NIA ENWL028

LV Predict

Closedown Report

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VERSION HISTORY

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REVIEW

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CONTENTS

GLOSSARY

Term	Description
BAU	Business as Usual
DFMEA	Design Failure Modes and Effects Analysis
DNO	Distribution Network Operator
EV	Electric Vehicle
GIS	Geographical Information System
HV	High Voltage
LCT	Low Carbon Technology
LV	Low Voltage
NaFIRS	National Fault and Interruption Reporting Scheme
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
OIP	Oil Impregnated Paper

1 EXECUTIVE SUMMARY

1.1 Aims

The Low Voltage (LV) Predict project aimed to develop a prototype predictive tool that can be used to predict the probability of underground LV network failure, in anticipation of widespread electrification of heating and transport placing increased demands on electricity network infrastructure. This tool can then be used to gain further understanding into factors contributing to underground LV network failure and could be used to inform proactive maintenance strategies.

1.2 Methodology

To understand how underground LV assets may fail, our project partners Fraser Nash and TNEI carried out an existing literature review, a review of LV network failure data, an operator workshop and a Design Failure Modes and Effects Analysis (DFMEA) study. This knowledge was used to create a probabilistic modelling framework schematic that illustrates the relationships between various parameters which impact the likelihood of LV network failure across the Electricity North West Ltd (ENWL) operating region.

1.3 Outcomes

By combining Physics-based and statistical modelling, a prototype probabilistic modelling framework has been created to simulate the probability of underground LV network failure.

1.4 Key learning

The results from a literature review, operator workshop, DFMEA, and the NaFIRS analysis indicate that thermal degradation (and subsequent water ingress) of the joint is the highest risk failure mode in low voltage cables and joints.

It is possible to build a probabilistic risk-based demand model for LV networks. These demand models can provide informed predictions on high quantiles of demand even with very little data, as the lack of data simply increases the demand uncertainty (and hence the asset risk).

A thermal model can be used to simulate ground temperatures and the cable heating effect when current flows through LV cables. For small customer groups with highly variable demand patterns, the thermal inertia of the cable has a big influence on the cable temperatures.

Peak cable temperature (and hence peak customer demand) has the greatest influence on thermal damage within the cable and joint.

The physical damage model appears to be most sensitive to changes in the cable conductor size and the number of customers, as well as the interaction between these parameters.

Estimates of remaining LV asset life must consider both the uncertainty associated with future damage but also uncertainty in the historical conditions (and therefore historical damage) the cable has experienced.

Remaining LV asset life can be predicted to varying degrees of degrees of accuracy and computational costs, with no single method that satisfies all requirements. The most effective evaluation method will need to be selected based on the priorities and requirements of future solutions.

1.5 Conclusions

The LV Predict project aimed to develop a prototype probabilistic modelling framework to simulate the probability of underground LV network failure. Physics-based and statistical modelling has been effectively combined to describe and model cable degradation processes in a realistic way while also accounting for uncertainties in a probabilistic framework. Further research and development is required fully develop interventions into Business as Usual (BAU) solutions.

1.6 Closedown reporting

This project was compliant with Network Innovation Allowance (NIA) governance and this report has been structured in accordance with those requirements.

This report and the associated documents are available via the Energy Networks Association's Smarter Networks learning portal at www.smarternetworks.org or via the Electricity North West website.

2 PROJECT FUNDAMENTALS

Title	Smart Heat
Project reference	NIA_ENWL028
Funding licensee(s)	Electricity North West Limited
Project start date	March 2022
Project duration	1 year
Nominated project contact(s)	InnovationTeam@enwl.co.uk

3 PROJECT BACKGROUND

Distribution Network Operators (DNOs) are responsible for the maintenance of the underground low voltage (LV) networks and assets in Great Britain. LV cables are subject to degradation due to various factors, including environmental conditions, the magnitude and shape of the demand profiles they supply, and the number of joints between components. This degradation will eventually lead to failure and interruptions to customer supply. The rates of degradation are widely expected to worsen due to the push for domestic customers to adopt low carbon technologies (LCTs) such as electric vehicles (EVs) and heat pumps as part of the transition to Net Zero. Their increasing presence on the LV networks is anticipated to lead to significant increases in peak demands and peak demand ramping rates in some areas, which will lead to more extreme temperature cycles for cables. The effect is likely to be more pronounced for some cables due to the tendency for the adoption of these LCTs to occur in clusters of close geographical proximity. The effect of more extreme conditions will be greater on older assets, which are already partially degraded by decades of use.

