF TEMPERATURE SENSORS ON TRANSFORMER

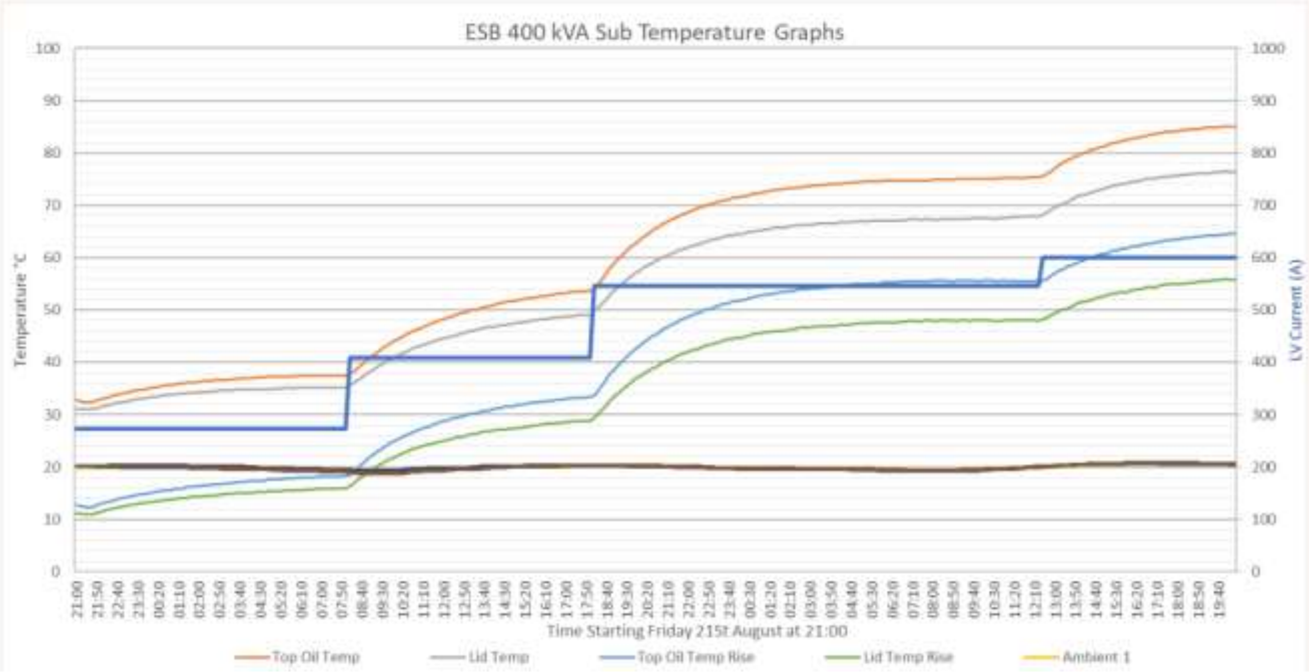


The transformer was loaded at various increasing currents and the temperature allowed to stabilise. The temperature is deemed to be stabilised when the top oil temperature increases less than 1°C per hour, for three consecutive hours.

The transformer was loaded at 50% rated current in the 21.5kV voltage regime which equates to 5.35 Amps being supplied on the HV windings and 273A circulating the LV windings. After top oil temperature stabilisation was achieved, the current supplied to the HV windings was increased to 75%, 8.025A HV, 409A LV. The transformer was then increase to 100% rated current; 10.74A HV, 546A. As this ran over night into a Sunday, the test was left running much longer than the minimum time required. Finally, the current was increased to 110%, 11.81A HV, 600A LV. Upon top oil temperature stabilisation of the final step, the transformer was deenergised.

Figure 4 below shows a trend of the measurements obtained from the test along with the temperature rise of the top oil and the lid. The temperature rise is the measured temperature minus the average ambient air temperature.

FIGURE 4: KYTE POWERTECH DATA FROM HEAT RISE TEST



The following observations can be made;

1. The ambient temperature was 20°C as shown by the brown/yellow graph.
2. The maximum top oil temperature for this specification of transformer is 65°C above ambient, hence the maximum top oil temperature is 85°C.The test successfully reached the maximum design rating of the transformer as the probe in the oil pocket reached 85°C as shown by the orange graph.
3. The transformer lid temperature as measured by a Kyte Powertech probe on the external surface of the lid reached 76.5°C as shown by the grey graph.
4. The thermal time constant at the different intervals were as follows;
    a. 50% load: 11 hrs approx.
    b. 75% load: 10 hrs approx.
    c. 100% load: 9 hrs approx.
    d. 110% load: 6 hrs approx.

The Comet Sigfox-enabled sensor data was then compared against the Kyte Powertech data, and this is shown in Figure 5 and Figure 6 below.

The VT IoT Trafo-Scope was a combined current and temperature prototype, where the temperature readings were taken from the transformer lid. The two Comet sensors were temperature-only sensors and were placed on the transformer lid and the transformer top oil level at the fins respectively.

The following observations were made;

1. The VT IoT Transformer-Scope sensor data compared very favourably with the Kyte Powertech data, for both current and temperature.
2. The temperature from the low-cost Comet Sigfox-enabled sensor correlated very well with the loading levels of a heavily loaded transformer in a controlled environment where ambient temperature of the factory floor was a constant 20°C.
3. There is very little difference in the temperature data by locating the sensor on the transformer lid vs. the top oil level on the fins.

Based on the observations, the project team deemed it viable to install several sensors to energised transformers on the electrical system as a field trial.

FIGURE 5: COMPARISON OF 'VT IOT'S 'TRANSFORMER SCOPE' SENSOR CURRENT + TEMPERATURE DATA

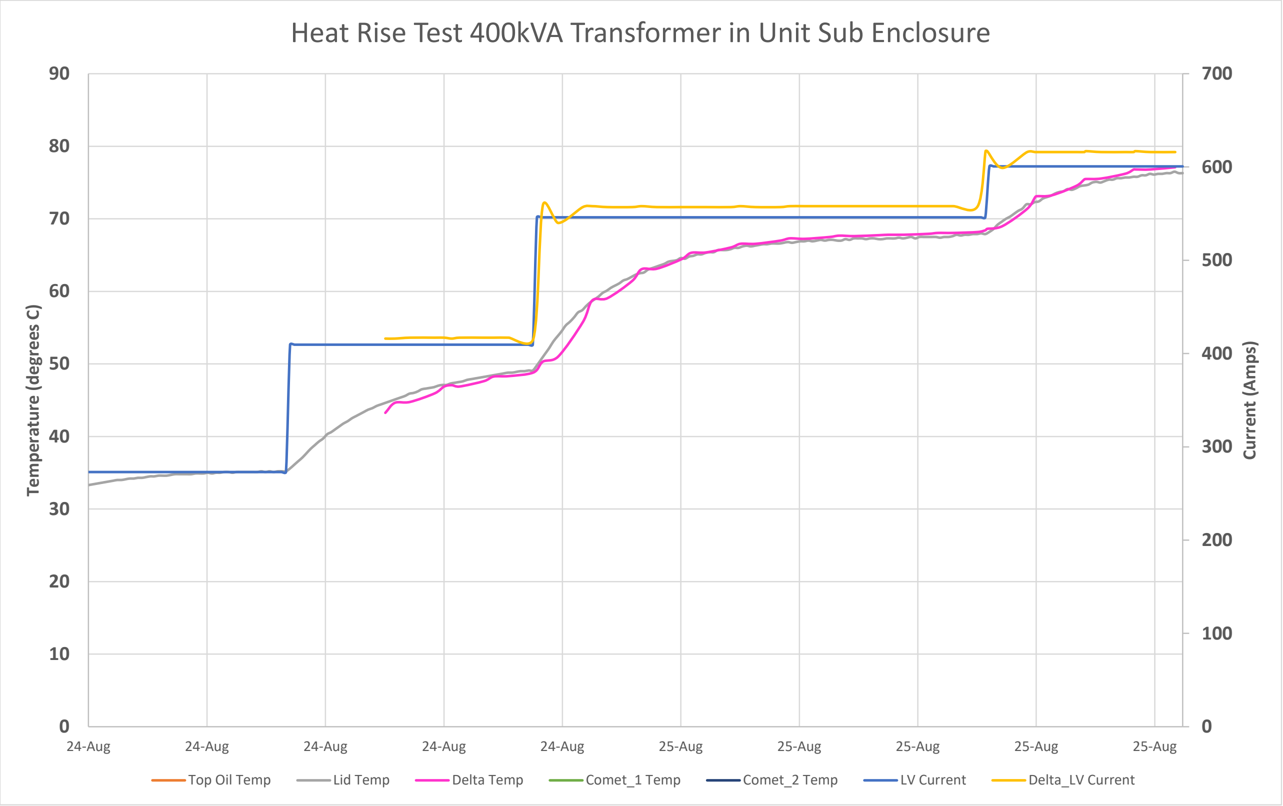
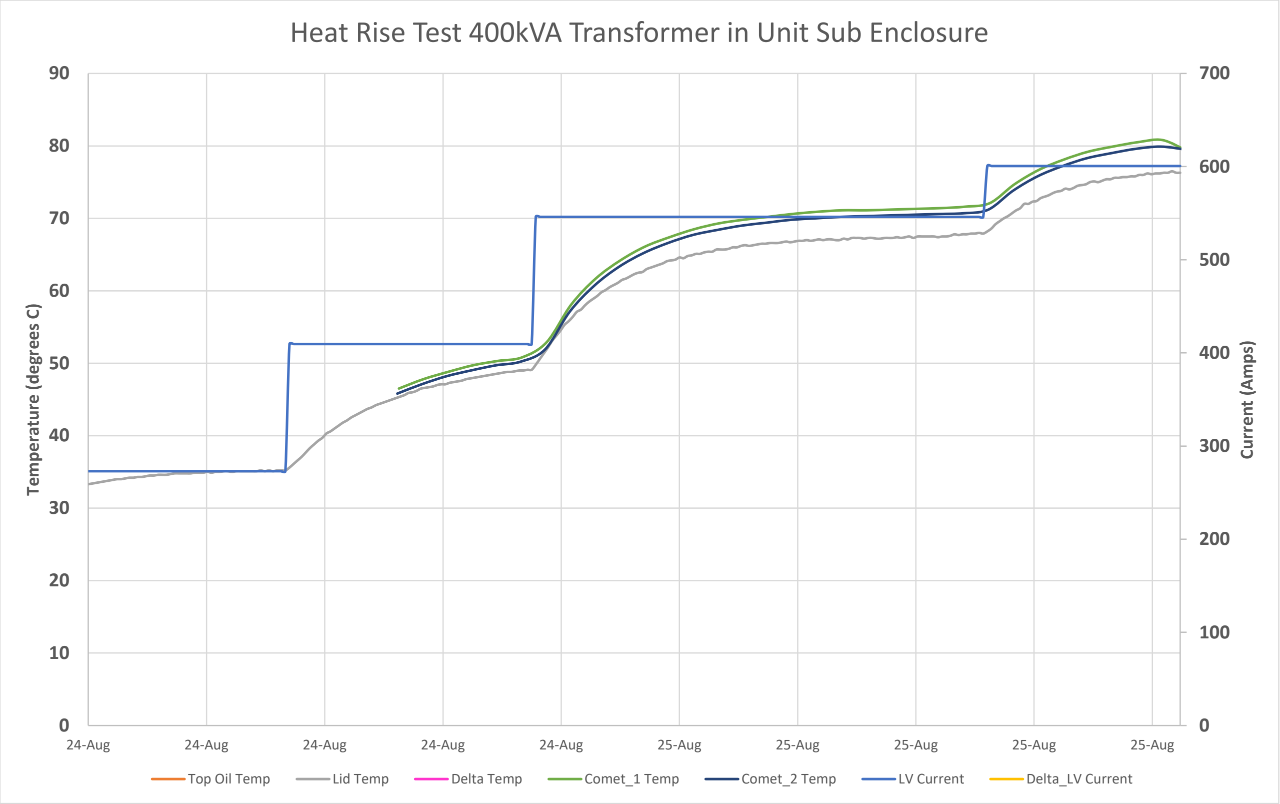


