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B1 Insulated Cables
PS1 Learning from Experiences

Installing passive sensing for condition monitoring of a 400 kV cable

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SUMMARY

HV cables are particularly susceptible to failures at joints and terminations, but can be challenging to instrument at these key locations using conventional monitoring technologies. This paper demonstrates the deployment and learnings from a passive sensing approach for a critical 400 kV cable circuit in Spain. The cable is 12.8 km long and has cross-bonded joints. Passive optical sensors have been retrofitted to 4 out of 16 sections of the circuit, but the sensors do not require power or other infrastructure at the monitoring locations. This enables continuous and cost-effective monitoring of phase current, sheath current, and cable joint temperature. A central optical interrogation device processes the optical signals from all sensors connected via a single-mode fibre, and it outputs measured waveform samples from these sensors at 4 kHz using the IEC 61850-9-2 Sampled Values protocol. A substation computer has been installed to collect data over a long period of time and perform processing and analysis. Practical installation guidance and learning experiences from the installation of the sensing platform are documented in this paper, including the complexities of installing sheath current sensors at the correct locations and issues experienced with CT saturation.

The paper describes opportunities for leveraging the sensing platform for data analysis purposes. The goal is to develop automated early warning signs of asset degradation or stress and identify installation issues, such as broken connections or insulation damage. Several methods are discussed in the paper, which broadly fall into two categories: 1) analytical and 2) statistical. The analytical methods involve using knowledge of the cross-bonded configuration with the real-time measurements to derive cable health metrics. For example, it is possible to use the ratio of sheath-to-phase current to readily identify common installation problems. There are several further techniques in the literature for automatically detecting additional failure modes with this type of cable circuit, which are described in the paper. A key strategy with the statistical methods is to remove "seasonality" effects from the data trends (such as daily cyclic variations) so that true deviations can be revealed and analysed. Furthermore, by monitoring sheath currents and temperatures at multiple sections along the cable, it is possible to perform analysis methods that cross-correlate data at different locations to find outliers – which may indicate asset health degradation or other issues. This visibility will be used to optimise the cable maintenance strategy (i.e.

avoiding routine manual inspections) and provide advance warning of possible damage. At the time of writing, the system is awaiting final commissioning, but future work will report on the findings of the analysis methods once sufficient data has been collected.

KEYWORDS

Cable Condition Monitoring, HV Cable, Cable Termination, Cable Joint, Passive Sensing, Distributed Electrical Sensing, Sheath Current, IEC 61850-9-2, Sampled Values

1 INTRODUCTION

Approximately two-thirds of high-voltage cable failures occur in joints and terminations, which can be vulnerable to installation issues and degradation over time. However, conventional monitoring approaches are usually not suitable or cost-effective for instrumenting these critical locations. For example, Distributed Temperature Sensing (DTS) does not provide adequate spatial resolution for pinpointing temperature-based anomalies at terminations, and Partial Discharge (PD) monitoring can be impractical, labour-intensive, and requires specialist analysis. Cables are typically deployed in underground tunnels or ducts which makes access difficult and time-consuming for periodic manual inspections.

The authors worked with the Spanish Transmission System Operator (TSO) to retrofit passive optical-fibre-based sensors to critical locations on a 400 kV underground cable asset. The purpose of the system is to provide visibility of electrical and mechanical parameters at multiple positions distributed along the cable, to deliver early warning of failure modes at these vital locations.

This paper summarises the passive sensing platform deployed on the HV cable, and the condition monitoring opportunities which this enables. Experiences with installing a monitoring system of this kind will be described. The opportunities for leveraging the data are discussed and demonstrated, including analytical methods based on knowledge of cable electrical properties and analysis of outliers in the data trends.

