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Distribution Asset Thermal Modelling

A Network Innovation Allowance Project

Closedown Report

September 2016

CONTENTS

GLOSSARY

Accelerated Thermal Ageing	The increase in ageing of the insulation system caused by increased in temperature. This can lead to failure in a long time, possibly years.
Bubbling	The creation of water bubbles in the paper and oil of transformers due to increased loading. This can lead to failure in a short time, possibly weeks and months.
Bubbling Inception Temperature	The temperature at which bubbling starts to occur.
DECC	Department of Energy and Climate Change (now called Department for Business, Energy and Industrial Strategy)
DNO	Distribution Network Operator
EV	Electric Vehicle
FEA	Finite Element Analysis
Hot Spot Temperature	The hottest point within the transformer under rated load.
IFI	Innovation Funding Incentive
IEC	International Electrotechnical Committee. An international standards organisation.
LCT	Low Carbon Technologies
LV	Low Voltage
Probability of Failure (PoF)	The probability of the hot-spot temperature exceeding the bubbling inception temperature.
PV	Photovoltaic. Commonly used acronym for solar generation
RMS	Root Mean Squared

VERSION HISTORY

Version	Date	Author	Status	Comments
1	28/09/16	G Bryson	Issued	

REVIEW

Name	Role	Date
A Howard	Programme Manager	04 October 2016
D Randles	Network Performance and Innovation Manager	04 October 2016
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APPROVAL

Name	Role	Date
Steve Cox	Head of Network Engineering	

1 EXECUTIVE SUMMARY

1.1 Aims

This research project investigated the effects that low carbon technologies such as Photovoltaic generation and Electric Vehicles have on the thermal ratings of low voltage cables and transformers. The project looked at the probability of failure of distribution transformers to these increased loads and the capability of cables to carry more capacity.

1.2 Methodology

The project was run as two independent streams both being carried out by the University of Manchester.

For transformers an assessment strategy was proposed which considered the hot spot temperatures and bubbling inception temperatures to devise a probability of failure. This method takes into account both the short term failures created by sudden changes in load and the longer term degradation. The assessment strategy was used to assess the probability of failure of a number of distribution transformers selected from the Electricity North West population. This assessment was performed for three uptake scenarios – business as usual, high range and extreme range. The application of this assessment strategy was formalised into an Excel database and associated user guide which can be used to assess other transformers.

For cables the university created a Finite Element Analysis (FEA) model of the cable and surrounding medium. The model was subjected to a number of numerical experiments in order to better understand the dynamic thermal behaviour of the underground cable and the impact of various environmental factors such as moisture content in the soil and seasonal changes in ambient temperature. A simple to use low-voltage cable thermal modelling tool, LV-TM, was developed in Microsoft Excel format using the FEA model as a basis. This simplified model allows a user to specify initial cable loading and the step change in the cable current as well as the ambient temperature in order to observe cable temperature time-profiles for three different soil moisture content levels.

1.3 Outcomes

The project has produced two easy to use excel based models; one for distribution transformers and one for low voltage cables.

The transformer model requires inputs such as EV penetration level, transformer rating, transformer age and customer numbers. The model will produce a probability of failure, a predicted loss of life and an expected lifetime. This will allow Network Operators to assess if an asset can cope with the additional demand or requires reinforcement.

The low-voltage cable model, LV-TM, allows a user to specify initial cable loading and the step change in the cable current as well as the ambient temperature in order to observe cable temperature time-profiles for three different soil moisture content levels.

1.4 Key Learning

The assessment of a selection of distribution transformers showed that EV charging has less effect on the acceleration of thermal ageing and the reduction of transformer lifetime than the immediate failure due to bubbling, since the peak load and hot-spot temperature will be compensated by the low values during the off-peak time and eventually lead to a moderate ageing. The probability of failure is affected by three factors including transformer age, peak load and installation condition where the peak load is found to be the dominant factor.

Simulation results demonstrated the ability of the LV cable used in the model to sustain short-term pulses of high-amplitude phase currents without exceeding the thermal constraint. The key observation from the simulations was that moisture in the soil had a significant impact on the thermal behaviour of the cable. In particular, dry soil conditions significantly increased the temperature experienced inside the cable and therefore reduced the current carrying capacity of the cable.

1.5 Conclusions

The project has successfully developed models to assess distribution transformers' and low voltage cables' capability to accept increased loads from low carbon technologies. Electricity North West will use the outputs from this project as a fundamental building block in developing the "Thermal Ratings Tool" as part of the Network Innovation Competition project, Celsius. The outputs from Celsius will redefine the transformer and cable ratings used by Electricity North West.

1.6 Closedown Reporting

This Network Innovation Allowance project is compliant with the associated governance and this closedown report is structured to meet these governance requirements whilst also providing additional information we believe useful in understanding the project. A version of this report is available via the Smarter Network learning portal which reflected the ordering in the portal and the summaries provided in sections 7 and 8.

2 PROJECT FUNDAMENTALS

Title	Distribution Asset Thermal Modelling
Project Reference	NIA_ENWL002
Funding Licensee(s)	Electricity North West
Project Start Date	July 2015
Project Duration	18 Months
Nominated Project Contact(s)	Geraldine Bryson (geraldine.bryson@enwl.co.uk)

3 PROJECT BACKGROUND

One of the key challenges facing DNOs today is a significant change in loading on LV networks from increased penetrations of Low Carbon Technologies (LCTs). The DECC projections for Electric Vehicle and Heat Pump uptake will lead to a marked increase in the daily peak demand placed on LV networks and combined with the observed increase in generation from domestic PV result in the potential for a significant change in the manner LV networks are utilised. These changes have the potential to significantly alter the existing power flows, which is expected to increase instances of distribution asset thermal overload risking premature ageing introduced by higher operating temperatures and potential asset failures particularly for transformers where resultant hotspots lead to a loss of insulation oil. The forecasted change in the utilisation of distribution assets is contrasted with the limited understanding of the behaviour and performance and their potential to accept increased loadings whilst achieving the expected economic lifetime.