FIGURE 6: COMPARISON OF 2 NO. 'COMET' TEMPERATURE-ONLY SENSORS



4.4. Deployment of Solution to Transformers in the Field

Value statement for Field Trials

Whilst it was reassuring to have obtained a positive result from the VT IoT Transformer-Scope measuring current and temperature in a controlled environment, it was necessary to deploy to the field to ascertain several additional findings;

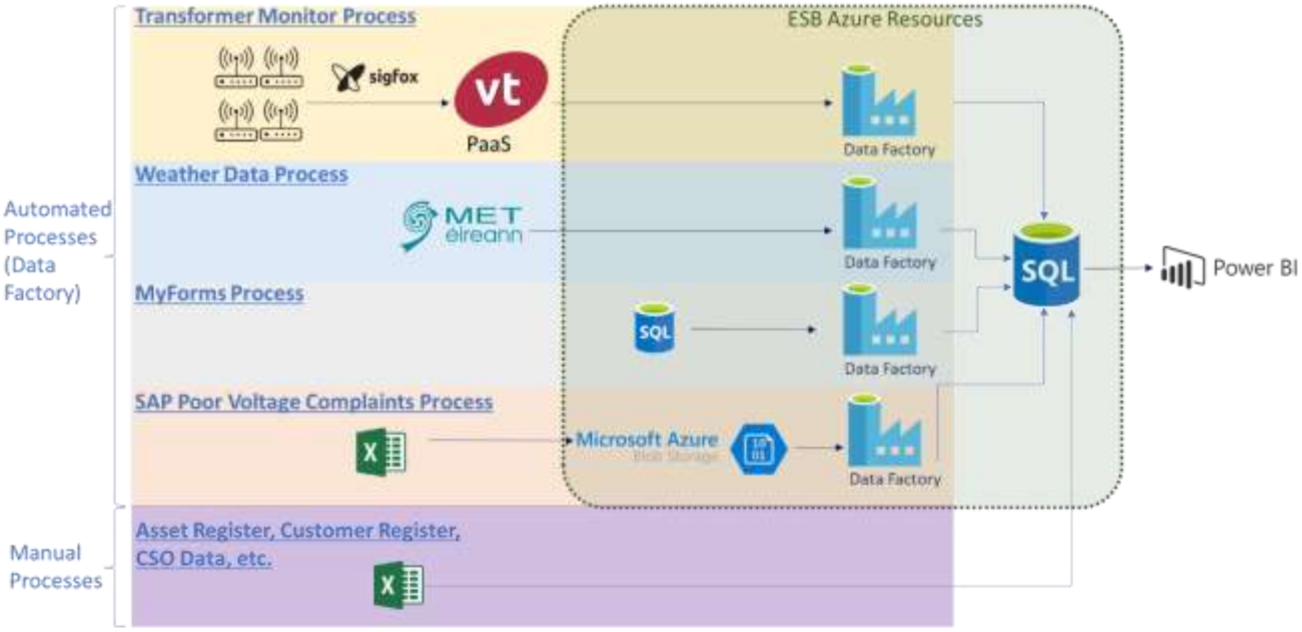
1. How would the sensor perform against a typical load curve, which would have different ramping time characteristics to that of a standard heat rise test?
2. Does the temperature correlate with the load on pole-mounted transformers which are exposed to wind-chill effects?
3. How would the sensor cope with non-ideal real-life scenarios of phase imbalance and possible breaches of other design limits, such as current density, etc, of the transformers?
4. How would the sensor perform from a communications reliability perspective?
5. Is it possible to automate the data ingestion from the monitors to an in-house ESB Networks database for merging with other ESB Networks datasets?
6. Is the solution, including the installation procedure required, suitable for widescale rollout?

Deployment

The project team developed an environment in the ESB Networks' Azure cloud to host the data, merge with other datasets, and carry out studies and analytics. The team also worked with VT IoT to develop an API (Application Programme Interface – allows an IT system to interface with another IT system) so that monitor data could be fetched automatically from VT IoT's 'Octopus' platform and stored in ESB Networks' Azure SQL database. Figure 7 below shows the data architecture deployed.

Therefore, the project team established the possibility of automating the data ingestion process for a scalable and more sustainable roll-out.

FIGURE 7: SOLUTION ARCHITECTURE DIAGRAM



VT IoT's Octopus platform was also used throughout the deployment for several purposes such as monitoring installations, monitoring transformers, performing data analytics and reporting, alerting and fleet wide insights.

FIGURE 8: VT IOTS OCTOPUS PLATFORM WAS USED TO MONITOR THE INSTALLED FLEET IN REAL TIME

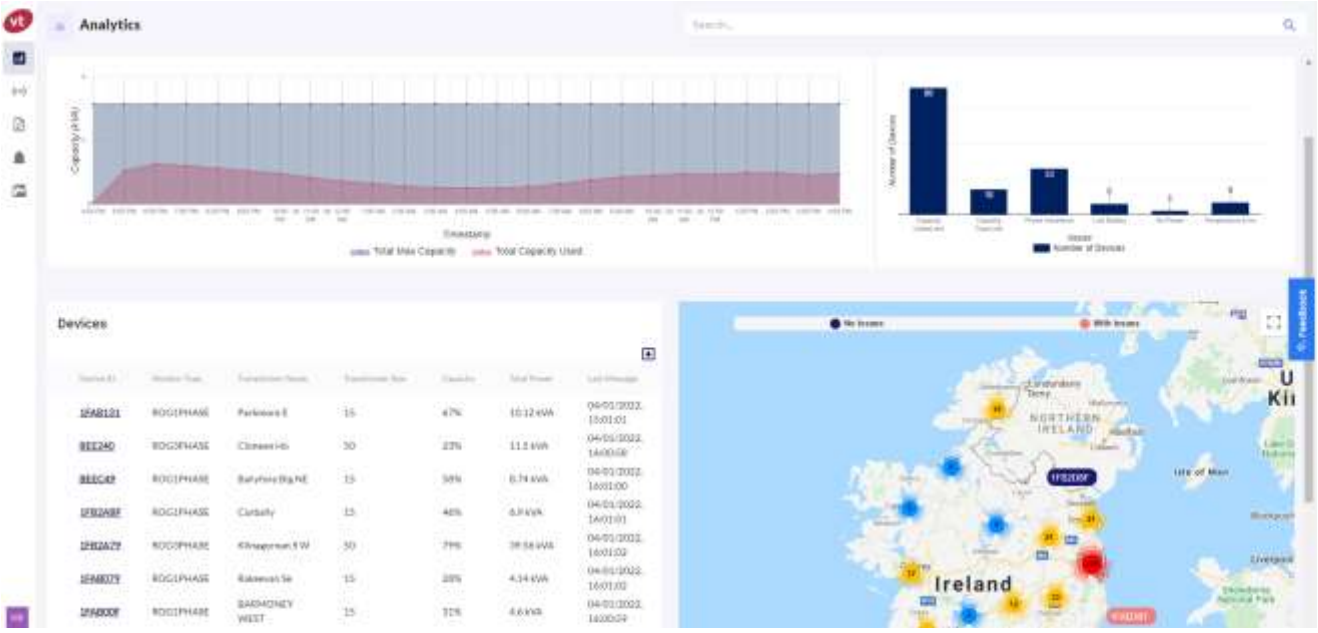


FIGURE 9: VT IOTS OCTOPUS PLATFORM WAS USED TO MONITOR THE PERFORMANCE AND OPERATION OF INDIVIDUAL TRANSFORMERS IN REAL TIME AND ACROSS CHOSEN TIME PERIODS

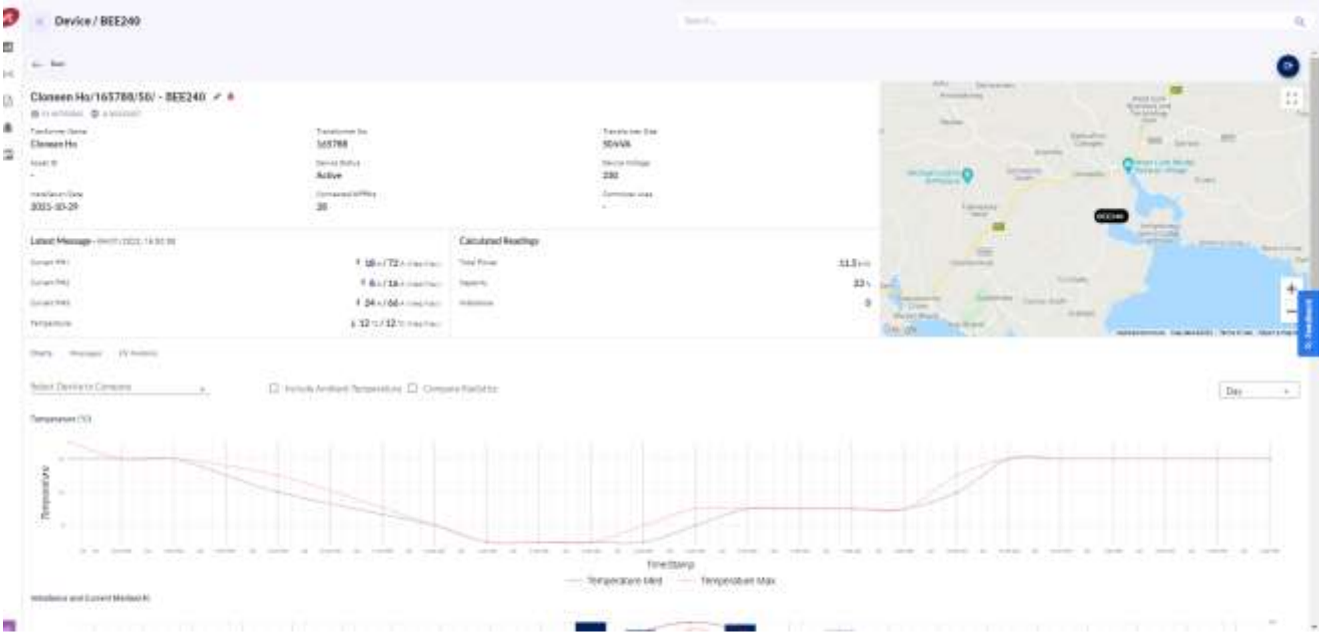
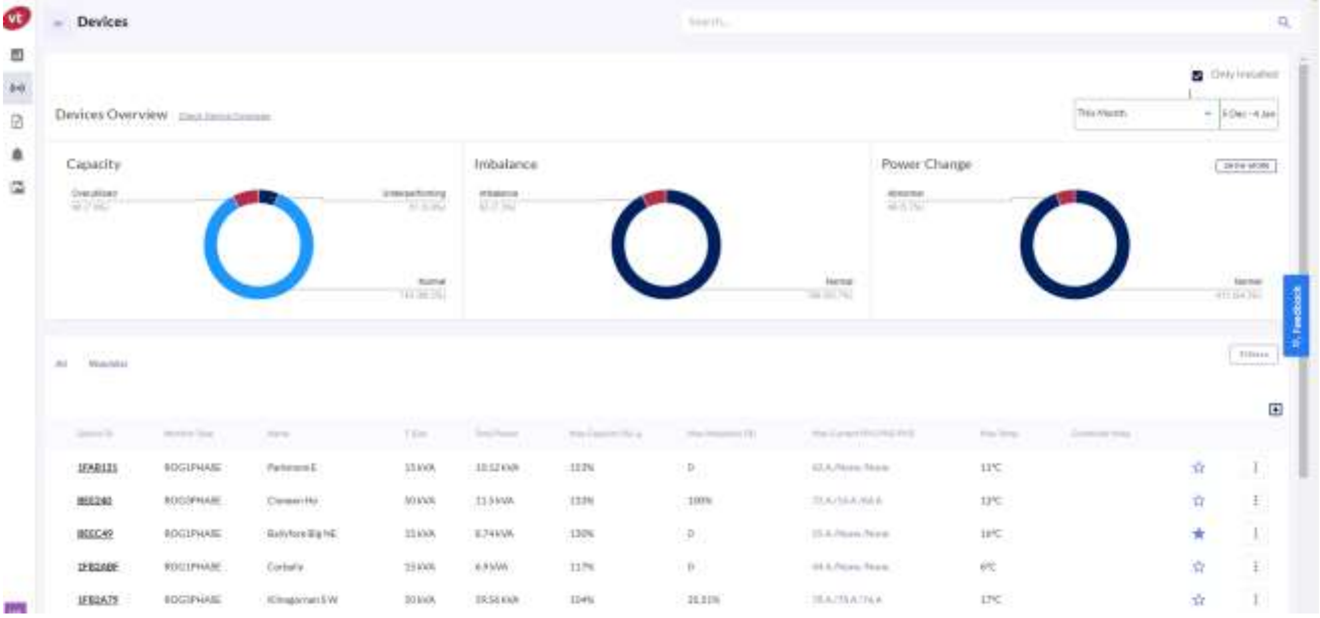