2 INSTRUMENTATION OF A 400 KV UNDERGROUND CABLE

2.1 Overview

The system instruments a critical 400 kV cable, which is in a tunnel that traverses under a major airport. Figure 1 shows the substation area at one end of the cable, including the transition point and tunnel entrance. The cable is cross-linked polyethylene (XLPE), approximately 12.8 km long, and is cross-bonded to reduce circulating sheath current levels. It is a double circuit, although only one three-phase circuit has been instrumented. In total, 21 current sensors and 12 temperature sensors have been deployed to comprehensively monitor the first four sections of the 400 kV cable. The system monitors the following:

- Phase current in each phase of the cable.
- Sheath/screen currents at the start of the cable (at the transition point).
- Sheath/screen currents at joints for all monitored sections of the cable.
- Point temperature on or close to each termination and joint.

(a)

(b)

Figure 1: Site photos of (a) the transition point and (b) the tunnel entrance

2.2 Passive Sensing Platform and 400 kV Cable Instrumentation Deployment

The deployed sensors are entirely passive, requiring no data networks or control power at the sensor locations. For current measurements, split-core current transformers (CTs) have been used (see Figure 4 (a)). A passive secondary converter (PSC) component converts the CT secondary signal to an optical signal. Only standard optical fibre is required to couple the remote PSCs. A centralised “interrogator” device, installed in the substation at one end of the cable, is connected to the sensor fibre and is able to access measurements from all sensors near instantaneously. The interrogator streams measurement data continuously for all sensors, providing waveform samples at 4 kHz using the IEC 61850-9-2 Sampled Value protocol. All sensor data is passed to a server which performs processing and analysis.

Figure 2 illustrates a schematic of the monitored cable sections, and the fibre route to each sensor location (where “CE1” refers to cable joint 1, etc.). Figure 3 provides further detail of the sensor locations and fibre splices. Figure 4 shows the two interrogators and data server installed in the substation’s protection and control room.