Electricity North West Limited (ENWL) plan to spend £14.3m between 2024 and 2028 to replace cables which are obsolete, over 75 years old, deemed likely to fail, or which may pose safety risks. Much of the academic research on electricity cable degradation focusses on high and medium voltage cables (1kV and higher voltages). This research cannot be readily applied to a low voltage network, as the primary driver for degradation in medium and high voltage cables is electrical-based degradation, which is unlikely to apply to LV cables.

18,000 km of the underground cables within ENWL's network have been in service for over 50 years. These older cables represent approximately 60% of the total length of cables in the ENWL network, some of which are of the 'oil impregnated paper' (OIP) type. OIP cables were phased out from the 1970s onwards and replaced by polymeric insulated cables. However, replacement of OIP cables is generally only carried out upon failure, as they can function well for many decades until an external factor initiates damage. This contrasts with newer extruded polymer cables, which generally fail once the outer sheath or insulation is damaged; allowing environmental factors (e.g. water) to initiate one of many degradation mechanisms.

A DNO may wish to address this issue by setting up a system of extensive monitoring of LV asset condition, given their duty of ensuring that cables are replaced before they are degraded enough as to present a high risk of failure. However, a widespread rollout of such an approach is not practical given the extremely large number of LV cables over which they have responsibility, the tight regulation of expenditure and the disruptive nature of physical inspections. As a result, in most cases DNOs tend to have very limited data about the usage and condition of their LV cables. There is, therefore, a need for a modelling approach that enables a DNO to assess the state of cable degradation accurately and quickly at a particular location, using easily accessible data. Such a model is essential for the formulation of targeted and judicious programs of inspection and replacement. Consequently, ENWL has commissioned Frazer Nash Consultancy (Frazer-Nash) and TNEI Services (TNEI) to research and develop a model.

This project will use various sources of data to feed into the model, including:

- Existing asset data (Cable type, age etc)
- NaFIRS failure data
- Weather (inc temperature, rainfall, seasonality and extreme weather events)
- Household density
- Third party intervention

4 PROJECT SCOPE

The aim of this project is to develop a prototype probabilistic modelling framework to simulate the probability of underground LV network failure. This will be based around the following tasks:

- Modelling framework development
- Modelling customer demand and cable temperatures
- Modelling LV Network degradation and remaining lifetime
- Interconnection of the models
- Potential further development of the models

5 OBJECTIVES

This project will provide a better understanding of failure modes of underground LV cables and create a modelling framework that can accurately predict the likelihood of failure from easily accessible data sources.

6 SUCCESS CRITERIA

Production of a report detailing:

- Development of a modelling framework
- Modelling customer demand and cable temperatures
- Physical modelling of LV network degradation
- Statistical modelling of LV network degradation

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

The full methodology for this work is detailed in the “LV Predict final report” produced by our partners, Frazer Nash and TNEI which is available on the ENWL website.

7.1 Development of a modelling framework

The modelling framework was developed with the goal of reliably predicting the when a cable was likely to fail. The following inputs/considerations were required for this process:

- Investigation of LV failure modes
- Constructing a database of all underground LV cables
- Outlining of modelling approach.

7.2 Modelling customer demand and cable temperature

The heating of underground cables due to the electrical currents required to flow through them is a major contribution to their degradation and eventual failure. Consequently, the pattern of required currents – i.e., the extreme peaks, the frequency and duration of flows that cause significant cable heating and the swings in temperature caused by extreme ramping up of current – is undoubtedly one of the main factors that influence the lifetime of a cable.

7.3 Physical modelling of LV Network degradation

To give a complete picture of the physical modelling of the LV network degradation and remaining lifetime, several techniques were used:

- Physical joint thermal stress modelling
- Physical joint damage modelling
- Physical modelling of other environmental factors
- Calculating remaining life using the physical model
- Overall sensitivity analysis of the physical damage model

7.4 Statistical modelling of LV network degradation

Two statistical models are used to predict cable damage as a function of temperatures, which are then applied to calculate the remaining lifetime of a cable.

- Statistical cable damage modelling
- Statistical life prediction modelling

8 THE OUTCOME OF THE PROJECT

The full results for this work is detailed in the “LV Predict Final Report” which is available on the ENWL website.