FIGURE 10: VT IOTS OCTOPUS PLATFORM WAS TO MONITOR AND ALERT ON TRANSFORMERS WHICH WERE BREACHING PRE-DEFINED CAPACITY THRESHOLDS OR APPROACHING POTENTIALLY PROBLEMATIC BEHAVIOUR



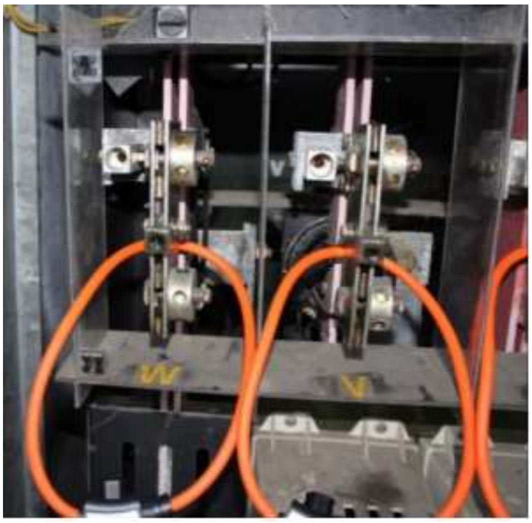
The VT Trafo-Scope monitor itself was specified for ease of installation whilst minimising the costs. For example, the sensor can be attached using magnetic attachment to the transformer tank, with flexible Rogowski coils to monitor phase current, with an in-built temperature probe at the back of the monitor casing to provide a level of insulation for the probe from ambient effects. Figure 11 to Figure 14 below show the form-factors of the monitor itself. A procedure document was produced on ESB Network~~’~~s’ document management system to ensure clear instructions to staff for a safe, efficient, and quality installation experience. The specification of the solution was hence proven to be suitable for a scalable and more sustainable roll-out. Some enhancements were noted by the team, and these are detailed out in section 5 below, ‘Learnings and Recommendations’.

FIGURE 11: SINGLE PHASE POLE MOUNTED

FIGURE 12: 3-PHASE POLE MOUNTED

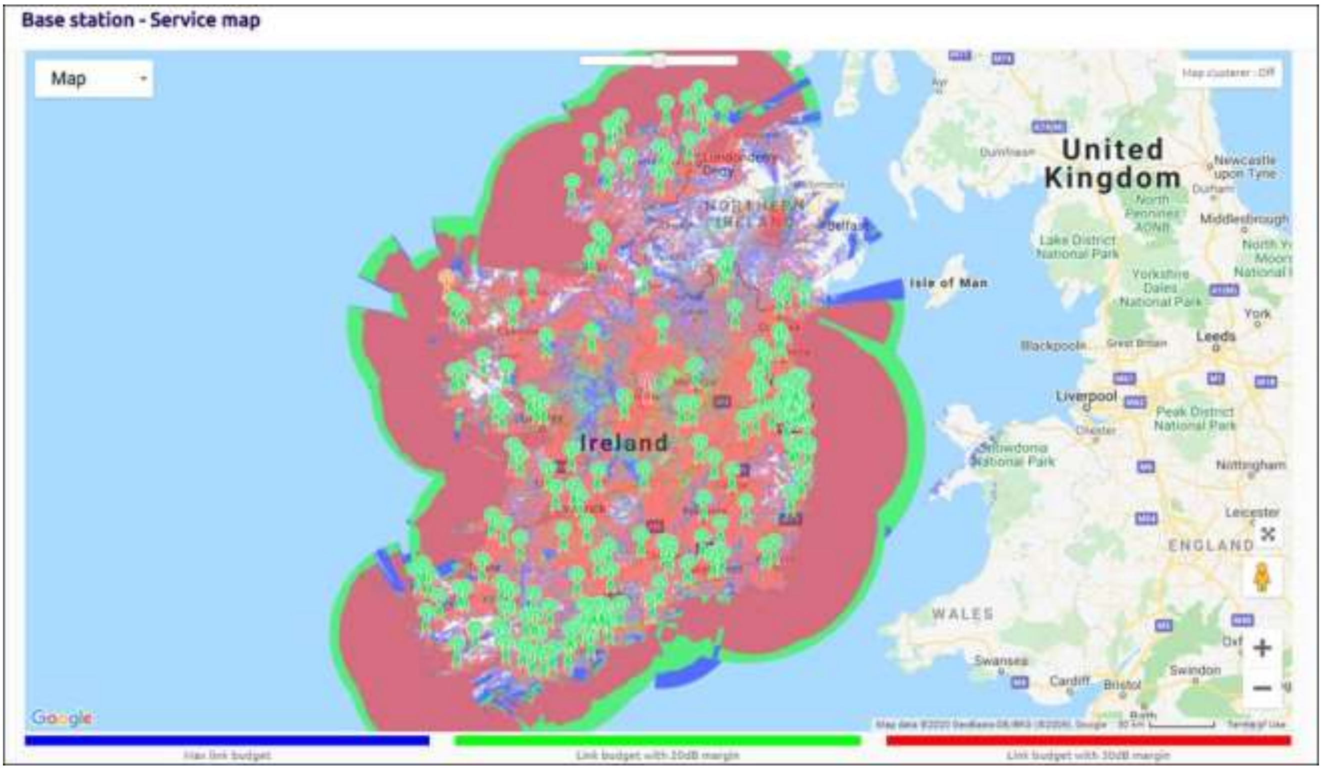
FIGURE 13: 3-PHASE GROUND MOUNTED

FIGURE 14: ROGOWSKI COILS AROUND TRANSFORMER DISCONNECTS ON RENLEY J TYPE PANEL



To assess the reliability of the telecommunications, the rollout was undertaken in two phases. Initially 60 sensors were deployed to ground mounted transformers in urban locations, namely; Cork, Dublin, and Limerick, and 20 sensors were installed on 200kVA pole mounted transformers. The locations were chosen carefully to ensure quality data would be harvested from transformers of interest, and that Sigfox coverage in the area was good, very good, or excellent. Refer to Figure 15 which shows the Sigfox coverage map used for this assessment. Coverage can also be established through the following link; https://coverage.sigfox.cz/

FIGURE 15: SIGFOX COVERAGE MAP



A whip antenna was used for these initial 80 sensors. Circa 7% of these devices experienced telecommunications issues, many of which were in South Dublin. A study was undertaken by our project partner, VT IoT, to ascertain the reason for the issues, and to recommend a solution. The team implemented a simple low-cost solution which would not delay the installations. This was to implement an external patch antenna as shown in Figure 16 below. The solution worked very well, and it was decided to implement it as standard for further rollout.

FIGURE 16: EXTERNAL PATCH ANTENNA PROTOTYPE

A second phase rollout took place in 2021 with a larger number of sensors, and it became evident that the patch antenna solution deployed in Q4 2020 wasn't robust enough. Signal attenuation due to the proximity of the antenna to the metallic surface of the unit substation caused many units to fail to communicate. Two solutions were trialled to rectify the issue. The first solution was to install 20mm depth of Styrofoam between the antenna and the metallic surface of the unit substation as per Figure 17 below. This rectified the problem in most cases. Another solution was to install a PUK antenna which entailed drilling the unit substation enclosure, as per Figure 18 below. The PUK antenna solution proved to provide the most reliable telecommunications. Therefore the project team successfully managed to establish a robust telecommunication specification for reliable access to data and made the use of a PUK antenna a standard feature.

FIGURE 17: 20MM AEROBOARD LAYER FOR EXTERNAL ANTENNA PROTECTED WITH VINYL MASTIC

FIGURE 18: INSTALLING A PUK ANTENNA

The sensors performed very well in the field. Due to diversity, domestic load aggregated to the transformer changes gradually in general, however the peak load is not maintained for long, and certainly not for the time required for the transformer to reach a heat rise steady state, as per the thermal time constants seen in the heat rise test. Hence in reality, ‘only some’ temperature rise of the transformer lid takes place and lags the power curve as expected. This is shown in Figure 19 and Figure 20 below.