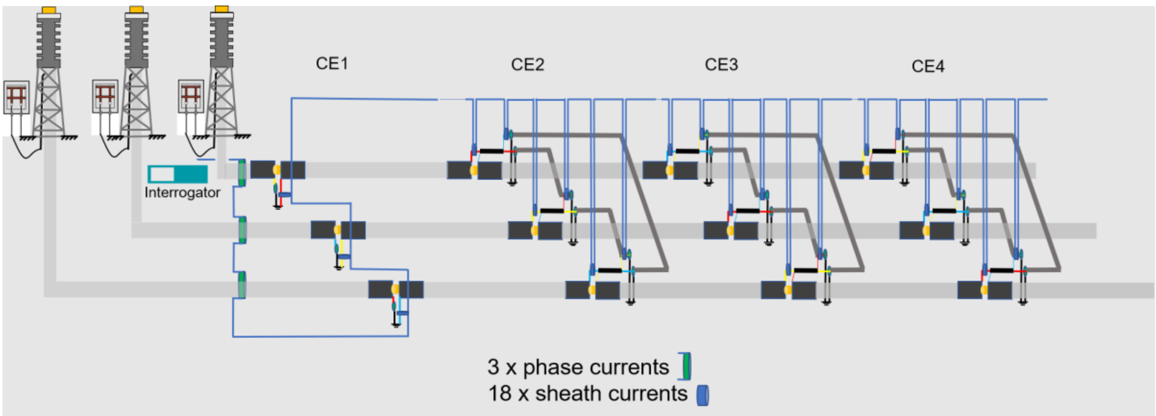

Figure 2: Cable schematic overview

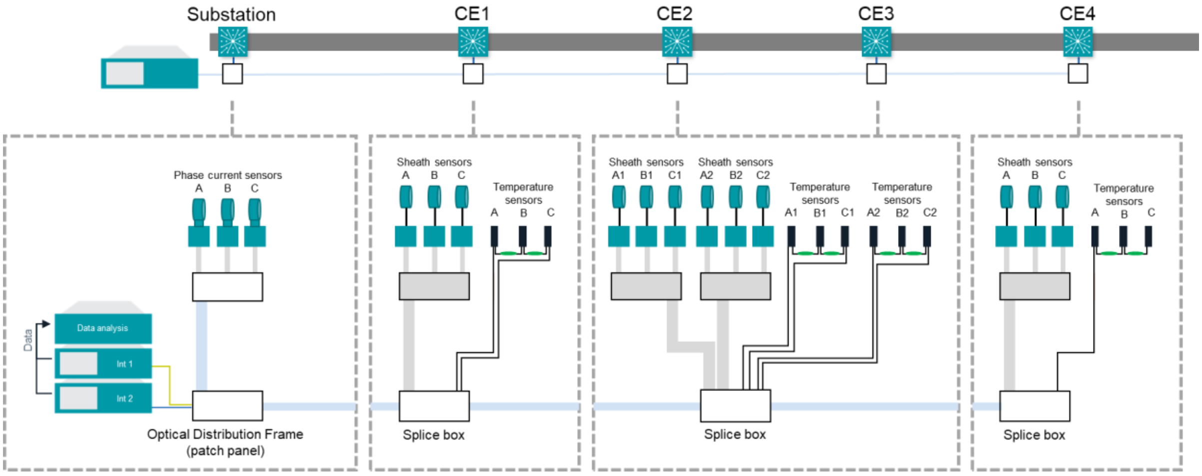

Figure 3: Sensors installed at each location

(a) (b)

Figure 4: (a) two interrogators and data analysis server installed in substation and (b) a sheath current monitoring CT installed at a cable joint

The temperature sensors, like the electrical sensors, use fibre Bragg grating technology for passive operation. They are designed to be surface-mounted on flat or curved surfaces. Figure 5 shows an example of a temperature sensor installed directly on a cable joint to provide a point temperature reading at that position.

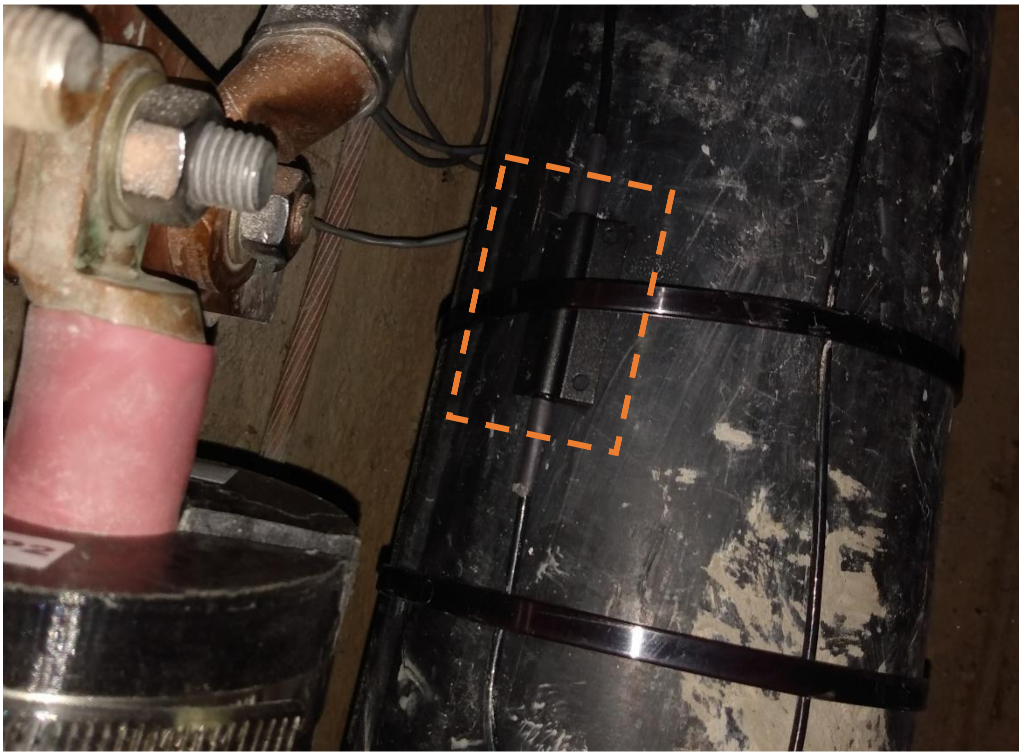

Figure 5: Temperature sensor installation on a cable joint

The system delivers waveform data from each sensor location. This enables several processing and analysis opportunities such as calculating harmonics and synchrophasors, and detecting transients such as incipient faults. Figure 6 shows the phase current waveforms captured during system installation.