8.1 Development of a modelling framework

Investigation of LV failure modes

Three areas of research were investigated to determine the most material LV network failure modes:

- *Failure modes within the NaFIRs data* - It is helpful to distinguish between two key types of failures: (i) those caused by the condition of the cables (primary drivers), and (ii) those caused by external influences (secondary drivers). The NaFIRS data suggests that most failures are due to primary drivers. Degradation-based failure mechanisms are the most common, with transient fault mechanisms (i.e. sporadic faults that result in a temporary loss of transmission) the second most common. Transient faults could be caused by several different mechanisms, such as water ingress or by tripping circuit breakers in the system. It is noted that this is a symptom of failure rather than a cause of failure. The third and fourth most common types of failure are third-party intervention and corrosion respectively.

- *Learnings from in service experience* **-** In-service experience of the LV network was provided by ENWL via a workshop session. It was established through anecdotal experience that approximately 95% of LV network failures occur at the joints, with relatively few failures occurring in the cables themselves. Further anecdotal evidence suggests that a significant number of failures occur after a change in weather (for example several days after rainy periods start or at the start of a warmer period).

- *DFMEA* - A failure tree was developed by the project team, incorporating subject matter expertise from ENWL, the existing knowledge of the Frazer-Nash and TNEI project team, and findings from a literature review. It shows, for example, that the condition of joints and cables is dependent on mechanical interference and environmental damage, as well as the initial condition of the joint/cable and history of previous failures.

The data gathered from the workshop, DFMEA, and NaFIRS analysis suggests that third-party intervention and thermal degradation of the joint are the most likely leading failure mechanisms for the underground LV network. Thermal degradation of the joint filler material can lead to water ingress, which could also lead to transient faults and damage to the conductors. In the modelling, prioritisation is given to the simulation of thermal degradation of the joint (and potential subsequent water ingress), as these failure modes are degradation-based and can be modelled as physical processes, unlike third-party failure causes, where the human factors are much harder to anticipate and predict. Hence, this could provide the most value as the key part of a predictive maintenance tool.

Constructing a database of all underground LV cables

The database was created by feeding data from ENWL's GIS system into the "NetworkX Python" package to identify LV cable feeders, and the numbers of customers connected to each of them.

The basic approach has been to construct node and edge graphs of the LV cable system supplied by each HV and LV secondary substation. Customer addresses are not exactly connected to the LV services within the GIS data. Therefore, it is assumed that each customer address is connected at the end of the closest LV service line. Once these graphs have been assembled, it is simple to count how many customers are connected downstream of each cable. The GIS data also contains other information about the cables such as the type of conductor and its cross-sectional area.

The physical simulation and statistical modelling in this project have only considered the aggregated LV feeder, rather than consider every single LV cable segment. Therefore, the modelling is based on the design and cross-sectional area of the first cable segment connected to the secondary transformer and the total number of customers downstream of this segment, rather than all the individual segments. This will typically be the main pinch point that degrades most quickly due to thermal stress.

Outlining of modelling approach.

The probabilistic failure model developed within this project focusses on how demand causes cable temperature to vary, and how temperature cycles can then cause damage within the cable. Consideration is given to how estimates of demand could be improved by using a partial penetration adoption of smart meters, and by potentially using information about demand on higher voltage levels.

The basic approach to this modelling framework is:

- Map out the connection between the variables.
- Use physical models and limited available data to generate "training data" (e.g., for cable temperatures and damage).
- Fit univariate models to the training data for each variable, which describe the probability of observing different levels of demand, temperature, damage etc., with an emphasis on extreme values of those variables (e.g., 1-in-10-year levels of demand).
- Use data-driven probabilistic machine learning methods to combine these univariate models to a single multivariate model, while still accounting for the structure of the relationships between parameters.

8.2 Modelling customer demand and cable temperature

There are two main topics of interest when modelling customer demand and cable temperature:

- The extent to which probabilistic predictions can be made (that are possibly quite uncertain) about the nature of these critical extremes of active power (kW) demand for a group of customers served by a cable, based on the type of data about those customers that might typically be available to a DNO. Also, the best methodology to make these predictions.
- The extent to which these predictions about demand extremes can be taken and combined with other readily available data about a cable. For example, the type of soil in which it is buried, the altitude of its location etc – to produce (uncertain) probabilistic predictions about the extremes of temperature and rates of change in temperature that the cable is likely to experience. Again, the best methodology to make such predictions needs to be established.

Once these topics were explored and methodologies developed and verified, with the model was run using the database of ENWL underground LV cables.