FIGURE 19: LOAD CURVE, PIPERSHILL 400KVA UNIT SUBSTATION (08/12/21)

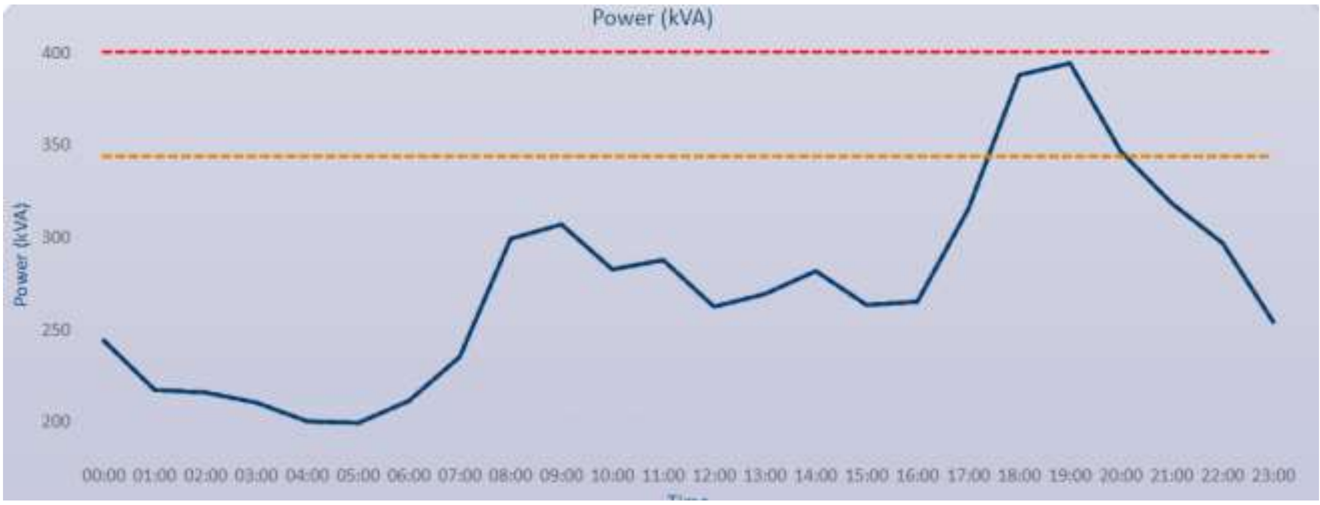
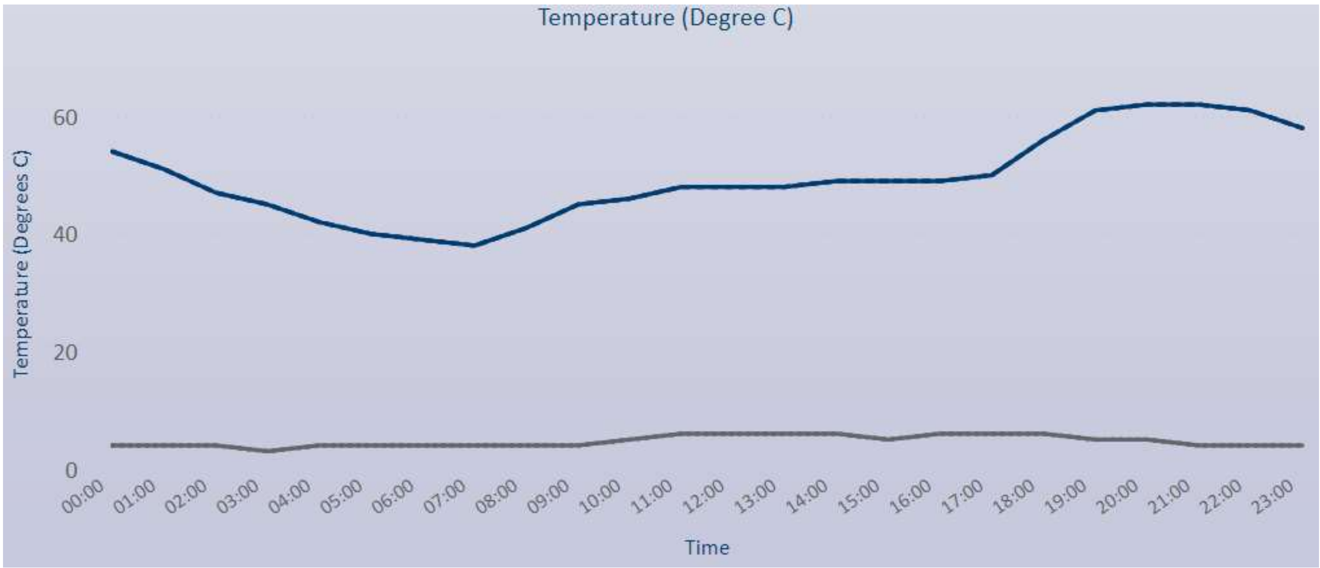


FIGURE 20: TRANSFORMER LID TEMPERATURE AND EXTERNAL AMBIENT TEMPERATURE



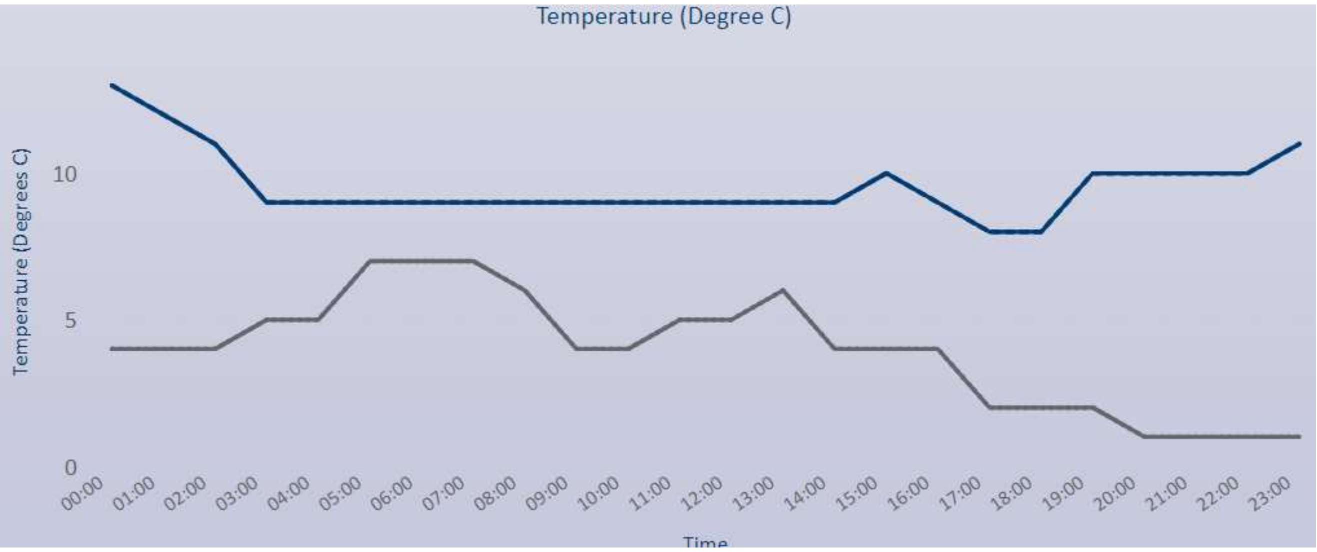
This means that a transformer could potentially be pushed beyond its phase current limit, whereafter the load could then drop, but the lid temperature of the transformer would not have had a chance to ‘heat up’ to provide a high temperature alarm on the temperature sensor. This possible cycling of high load followed by lower load of the transformer may challenge the current density and winding hot spot temperature design limits. This phenomenon would present itself especially in poorly balanced 3 phase transformers, where one heavily loaded winding would create a risk of failure.

A possible future scenario would be where smart tariffs would encourage a loss of diversification, where the peak load would shift to another time, and where the peak is maintained for a period of hours stressing the hot spot or top oil temperature design limits. Analysis was undertaken on this aspect and is detailed out further in the following section.

Analysis was also carried out on pole mounted transformers to establish the relationship between current and temperature. It can be seen in Figure 21 and Figure 22 below, that the impact of ambient conditions influences and creates unreliable data at the temperature probe used to measure the transformer tank temperature at the top oil level. The data from a full monitor rollout indicates that pole mounted transformers don’t have the same relationship between load and temperature as ground mounted transformers, in fact there is almost no correlation between load and temperature with pole mounted transformers.

FIGURE 21: LOAD CURVE, REASK H.S. 200KVA POLE MOUNTED TRANSFORMER (06/12/21)

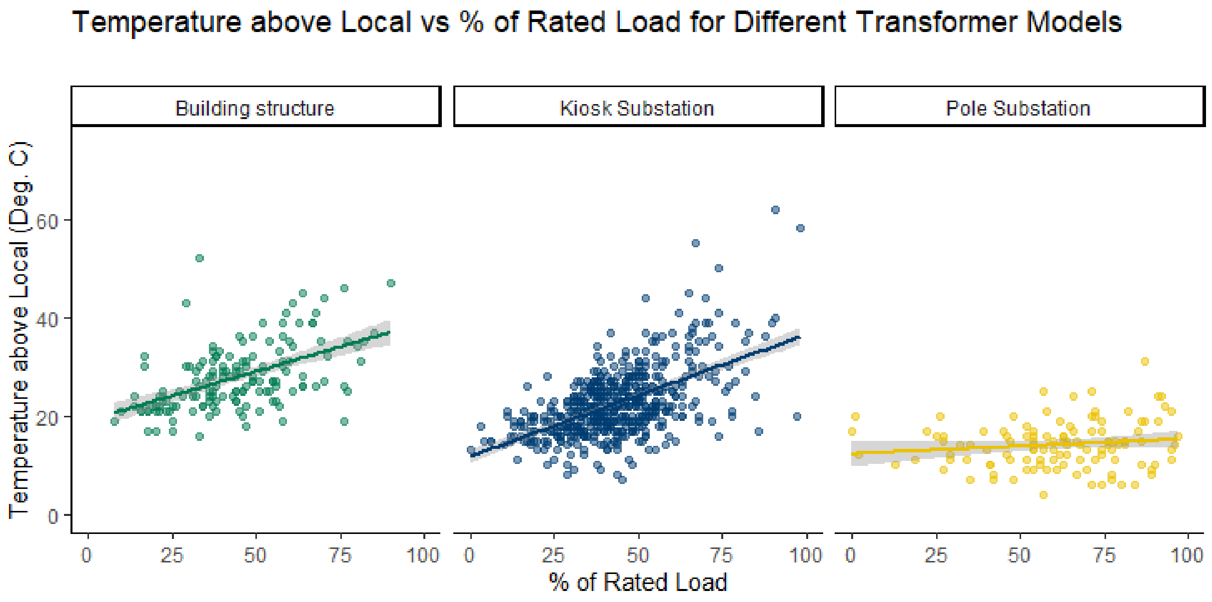
FIGURE 22: TRANSFORMER LID TEMPERATURE AND AMBIENT TEMPERATURE



The user interface for the solution was developed in Microsoft PowerBI online. The following observations from the data can be made;

1. Figure 23 below shows the results of the field trail, where each dot in the chart is a transformer, its position on the chart a function of its temperature rise above ambient, and the % rated load of the transformer. Results indicated that Temperature-only monitoring is possibly a viable solution for unit substations and indoor substation. Pole mounted transformer are too exposed to the effects of weather, wind, solar gain, etc. to be functional as temperature sensors.
2. The low-cost current and temperature monitor however may in fact prove to be a more valuable asset than a temperature-only solution for serving the needs of our customers. This idea is explored further in the next section.

FIGURE 23: CORRELATION BETWEEN TEMPERATURE RISE AND % RATED LOAD OF 1,000 TRANSFORMERS



4.5. Key Results: Using data to understand the MV/LV transformer asset

MV/LV Transformer Analysis

ESB Networks have a fleet of approximately 270,000 MV/LV transformers. Table 1 below shows the volume of transformers broken down by type.

TABLE 1: FLEET OF MV/LV TRANSFORMERS

Transformer Types	Range of kVA ratings	No. transformers on system	No. customers connected	No. transformers with sensors installed
Ground Mounted Transformers (3-phase)	200, 400, 630, and 1000kVA	25,000	1,425,000	800
Pole Mounted Transformers (3-phase)	50, 100, 200, and 300kVA	22,000	240,000	130
Pole Mounted Transformers (1-phase)	5, 15 and 33kVA	225,000	700,000	70

The fleet of transformers range from assets which are over 50 years old, to more modern transformers. The design criteria and models would be required for all the different types of legacy transformers currently energised on the system to establish the actual design limitations of each model. The latter is not a realistic option, so the project team engaged Kyte Powertech again to establish a ‘rule of thumb’ which could be used to identify transformers with data profiles for which ESB Networks should be concerned.