A greater understanding of the thermal behaviour exhibited by distribution assets could be used by DNOs to maximise their lifetime by applying new understanding to network design, maintenance and asset management procedures.

This project is being raised to complete work on two projects raised under IFI funding; "Distribution Transformer Real Time Thermal Ratings" and "Dynamic Thermal Analysis of Low Voltage Underground Cables."

The project will be split into two distinct methods:

1. Building upon work already completed within the IFI project, a thermal failure model for distribution transformers will be developed taking into account load profiles, transformer manufacturers, designs and ageing conditions. This model can then be used to categorise the DNOs distribution transformer population and identify those types which have an increased probability of failure associated with future loadings scenarios.
2. A prototype network design tool for LV cables using high fidelity Finite Element Analysis (FEA) models will be developed. This tool will assist in establishing how LV cables behave thermally over time when either balanced or unbalanced currents are applied and will provide DNOs with access to a catalogue of simplified thermal models that reflect typical installation scenarios. These models can be used by DNOs to help support network investment planning activities.

4 PROJECT SCOPE

The project will cover all common types of distribution (11kV or 6.6kV to 415V) transformers and low voltage (415V) cables installed by Electricity North West.

5 OBJECTIVES

- To develop a Thermal Failure Model for distribution transformers

- To develop an LV cable network design tool based on thermal models of typical installation scenarios.

6 SUCCESS CRITERIA

- A database which describes a distribution transformer's thermal performance and probability of failure under different loading scenarios which can be used to project future investment plans

- An Excel-based network design tool for LV cables which will use predefined inputs and FEA models to produce a maximum and minimum operating temperature envelope which can be used to demonstrate whether the cable can accept new LCTs.

7 PERFORMANCE COMPARED TO THE ORIGINAL PROJECT AIMS, OBJECTIVES AND SUCCESS CRITERIA

7.1 Summary for Portal

The University of Manchester proposed an assessment strategy to assess the adaptability of the distribution transformer population to new loads such as Electric Vehicle charging. The strategy contains two parts – thermal modelling and thermal failure modelling. Thermal modelling estimates the hot-spot temperature of individual distribution transformers and thermal failure modelling defines and quantifies the short term failure probability. The assessment strategy requires input data including transformer age and rating, installation condition (indoor/outdoor), customer information (number and type), ambient temperature, thermal parameters and EV penetration levels. The outputs are yearly loss-of-life, expected lifetime and probability of failure (PoF).

The IEC loading guide provides a set of values of the thermal parameters for distribution transformers. This research proposed two new methods for refining these thermal parameters: curve-fitting and calculating.

Electricity North West purchased and installed distribution transformers with fibre optics installed to enable measurement of the hot spot temperatures. The hot spot temperatures were calculated using the three methods (IEC, curve fitting and calculating) and compared with the measurements under cyclic loads.

The increased loads caused by electric vehicle charging may cause the failure of transformers due to bubbling, which decreases the dielectric strength of the transformer insulation system eventually leading to breakdown. Bubbling is triggered by temperature; therefore the bubbling inception temperature is regarded as the critical hot-spot temperature to be avoided. In order to investigate the effect electric vehicle charging has on distribution transformers, PoF due to bubbling under the different scenarios was modelled. The PoF is defined as the probability of the hot-spot temperature exceeding the bubbling inception temperature.

The strategy was used to assess the probability of failure of 150 distribution transformer under three electric vehicle uptake scenarios:

- business as usual (0% penetration),
- high range (32% penetration) and
- extreme range (58.9% penetration).

A high-fidelity dynamic thermal model, using Finite Element Analysis (FEA), of an underground LV cable was developed by the University of Manchester.

In the context of thermal modelling of the underground cable FEA breaks down the spatial representation of a system into a large number of small, ideally infinitesimal, regions, denoted as nodes, each of which exchanges heat with the adjacent nodes through mutual thermal resistance and each of the nodes having associated with them thermal capacity.

To create a FEA model a two dimensional cross-sectional drawing of a cable was created and then placed inside the square shaped area representing the surrounding medium. The drawing was then imported into the software package and each of its objects allocated the material properties of the component that they represent. A mesh was then defined which represents an interconnected network of individual nodes

An electrical model was used to determine the phase current profiles to be used as inputs to the thermal model in order to calculate temporal variation of temperature in the cable. Simulations were executed by specifying the duration, time step size and the inputs for all variables, including the phase current and ambient temperature, at every time step. The FEA model then computes the temperature time-profile for each of the nodes.

Using FEA analysis as described above can be unwieldy, therefore a simple to use low-voltage cable thermal modelling tool, referred to here as LV-TM, was developed. LV-TM is based on relatively simple algebraic expressions relating ambient temperature, initial load and step change in load to the maximum temperature reached inside the cable at specific time increments, after a step change in the load is applied.

