CIGRE 2025 International Symposium
Palais des Congrès de Montréal, Québec, Canada
September 29 to October 3, 2025

10494
B1 INSULATED CABLES
PS2 Application of technologies, information technology (IT) and artificial intelligence (AI)

Finding Damage and Failures in HV Cables using Passive Sensing

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SUMMARY

Over half of the outage time for high-voltage cables is due to failures that occur in joints and terminations. These weak points are challenging to initially install correctly and can be vulnerable to degradation over time. However, conventional monitoring approaches are sometimes not suitable or are not 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, requires specialist analysis, and does not always reveal damage when the system is operating at nominal voltage. Cables are often deployed in underground tunnels or ducts which makes access difficult, unpleasant, and time-consuming for periodic manual inspections.

The authors worked with the Spanish Transmission System Operator (TSO), to retrofit passive 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 damage and failure modes in these vital locations. 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) and at the joints for all monitored sections of the cable.
- Point temperature on each termination and joint.

In total, 21 current sensors and 12 temperature sensors have been deployed to comprehensively monitor the first three sections of the 400 kV cable. The 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, with the CT secondary connected to the passive sensor inputs. Only standard optical fibre is required to couple the remote sensors. 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 synchronised waveform measurements from all sensors nearly instantaneously.

The paper examines all data collected to date, and comments on outcomes from the online monitoring of currents and temperature at multiple locations. For example, as documented in CIGRE B1 report 825 ("Maintenance of HV Cable Systems"), there are clear failure modes in the cross-bonding of sheath connections which can be readily identified from online monitoring of sheath currents with relatively simple heuristics, and the paper highlights how this analysis can be performed continuously and automatically. There are other outliers which can readily be identified, such as a measurement deviating from its normal behaviour, or temperature at one location differing from measurements at other similar locations. Detection of these anomalies will facilitate and optimise maintenance.

KEYWORDS

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

1 Introduction

Approximately 57% of the outage time of high-voltage cables is due to failures occurring in joints and terminations [1], which can be vulnerable to installation issues and degradation over time. However, conventional monitoring approaches are sometimes 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 often 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. 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 (b)). 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. Only analogue signals (a modulation of wavelength for each sensor) are transferred on the fibre. 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 robust substation 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.

