# Real Time Monitoring of Power Cables by Fibre Optic Technologies
# Tests, Applications and Outlook

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**Abstract :** The change in operating conditions of HV underground cable links has led many utilities to consider on-line and/or off-line temperature monitoring via optical fibres. This paper describes the test program and preliminary results obtained on a 400 kV test installation, including various methods of cable installation, different kinds of temperature sensors and the implementation of a real time monitoring system. Simulation of different operating scenarios (steady-state and transient overloading) was performed and the resulting ampacities were evaluated.
The paper discusses the outlook for the application of such monitoring technologies.

**Keywords :** Distributed temperature sensing, dynamic feeder rating.

**Résumé :** L'évolution des conditions d'exploitation des liaisons souterraines HT a conduit de nombreux exploitants à envisager le monitoring en température des liaisons. Cet article décrit le programme d'essais mis en œuvre sur une boucle d'essais 400kV incluant sur son parcours différents modes de pose, différents types de capteurs de température ainsi qu'un système de monitoring spécifique. La simulation de différents modes de fonctionnement (régime permanent et régime de surcharge transitoire) a été réalisée et les intensités résultantes évaluées.

Cet article discute des perspectives d'application de ce type de monitoring.

**Mots clés :** Mesure de température répartie, contrôle dynamique de capacité de transport.

## 1. Introduction

During the lifetime of a buried power cable, typically 40 years, its thermal environment can evolve due to modifications of the network configuration and changes in the local surroundings. This phenomenon is particularly sensitive and difficult to control in urban areas.

The dimensioning of an extruded cable link is governed by the maximum allowable temperature on the cable conductor. If this temperature is exceeded, the lifetime and reliability of the cable circuit can be reduced. This can lead to unexpected premature breakdowns.

Moreover, economic factors are driving utilities to use their cable circuits to achieve maximum allowable ampacity rating, thus using up previously allowed safety margins.

Real time temperature monitoring tools are now available to users, allowing them to maintain network reliability even though the network is being operated harder.

Thanks to the development of distributed temperature measurement using optical fibres, it is possible :

- to monitor the temperatures reached along the entire cable route.
- to compute the maximum acceptable ampacity taking into account the simultaneously measured thermal conditions.

Within the study of new XLPE 400kV power cable, SAGEM, in collaboration with KINECTRICS and SENSA, decided to carry out a study which would compare temperature measurements and ampacity rating calculations obtained according to various protocols.

This paper describes the configuration of the test loop, its instrumentation as well as the specific tests performed during this study.

## 2. Presentation of the test cable loop

In order to be able to draw reliable conclusions from the measurement techniques and calculations used, it was essential to operate this test in a thermal environment which was as controlled as possible. The hereafter described tests were carried out on a cable loop installed in a representative configuration of the network and in a thermal environment of which the main thermal characteristics were known or evaluated according to the IEC standards.