The current version of LV-TM considers a particular type of cable current profile, which is a constant amplitude step/pulse preceded by constant initial current, and it assumes user-specified constant ambient temperature. The LV-TM tool computes estimates of cable temperature for each of the three specific soil moisture contents levels (dry, regular and wet). LV-TM provides a useful initial version of an easy-to-use thermal modelling tool, which is implemented in Microsoft Excel and allows an engineer to evaluate the impact of various step/pulse changes in the cable loading and the impact they have on the cable temperature.

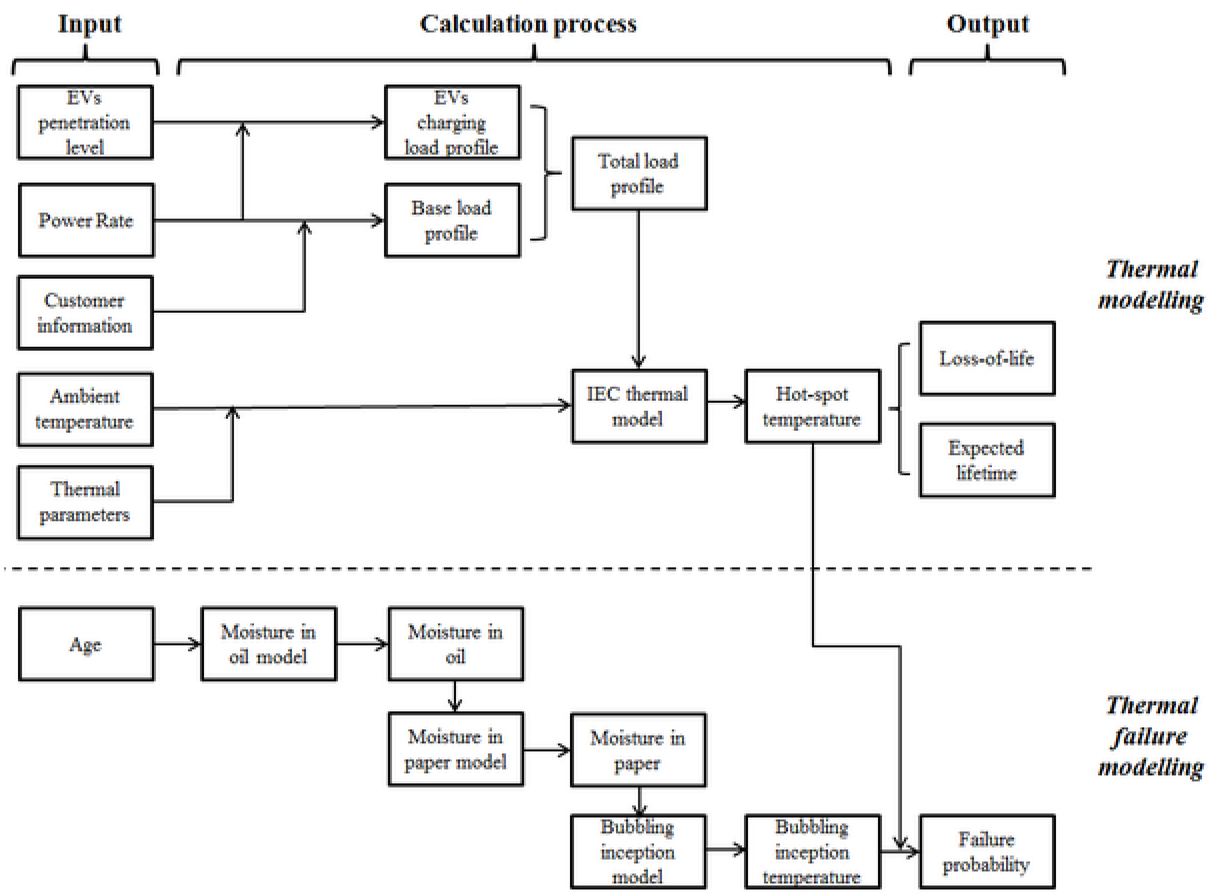
The methodology that is used to develop this tool can be extended to other cable types and/or feeder arrangements in the future. Additionally, LV-TM can be extended to other time-varying load and ambient temperature profiles as well as different types of soil and levels of soil moisture content.

Full details of this development work can be found in the closedown report on the Electricity North West website.

7.2 Transformer Modelling

In order to assess the adaptability of the distribution transformer population, a systematic strategy (Figure 1) was proposed by the University of Manchester. Full details of the strategy and its application can be found in Appendix 1.

Figure 1 - Detailed diagram of assessment strategy

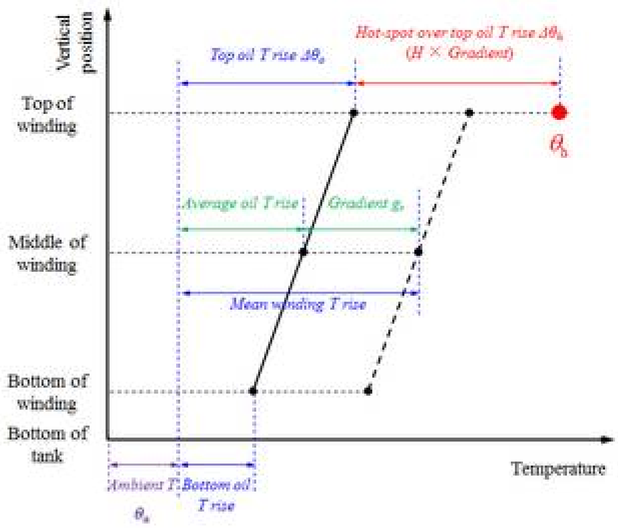


The strategy contains two parts – thermal modelling and thermal failure modelling. Thermal modelling estimates the hot-spot temperatures of individual distribution transformers, which are essential to calculate the loss-of-life and lifetime. Thermal failure modelling defines and quantifies the short term failure probability of distribution transformers under a number of Electric Vehicle (EV) uptake scenarios. The assessment strategy requires input data including transformer age and rating, installation condition (indoor/outdoor), customer information (number and type), ambient temperature, thermal parameters and EV penetration levels as defined by the EV uptake scenarios. The final outputs are yearly loss-of-life, expected lifetime and PoF.