To research these topics, suitable data was used; consisting of demand sequences (i.e., time series) for relatively small groups of domestic customers, for which basic data is available (i.e., annual energy consumption values). It is assumed that, in practice, the DNO would not have access to the former data (notwithstanding their ability to access smart meter data), but that a DNO would have access to annual consumption values.

By extracting key statistics from these time series, a statistical model can be fitted. How sequences of demand values for customer groups converts to a sequence of cable temperatures must be understood. Obtaining coincident time series of power demand and temperature enables the fitting of a statistical model capturing the relationship between extreme demands and extreme changes in demand, and also extreme temperatures and extreme changes in temperature. While such a model is entirely statistical, acquiring the coincident time series of temperature, given a demand time series, requires physical modelling – specifically, a physics-based cable temperature model. The same need for complementary physical and statistical models is true as the model development progresses from temperature to damage and from damage to risk of imminent failure.

8.3 Physical Modelling of LV network degradation

Physical joint thermal stress modelling

Heating of LV cables and joints can lead to differential thermal expansion due to the interface between different components, which can result in thermal stress applied to parts of the LV network. To understand this effect in more detail, results from the cable and joint temperature model are fed into a joint stress model. Specific interest is taken in the cable joints, as operational experience suggests that this is where 95% of failures occur in the network.

Physical joint damage modelling

Stresses in the joint can damage the joint material, leading to eventual joint failure. To understand joint failure in more detail, stresses from the joint stress model are first converted from a continuous time series into discrete stress cycles Next, the discrete stress cycles are used as part of a physical model of joint damage. Finally, a sensitivity analysis of temperature on the physical joint damage model is carried out.

Physical modelling of other environmental factors

The probabilistic modelling framework for the LV network also considers other environmental effects. Work in this project has focused on understanding the influence of electrical-based degradation and chemical-based degradation on the LV network.

Calculating remaining life using the physical model

Once the physical damage has been calculated using the physical damage model, the damage results can be used to calculate the remaining life in the underground LV assets. Future life calculations require knowledge of the asset age, previous loading history, expected future loading, and expected degradation rate. Currently, some of this information is unknown, therefore assumptions must be made when calculating the remaining asset life. Several methods are proposed here to calculate the remaining asset life, each of which have different benefits and drawbacks.

Overall sensitivity analysis of the physical damage model

A global sensitivity analysis is performed to understand how each variable for the underground LV asset may influence the asset damage.

8.4 Statistical modelling of LV Network degradation

Statistical cable damage modelling

The final model in the statistical modelling chain linking demand, temperatures, and damage converts high quantiles of temperature to a predicted probability distribution for damage sustained within a year. Target values of annual damage were calculated using the physical models and capped at one, where a damage of one represents a failed cable. For simplicity, only total damage has been considered, but it may be more appropriate to jointly predict a bivariate distribution of plastic damage, and fatigue plus creep damage, due to the differing ways in which these forms of damage are sustained.

Statistical life prediction modelling

From the model for damage, it is possible to determine the probabilities of different levels of a cable's remaining useful life. Of significance is the ability to calculate the probability of useful life reducing below a certain threshold over a specified duration (e.g., less than a year of useful life within the next five-year price control). In addition, it has been shown that a partial adoption of smart meters can reduce the uncertainty associated with all predictions (demand, temperature and damage). This functionality emerges from the ability of the model to predict annual damage sustained by a cable with a specific number of customers, of a specified construction, with soil thermal resistivity estimated from the cable location. By simulating the damage for a sequence of years, perhaps under a scenario for growing LCT adoption or changing annual energy consumption, a large set of samples of a sequence of damage can be produced.

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

There were no modifications required to the planned approach during the project.

10 LESSONS LEARNED FOR FUTURE PROJECTS

A number of high level observations were highlighted during the project:

- Different soil types have a strong influence on the cable life. The cables are particularly sensitive to peat, as it has a low thermal conductivity. This means temperature cannot easily dissipate from the cable when it heats up, thus causing damage and reducing the remaining life. Cables aren't often buried in peat, but in some geographical conditions it may be the only real option for network planning.

- Cables are sensitive to changes in ground temperature. Increased soil temperature increases the cable temperature, which increases cable damage and leads to a reduction in cable life.

- Increasing the proportion of customers that have EVs can, without smart charging, significantly increase cable damage and lead to a significant reduction in cable life. In this case, 10% EV usage can provide a life of over 100 years, but when the EV proportion is raised to 100% then the life will be reduced to approximately a decade for a standard soil composition.