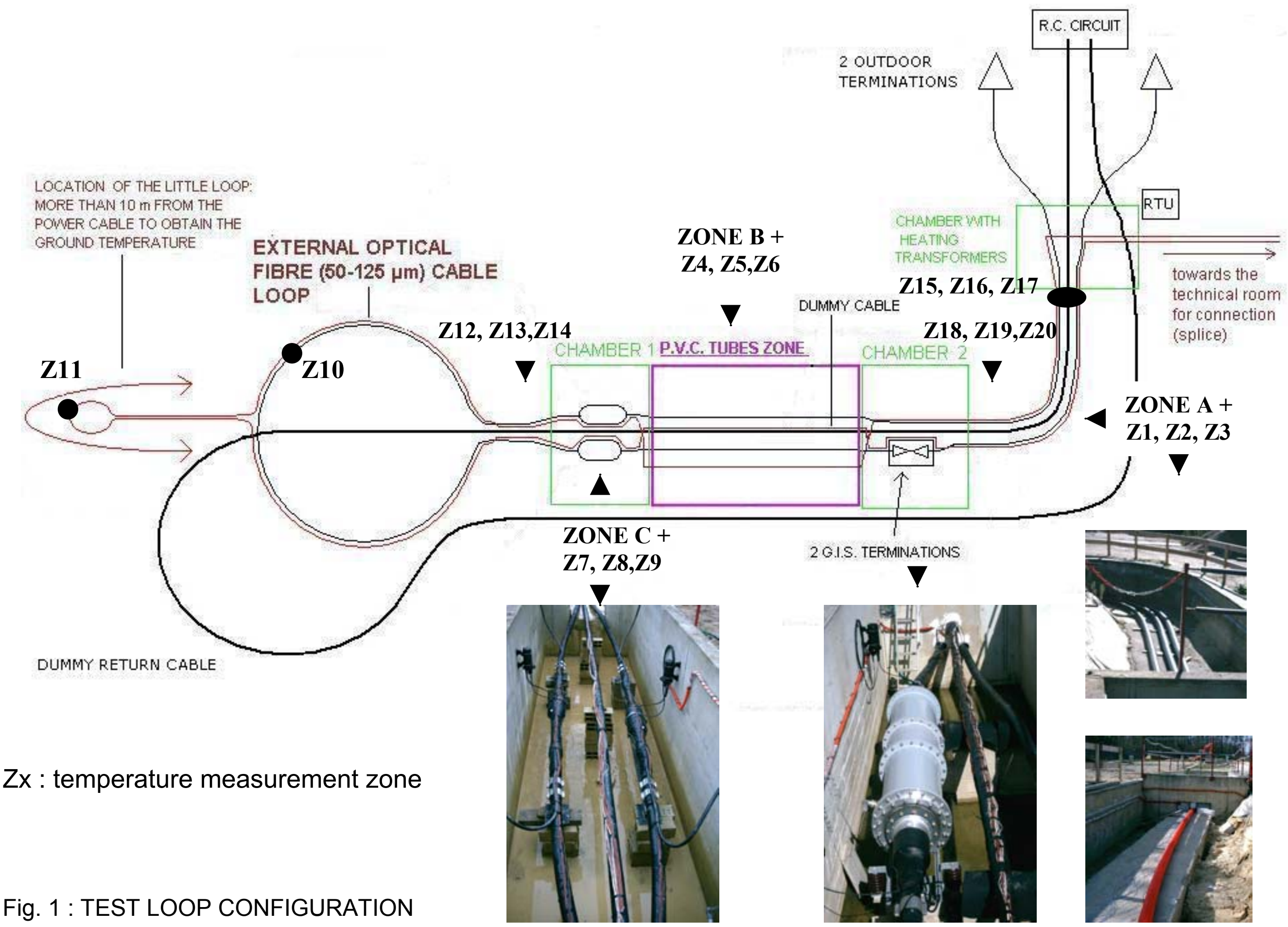
### 2.1 Presentation of the cable, accessories and ways of laying

The test loop, of an overall length close to 200m, includes 2 main circuits :

- a length of cable with voltage applied
- a length of cable, used as a dummy cable, (without voltage applied) and made up of the same cable as that of the loop with voltage applied.

The thermal configuration of this system is equivalent to a three-phase cable system (fig. 1) and various laying techniques are included :

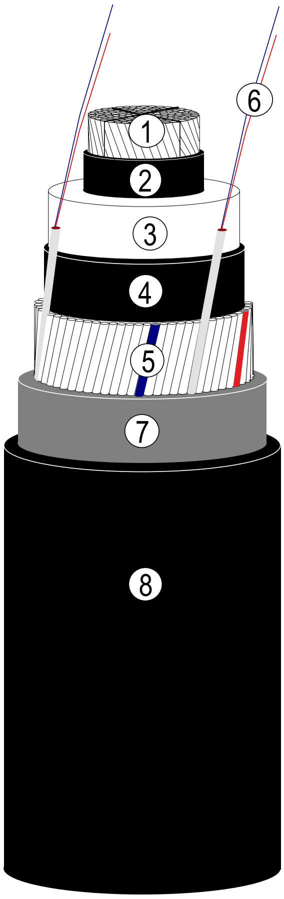
- Zone A : directly buried cable (1,30m under ground surface) laid in flat formation in weak concrete,
- Zone B : cable laid in PVC ducts in trefoil formation. The ducts are embedded within concrete.
- Zone C : joint chamber with cable and premoulded joints, also buried in weak concrete.



Zx : temperature measurement zone

Fig. 1 : TEST LOOP CONFIGURATION

The 400kV XLPE cable used (fig. 2) is made up as follows :



*Conductor* :
① 2000mm² Copper segmented with enamelled wires

*Insulation :*
②,③,④ XLPE

*Metallic screen* :
⑤ aluminum wires
⑦ aluminium foil
⑥ optical fibres within stainless steel tubes included in the aluminum wire layer.

*External protective sheath*

⑧ HDPE over aluminum foil.

