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Laboratory Test Facility for Real-Time Thermal Rating Validation of Insulated Power Cables

S. Bustamante[1, a], M. Sotelo[2, b], M. Manana[1], A. Arroyo[1], P. Benavente[1], E. Sainz-Ortiz[1], and L. Vejo[1]

[1] Department of Electrical Engineering and Energy Engineering
E.T.S.I.I.T., Universidad de Cantabria
Avda. Los Castros 46, 39005 Santander, Cantabria, Spain
[a] E-mail: bustamantes@unican.es

[2] UPTECH SENSING
Pol. Ind. Mutilva Baja, Calle E, 18, 31192, Aranguren, Navarra, Spain
[b] E-mail: marco.sotelo@uptech-sensing.com

Abstract. This paper presents the design, construction, and commissioning of a laboratory-scale pilot installation developed for the experimental validation of Real-Time Thermal Rating (RTTR) algorithms applied to insulated high-voltage power cables. The pilot is designed to provide high-resolution and reliable thermal measurements under controlled operating conditions. It combines point-wise temperature sensing using platinum resistance temperature detectors (Pt100 sensors) with Distributed Temperature Sensing (DTS) via optical fibres integrated within the cable. Particular emphasis is placed on the physical implementation of the pilot, including cable configuration, temperature sensor deployment, data acquisition architecture, and instrumentation details. The installation was developed in two phases, evolving from an initial configuration with seven Pt100 temperature sensors to a final setup with fifteen Pt100 sensors, including reduced-diameter probes for improved conductor temperature measurement. This paper focuses on the laboratory pilot as an experimental platform, which will form the basis for the subsequent validation of dynamic cable management algorithms.

Key words. Distributed Temperature Sensing, DTS, insulated power cables, Real-Time Thermal Rating, RTTR.

1. Introduction

The growing integration of renewable energy sources and the progressive electrification of energy systems are placing increasing demands on existing transmission and distribution infrastructure. Against this backdrop, Real-Time Thermal Rating (RTTR) techniques have emerged as a vital tool for enhancing the operational flexibility of power cables [1]-[3]. RTTR dynamically adapts the admissible current based on the actual thermal state, rather than relying on conservative static assumptions.

Reliable validation of RTTR algorithms requires accurate and spatially resolved temperature measurements obtained under representative and controlled conditions. However, full-scale field validation is often costly and difficult to reproduce. Laboratory-scale pilot installations therefore play a crucial role in bridging the gap between theoretical development and real-world deployment.

This paper presents a laboratory pilot installation that has been specifically developed to support the validation of RTTR algorithms for insulated power cables. This paper focuses on the experimental infrastructure itself, detailing its construction, instrumentation, and measurement capabilities.

2. Insulated Cable Description

The laboratory pilot is based on a single-core insulated high-voltage power cable that was specifically selected to represent underground transmission installations. The cable being tested is a VOLTALENE RHE-RA+OL 76/132 kV cable with a 630 mm² aluminium conductor.

Its main internal structure consists of a stranded aluminium conductor, an inner semiconductive layer, XLPE insulation, an outer semiconductive layer, a metallic screen, and an external protective sheath. In addition to the electrical layers, eight optical fibres are integrated within two metallic tubes located in the metallic screen region. This configuration enables the use of Distributed Temperature Sensing (DTS) along the cable to provide continuous temperature profiles, which complement the point measurements obtained from platinum resistance temperature detectors (Pt100). A schematic cross-sectional view of the cable structure and the location of the optical fibres is shown in Fig. 1.

The availability of both point-wise and distributed temperature measurements makes this cable particularly suitable for RTTR validation, as it enables the cross-verification of temperature measurements and the detailed analysis of axial and radial thermal gradients.

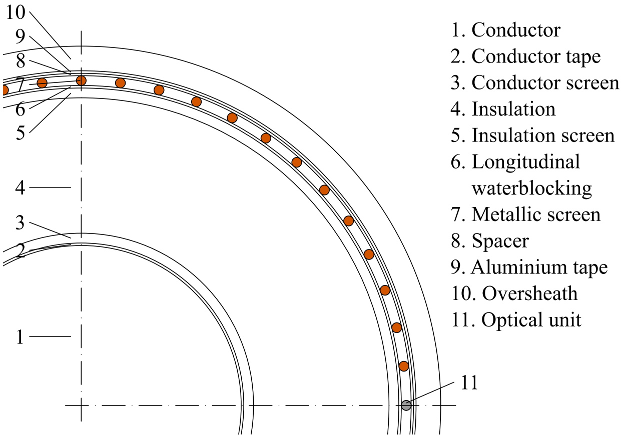

Fig. 1 Cross-sectional structure of the 76/132 kV insulated cable with integrated optical fibres (not to scale).