7.2.1 Determination of Hot Spot Temperature

Hot spot temperature can be regarded as a function of the load. However, under the same load profile different transformers will have different hot spot temperature profiles. IEC 60076-7 (IEC loading guide) provides a set of thermal functions based on the thermal diagram shown in figure 2.

Figure 2 – IEC Thermal Diagram



The IEC loading guide provides a set of values of the thermal parameters for distribution transformers (table 1), which are considered conservative and lead to an over-estimated hot-spot temperature. In order to obtain more accurate hot-spot temperature by taking consideration of individual differences in designs, these parameters should be refined for individual transformers. In this work, methods were proposed and validated for the refinement of the thermal parameters for individual transformers.

The research proposed two methods for refining the thermal parameters: curve-fitting and calculating. The curve fitting method uses measured hot spot and top oil temperatures obtained from extended heat run tests; for the extended tests heat runs are carried out at different loadings (0.7, 1.0 and 1.25). The calculating method uses the measurements from a standard heat run test.

A comparison of the thermal parameters defined in the IEC loading guide and those obtained by the two methods is shown in table 1.

Table 1: Comparison of the Thermal Parameters

	$\Delta\theta_{or}$	R	$H \times g_r$	x	y	τ_o	τ_w	k_{11}	k_{21}	k_{22}
IEC	60	9	16.36	1.1	0.8	1.60	180	4	1	1
Curve-fitting	56.2	8.67	8.44	0.72	1.08	180	21.7	1.18	2.83	0.91
Calculating	50.4	8.67	14.5	0.77	2.39	159.6	11.3	1.26	1	2

Electricity North West purchased and installed distribution transformers with fibre optics installed to enable measurement of the hot spot temperatures. The hot spot temperatures were calculated using the three methods (IEC, curve fitting and calculating) and compared with the measurements under cyclic loads.

The results of this comparison are shown in figure 3 and table 2.

Figure 3 – Comparison of measured hot spot temperature with those obtained by the three methods

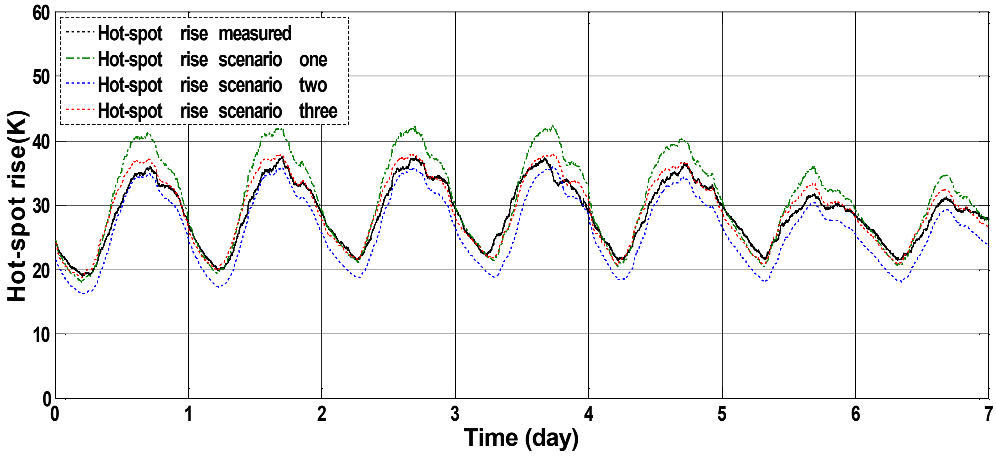


Table 2: Error analysis of the hot spot temperatures

Refinement method	Maximum error (K)	Mean error (K)
Curve-fitting	4.16	0.40
Calculating	-7.40	-2.38
IEC	8.15	3.58

The error analysis in table 2 shows that the maximum error is reduced from 8.15 K to 4.16 K with the curve-fitting method and -7.40 K with the calculating method. The mean error is almost eliminated by using the curve-fitted parameters. Therefore, the curve-fitted method is preferred to refine thermal parameters when predicting hot-spot temperatures under dynamic loads but it is understood that the calculating method would be more widely applicable to the distribution transformer population.

7.2.2 Determination of Probability of Failure

Increased loads caused by electric vehicle charging may cause the failure of transformers due to bubbling, which decreases the dielectric strength of the transformer insulation system eventually leading to breakdown. Bubbling is triggered by temperature; therefore the bubbling inception temperature is regarded as the critical hot-spot temperature to be avoided. For example, 140 °C is stated in IEC loading guide as the hot-spot temperature limit for distribution transformers under normal cyclic loads due to the concerns over bubbling.

In order to investigate the effect electric vehicle charging has on distribution transformers, PoF due to bubbling under the different scenarios was modelled. The PoF is defined as the probability of the hot-spot temperature exceeding the bubbling inception temperature.