Fig. 2 : 2000mm² Copper XLPE 230/400(420)kV

### *2.2.* Temperature sensors

Different kinds of temperature sensors are installed on the test loop. Optical fibre loops are used to measure the temperature profile along the entire cable loop and thermocouples are also installed at specific locations along the cable loop.

As indicated above, 2 stainless steel tubes including optical fibres are positioned in the metallic screen of the test cable. One tube comprises 50/125µm multimode fibres and another tube comprises 60/125µm multimode fibres. The optical fibre circuit is completed with optical splices and terminations.

Positioning of the optical fibres in the cable metallic screen has the following advantages:

- The optical fibres are laid simultaneously with the power cable,
- mechanical protection of the fibre is ensured by the metallic screen and the cable outersheath.
- recorded temperatures are more representative of the conductor temperature because these fibres are closer to the cable conductor, and its temperature response is faster than an external fibre fixed on the outersheath.

In addition to these integrated fibres, another external optical fibre circuit, was laid and fixed on the cable outersheath for comparison purposes. This technique, is an alternative method although it is less sensitive to the changes in conductor temperature.

The dummy cable (without voltage applied) allows accurate temperature measurement, of each zone, on the conductor and on the external sheath of the cable. Thermocouples are used as the reference sensors for checking and comparing the measurements and calculations made by the monitoring systems and various optical fibre loops. The thermocouples used are of a shielded design.

## 3. **Presentation of the temperature and monitoring systems**

### *3.1.* Distributed Temperature Sensor System

Distributed Temperature Sensor (DTS) systems and their application to power cable monitoring have been described elsewhere [1],[2],[3]. Nowadays DTS is widely specified as a condition monitoring and asset management tool when new power cable installation projects are implemented. Typical attributes of an 8 km, multimode DTS system, using double-ended measurement are summarized below:

- Temperature resolution -1$^{0}$ C
- Accuracy - 1$^{0}$ C
- Positional resolution - 1 m
- Hot spot (spatial) resolution - 1 m
- Measurement time (@ 8 km & 1$^{0}$ C) < 2 min

Typically, the temperature data is stored and is available either locally or via a communication connection to a remote site where the complete temperature profile of the cable can be visualized at any point in time. Because there are so many data points collected by the DTS, it is common to divide the cable into a number of zones and to periodically transmit the maximum, average, or rate of change of temperature, within the zones, in to a SCADA system. The DTS can also be configured to close relay contacts associated with settings within a zone. In cable tunnels, it is quite common for the DTS system to provide the combined functionality of a fire detection sensor, tunnel temperature sensor (for ventilation control) and as a power cable monitoring sensor. In these applications multiple fibre loops are sensed, using the internal optical switch of the DTS. Transmission and distribution utilities are recognizing the benefits of continuous monitoring using DTS and are connecting the temperature monitoring system into control, alarm and communication schemes in order to contribute to the automation and efficient operation of the network.

Some of the benefits of DTS can be summarized as follows:

- Providing footprints of cable temperature profiles
- Confirming route design thermal characteristics
- Establishing the position of cable hot spots
- Providing early warning of cable failure
- Enabling network contingency management
- Enabling calculation of enhanced cable ratings

In the majority of DTS systems installed to date, other than alarm and SCADA data, evaluation of the DTS data is done off-line. Some utilities are now looking to increase further the automation of their network and use the data from the DTS for purposes of on-line, real time ampacity rating of cables. This means that for this functionality, the DTS becomes the data acquisition system for the cable rating computation and the output is ratings in preference to temperature.

The system used during the test is a **DTS 800** instrument with a specification similar to that described above. The different optical fibre loops are connected to the DTS in a bay placed in the control room (fig. 3)

### 3.2. Real Time Monitoring System

The real time monitoring system consists of four key modules, the temperature and load current sensing equipment, a data acquisition system, a real time rating system and a display/archival system. A pictorial overview of the system as installed at the test site is given in fig. 3.

The data acquisition system is intended to capture the necessary input parameters of load current and cable surface and soil ambient temperatures for input to the real time monitoring system. The load current is obtained from a current transducer (CT) sensor mounted in a spare metering circuit.

Cable surface and soil ambient temperatures are obtained from thermocouples located strategically along the cable route. A total of 22 temperature monitoring points (fig. 1) were installed on the test loop. All thermocouple and sensor inputs are connected to a single, centrally mounted cabinet housing the data acquisition hardware, as depicted in fig. 3.