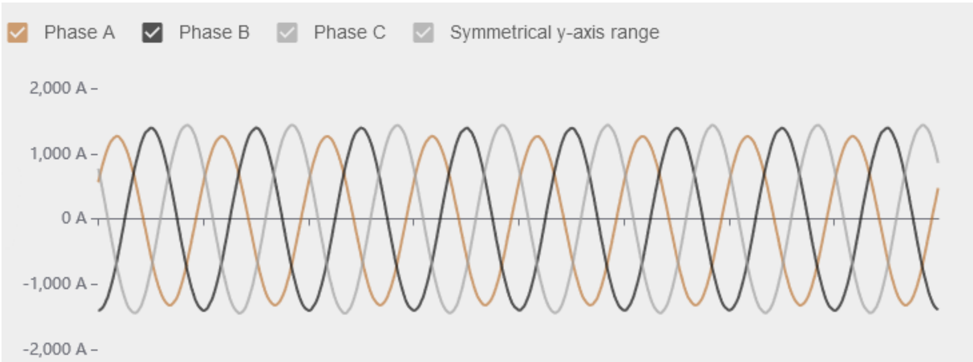

Figure 6: Example of phase current waveform capture

This platform is used for condition monitoring in this deployment, but is also capable of performing protection applications. In particular, it is well suited to protecting mixed circuits with sections of both overhead lines (OHLs) and cables, because passive sensors can be deployed at remote transition points without needing conventional infrastructure. This allows for intelligent control of auto-reclose systems.

3 OBSERVATIONS FROM INSTALLATION OF SENSORS

In advance of the installation of fibre-based passive sensing, it is essential to use an optical time-domain reflectometer (OTDR) to check the quality of the fibre and ensure there are no breaks or excessive attenuation.

The large number of installed sensors and inherent complexity of the sheath wiring of cross-bonded cables leads to complications with the installation process. It is difficult to install the sheath CTs on the correct cable section. Additionally, sensors and CTs must be installed according to the design on the correct phase and location. This enables the commissioning engineer to verify all sensors are operating as expected. Rigour in the installation instructions, accurate diagrams, and careful labelling of all components before and after installation is required. It is also useful if the polarity of an installed CT can be readily changed through software configuration, as this is generally easier than repeating the CT installation.

It is important to ensure that the diameters of all CTs are appropriate. Typically, this will involve a site visit to the visually inspect the installation areas. In particular, the phase current CTs should be large enough to fit around the phase conductor and the sheath connection (because the sheath should typically be looped back through the CT to improve the accuracy of the phase current measurement).

CT saturation was experienced at one sheath monitoring location which exhibited significantly higher current levels than expected. The typical harmonic pattern of CT saturation was observed in the commissioning process (due to the high sampling rate of the monitoring system), so alternative CTs with a higher rating could be sourced.

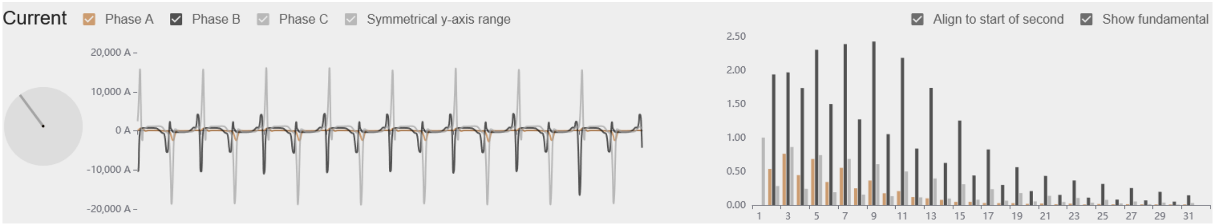

Figure 7: CT saturation waveforms and harmonic spectrum

Depending on the system conditions, the sheath current waveforms at other locations may be dominated by a zero-sequence component as shown in Figure 8. Therefore, care must be taken when commissioning these sensors, as a simple positive sequence RMS calculation may provide a confusing indication of the real system behaviour.