- In most cases creep damage is the dominant failure mode for the cable joints.

- Fatigue damage is extremely sensitive to the initial crack size in the cable joint. This indicates that under certain conditions, the presence of defects in the joint filler material could influence the degradation of the cable joint.

11 PLANNED IMPLEMENTATION

This desktop research project has demonstrated the potential benefits of a predictive tool to manage LV underground network failure.

To facilitate implementation into BAU, further development would improve the modelling framework:

Improving the skill and reliability of the model*:*

- Using additional historic data, covering a wider range of years, in both the physical modelling and the statistical modelling. This should allow the model to account for trends in how demand has changed over time, but also allow it to more reliably reflect the extra variation in peak demands that is expected to occur due to factors like extremely cold winters.

- Generating a much larger set of physical model training data for use in training simulations, based on a larger set of historic demand records, and also ensuring a sufficiently large number of samples exist where cables experience high temperatures and are subjected to higher amounts of damage.

- Including other sources of demand, such as non-domestic customer demand and heat pumps, within the physical modelling and statistical modelling. This could also include simulating the impact of smart charging of electric vehicles and/or other demand-side response measures and propagating this through to the temperature and damage modelling.

- Demonstrating the use of both LV cable monitoring data and higher voltage monitoring data within the modelling framework, including quantification of the possible benefits of deploying this type of monitoring technology.

Expanding the model to other network assets:

- Further development of cable temperature models to include aspects that affect cables for higher voltage levels including dielectric heating, cables in ducts, as well as integration of thermal models for transformers and potentially overhead lines.

- Failure analysis (e.g., the production of a DFMEA and a failure tree) and degradation modelling for other categories of asset and other failure mechanisms (higher voltage level cables, transformers, and potentially overhead lines).

- Integration of power systems modelling (at a minimum, load flow, but possibly fault-level analysis) into the physical modelling process.

- Determining an appropriate treatment of degradation causes by assets with a contracted level of capacity.

- Modifying statistical modelling approaches to work in a setting where there is more data available, but potentially more uncertainty arising due to variation in demand and weather between years.

Applying the model in decision-making

- Further research may be required before the modelling framework could be applied meaningfully within decision-making processes, or to derive the most value from the model outputs.

- One important exercise is the validation of the various stages of the physical model against real measurements. LV Predict has assumed that the outputs of the physical models of temperature and stress cycles are accurate, but this could be validated through comparison with actual measurements, where these exist. For example, the cable and transformer temperature measurements made in the Celsius project could be used for validation of an LV cable temperature model tailored to that specific circuit, or an expanded LV transformer temperature model.

- It would also be more meaningful for the model to be able to predict the likelihood of a cable (or other asset) experiencing an actual fault (e.g., within the next year), rather than just predicting the total cumulative damage it has been subjected to. This would involve implementing the final link between cumulative damage and failure probability, which likely depends on analysing the NAFIRs data alongside the finalised version of the model.
- With a model capable of predicting failure risks, it would be possible to use the model to make asset management decisions based on trading off costs and benefits. The model of failure probability would be used to quantify the risk of customers being disconnected due to faults, which would be helpful as DNOs are penalised for Customer Interruptions and Customer Minutes Lost. This could be used to schedule interventions more efficiently and could help to justify more proactive asset maintenance and replacement.
- One additional benefit of proactive maintenance could be the avoidance of supply chain constraints that might otherwise affect the necessary rollout of new assets on the LV network. With such a high volume of network assets across all the GB DNOs, there is a pronounced risk that, if a significant proportion of these require intervention in a short space of time, this may not be possible due to availability bottlenecks within the supply chain. This could be addressed through a further addition to the modelling framework to consider the supply chain requirements for LV cables (and other assets), and the prospect of disruption.

12 DATA ACCESS

There was no new data gathered as part of this project. All data used existed already from previous projects.

Electricity North West's innovation data sharing policy can be found on our website.

13 FOREGROUND IPR

The default IPR position has been applied to this project, and there has been no relevant foreground IPR registered as part of this project.

14 FACILITATE REPLICATION.

As all GB DNOs use similar cable types which are subjected to similar conditions the model is applicable to all DNOs but as stated in the Planned Implementation section the model requires further development before it can be deployed in BAU. ENWL are exploring the next steps for the model development.

15 OTHER COMMENTS

None.