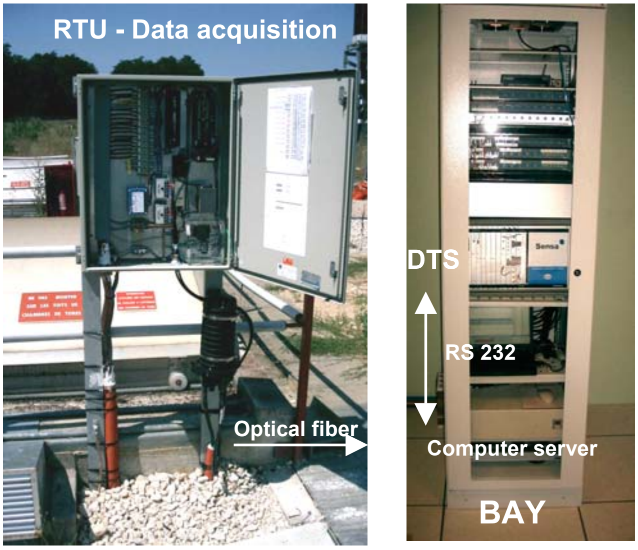


Fig. 3 : Real time monitoring system
RTU - data acquisition hardware placed outdoor
Bay in the control room including
a- DTS 800,
b- Computer server

All current and temperature data is passed to a computer server located in the control room via a fiber optic connection, thereby providing complete electrical isolation.

In parallel, cable surface and soil ambient temperatures are obtained from the DTS equipment described above. A total of 10 locations are being monitored by the data acquisition system. The connection between the DTS and the computer server is made via an RS232 link.

The computer server is the heart of the system, continuously gathering load and temperature data and providing updated ampacity ratings for display and archiving. The server stores the relevant thermal models of the cable loop and performs advanced real time computations to determine the limiting rating of the monitored cross section. The system is presently configured to compute ratings at a single cross section in Zone A (see fig. 1) A facility is also available to download historical information stored on the server.

### 3.3. Modeling of the Thermal Environment

The computational program can perform calculations in real time of steady-state and emergency ratings and can display the computed conductor temperature. Calculation of the steady-state ratings are performed using IEC 60287 procedures [4] with a user-specified step load function. The program can also consider recorded load variations over the last 24 hours and will assume the same variations during the following period. The duration of this period is such that the steady-state conditions are achieved. Time-dependent ratings are based on the method described in the IEC Standards 853-1 and 2 [5]. Similarly as in the steady-state case, two modes of load representation can be considered during the emergency period:

(1) a step function can be applied, or
(2) the load curve from the last 24 hours can be scaled.

During the steady-state and time-dependent calculations, the thermal and electrical parameters of the model are continuously adjusted so that the computed and measured cable surface temperatures match. The computational engine of the Dynamic Feeder Rating (DFR) system permits simultaneous analysis for several cable cross-sections in a multiple cable installation.
The cable design is modeled by taking into account all details pertaining to the conductors and insulating systems and the type of cable construction, addressing thermal and electromagnetic losses. Most parameters evaluated by the engine (for example thermal resistances and capacitances, loss factors, electrical resistances, heat transfer coefficient and air velocity for fluid flows) are calculated for a given operating point, geometrical dimensions and selected material characteristics. The thermal circuit is modeled by an analogous electrical circuit in which voltages are equivalent to temperatures and currents to heat flows. If the thermal characteristics do not change with temperature, the equivalent circuit is linear and the superposition principle is applicable for solving any form of heat flow problem.

## 4. Program of tests

The aim of the tests consists in performing thermal cycles with controlled parameters (heating, cooling cycle duration, induced ampacity rating).
This protocol allows the accuracy of the calculations to be checked.

Two test sequences are proposed :

- one representative of a **steady-state operation**,
- the other simulating a **transient operation**.

The analysis and calculations of ampacity ratings are carried out in the predetermined zones Zx (fig. 1). The maximum allowable ampacity corresponds to that of the hottest zone of the cable route measured by the various temperature sensors (thermocouples, external or internal optical fibre). The values of acceptable ampacity of each zone are also calculated and compared.