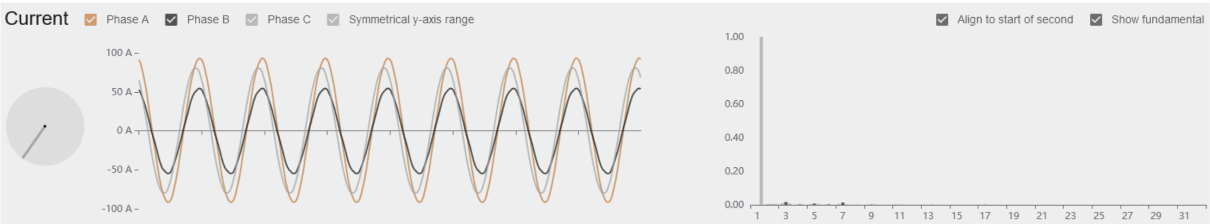

Figure 8: Typical sheath current waveforms and harmonic spectrum

4 CONDITION MONITORING CAPABILITY

4.1 Overview

A key benefit of the system is the ability to examine trends in the electrical and temperature measurements, at multiple locations, over time. All measurements are streamed into a ruggedised substation computer in real-time, which processes the raw measurements into phasors, harmonics, and other derived metrics, and stores the outputs into a database for detailed analysis. Figure 9 illustrates the dashboard of measurement data during the installation and commissioning process. Section 5 will highlight in more detail how this analysis can be performed continuously and automatically.

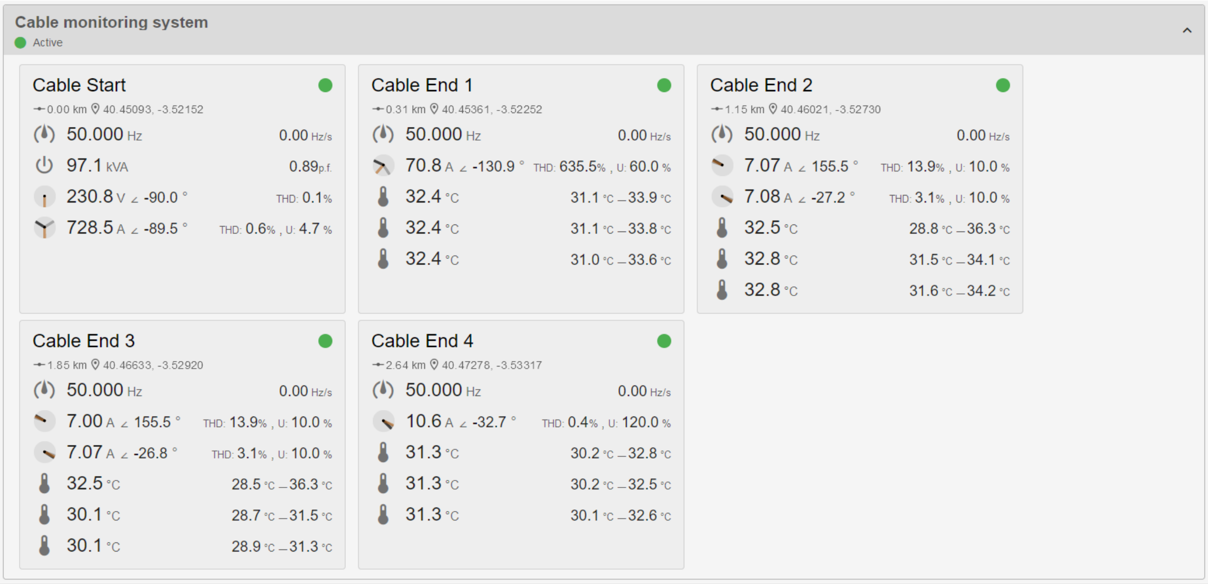

Figure 9: Snapshot of measured phase current, sheath current, and temperature values during system commissioning