Research has shown that the bubbling inception temperature is dominantly controlled by the moisture level in the paper. Due to this domination it is essential to model the moisture content in the paper. As it is difficult to sample the papers and measure the moisture content in operational transformers equilibrium curves have been developed to allow the moisture content to be estimated.

With the equilibrium curves the moisture in the paper can be determined and applied in the bubbling inception model to calculate the inception temperature and compare with the hot spot temperature of the transformer to determine if the transformer will fail.

7.2.3 Electric Vehicle Scenarios and Modelling

Three electric vehicle uptake scenarios were investigated business as usual (0% penetration), high range (32% penetration) and extreme range (58.9% penetration). When modelling the charging load the numbers of vehicles are determined by multiplying the penetration level by the number of customers connected to the transformer.

In order to simulate the charging load, a stochastic approach is used, which models vehicle types, charging power, charging start time and state of charge transferred to the battery.

Based on a statistical analysis of the available technologies and usage this work used:

- Vehicle types: 50% Nissan Leaf and 50% Mitsubishi Outlander
- Charging power: 70% 7kW and 30% 3kW with a charging efficiency of 85%
- Charging start time: follows a normal distribution curve with a mean of 18:30 and a standard deviation of 1 hour.
- State of charge: all vehicles are charged once a day and always charged until full.

7.2.4 Assessment of distribution transformer population

The strategy described above was used to assess the PoF of 150 distribution transformers selected from the Electricity North West population.

7.3 Cable Modelling

The main critique of the thermal rating methods currently used is that they mostly ignore the presence of thermal inertia which may have significant impact, particularly during normal but possibly significant temporal variations in the load. This has become particularly relevant in recent years with the introduction of low-carbon technology loads, such as electric vehicles and heat pumps, which may cause significant changes in temporal variation of load patterns experienced by the low voltage underground cables. Therefore, it becomes important to more thoroughly understand how the cable current affects its temperature for various scenarios.

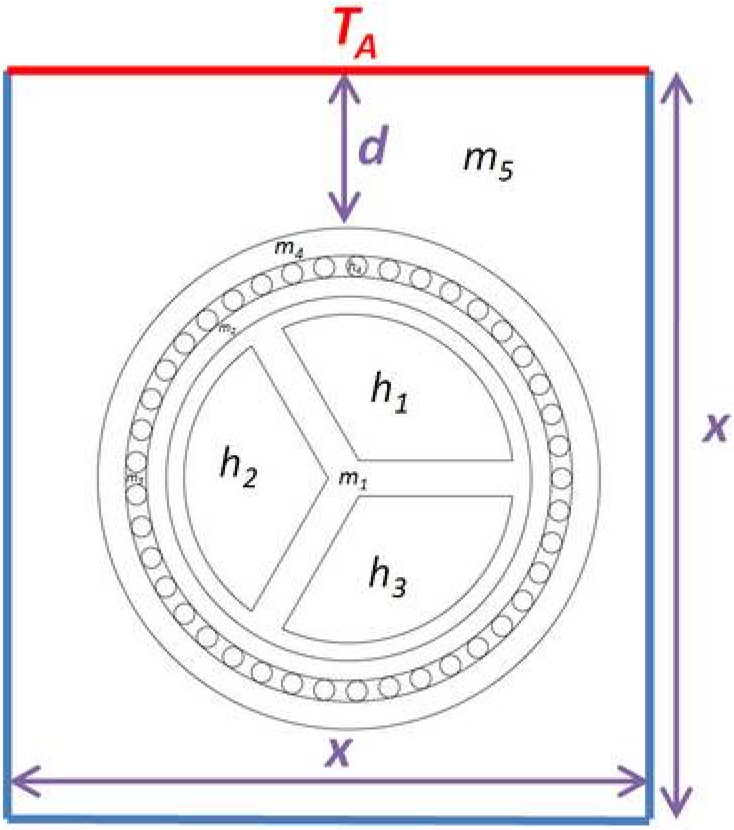
In order to understand and then fully exploit the presence of thermal inertia, a high-fidelity dynamic thermal model of the underground LV cable was developed by the University of Manchester; further details are provided in appendix 2.

In the context of thermal modelling of the underground cable, Finite Element Analysis (FEA) breaks down the spatial representation of a system into a large number of small, ideally infinitesimal, regions, denoted as nodes, each of which exchanges heat with the adjacent nodes through mutual thermal resistance and each of the nodes having associated with them thermal capacity.

To create a FEA model a two dimensional cross-sectional drawing of a cable is created and then placed inside the square shaped area representing the surrounding medium, e.g. soil. Within the drawing, each unique feature which could be a conductor or a concentric insulator layer inside the cable or the surrounding medium is represented as an individual object.

Figure 4 contains an example of a labelled drawing used to create the model for and LV cable placed in a square shaped area which represents the surrounding medium. Each unique object in the figure is labelled using either an *h* or an *m* to denote a heat source or a physical material respectively. The red line in the figure is used to indicate that the ground surface is modelled as a temperature source, denoted as T_A, and represents the ambient ground surface temperature. The blue lines represent the surfaces that are modelled as thermal insulators.