Challenges & Risks of overloading existing transformers

One possible solution to meet the additional demand of LCT is to allow for overloading of existing transformers. However there are considerations and risks associated with overloading existing transformers such as;

1. The past loading history of the transformer is generally not known due to the lack of monitoring data. The paper insulation ages with time and becomes more brittle, causing a risk to the integrity of the dielectric.
2. Transformer accessories such as bushings, tap changers, and internal connections also must withstand overloading, and historical design limits for these is generally not known.
3. Generally the thermal characteristics of the transformer are not well known, such as top oil and winding rises over ambient, and gradients of the windings. Without this data, an overloading study cannot be performed.
4. Is there a risk of bubbling due to moisture content in the insulation or due to supersaturation of oil with gasses? Bubbling in transformers reduces dielectric integrity of a transformer. When bubbles are formed, they tend to rise through the windings and reduces the dielectric strength. As a result, either partial discharges or catastrophic dielectric failures occur. Bubbling in oil can occur either in free breathing transformers because of moisture content or in units equipped with gas cushion because of supersaturation of oil
5. Is the tank able to cope with fatigue type loadings due to overloading? Transformers with gas cushion will be subjected to fatigue type loading where the welded parts will be stressed under cyclic type loading. Before overloading existing transformers regularly, it should be ensured that the tank is able to cope with these loading conditions, otherwise oil leakages may occur. Due to joule heating and no-load losses, a certain amount of heat is dissipated from the transformer through the cooling surfaces, also called fin-walls, to the environment. These fin-walls are made from thin steel with a thickness of circa 1.2mm to provide flexibility to cope with the built-up internal pressure. Because of the load and ambient temperature variations, pressure built-up inside the transformer varies causing expansion – contraction of the fin-walls while exerting them fatigue type mechanical stresses. These stresses reach maximum values at the more brittle welded regions and if not controlled, can cause oil leakages in time. As a result, “limiting pressure” should not be exceeded to ensure that welded regions will remain intact. This is more important in future as the cyclic loading on transformers will increase due to EV charging and heat pump usage.

Modelling the maximum loading condition

Kyte Powertech undertook a study on a Kyte Powertech model 400kVA mineral oil transformer which is currently energised on ESB Networks’ electrical network. The study was to model the maximum loading condition that this transformer can withstand. Learnings and recommendations from this study are listed in section 5 below. The results of the study for this particular transformer are as follows;

1. Limitations of components; ‘Risers’ and ‘limiting pressure’ were the first two design limitations. Bushings, tap changers, foil & wire current densities were within design criteria as load was increased in the simulation. Risers reach 4.3A/mm^2 when load is 460kVA. As a result, this is the first limitation and so the transformer cannot be loaded above 460kVA (115% overloading).
2. The ‘limiting pressure’ was analysed in greater detail. The following table shows the time that a transformer can be loaded for, while experiencing the limiting pressure. The table can be used so that once the initial load on the transformer is known (the average load over 1 hour preceding the event), and once the ambient temperature inside the transformer enclosure is known, then the safe loading time at the limiting pressure point is known.

TABLE 2: EXPOSURE LIMITS AT LIMITING PRESSURE

Initial Load (% Nameplate rating)	Loading Time (min)	Ambient Temperature inside enclosure (Note 1, Note 2)
100.00%	10	40°C + 10K
80.00%	90	
50.00%	160	
25.00%	200	
100.00%	90	30°C + 10K
80.00%	170	
50.00%	250	
25.00%	285	

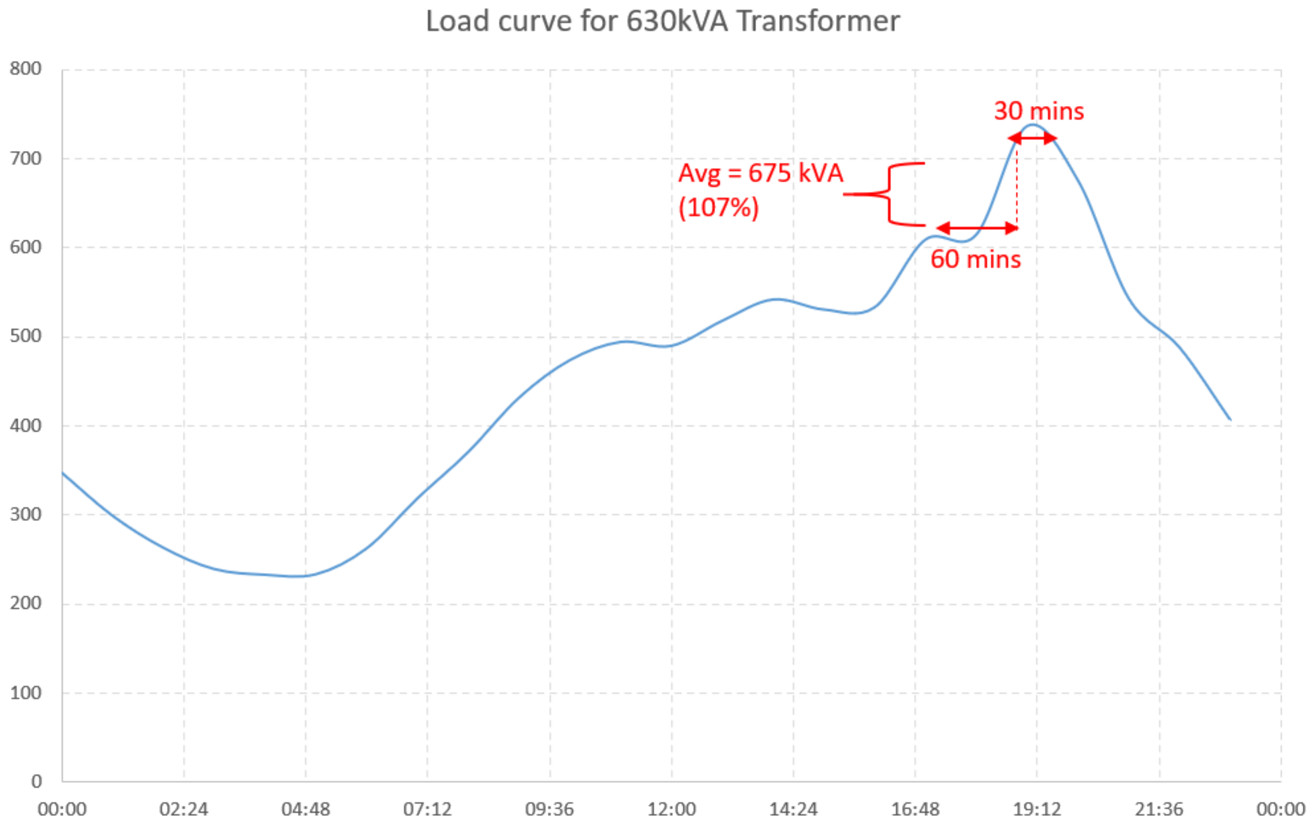
The usefulness of the table is demonstrated as follows by example. If the ambient outside temperature is 30°C and the load on transformer is 50% prior to overloading, then the transformer can be loaded with 460kVA for 250 minutes before reaching the “limiting pressure”. But if the load prior to overloading is 80%, then the overloading time is only 170 minutes. Linear interpolation can be used to provide rough estimates for other values.

Note 1: 10 Kelvin is added to the outside ambient temperature due to the transformer being situated in an enclosure such as a unit substation or a building.

Note 2: It is important that 3 hours of cooling takes place between two consecutive overloading events. The transformer which was modelled can be loaded up to 460kVA (115%) continuously below 25°C+10 Kelvin.

A data extract from the UI dashboard is shown in Figure 24 below for a 630kVA transformer. It is readily seen that the transformer is overloaded at peak for approximately 30 mins. The average load on the transformer for the previous hour was 675 kVA (107%). The ambient air temperature inside the unit substation was 45°C. Invoking the use of Table 2 shows that we need to interpolate and that the loading time should be limited to 50 mins ($\frac{90\,\mathrm{min} + 10\,min}{2}$), by interpolating on the ambient temperature, if the transformer were 100% loaded in the previous 1 hour. In our example, the transformer was loaded to 107% in the previous hour. This time, extrapolating on nameplate rating, would suggest a maximum loading time of 20 mins. As the loading time is 30 mins, it is shown that the transformer is exceeding the limiting pressure.

FIGURE 24: USING THE READY RECKONER TABLE FOR LIMITING PRESSURE ON A 630KVA TRANSFORMER LOAD CURVE

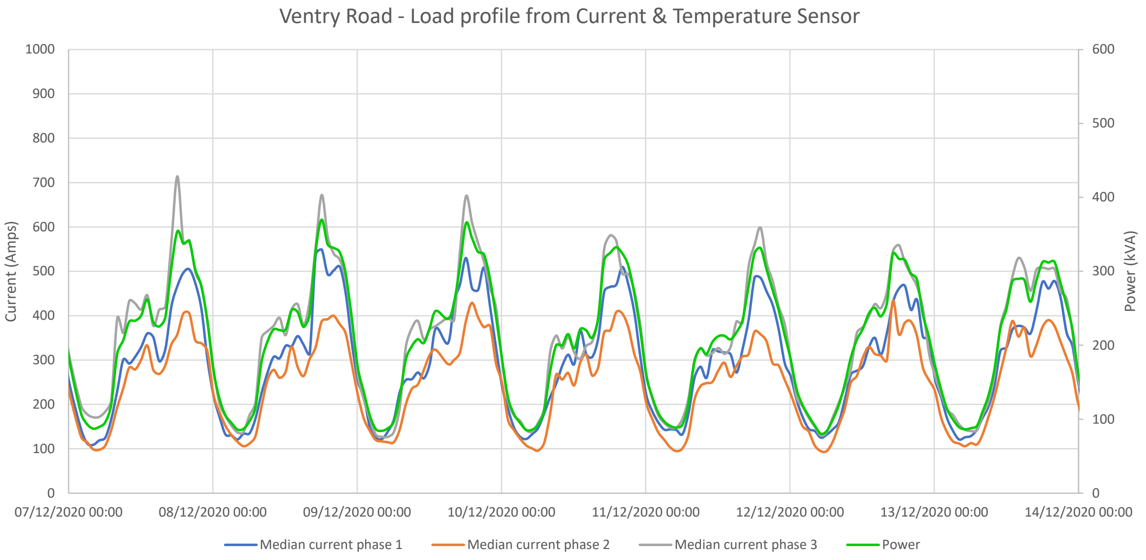


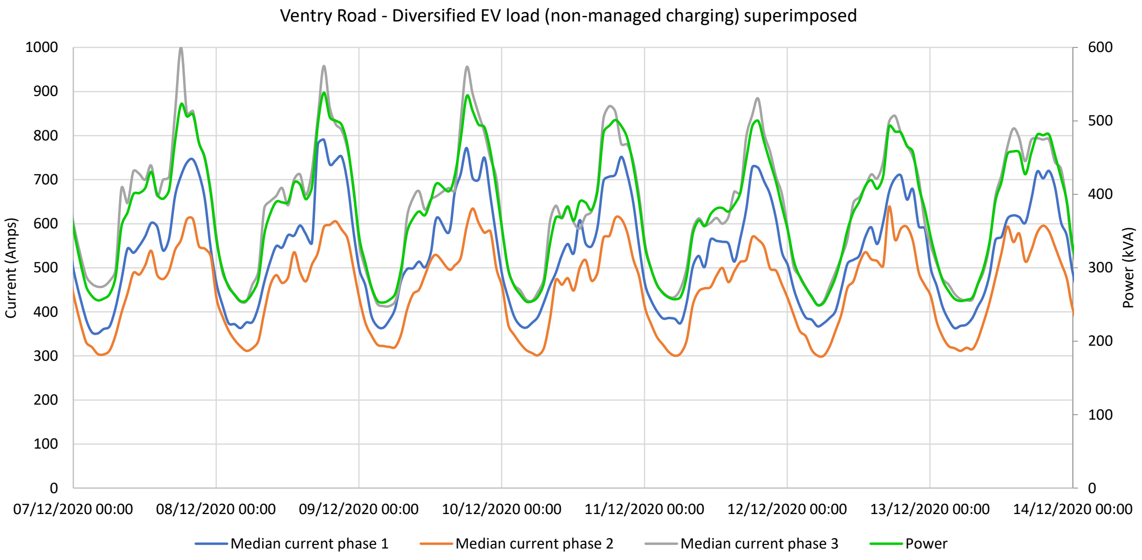
3. Due to cyclic load expectancy, top oil should be limited to 115degC for O class oils following IEC 60076-7. For K class, IEC 60076-14 Annex-C recommendations can be followed. Hot-spot temperature is also critical in that transformers should be designed to prevent bubbling. Hot-spot limit of 130degC is acceptable for O class and 140degC for K class considering that transformers are integrally filled.