4.2 Comparison with Conventional Monitoring Approaches

Table 1 provides a summary of monitoring technologies which could be used for cable condition monitoring. Clearly, conventional approaches all have disadvantages such as requiring an outage for performing measurements, requiring significant infrastructure at sensor locations, or offering incomplete information for detecting failure modes early. By contrast, passive electrical sensing delivers continuous streaming of sensor data without needing power or other equipment at remote locations. It also reduces the need for periodic manual inspection.

Monitoring approach	Power and electronics required at sensor locations	Interpretation of results	Continuous monitoring or manual inspection?	Outage required for measurement campaign?
Manual visual inspection of cable joints	Yes, for portable equipment	Manual, subjective	Manual and labour-intensive	Depends on measurements required
Conventional CTs and other sensors	Yes, merging unit, or equivalent digitisation electronics	Normal	Continuous	No
Partial discharge	Yes, high-frequency CTs, ultrasonic transducers, or similar	Complex	Manual	No
Dielectric loss/tan-delta	Yes, needs special equipment to inject low frequency signals	Complex, but handled by test equipment	Manual	Yes
Distributed temperature sensing (DTS)	No	Can only detect a limited set of failure modes	Continuous	No
Passive distributed electrical sensing	No	Normal	Continuous	No

Table 1: Summary of monitoring approaches for cable condition monitoring

5 ANALYSIS OF MONITORING DATA

5.1 Overview

At the time of writing, some parts of the monitoring system are awaiting final commissioning, e.g. to resolve the CT saturation issues, so no long-term data is available for analysis at this stage. However, the following subsections explain the types of analysis and metrics which will be applied to leverage the sensing platform and deliver novel cable health indicators. Future work will report on applying these methods to data from the installed system.

5.2 Analytic and Heuristic Methods

As documented in CIGRE B1 report 825 ("Maintenance of HV Cable Systems") [1], there are clear failure modes in the cross-bonding of sheath connections which can be readily identified from online monitoring of sheath currents and relatively simple heuristics. In particular, the ratio of sheath-to-phase currents as a robust and rapid indicator of cable health, such as detecting errors in the cross-bonding connections or an incorrect earth bonding. Figure 10 illustrates a cable-specific dashboard for the monitoring data. The dashboard plots time series and scatter plots of the ratio of sheath-to-phase current as observing this metric can help to easily identify cable issues. Additionally, an overview of all sensor locations and values helps to highlight any outliers and alarms.

Additional metrics can be calculated from sheath current measurements which cater for further failure modes such as [2], [3], [4], [5]:

- Open sheath conductor

- Flooded linkboxes
- Short circuits of the cross-bonded sheaths at the cable joints
- Relative dielectric loss factor using a leakage current separation method
- Defect detection and localisation criteria for various cable topologies and operating conditions

Figure 10: Cable asset monitoring view (using simulated data)

5.3 Data Analysis Methods

Temperature and current time series data are a valuable resource for the detection, diagnosis, and prediction of cable joint and termination faults. At a basic level, outliers in time series data can be linked with spurious short-term changes caused by abrupt faults or deviations in normal behaviour. This can be extended, however, as the characteristics of outliers (e.g. their duration, magnitude, frequency of occurrence, or co-occurrence and relationships with other variables) can indicate the presence of incipient faults and long-term degradation.

Outliers in time series data take several forms. They can be single data points that diverge from the local time series, windows of time that show abnormal behaviour compared to previous windows, or a consistent divergence of a cable termination's parameters compared to the rest of the population. Removing the impacts of seasonality (e.g. daily or annual ambient temperature fluctuations), often improves the ability to detect fault indicators. This supports operators in fault diagnosis e.g. gradual increases in sheath circulating current can indicate electrical unbalance, indicating an increased risk of insulation breakdown. Figure 11 illustrates this concept for temperature measurements, where the raw data is seasonally decomposed to find true outliers.