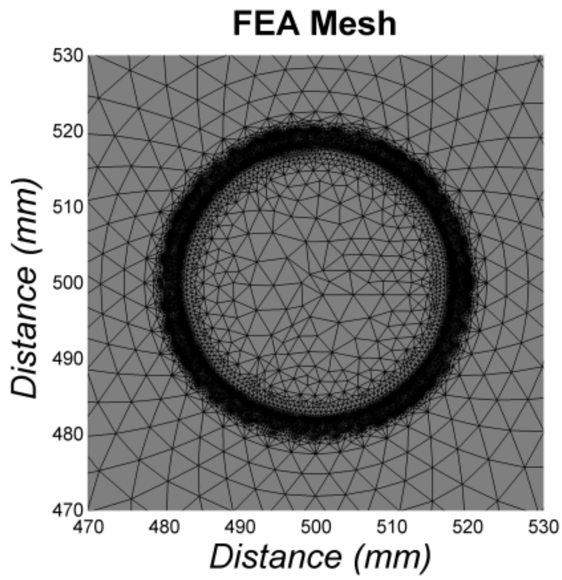
Figure 4: Cross sectional view of an LV cable in a surrounding medium



The drawing is then imported into the software package and each of its objects is allocated the material properties of the component that they represent.

A mesh is then defined which represents an interconnected network of individual nodes and the example for an LV cable is shown in Figure 5.

Figure 5: FEA Model Mesh of an LV Cable



An electrical model was used to determine the phase current profiles to be used as inputs to the thermal model in order to calculate temporal variation of temperature in the cable.

Simulations were executed by specifying the duration, time step size and the inputs for all variables, including the phase current and ambient temperature, at every time step.

The FEA model computes the temperature time-profile for each of the nodes. The amount of data produced can easily become overwhelming and unmanageable. In order to address this issue the nodes are grouped into the layers. Then for each layer at every sampling instant both the maximum and the minimum temperature, found across all the nodes belonging to that particular layer, are identified and stored.

Using FEA analysis as described above can be unwieldy, therefore a simple to use low-voltage cable thermal modelling tool, referred to here as LV-TM, was developed (Appendix 3). LV-TM is based on relatively simple algebraic expressions relating ambient temperature, initial load and step change in load to the maximum temperature reached inside the cable at specific time increments, after a step change in the load is applied.

The current version of LV-TM considers a particular type of cable current profile, which is a constant amplitude step/pulse preceded by constant initial current, and it assumes user-specified constant ambient temperature. In its current form the LV-TM tool computes estimates of cable temperature for each of the three specific soil moisture contents levels, which are ‘dry’, ‘regular’ and ‘wet’. LV-TM provides a useful initial version of an easy-to-use thermal modelling tool, which is implemented in Microsoft Excel, which allows an engineer to evaluate the impact of various step/pulse changes in the cable loading and the impact they have on the cable temperature.

The methodology that is used to develop this tool can be extended to other cable types and/or feeder arrangements in the future. Additionally, LV-TM can be extended to other time-varying load and ambient temperature profiles as well as different types of soil and levels of soil moisture content.

8 THE OUTCOME OF THE PROJECT

8.1 Summary for Portal

The strategy described above was used to assess the PoF of a number of distribution transformers.

The results showed that EV charging has less effect on the acceleration of thermal ageing and the reduction of transformer lifetime than the immediate failure due to bubbling, since the peak load and hot-spot temperature will be compensated by the low values during the off-peak time and eventually lead to a moderate ageing even under high EV penetration such as Extreme-range scenario.

The PoF is affected by three factors including transformer age, peak load and installation condition where the peak load is found to be the dominant factor.

The application of this assessment strategy was formalised into an Excel database and associated user guide which can be used to assess other transformers. The excel model requires the following inputs:

- EV penetration level in percentage format.
- Power rating in kVA
- Age
- Whether the transformer is installed indoor or outdoor installation
- Customer number of each profile class from PC1 to PC8.

The model will produce the PoF, the loss-of-life and expected lifetime.

An LV cable was modelled using a high-fidelity Finite Element Analysis approach. The model was subjected to a number of numerical experiments in order to better understand the dynamic thermal behaviour of the underground cable and the impact of various environmental factors such as moisture content in the soil and seasonal changes in ambient temperature

Simulation results demonstrated the ability of the LV cable to sustain short-term pulses of high-amplitude phase currents without exceeding the thermal constraint. The key observation was that the moisture in the soil had a significant impact on the thermal behaviour of the cable. In particular, dry soil conditions significantly increased the temperature experienced inside the cable and therefore reduced the current carrying capacity of the cable

A simple to use low-voltage cable thermal modelling tool, LV-TM, was developed in Microsoft Excel format. This simplified model allows a user to specify initial cable loading and the step change in the cable current as well as the ambient temperature in order to observe cable temperature time-profiles for three different soil moisture content levels. The methodology used to develop this tool can be extended to other cable types and/or feeder arrangements in the future. Additionally, LV-TM can be extended to other time-varying load and ambient temperature profiles as well as different types of soil and levels of soil moisture content.

Full details of the results can be found in the closedown report on the Electricity North West website.

8.2 Transformer Modelling

The strategy described in section 7.2 was used to assess the PoF of a sample of 150 distribution transformers.

To investigate the loss of life under the different scenarios, Monte-Carlo simulations were conducted on the transformers so that the randomness of EV uptake was taken into account. Results of the load, hot-spot temperature and loss-of-life from all repetitions are averaged and presented as the final result for each transformer. A statistical analysis of yearly RMS and peak loads under the three EV uptake scenarios is presented in table 3, which shows the percentages of the sample of transformers in the different load ranges.