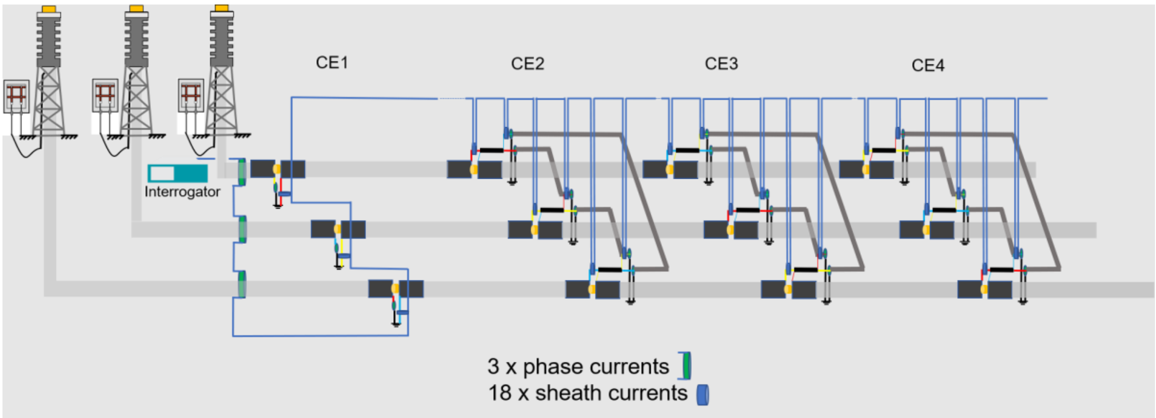

Figure 2 – Cable schematic overview

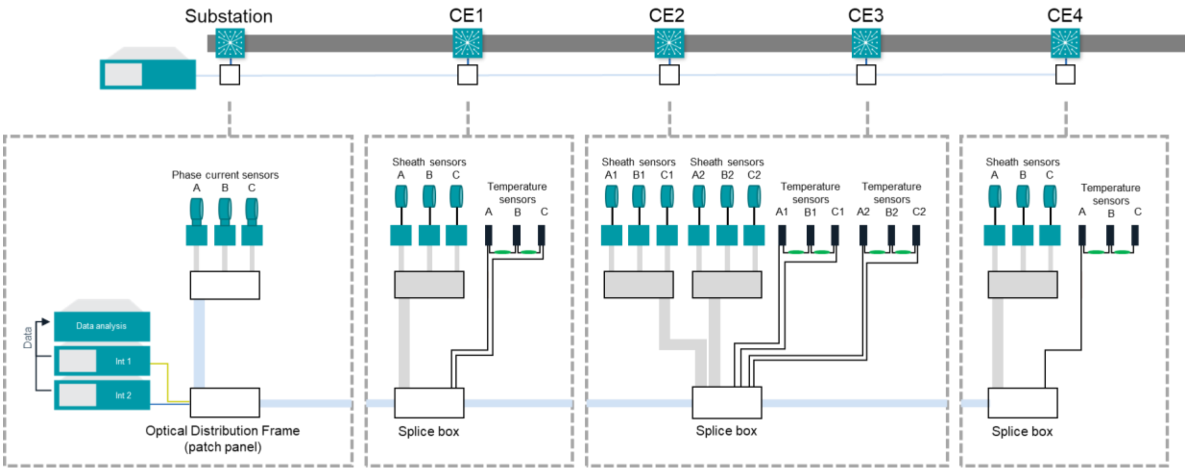

Figure 3 – Sensors installed at each location

(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 at a cable joint to provide a point temperature reading at that position.

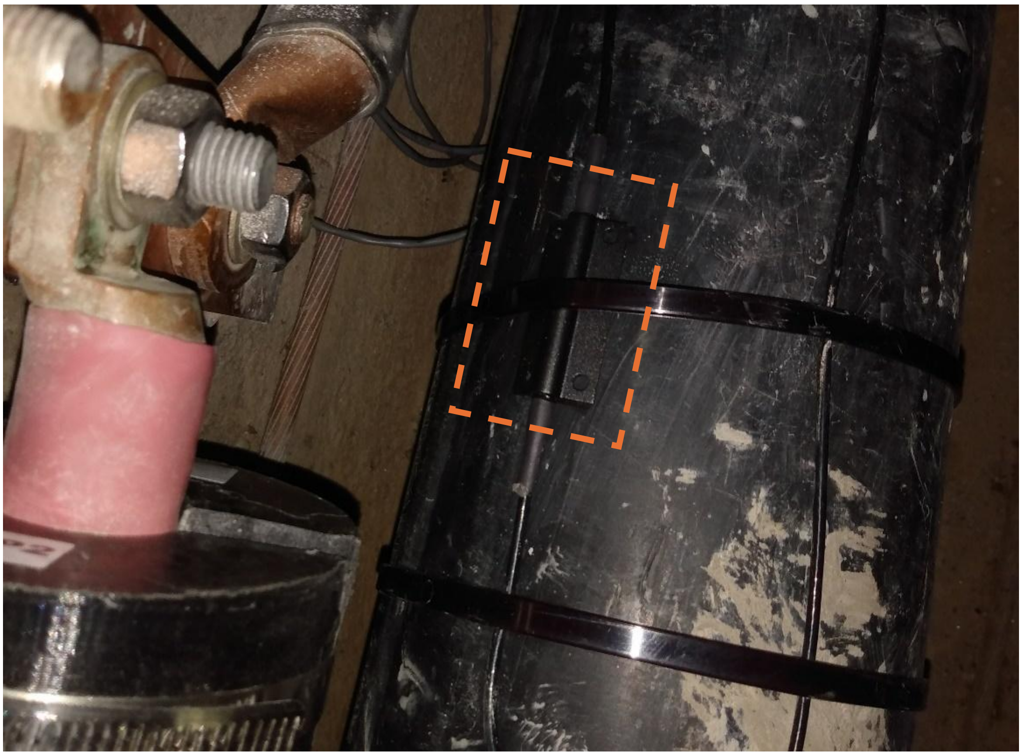

Figure 5 – Temperature sensor installation at a cable joint

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 a snapshot of the phase current waveforms captured during December 2024.