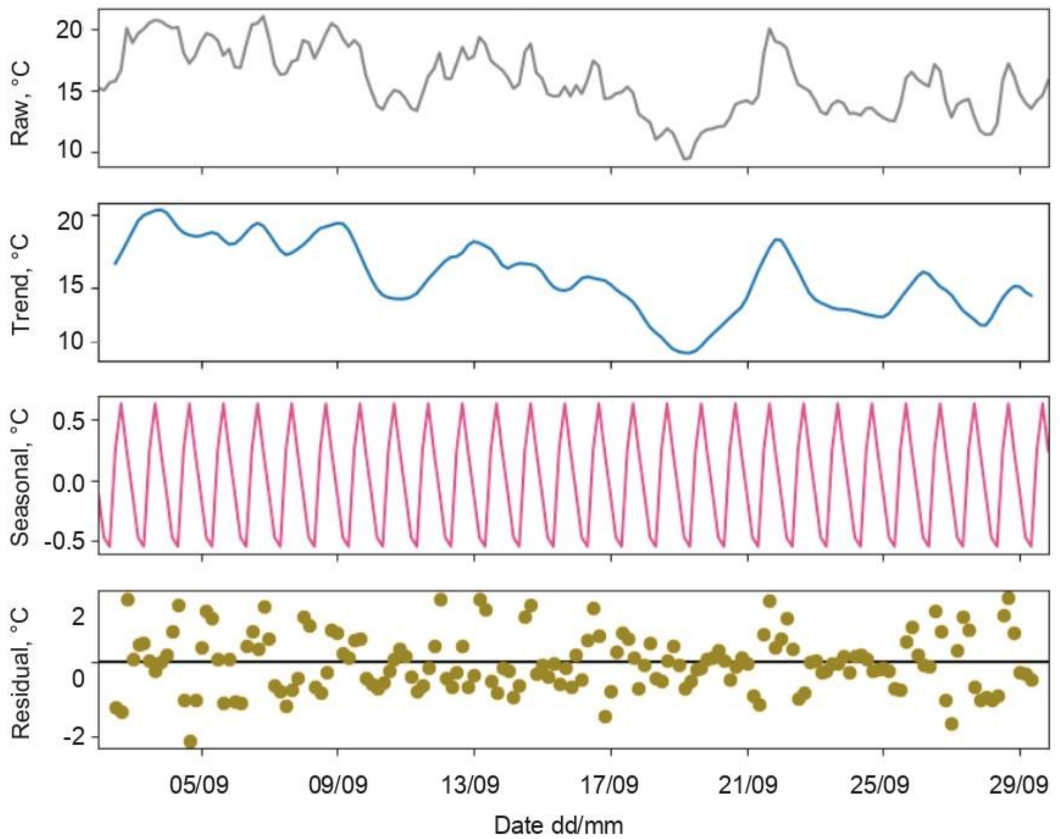

Figure 11: Illustration of de-seasonalisation of temperature data

Algorithms have been developed to leverage combinations of classical time-series and outlier detection methods, data- and physics- informed models, and assessments of the distributions of measured parameters over time. Figure 12, for example, shows one year of monthly cable termination temperature distributions prior to de-seasonalisation.