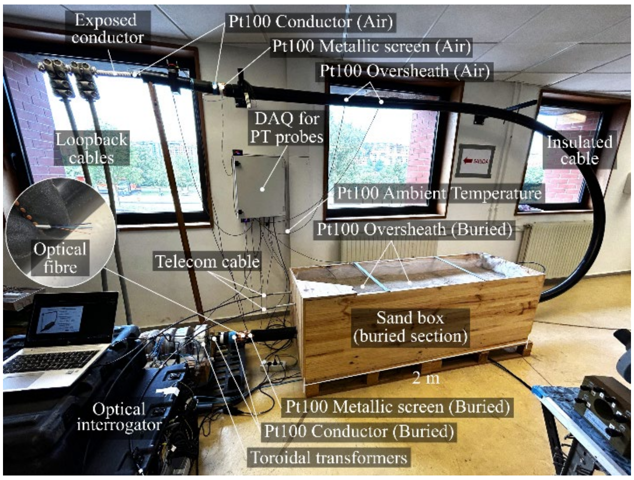

Fig. 2 Overview of the laboratory pilot installation.

3. General Description of the Laboratory Pilot

The pilot installation has been designed to reproduce the thermal behaviour of an insulated high-voltage power cable under controlled electrical loading. The experimental setup consists of a closed-loop cable configuration, with the current generated by toroidal transformers connected in parallel and supplied by a 0–230 V AC source.

Two representative thermal environments are reproduced within the laboratory:

- A section of cable that is buried directly in a sand-filled container to emulate underground installation conditions.
- A section of cable installed in air and protected from direct solar radiation, which is representative of gallery or tunnel installations.

Fig. 2. shows an overview of the complete laboratory pilot installation, including the buried and air-installed cable sections and the main instrumentation elements. This dual configuration enables different heat dissipation mechanisms to be analysed while maintaining a compact and controllable laboratory setup.

The laboratory pilot comprises an insulated power cable with a total length of approximately 10 metres, with a section of around 2 metres installed in a sand-filled container to emulate underground installation conditions. The average burial depth is approximately 30 centimetres, measured from the cable axis to the surface. This configuration enables representative underground thermal boundary conditions to be reproduced while maintaining accessibility for instrumentation and inspection.

The electrical scheme of the laboratory pilot installation is shown in Fig. 3. The setup is designed to allow controlled current injection into the insulated cable under test, enabling steady-state and transient operating conditions that are representative of real cable operation.

The cable under test is arranged in a closed-loop configuration to ensure continuous current circulation.

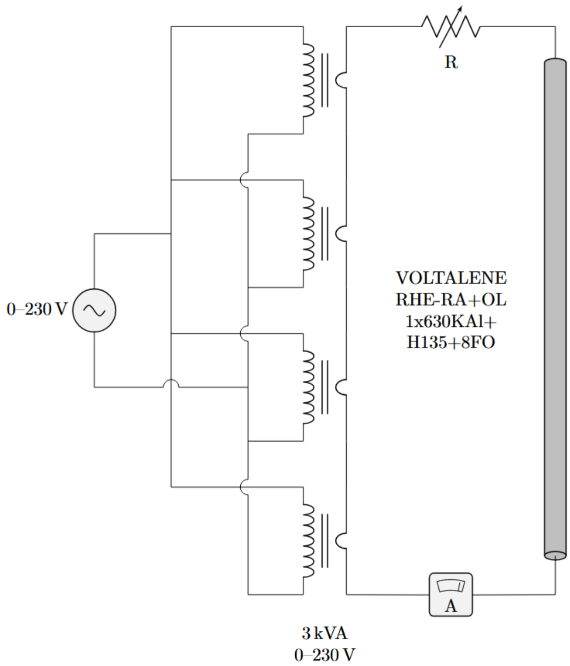

Fig. 3 Electrical diagram of the pilot current injection system (0–230 VAC source + toroidal transformers + loop).