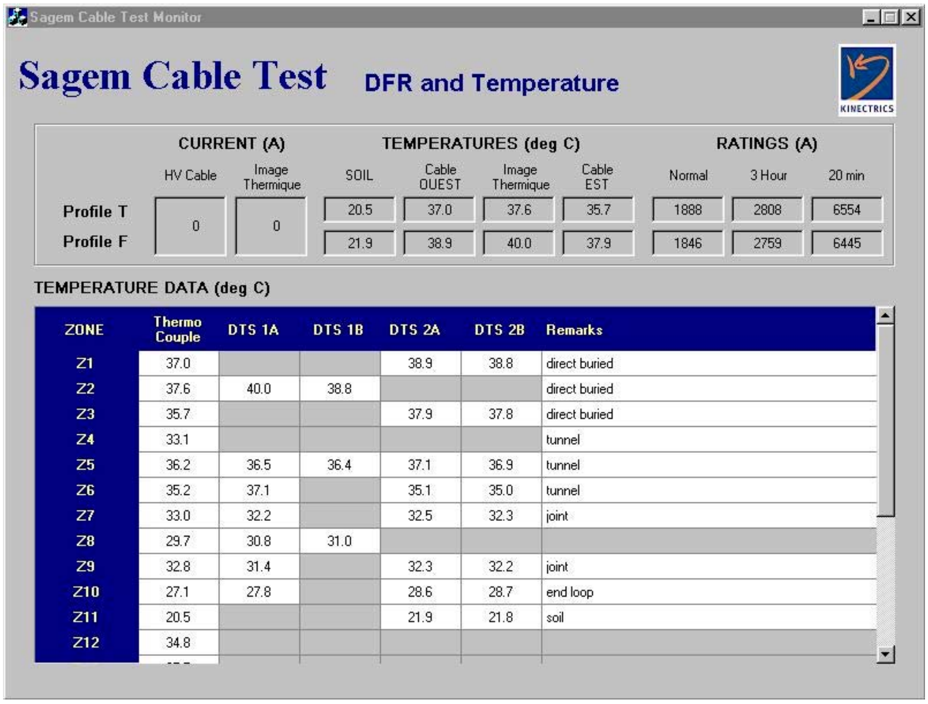
To check the accuracy of ampacity calculations capacity, the so calculated ampacity is then voluntarily induced into the test loop, as in the case of a real time monitoring by software. The temperatures are recorded over the determined duration of the cycle.

The thermal environment of the loop is modelled by the software specifying the geometry and the thermal characteristics of the various components. Those retained for this evaluation correspond to the data appearing in IEC standard.

## 5. Tests results

The tests are still in progress. The full results will be published in a separate document presenting the detail of measurements and conclusions reached.

Fig. 4 is an example of DFR display which shows the zone calculation measurements and rating calculation.



Sagem Cable Test DFR and Temperature

| | CURRENT (A) | | TEMPERATURES (deg C) | | | | RATINGS (A) | | |
|---|---|---|---|---|---|---|---|---|---|
| | HV Cable | Image Thermique | SOIL | Cable OUEST | Image Thermique | Cable EST | Normal | 3 Hour | 20 min |
| Profile T | 0 | 0 | 20.5 | 37.0 | 37.6 | 35.7 | 1888 | 2808 | 6554 |
| Profile F | | | 21.9 | 38.9 | 40.0 | 37.9 | 1846 | 2759 | 6445 |

TEMPERATURE DATA (deg C)

| ZONE | Thermo Couple | DTS 1A | DTS 1B | DTS 2A | DTS 2B | Remarks |
|---|---|---|---|---|---|---|
| Z1 | 37.0 | | | 38.9 | 38.8 | direct buried |
| Z2 | 37.6 | 40.0 | 38.8 | | | direct buried |
| Z3 | 35.7 | | | 37.9 | 37.8 | direct buried |
| Z4 | 33.1 | | | | | tunnel |
| Z5 | 36.2 | 36.5 | 36.4 | 37.1 | 36.9 | tunnel |
| Z6 | 35.2 | 37.1 | | 35.1 | 35.0 | tunnel |
| Z7 | 33.0 | 32.2 | | 32.5 | 32.3 | joint |
| Z8 | 29.7 | 30.8 | 31.0 | | | |
| Z9 | 32.8 | 31.4 | | 32.3 | 32.2 | joint |
| Z10 | 27.1 | 27.8 | | 28.6 | 28.7 | end loop |
| Z11 | 20.5 | | | 21.9 | 21.8 | soil |
| Z12 | 34.8 | | | | | |