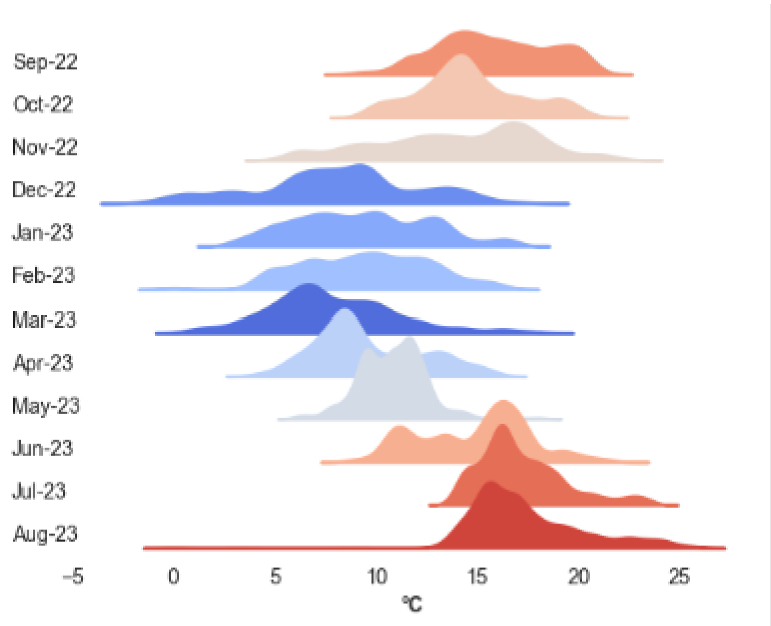

Figure 12: Monthly distributions of cable termination temperatures over a one-year period

Full data sets, such as the one summarised in Figure 12, are not always immediately useful to operators. Indeed, the aim is often to reduce the large volumes of data acquired by the monitoring system into a reduced set of transparent metrics. These metrics can be tracked and related, and so used to support an operator's decision-making. The predictive power of some metrics enables operators to shift towards proactive, rather than reactive, maintenance strategies. These strategies reduce repair costs, minimise outage time, and enhance the reliability and resilience of terminations/joints and the electrical systems they underpin.

6 CONCLUSIONS AND FUTURE WORK

Most power cable faults can be traced back to issues with terminations and joints. Monitoring sheath currents and temperatures continuously in these locations provides early and economical failure warnings across every cable section.

This paper has described how distributed passive sensing has been installed on a 400 kV cable to provide comprehensive monitoring of the health of the cable. The system will collect data and perform analysis of trends, especially for sheath current behaviour. This will be used to create automated metrics which will provide early warning of asset failure.

Future work will involve adapting the system to other types of cable arrangements, such as with linkboxes, different earthing systems, and transposed cables. The approach will also be combined with DTS to capture additional failure modes, and offer a comprehensive real-time thermal rating (RTTR) solution.

BIBLIOGRAPHY

[1] CIGRE B1 WG B1.60, ‘Maintenance of HV Cable Systems’, CIGRE B1, Technical Brochure 825, 2021. [Online]. Available: https://www.e-cigre.org/publications/detail/825-maintenance-of-hv-cable-systems.html

[2] X. Dong *et al.*, ‘Analysis of cable failure modes and cable joint failure detection via sheath circulating current’, in *2014 IEEE Electrical Insulation Conference (EIC)*, Jun. 2014, pp. 294–298. doi: 10.1109/EIC.2014.6869395.

[3] X. Dong, Y. Yang, C. Zhou, and D. M. Hepburn, ‘Online Monitoring and Diagnosis of HV Cable Faults by Sheath System Currents’, *IEEE Trans. Power Deliv.*, vol. 32, no. 5, pp. 2281–2290, Oct. 2017, doi: 10.1109/TPWRD.2017.2665818.

[4] Y. Yang, D. M. Hepburn, C. Zhou, W. Zhou, and Y. Bao, ‘On-line monitoring of relative dielectric losses in cross-bonded cables using sheath currents’, *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 2677–2685, Oct. 2017, doi: 10.1109/TDEI.2017.005438.

[5] M. A. Shokry, A. Khamlichi, F. Garnacho, J. M. Malo, and F. Álvarez, ‘Detection and Localization of Defects in Cable Sheath of Cross-Bonding Configuration by Sheath Currents’, *IEEE Trans. Power Deliv.*, vol. 34, no. 4, pp. 1401–1411, Aug. 2019, doi: 10.1109/TPWRD.2019.2903329.