Table 3: Percentage of transformers in different load ranges under three EV uptake scenarios

RMS load (p.u.)	**0 - 0.3**	**0.3 – 0.6**	**0.6 – 0.9**
BAU scenario	46%	51.3%	2.7%
High-range scenario	34.7%	59.3%	6%
Extreme-range scenario	28.7%	56%	15.3%
Peak load (p.u.)	**0 - 1.0**	**1.0 - 2.0**	**2.0 - 3.0**
BAU scenario	98%	2%	0
High-range scenario	58%	41.3%	0.7%
Extreme-range scenario	30%	57.3%	12.7%

The number of overloaded transformers is increasing with the penetration of EVs, depending on the penetration level the peak load can be doubled or tripled. Since the high peak load is compensated by the low load values during a day, the RMS load does not increase as much as the peak load.

A similar analysis of hot-spot temperatures under three EV scenarios is presented in Table 4. It can be seen the peak hot-spot temperature is significantly influenced by EV penetration.

Table 4: Percentage of transformers in different hot spot temperature ranges under three EV uptake scenarios

Mean hot-spot temperature (°C)	**6 - 40**	**40 - 60**	**60 - 80**
BAU scenario	76%	24%	0
High-range scenario	61.3%	37.3%	1.4%
Extreme-range scenario	48.7%	47.3%	4%

Peak hot-spot temperature (°C)	**0 - 60**	**60 - 120**	**120 - 180**	**180 - 240**
BAU scenario	85.3%	14.7%	0	0
High-range scenario	43.3%	52.7%	4%	0
Extreme-range scenario	20.7%	52%	24%	3.3%

The results show that even though the peak hot-spot temperature can go up to 230°C the highest mean value is only 72°C. Since the peak temperature only lasts for few hours during a day, it may contribute less to the yearly loss-of-life than the mean temperature. Therefore, the dominant value will be the yearly mean hot-spot temperature in terms of yearly loss-of-life, and EV charging only poses a limited impact on it.

It may be concluded that EV charging has less effect on the acceleration of thermal ageing and the reduction of transformer lifetime than the immediate failure due to bubbling, since the peak load and hot-spot temperature will be compensated by the low values during the off-peak time and eventually lead to a moderate ageing even under high EV penetration such as Extreme-range scenario.

Short term risks for distribution transformers under the different scenarios are essentially due to bubbling. Bubbling inception temperatures are decreasing with transformer age due to the accumulation of moisture in paper. For young transformers, the bubbling inception temperature is around 120°C; while for transformers over 50 years old, it can be lower than 100°C. If a PoF of over 50% is defined as “high risk” the number of transformers in high risk under each EV scenario is presented in table 5.

Table 5: Number of transformers (from the 150 sample size) with PoF over 50%

EV scenario		**BAU**		**High-range**		**Extreme-range**	
Indoor/outdoor installation		*Indoor*	*Outdoor*	*Indoor*	*Outdoor*	*Indoor*	*Outdoor*
Age group	*0 – 20 years*	0	0	2	4	6	7
	20 – 40 years	0	0	4	5	7	12
	40 – 60 years	0	0	6	1	15	6
	Total	0	0	11	10	28	25

Under the High-range scenario, only 21 out of 150 transformers are in high risk equivalent to 14%. Whilst under the Extreme-range scenario, 53 transformers or 35.4% are categorised as high risk.

Investigation of PoF under the three EV scenarios has shown:

- Under BAU scenario no transformers are categorised as high risk.
- Under High-range scenario 14% of the transformer assessed are categorised as high risk, and
- Under Extreme-range scenario this percentage will increase to 35.4% of the transformer assessed are categorised as high risk.

The PoF is affected by three factors including transformer age, peak load and installation condition where the peak load is found to be the dominant factor.

The application of this assessment strategy was formalised into an Excel database and associated user guide (Appendices 4 and 5) which can be used to assess other transformers. The Excel model requires the following inputs:

- EV penetration level in percentage format.
- Power rating in kVA
- Age
- Whether the transformer is installed indoor or outdoor installation
- Customer number of each profile class from PC1 to PC8.

The model will produce the probability of failure, the loss-of-life and expected lifetime.

8.3 Cable Modelling

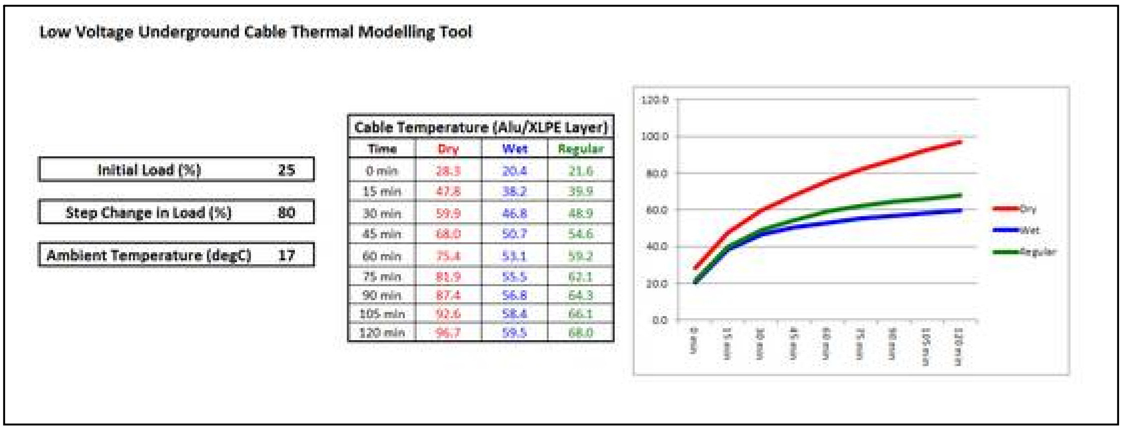
An LV cable was modelled using a high-fidelity Finite Element Analysis approach. The model was subjected to a number of numerical experiments in order to better understand the dynamic thermal behaviour of the underground cable and the impact of various environmental factors such as moisture content in the soil and seasonal changes in ambient temperature. Details of these experiments can be found in Appendix 2.