A toroidal current transformer installed in the power circuit provides real-time current measurement, enabling direct correlation between electrical loading conditions and the cable's resulting thermal response.

The electrical scheme has been designed to ensure safe operation, measurement repeatability, and the flexibility to upgrade the pilot installation in future.

4. Temperature Measurement and Instrumentation

A. Pt100 Sensor Technology

Pt100 sensors have been selected as the primary temperature sensing technology due to their accuracy, long-term stability, and suitability for industrial and research applications. All sensors comply with IEC standards and use three-wire measurement schemes to minimise the effects of lead resistance [4].

B. Distributed Temperature Sensing (DTS) System

In addition to point-wise temperature measurements, the pilot installation incorporates an optical fibre-based DTS integrated within the power cable. The cable under test includes eight optical fibres arranged in two metallic tubes located in the metallic screen region, enabling continuous temperature monitoring along the cable's entire length.

The DTS system is based on Brillouin optical backscattering. Short pump laser pulses are launched into one end of the optical fibre, while a continuous-wave probe signal is injected from the opposite end. The interaction of these counter-propagating signals generates stimulated Brillouin scattering along the fibre. The backscattered signal is detected and processed, and the resulting Brillouin frequency shift (BFS) is correlated with temperature variations to obtain a continuous temperature distribution along the fibre. For this study, the gauge length (spatial resolution) was 0.4 m, the spatial sampling interval was 0.1 m, and the acquisition period was 2 min.

This distributed measurement capability complements the Pt100 sensors in several ways. While Pt100 probes provide highly accurate and fast-response temperature measurements at discrete locations, DTS offers continuous axial temperature profiles. This enables the identification of thermal non-uniformities, localised hotspots, and boundary effects, which cannot be captured by point sensors alone. Consequently, the combined use of Pt100 and DTS measurements provides a more comprehensive and robust thermal characterisation of the cable, which is particularly valuable for validating RTTR algorithms under non-uniform and transient operating conditions [5].

C. Sensor Deployment Strategy

The temperature monitoring system was developed in two successive phases:

Phase 1 – Initial configuration: The pilot was initially instrumented with 7 Pt100 sensors, each with a nominal probe diameter of 5 mm. These sensors were intended to provide temperature measurements at key locations, such as the ambient air, the cable conductor, and the outer sheath, in both buried and air-installed sections. However, due to their length and diameter, the conductor-mounted probes could not be fully embedded within the cable in either section. Consequently, part of the sensing element remained exposed outside the cable, resulting in measurements that were not fully representative of the actual conductor temperature.

Phase 2 – Extended configuration: Based on the limitations identified in Phase 1, the instrumentation was upgraded to include a total of 15 Pt100 sensors. In addition to improving the spatial resolution, four reduced-diameter (2 mm) Pt100 probes were incorporated to allow closer placement to the conductor and metallic screen. This upgrade enabled reliable measurement of the conductor temperature in the air-installed cable section. However, direct conductor temperature measurement in the buried section remains constrained as the sensors installed in this phase are located in cable sections that are exposed to air.
The DTS system was deployed in parallel with the Pt100 instrumentation using the optical fibres integrated within the cable. These fibres were routed from the cable terminations to an external DTS interrogator unit that was installed in the laboratory control area. Proper fibre handling, a minimum bending radius and mechanical protection were ensured throughout the installation process to preserve the integrity of the measurements and ensure long-term reliability.

Combining discrete Pt100 sensors with distributed optical fibres enables the simultaneous monitoring of conductor, metallic screen, and outer sheath temperatures, as well as continuous axial temperature profiles. This approach also highlights the challenges associated with directly measuring conductor temperature in buried cable sections.

Table 1 summarises the complete temperature sensing configuration implemented in the laboratory pilot, including sensor types and quantities, probe dimensions, and measurement locations for both development phases. The table illustrates the progressive increase in spatial resolution and the complementary nature of the discrete Pt100 sensors and the distributed optical fibre measurements.

D. Mechanical Integration

Special care was taken during the mechanical integration of the sensors to ensure good thermal contact, electrical insulation, and long-term stability. Sensors mounted on the conductor are installed either on exposed conductor sections or through dedicated perforations. Oversheath and ambient sensors, meanwhile, are surface-mounted or free-standing, respectively. Despite these precautions, the mechanical constraints of the buried section limit direct access to the conductor, as discussed in Section 6.