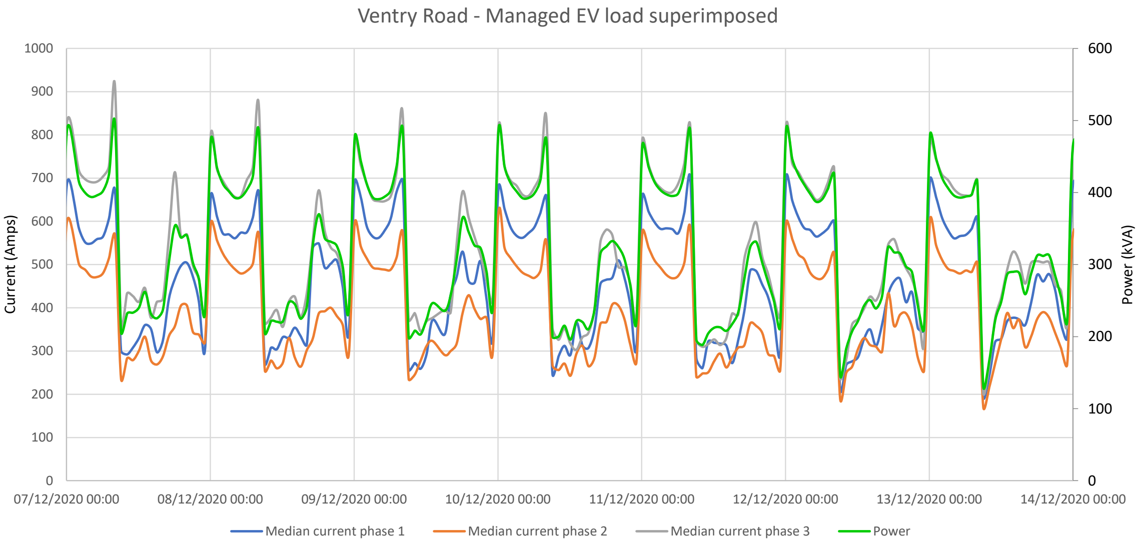
4. The load profile (phase current and transformer lid temperature) from the IoT sensor on the nominated 400kVA mineral oil transformer was then analysed. A representative ambient air temperature daily profile from the Met Eireann website was used in the simulations, given that the sensor does not monitor 'outside the enclosure' ambient temperature.

   Three load profiles were analysed (see Figure 25 below):
   a. Existing load profile as provided by the sensor
   b. Possible future load profile assuming 25% EV penetration, with non-managed charging adopted by customers
   c. Possible future load profile assuming 25% EV penetration, with managed charging adopted by customers (most charging happening in off-peak night hours)

FIGURE 25: LOAD PROFILES SUPPLIED FOR ANALYSIS


Ventry Road - Load profile from Current & Temperature Sensor


Ventry Road - Diversified EV load (non-managed charging) superimposed


Ventry Road - Managed EV load superimposed

The existing load profile with the simulated top oil and hot spot temperature is shown in Figure 26 below. The calculation predicts a max top oil temperature of 40°C whereas measurements from the sensor was 35°C. The difference could be down to the choice of ambient temperature for that day, as ambient temperature is not measured by the sensor.

FIGURE 26: HOT SPOT AND TOP OIL TEMPERATURE FOR GIVEN LOAD PROFILE FROM SENSOR

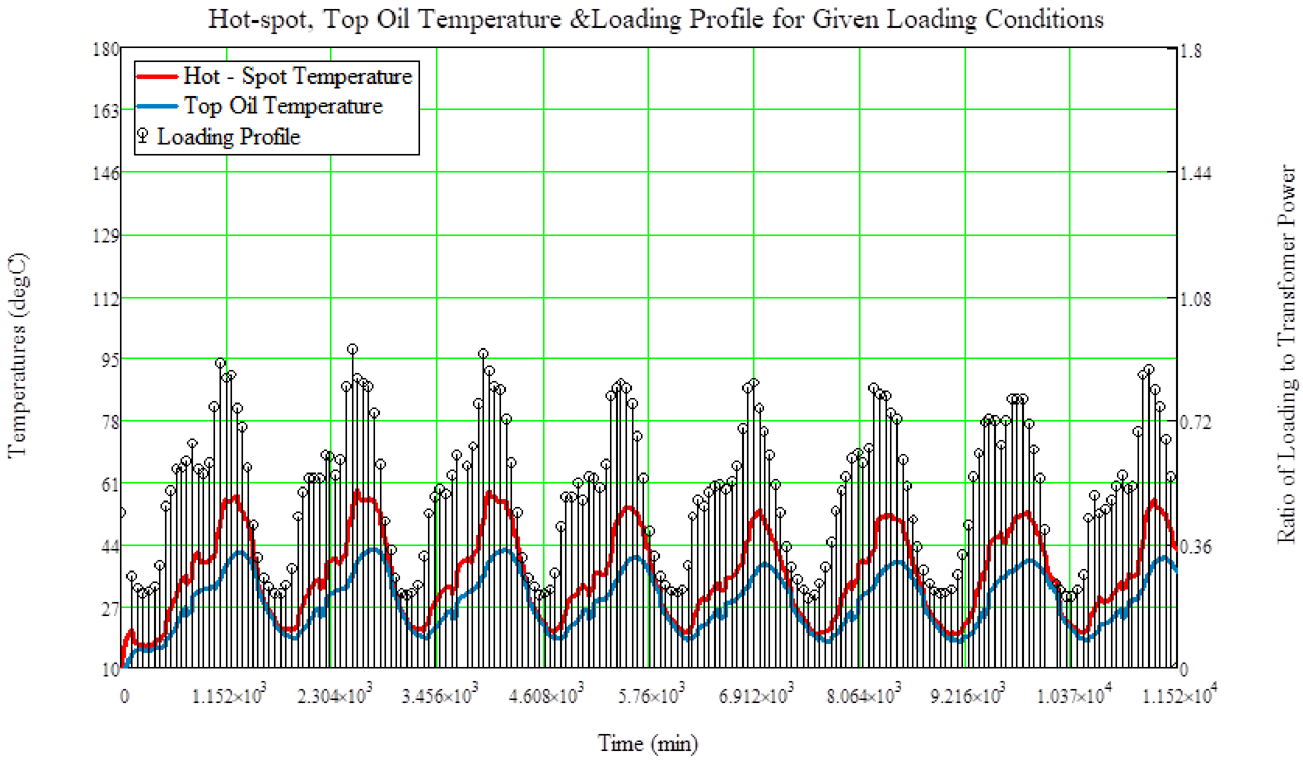


Figure 27 and Figure 28 below show the results of simulations for a non-managed EV charging load profile.