Simulation results demonstrated the ability of the LV cable to sustain short-term pulses of high-amplitude phase currents without exceeding the thermal constraint. The key observation from these numerous simulations was that the moisture in the soil had a significant impact on the thermal behaviour of the cable. In particular, dry soil conditions significantly increased the temperature experienced inside the cable and therefore reduced the current carrying capacity of the cable. On the other hand, wet soil conditions lowered the temperature and allowed high levels of increased current to flow through the cable without breaching the thermal constraint. Whilst soil moisture content had a significant impact on the cable temperature, the impact of seasonal changes on ambient temperature had a much smaller, linear and directly proportional impact on the cable temperature. In fact, average ambient temperature difference between seasons was replicated in the seasonal temperature difference inside the cable.

A simple to use low-voltage cable thermal modelling tool, LV-TM, was developed in Microsoft Excel format. Appendices 3 and 6 contain the model and associated user guide. This simplified model allows a user to specify initial cable loading and the step change in the cable current as well as the ambient temperature in order to observe cable temperature time-profiles for three different soil moisture content levels.

A screenshot of the LV-TM tool is provided in figure 6.

Figure 6: Graphical User interface of the LV-TM Tool



The methodology used to develop this tool can be extended to other cable types and/or feeder arrangements in the future. Additionally, LV-TM can be extended to other time-varying load and ambient temperature profiles as well as different types of soil and levels of soil moisture content.

9 REQUIRED MODIFICATIONS TO THE PLANNED APPROACH DURING THE COURSE OF THE PROJECT

There were no required modifications to the planned approach. Work progressed well and the project completed ahead of schedule.

10 VARIANCE IN COSTS AND BENEFITS

10.1 Cost variance

The original project was £260k. The project has been delivered to within 10% of budget, with a final cost of the project of £253k. The main cost variance was in installation of the transformers with fibre optics and this was due to combining this installation with ongoing capital works to minimise both disruption to customers and the overall cost.

Item	Category	Estimated Costs £k	Final Costs £k rounded	Variance
1	Project Management	15	15	-0.67%
2	Installation	35	30	-14.86%
3	Research Support – Transformer Modelling	80	80	-0.01%
4	Research Support – Cable Modelling	130	125	-3.74%
	Total	**260**	**250**	

10.2 Benefit variance

There is no benefit variance associated with this project as it successfully delivered on all the benefits predicted in the project registration.

11 LESSONS LEARNT FOR FUTURE PROJECTS

The project successfully developed two models which can be used to assess the capability of distribution transformers and low voltage cables to accept new low carbon technologies.

Using the models we assessed the capability of LV cables to accept new loads / generation and the probability of failure of distribution transformers with different uptakes of electric vehicles.

The assessment of a selection of distribution transformers showed that EV charging has less effect on the acceleration of thermal ageing and the reduction of transformer lifetime than the immediate failure due to bubbling, since the peak load and hot-spot temperature will be compensated by the low values during the off-peak time and eventually lead to a moderate ageing. The probability of failure is affected by three factors including transformer age, peak load and installation condition where the peak load is found to be the dominant factor.

Simulation results demonstrated the ability of the LV cable used in the model to sustain short-term pulses of high-amplitude phase currents without exceeding the thermal constraint. The key observation from the simulations was that moisture in the soil had a significant impact on the thermal behaviour of the cable. In particular, dry soil conditions significantly increased the temperature experienced inside the cable and therefore reduced the current carrying capacity of the cable.

These models do have some limitations regarding the types of transformers and cables they can be applied to. Electricity North West intends to use the methodologies developed in this project as part of our Network Innovation Competition project, Celsius.

12 PLANNED IMPLEMENTATION

As stated previously, Electricity North West will implement the learning from this project through the Celsius project (www.enwl.co.uk/Celsius).

Celsius will use the learning from this project alongside outputs from monitoring equipment to develop a "Thermal Ratings Tool" which can be applied to all distribution transformers and low voltage cables.

The Distribution Asset Thermal Monitoring project is thus considered as a forerunner project enabling Celsius. The outputs from Celsius will redefine the transformer and cable ratings used by Electricity North West.

DNOs can utilise the models as part of their planning processes.

13 FACILITATE REPLICATION

The objective of this project was to investigate the thermal capability of distribution transformers and low voltage cables when new low carbon technologies are connected to the network.

As a direct outcome of this project Electricity North West has produced and made publicly available:

- The transformer thermal model and associated user guide, and
- The cable thermal model and associated user guide.

This information is contained both in this report and in the appendices and will be made available for download via the Electricity North West website. (www.enwl.co.uk/thefuture)

The reports from the University of Manchester provide details on the development of the models and their limitations. These reports will be made available on the Electricity North West website.

DNOs can use the reports and models to inform their own planning processes.

14 APPENDICES

Appendix 1	Thermal Monitoring and Thermodynamic Modelling of Distribution Transformers
Appendix 2	Dynamic Thermal Modelling of Low Voltage Underground Cables
Appendix 3	Cable Thermal Model
Appendix 4	Transformer Thermal Model
Appendix 5	Transformer Thermal Model User Guide
Appendix 6	Cable Thermal Model User Guide