Table 1. - Summary of temperature sensors and measurement locations.

Sensor type	Quantity	Diameter	Location	Installation condition	Purpose
Pt100 RTD	7	5 mm	Conductor / outer sheath / ambient	Air and buried sections	Initial thermal monitoring and system validation (Phase 1)
Pt100 RTD	4	2 mm	Conductor / metallic screen	Air and buried sections	Improved conductor temperature measurement (Phase 2)
Pt100 RTD	4	5 mm	Outer sheath / ambient	Air and buried sections	Boundary and reference temperature monitoring (Phase 2)
Optical fibre (DTS)	8 fibres (2 tubes)	–	Metallic screen region	Along full cable length	Distributed axial temperature profiling

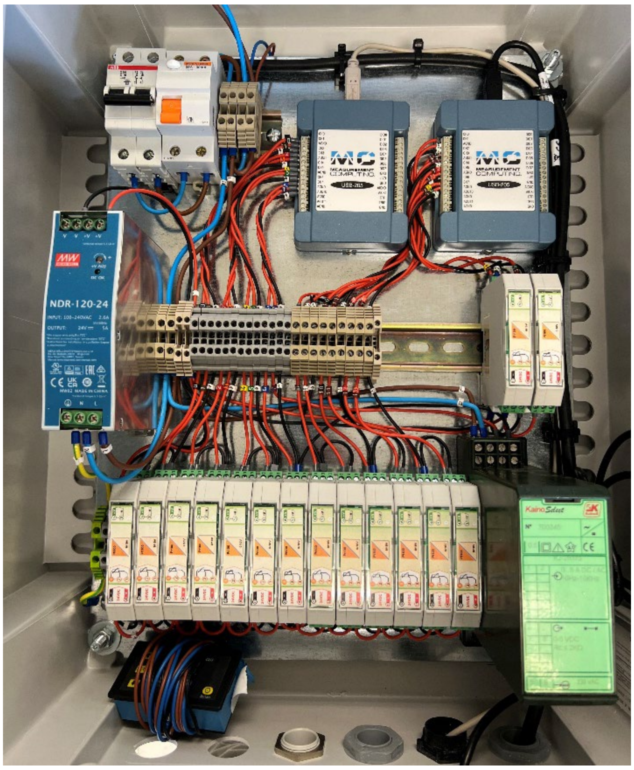
Fig. 4 Data Acquisition System.

5. Data Acquisition System

All temperature sensors, including Pt100 probes and the DTS system, operate independently of the power circuit, yet are time-synchronised via the data acquisition system. All Pt100 sensors are connected to dedicated signal conditioning modules that provide a stable excitation current, linearisation and galvanic isolation. The conditioned signals are acquired using a multi-channel data acquisition unit that is based on a Measurement Computing USB-205 interface.

The acquisition system provides the following:

- Synchronous sampling of all temperature channels.
- Real-time current measurement via a toroidal current transformer.
- Continuous data logging and real-time visualisation.

Fig. 4 shows a general overview of the complete data acquisition architecture, including signal conditioning, acquisition hardware, and communication interfaces.

A custom software application developed in Python handles data acquisition, storage, and visualisation, enabling direct interfacing with RTTR algorithms during experimental campaigns.

The acquisition system provides real-time visualisation of the temperature measurements. Fig. 5 shows an example of the graphical user interface of the acquisition software, displaying the real-time evolution of selected Pt100 temperature channels together with the measured load current.

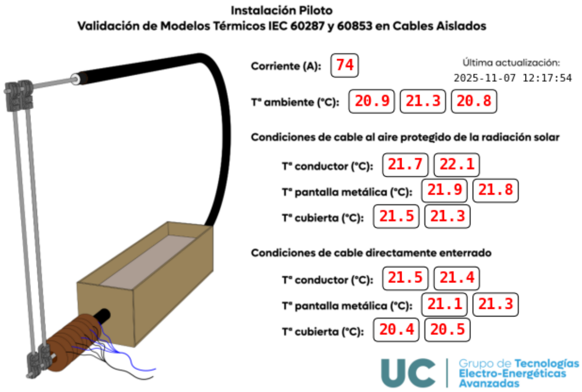

Fig. 5 Real-time graphical interface of the Pt100 temperature acquisition system showing selected temperature channels and load current during operation.