FIGURE 27: TOP OIL AND HOT SPOT TEMPERATURES FOR 'NON-MANAGED EV CHARGING' LOAD PROFILE

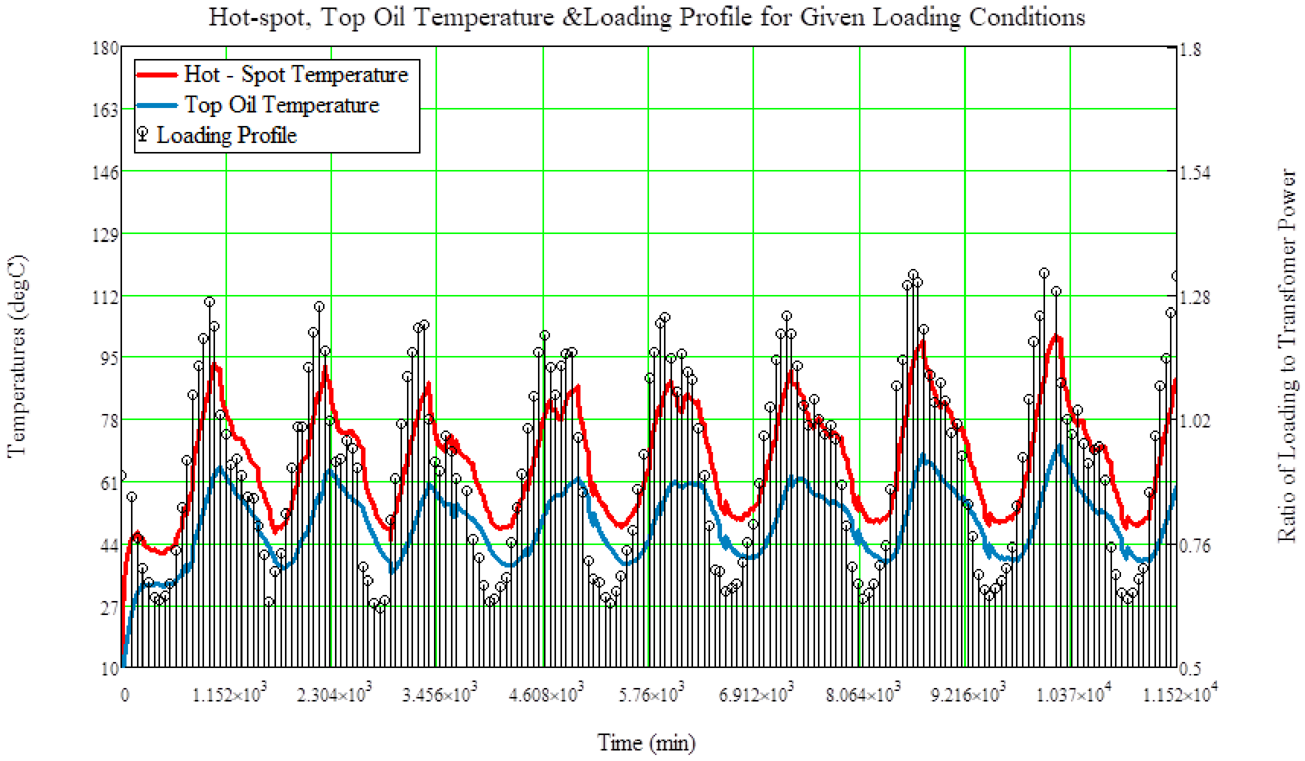


FIGURE 28: LOSS OF LIFE FOR NON-MANAGED EV CHARGING LOAD PROFILE OVER 1 WEEK

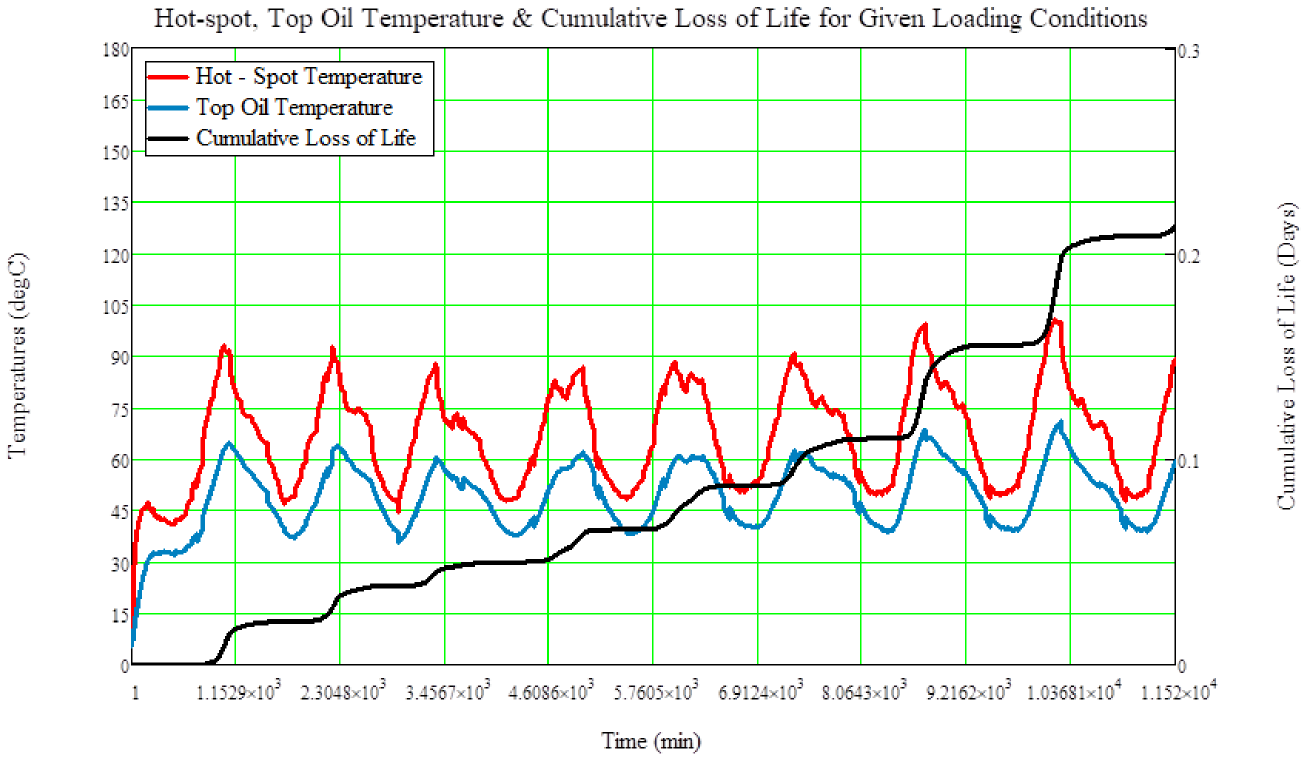


Figure 29 and Figure 30 below show the results of simulations for a managed EV charging load profile.

FIGURE 29: TOP OIL AND HOT SPOT TEMPERATURES FOR 'MANAGED EV CHARGING' LOAD PROFILE

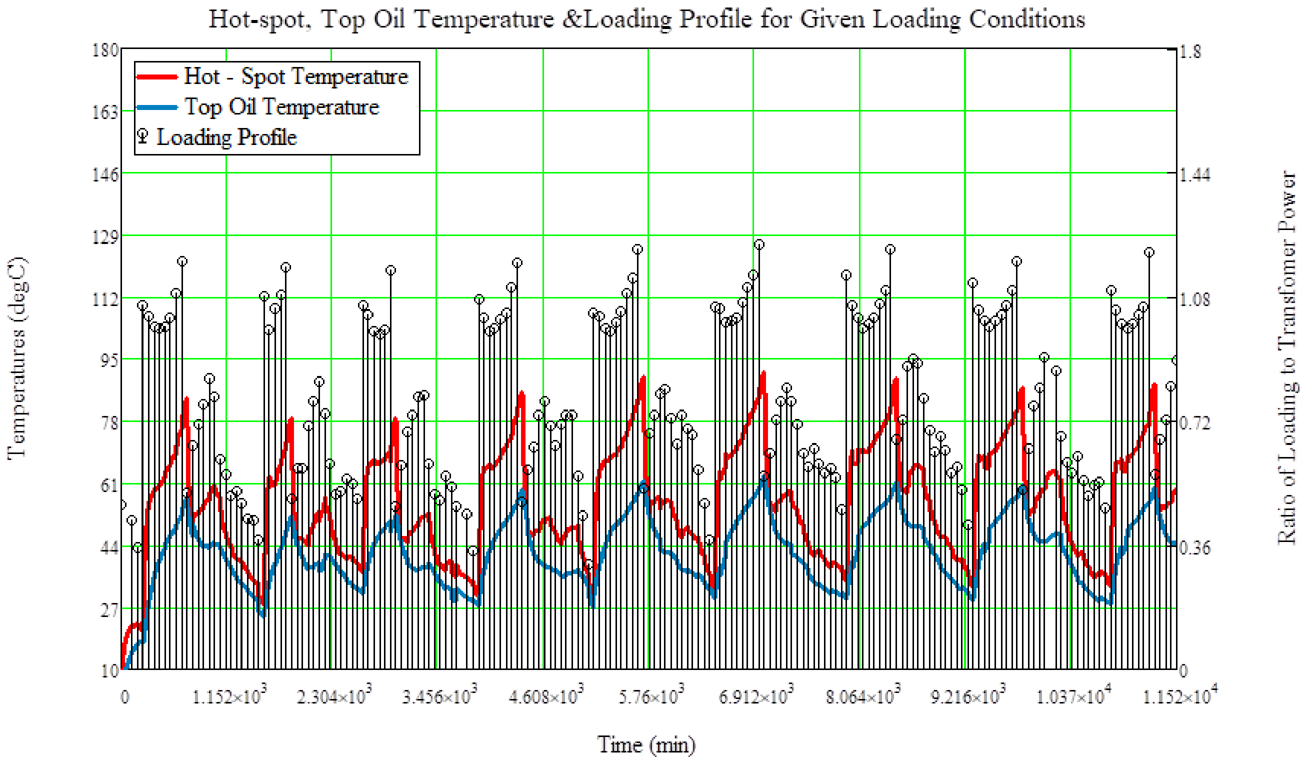
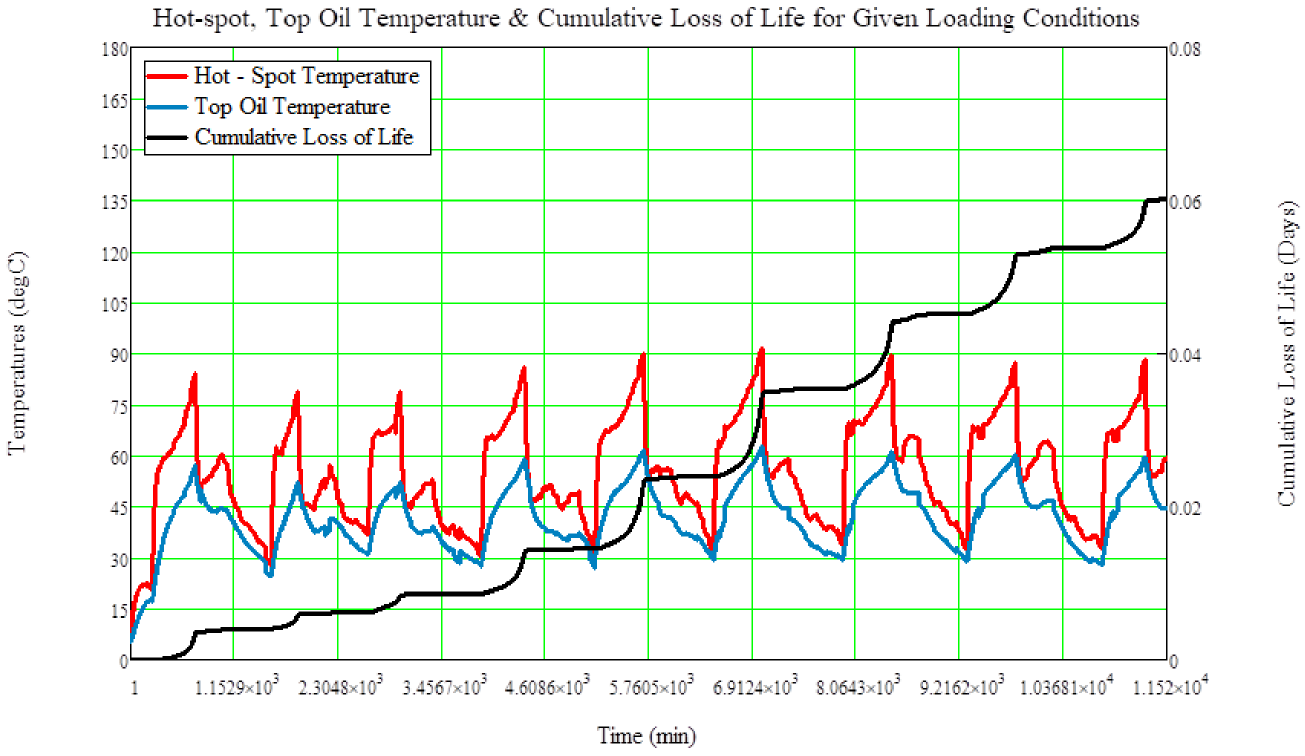


FIGURE 30: LOSS OF LIFE FOR MANAGED EV CHARGING LOAD PROFILE OVER 1 WEEK



Summary of results

The results of the three simulations are shown in Table 3 below.