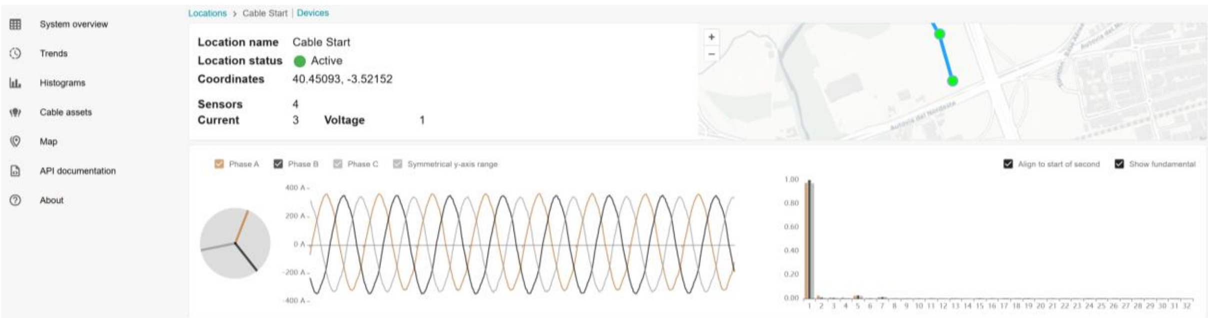

Figure 6 – Example of phase current waveform capture

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 Condition monitoring capabilities

3.1 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 7 illustrates the dashboard of measurement data during the installation and commissioning process. Section 4 will highlight in more detail how this analysis can be performed continuously and automatically.

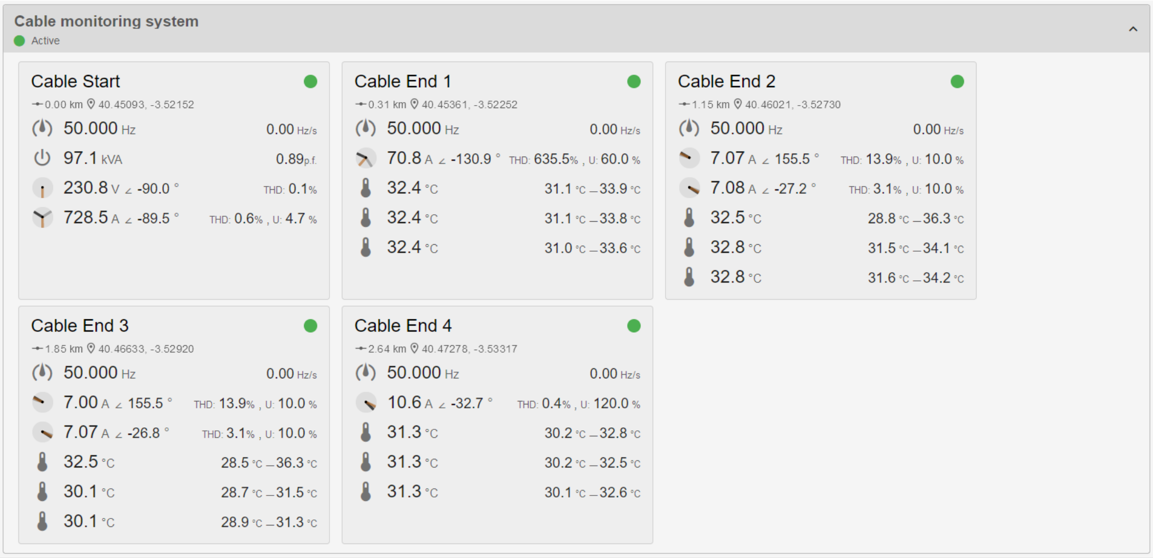

Figure 7 – Snapshot of measured phase current, sheath current, and temperature values during system commissioning

3.2 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 damage and 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. An effective solution for maintaining cables throughout their lifetime therefore demands a combination of monitoring technologies.