This interface is used during experimental campaigns to monitor sensor behaviour, detect anomalies, and observe transient thermal responses directly during load changes.

6. Preliminary Experimental Tests

Prior to the full RTTR validation experiments, a series of preliminary tests were conducted to verify the correct operation of the laboratory pilot installation, and to ensure that the data acquired was reliable and consistent.

Firstly, sensor consistency tests were performed by exposing all Pt100 temperature sensors to identical thermal conditions to allow verification of measurement coherence and calibration consistency across channels. Secondly, maximum current tests were carried out by gradually increasing the injected current to determine the safe operating limits of the pilot installation and the associated power equipment. Finally, thermal inspections based on infrared thermography were conducted to identify potential hotspots in connectors, supports, and auxiliary components to ensure the setup's safe and reliable operation.

These preliminary tests confirmed both the robustness of the pilot installation and the suitability of the measurement system for subsequent experimental campaigns.

In addition to these basic verification tests, a comparative analysis was conducted to evaluate the accuracy of conductor temperature measurements under various installation conditions. Fig. 6 shows an example of this, combining experimental temperature measurements and numerical results obtained from a simplified finite element model (FEM) of the cable.

The figure includes temperature measurements obtained from Pt100 sensors installed in the vicinity of the buried cable section. These include both 5 mm and 2 mm diameter probes, as well as the temperature of the cable sheath in the buried section. DTS measurements corresponding to the buried cable section are also shown. For comparison purposes, temperature estimations based on the FEM are included for both buried and air-installed cable configurations, while the load current is represented on a secondary vertical axis.

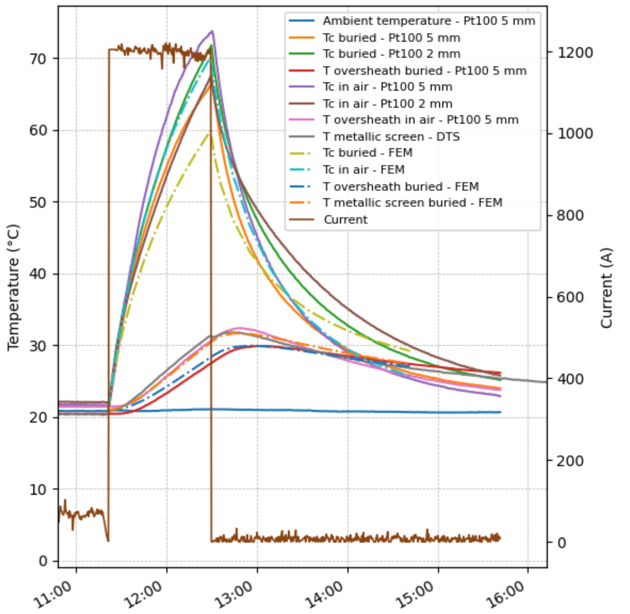

Fig. 6 Comparison between measured and simulated temperatures for the buried and air-installed cable sections, including Pt100 and DTS measurements for the buried section, and FEM-based temperature estimates.

The comparison reveals that the measured conductor temperatures are significantly closer to the FEM-simulated temperature of the air-installed cable conductor than to that of the buried cable conductor. This behaviour suggests that the conductor temperature sensors assumed to represent the buried section are influenced by air installation conditions in the current configuration. Consequently, the actual conductor temperature of the buried cable section cannot be directly measured, but must be inferred indirectly.

This preliminary analysis identifies the primary limitation of the current pilot configuration with regard to measuring the temperature of buried conductors and establishes an experimental basis for the future upgrade outlined in the Section 8.

7. Relevance of the Pilot for RTTR Validation

From an RTTR perspective, the developed laboratory pilot enables several key analyses that would be difficult to perform in real network installations. Firstly, it allows direct comparison of temperatures estimated by RTTR algorithms with temperatures measured at multiple physical locations within the cable, including the conductor, metallic screen, and outer sheath.

Secondly, combining Pt100 sensors and DTS monitoring enables spatial temperature gradients along and across the cable to be assessed. While Pt100 sensors provide high accuracy point measurements with a fast dynamic response time, DTS offers continuous temperature profiles along the length of the cable. This dual monitoring approach is especially valuable for validating RTTR algorithms under non-uniform thermal conditions.