TABLE 3: RESULTS OF SIMULATIONS ON A 400KVA MINERAL OIL TRANSFORMER

Load Profile	Hot Spot Temperature	Top Oil Temperature	phase current (Riser current density)	Peak power	Limiting pressure	Decision for reinforcement
As-is profile from sensor data	57°C (Within design limit as < 130°C)	42°C (Within design limit as < 115°C) (See Note 1)	L3 peaks at a median phase current of 714A. (Outside of design limit as > 627A)	354kVA (Ok as < 460kVA)	N/A as not overloaded	Rebalance phases to bring riser current density within design limits
A non-managed EV charging load profile	100°C (Within design limit as < 130°C)	70°C (Within design limit as < 115°C)	L1: 1000A peak L2: 750A peak L3: 610A peak (Outside of design limit as > 627A)	534kVA (Not ok as > 460kVA)	Pressure exceeded	Rebalance phased and uprate transformer
A managed EV charging load profile	91°C (Within design limit as < 130°C)	61°C (Within design limit as < 115°C)	L1: 910A peak L2: 700A peak L3: 600A peak (Outside of design limit as > 627A)	495kVA (Not ok as > 460kVA)	Pressure exceeded	Rebalance phases and uprate transformer

Note 1: There are two definitions from IEC which determine the maximum top oil temperature; continuous loading and overloading/emergency loading. The transformer which was modelled for this analysis is designed for continuous rating and this is what a heat rise test measures. E.g. Assuming 40°C ambient temperature inside the MV/LV substation enclosure + 60K rise over ambient gives 100°C for continuous operation. However, for overloading, IEC 60076-7 Table 4 allows up to 115degC for top oil temperature. As the loading due to EV's is similar to regular overloading, we can allow up to 115°C for top oil temperature. As a result, we can limit top oil temperature to 115°C. There is no guarantee that all transformers will be loaded in a similar fashion to what was modelled here. As a result, in order to provide solid rules that will cover other transformers as well, consideration of worst-case scenario is useful. Therefore, a DSO may consider a slightly conservative rule of thumb of say 85-90°C as representing a very heavily loaded transformer which should be uprated.

Conclusion on data profiles which infer the need to uprate the transformer

Whilst the heat rise test indicated that transformer lid temperature would be a good proxy for transformer overloading, in reality the load shape (peakiness, length of time at high load, length of time at low load to cool down) is as important to monitor. This suggests that measuring the phase current as well as transformer lid temperature is necessary to determine whether a transformer should be uprated or not.

ESB Networks policy is not to incur an accelerated loss of life on MV/LV transformers by overloading them. This policy aligns to having a reliable network for our customers. Therefore if the data from the sensors is TRUE for any of the following design attributes, the decision should be to uprate the transformer and/or rebalance the load on the phases;

1. Transformer lid temperature >= 85°C
2. Peak phase current >=627 Amps (allowance for 115% overloading; $\frac{400kVA\,(1.15)}{(423V)\sqrt{3}}$)
3. Peak power >= 460kVA (115% overloading)
4. Duration at limiting pressure >= as that calculated from Table 2.

5. LEARNINGS AND RECOMMENDATIONS

There were many learnings having implemented a project for a new use-case with new technologies. The learnings are listed below and categorised in order of the project lifecycle;

Solution Specification

The overall solution functional specification was robust, well defined, and performed well. Enhancements for future rollout should include;

1. Use of a PUK antenna as standard for ground mounted installations, so that we achieve a ‘first site visit resolution’ standard with the installation technicians. Site revisits to address poor telecommunications is a quality issue which increases costs and causes disruption to other work programmes.
2. A longer antenna lead or an extension antenna lead (we specified 1m as standard) would have enabled the installation technicians to move the antenna outdoors in indoor block-built substations.
3. The solution entailed the project team engaging our in-house ESB Networks mobile application team to develop a Microsoft MyForms template for the installation technicians to register the installation of the sensors. This form captured key asset information such as the serial number of the sensor, the transformer ID, and several photographs. This allowed the project team to match the data received from the sensor with the correct transformer on the network. The project team experienced several incorrect registrations by the installation technicians. A better approach would be to implement bar-code scanning, in conjunction with photographic text recognition for the transformer ID number/GPS or similar location built into the sensor, both of which would have minimised the manual data input on site. Furthermore, the Azure back-end where the Form data resides is not editable by the project team, so that any corrections had to be done by asking the installation technician to resubmit the form on their mobile device. A better approach would be to allow edit access to the central team to correct simple mistakes in the metadata such as transformer ID, Serial no of sensor, etc. It should be noted that VT IoT are currently developing a specific installation application that would directly feed all installation data and photos to the Octopus platform. The Application will also contain step by step videos to assist the installation engineer and allow real time trouble shooting.
4. A second temperature probe to measure ambient temperature inside the transformer enclosure may be in theory a more accurate way to establish the temperature rise between top oil temperature and ambient. However, it is believed that a second probe is unnecessary given that there are means to estimate the ambient from the probe on the transformer tank and the Met Eireann weather data which is publicly available.

Sensor installation

The installation of the sensors went well in general. VT IoT provided a web application for installers to verify device coverage and installation (to be embedded in the new VT Installation App going forward), as per Figure 31 below.

FIGURE 31: VT IOT INSTALLATION AIDE WEB APPLICATION USED BY INSTALLERS TO VERIFY ON SITE COVERAGE AND CORRECT INSTALLATION

Serial Number: 2020-00111

Device ID: BEEC4A

Status: Call VT technician on (01) 532 6936

No data available

A formal ESB Networks document was developed and approved for the installation and comms testing of the monitor, and due to Covid-19, several briefings were given over MS Teams to supervisors and installation technicians, so that key quality and safety points were highlighted. The resource strategy was to use internal ESB Networks' Network Technicians to undertake the sensor installation. There are 32 planner groups which define the different geographical areas across the network. Each planner group had a point of contact (area supervisor) and several installation technicians assigned.

1. Due to the resourcing strategy outlined above, there were 46 installation technicians undertaking the work to install the sensors. A centralised approach with a core team of installers should be considered for a wider-scale rollout which may improve compliance as well as decreasing the risk of programme completion due to other competing work programmes. LV live working technical approvals are required for this work.
2. A wide-scale rollout should avail of the opportunity to integrate the work with other suitable work programmes. For example, each MV/LV ground mounted transformer has a site visit scheduled on a 4-year cyclic programme. Consideration should be given to combining sensor installation with other regulatory programmes so avail of efficiencies and optimise the cost-benefit of the solution.
3. A PowerBI dashboard was created to track the progress of sensor installations, with monthly reports issued to the installing organisation. This helped greatly with achieving the delivery of the programme. The use of data integration and analytics for automating the tracking of programme delivery should be considered widely by ESB Networks for other work programmes.
4. The solution specification was centred on minimising the material cost of the sensor plus the installation costs. Every effort was made to make the installation safe, easy, and efficient to carry out. An incremental increase in the cost of the sensor itself (such as the addition of magnetic attachments) has a big saving on the overall cost as it improves productivity of the installations. To this end, a possible enhancement would be to investigate sensor location

functionality (e.g. GPS), so that the sensor can be installed on any asset at any part of its lifetime, and for the central data monitoring team to be able to automate the tagging of the sensor to the correct asset, avoiding human error by the installation technicians.

5. Most installations can be done live by the installation technicians hence avoiding outages and inconvenience to our customers. The only installations which require outages are pole mounted transformer with more than 2 LV outlets. This is because the common point at LV is at the LV bushings of the transformer, which is within the proximity zone for both the MV and LV conductors. It was determined that this work cannot be done safely using live working procedures.

Future ESB Networks Specification of MV/LV Transformers

As mentioned in section 4, Kyte Powertech studied a 400kVA mineral oil transformer. The following findings were recommended;

1. The expected loading profile of LCT is cyclic in nature, and so particular attention should be given to the transformer tank withstand. Cyclic loading on the tank due to expansion and contraction of cooling oil generates fatigue type stresses on welded corners and cracks occur earlier than static loads. Kyte Powertech tested a number of tanks in 2020 for this purpose and found some limiting pressures. As such, ESB Networks should consider including in the technical specification for MV/LV transformers that manufacturers should validate their designs with fatigue tests. (EN 50464-4 can be followed).
2. Critical components for current carrying capability are risers, foil, wire, tap changer, HV and LV internal connections and LV and HV bushings. Heavy current density on these components should not be allowed, and the DSO should specify minimum acceptable limits in future technical specifications. For instance, 2.35A/mm^2 for Alu and 4.3A/mm^2 for Cu components during max overloading. Tier-2 helps to ensure that wire and foil current densities are low but other components should also be considered in the design stage. For bushings, supplier recommendation should be sought for critical cases. Preferably, high temperature resistant gaskets are good practice for critical equipment like bushings to ensure that gaskets will not be relaxed due to thermal cyclic effects and not aged.
3. Due to cyclic load expectancy, top oil should be limited to 115°C for O class oils following IEC 60076-7. For K class, IEC 60076-14 Annex-C recommendations can be followed. Hot-spot temperature is also critical in that transformers should be designed to prevent bubbling. Hot-spot limit of 130°C is acceptable for O class and 140°C for K class considering that transformers are integrally filled. No free-breathing or gas cushion transformers should be accepted (some manufacturers can recommend this due to fatigue test requirement, but it should be noted that cyclic load on gas cushioned units can cause partial discharge generation due to dissolved gasses and will jeopardise ageing parameters due to presence of oxygen for instance).
4. The neutral terminal (cable size and components integral to the transformer) should be double the size of the phase. IEEE standards advise as such also. This is to protect against the triplet harmonics (3rd, 9th, 15th, etc.) that flow through the neutral.
5. Smaller laminate thickness was discussed as a mitigation option for reducing eddy losses in the core: The standard laminate thickness is 0.23mm currently, however 0.2mm and 0.18mm options were explored previously by Kyte Powertech. The supply chain for this material is such that supply for the latter material is not reliable, and in general, manufacturers prefer to manufacture the 0.23mm thickness laminate.
6. The industry is trending towards using biodegradable oil in the long term. Consideration should be given to specifying the use of same with Nomex910 thermal paper going forward. Such designs would have a better temperature tolerance and can operate at higher temperatures without loss of life, when compared to conventional Kraft paper insulation.

7. If the flux density of the transformer is close to saturation, it could damage inverter technology connected to the LV network downstream. Consideration should be given to specifying the maximum flux density allowed.
8. Consideration should be given to including a low cost IoT sensor as part of the technical specification for ground mounted MV/LV transformers, or alternatively, including a provision in unit sub enclosures for installation of a PUK antenna if desired.

Other utility use-cases for IoT

The project has demonstrated how to implement an IoT solution which is scalable and low-cost. ESB Networks and other utilities could look at other use cases where low cost LPWAN type sensors might play a role in providing reliable low carbon electricity to customers. For example, five of these monitors were successfully trialled by another team on HV cable sheath bonding leads to measure circulating current. The design of the monitor is flexible in that the temperature probe can be swapped out for a moisture sensor if required.

Validation of Smart Meter Data Transformer Overload Use Case

Once the GDPR issues with smart meter are addressed, a study could be done to compare the "bottoms-up" aggregation of interval data from Smart Meters with the load from the sensors deployed to the corresponding transformers. The analysis could include a sensitivity study on the minimum penetration of smart meters/actual data required to infer the transformer loading, amongst other studies.

6. FINAL TIMELINES

PO issued: July 2020
Sensor prototype design and build and proof of concept: September 2020
Heat rise test: September 2020
Field trial no.1: October 2020 – January 2021
Field trial no.2: January 2021 – December 2021

7. FINAL COSTS

The final project cost of €700,000 includes;

- ESB Networks Azure configuration
- Sensor hardware & use of Octopus platform (PaaS)
- Heat Rise test
- Deployment of circa 1,000 sensors for field trials
- Project team cost

8. NEXT STEPS – BAU / TRANSFER OF OWNERSHIP

The Electrification LV system development allowance team are using the data from the deployed sensors to identify constraints in the fleet of transformers. This data can then be extrapolated to other transformers in the fleet, with similar kWh loading profiles. Transformers will be identified for uprating based on a combination of the kWh readings and/or data from the sensors where deployed.

The National Networks Local Connections (NNLC) programme have a requirement to deploy a substantial number of LV monitors during PR5 in anticipation of flexibility services, and the learnings and recommendations from this trial will be disseminated in full to that programme.