Fig. 4 : DFR display example

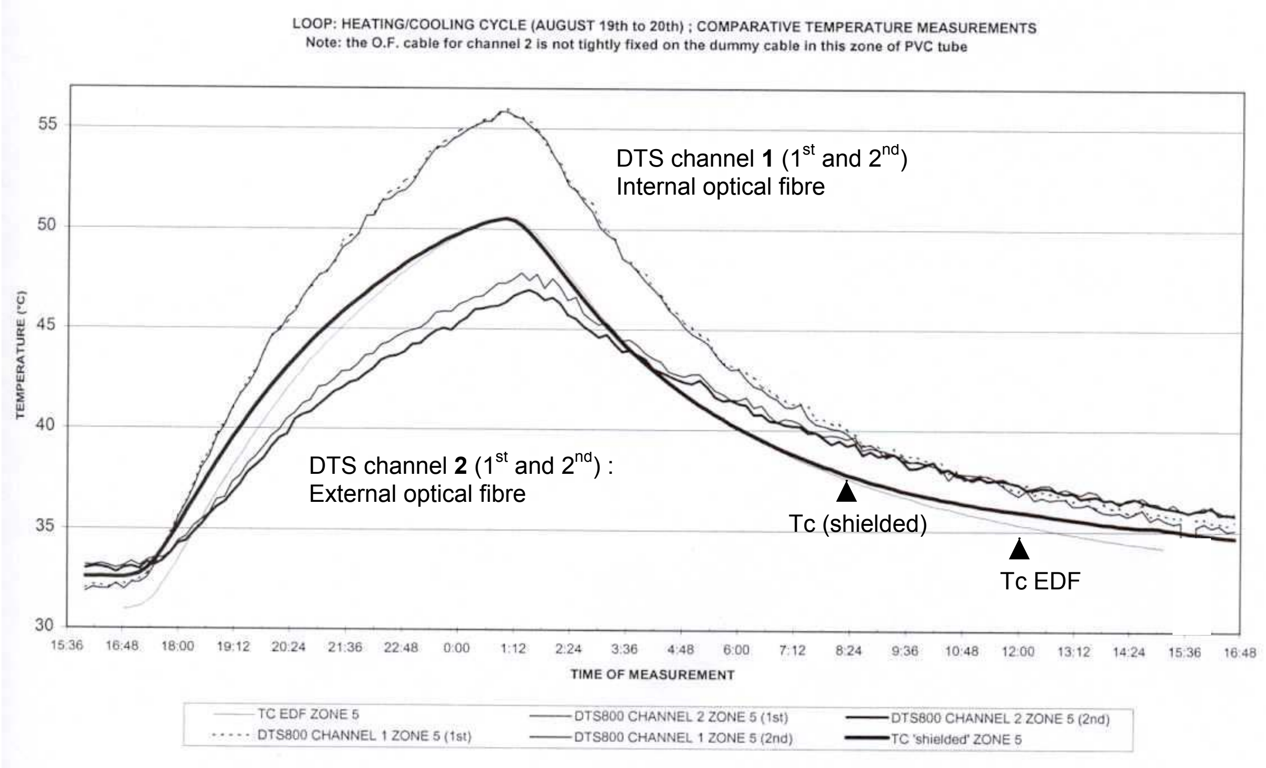


Fig. 5 : Temperature measurements in Zone 5 (PVC ducts ) during a daily heating cycle

Some preliminary results have been obtained with heating/cooling cycles (8 hours on and 16 hours off). producing 100°C on the conductor at the hottest zone of the cable route.

It was found necessary to calibrate the DTS and thermocouple measurements, following initial analysis. There was good correlation between the DTS and thermocouple measurements at the same points along the cable (fig. 5 - cooling period) and the steady state and dynamic ratings were of comparatively similar magnitudes and compared favorably with calculated values.

## 6. Conclusion and outlook

A real time dynamic rating system has been implemented using the temperature values generated from an optical fibre DTS monitoring system. The preliminary results from the measurements and computations are encouraging, however the test sequences have not yet been completed and further results will be published at a later date.

The authors believe that the system described can be used to provide additional benefits over the already established benefits of using distributed temperature measurements for power cable monitoring. The combination of DTS measurement and real time modelling will provide utilities with additional functionality that will further assist with the economic and reliable management of utility networks and interconnections.

## 7. References

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[2] Funnell and Harrison, *"Remote temperature measurement for 132 kV cables",* CIRED, 1991.
[3] Barber, Jansen Nokes, Gatland, "Fibre optic monitoring takes the heat off cables", Modern Power Systems, Dec 1999.
[4] IEC 60287 : *"Electric cables - calculation of the current rating"*
[5] IEC 853-1, 853-2 : *"Calculation of the cyclic and emergency current rating of cables"*

## 8. Glossary

*DTS* : Distributed Temperature Sensor
*SCADA* : Supervisory Control and Data Acquisition
*RTU* : Distributed terminal unit
*DFR* : Dynamic Feeder Rating

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