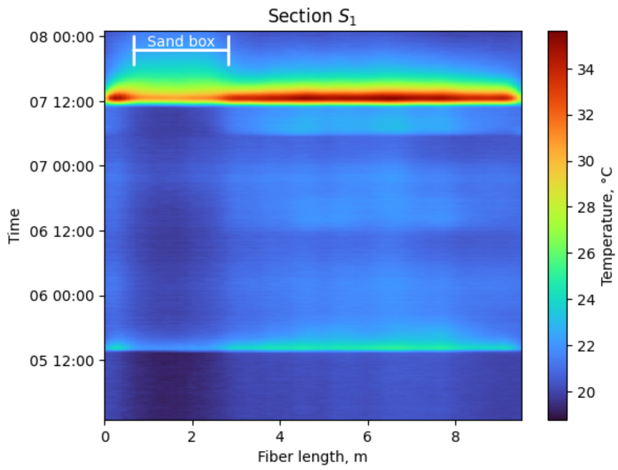

Fig. 7 DTS temperature heatmap showing the cable, with the buried section (sand box) highlighted and surrounded by air-installed sections.

Fig. 7 shows an example of a DTS-based temperature heatmap obtained along the cable during operation. The figure illustrates the distributed axial thermal profile captured by the optical fibres, enabling localised hotspots and boundary effects to be identified that would otherwise go undetected using discrete sensors alone.

Typical results that can be obtained using the pilot include: (i) transient temperature evolution during load changes; (ii) steady-state temperature distributions for different installation conditions; and (iii) a comparison between conservative static ratings and dynamically calculated ampacity based on real-time thermal data.

Although the scope of this paper does not extend to detailed RTTR results, the pilot provides the experimental foundation required to demonstrate the conservatism, responsiveness and practical applicability of dynamic thermal rating algorithms.

8. Conclusions

The developed laboratory pilot provides a controlled and highly instrumented environment for the experimental validation of RTTR algorithms applied to insulated power cables. A key advantage of the installation is its ability to combine discrete, high-accuracy Pt100 temperature measurements with DTS, enabling local and distributed thermal monitoring under reproducible laboratory conditions. The pilot enables analysis of the steady-state and transient thermal behaviour of cables in various installation scenarios, which is crucial for evaluating dynamic cable rating strategies.

The progressive evolution of the temperature sensing system, from an initial configuration of seven Pt100 sensors to a final setup of fifteen sensors, was driven by the need to improve conductor temperature monitoring, particularly in the vicinity of the buried cable section. The initial 5 mm diameter Pt100 probes were too long to be fully embedded within the cable, resulting in the sensing element being partially exposed and the conductor temperature being measured incorrectly. While the introduction of additional sensors and reduced-diameter probes (2 mm) enabled reliable conductor temperature measurements, these corresponded to cable sections installed in air rather than the buried section.

This limitation highlights one of the main constraints of the current pilot configuration. Direct measurement of the temperature of the conductor in the buried cable section has not yet been achieved, as drilling or perforating the cable in this area could damage or sever the optical fibre tubes used for DTS monitoring. To address this, a new development phase is planned, during which controlled perforations will be made in the buried cable section to allow temperature sensors to be installed both on the metallic screen and in direct contact with the conductor. Special care will be taken to preserve the integrity of the DTS fibres during this process.

The laboratory pilot has clear potential applications in the experimental validation of RTTR algorithms, the assessment of conservative assumptions in static cable ratings, and the investigation of transient thermal phenomena under variable loading conditions. Beyond RTTR validation, the installation can also serve as a test platform for advanced thermal monitoring technologies and cable diagnostic methods, supporting future research and development in dynamic cable management and power system optimisation.

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References

[1] IEC 60287-1-1:2023, Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General, IEC, 2023.
[2] IEC 60853-2:1989/AMD1:2008, Calculation of the cyclic and emergency current rating of cables - Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages, IEC, 2008.
[3] CIGRE WG B1.35., TB 640 - A Guide for Rating Calculations of Insulated Cables, CIGRE, 2015.
[4] IEC 60751:2022, Industrial platinum resistance thermometers and platinum temperature sensors, IEC, 2022.
[5] CIGRE WG B1.45, TB 756 - Thermal monitoring of cable circuits and grid operators' use of dynamic rating systems, CIGRE, 2019.