Table 1 - Summary of monitoring approaches for cable condition monitoring

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	Straightforward	Continuous	No
Online partial discharge	Yes, high-frequency CTs, ultrasonic transducers, or similar	Complex	Can be continuous, but useful results often not feasible at nominal voltage [2]	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	Straightforward	Continuous	No
Passive distributed electrical sensing	No	Straightforward	Continuous	No

4 Analysis of monitoring data

4.1 Analytic and heuristic methods

As documented in CIGRE B1 report 825 ("Maintenance of HV Cable Systems") [3], 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 8 illustrates this approach with real data, via cable-specific dashboard for the monitoring data. The dashboard includes a scatter plot of the ratio of sheath-to-phase current. In this example, using data from December 2024, there is a cluster of data points from one joint location which differs from the pattern seen in the remaining data points at all other joints. It can therefore be concluded that these outliers highlight an unhealthy joint, but the remaining joints are healthy. In this case, further investigation revealed that the root cause was CT saturation on one of the sheath current CTs which led to abnormally high measured current values.

***Figure 8** – Outliers detected in ratio of phase to sheath current*

Additional metrics can be calculated from sheath current measurements which cater for further failure modes such as [4], [5], [6], [7]:

- 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

4.2 Historical data analysis results

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 9 applies this by comparing several metrics together and highlights the difference in behaviour at each joint location, from data captured in July 2024. The results show a tendency for higher temperatures at joint location 2. Further long-term analysis will determine if this behaviour is statistically significant and indicative of asset damage or a maintenance issue. This information can help operators more efficiently and cost-effectively manage the cable.

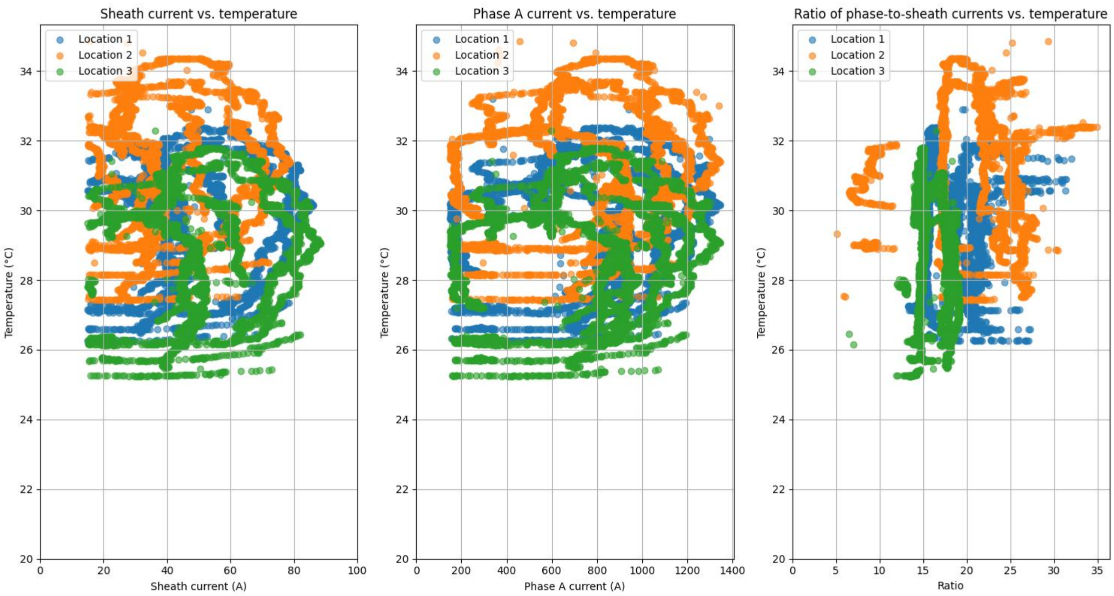

***Figure 9** – Data suggests a general deviation at location 2 (orange data points)*

5 Conclusions

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 critical 400 kV cable circuit 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, and help to reduce the costs of cable operations and maintenance.

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.

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