THERMAL MONITORING OF HIGH VOLTAGE (44kV – 132kV) CABLES

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ABSTRACT

Since the Auckland disaster of 1998, which saw the CBD of New Zealand's capital without power for 21 days due to failure of critical high voltage underground cable links, there has been growing interest in thermal monitoring of cable circuits. In addition, the increasing requirements for better utilisation of existing and future power transmission links has further aided the development of this monitoring/management system based on thermal measurements. This paper indicates the current international trends in this field and includes the progress that South Africa has made over the past year in developing the use of real time thermal monitoring as applicable to local conditions.

A real time thermal monitoring system consists of four main components – the thermal sensor; the measurement equipment; the software package required to capture and view results, consisting of a SCADA controller and a Graphical User Interface; and the software package which manipulates the thermal measurements, via appropriate mathematical models, into meaningful data.

Theory and results, on work done in a laboratory environment and practical work done in the field, on fully operational high voltage circuits, are presented. Although this technology is locally still in its infancy, initial indications are that real time thermal monitoring is an excellent method of demonstrating the potential capability of a cable circuit.

Keywords: Power cables, Thermal monitoring, SCADA, Cable circuit management.

1. INTRODUCTION

The availability of power is increasingly becoming an issue that utilities have to guarantee to their clients. Lack of service has become totally unacceptable and extremely costly. Recent examples include the Auckland disaster of 1998, which saw the CBD of New Zealand's capital without power for 21 days and the black-outs experienced in California in 2001.

In addition, the installation of energy transmission links is an investment that must be exploited to its maximum extent and one which must be economically maintained and utilised for several decades.

In recent years, in response to utility requirements, a thermal monitoring system on underground cable links has been developed. The system, referred to as Real Time Thermal Rating (RTTR), uses thermal monitoring as a basis for calculating relevant operational parameters specific to cable circuits. It can be integrated into an existing SCADA system and utilised to constantly monitor the cable link, thereby avoiding unnecessary outages and maximising cable efficiency.

Being a relatively new technology, with no systems currently installed in South Africa, this paper is intended to give some insight into the operation of the system based on the theory. In addition, economical advantages of the system are demonstrated by means of typical examples and results obtained from installations in various other locations around the world.

2) THE REAL TIME THERMAL RATING SYSTEM (RTTR)

The design and daily management of power transmission links relies on statistical assumptions, based on IEC specifications [3,4], regarding the operating conditions and the thermal environment of the link. This leads to cable systems that are designed with safety margins which do not compare favourably when evaluated against actual thermal conditions and the cyclic nature of the load. Consequently, the large economical investment associated with a high voltage power transmission link is not fully exploited.

In order to increase the link usage, without reducing the safety margins normally assumed, the real time measurement of environmental parameters and circuit loading conditions is necessary. Real time evaluation of the actual thermal conditions and their trends i.e. thermal monitoring, has been developed and installed on several links around the world. The use of this solution has demonstrated that it is possible to dynamically predict thermal instabilities and overload conditions thereby avoiding not only dangerous operating conditions but also unwanted outages.

Integration of the system into SCADA (Supervisory Control And Data Acquisition) has led to an advanced system that significantly aids in the management of a power cable transmission link. Following full scale, long term development tests [1] the RTTR system has gained acceptance with many utilities and is now installed on several operational links.

2.1) Scope of the system

The purpose of the system is to monitor and manage several parameters such as cable temperatures, circuit loads and environmental conditions on a continuous basis. The acquired data is input in to a mathematical model, and together with the physical parameters of the link i.e. geometry, captured into a database. The mathematical model evaluates, in real time, conductor temperature, thermal transients, permissible overloads, steady state ampacities, time to reach the design over temperature, and the moisture content and migration of the soil.

The system can be applied to: directly buried cables; cables in free air; cables in troughs or ducts; cables in tunnels; forced air-cooled cables and submarine cables.

2.2) System Components

The main components of the RTTR system are as follows (see Fig.1):

- the distributed temperature sensor instrument;
- the optical sensor
- the mathematical model;
- the SCADA controller;
- the user interface.

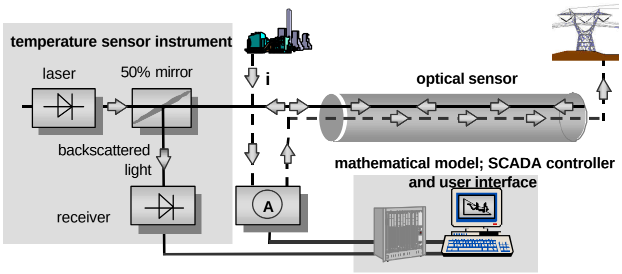

Fig.1 : Components of the RTTR system

2.2.1) The distributed temperature sensor instrument (DTS)

The temperature is measured by means of a commercially available system using optical-fibre sensors. It is based on optical time-domain reflectometry and evaluation of the backscattered light, which is due to several mechanisms including density and composition fluctuations (Rayleigh scattering) and Raman and Brillouin scattering due to molecular and bulk vibrations respectively [2].

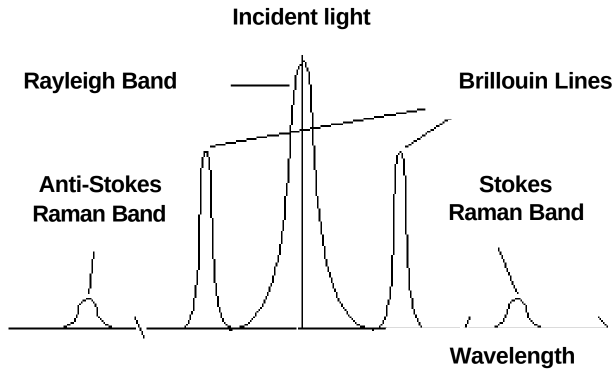

Fig. 2 : The backscatter spectrum

The amplitude of the Stokes and Anti-Stokes peaks correlates linearly to the local temperature of that portion of the fibre that has generated the backscatter. The time of arrival of the backscattered signal is also linearly correlated to the position that generated the backscatter. Combining the two pieces of information allows a full trace of temperature, as measured along the whole fibre, to be obtained.

2.2.2) The optical sensor

Two types of optical fibre can be utilised together with the DTS instrument: multi-mode and single mode fibres. Table 1 shows the different performance parameters associated with the two types of fibres.

Table 1 : Performance parameters of different fibres

Fibre type	Multi-mode	Single mode
Max. length	12 km	30 km
Spatial resolution	0.25 - 1 m	4 – 10 m
Temp. resolution	± 0.2 °C	± 0.5 °C
No. of fibres	8	4

The approach to fibre placement varies. Placing the fibre in the conductor is not possible due to practical limitations during manufacture, jointing and terminating, and the voltage at which cable systems, equipped with DTS capability, normally operate.

Whilst having the fibre as an integral part of the power cable, other than in the conductor, does have its merits, problems such as how the fibre is treated in joints and terminations as well as interference with the integrity of the power cable, should a problem occur on the fibre, arise [8].

Experience has shown that the best position for the sensor is in fact on the outside of the cable, housed in a stainless steel or polyethylene tube (Fig. 3).

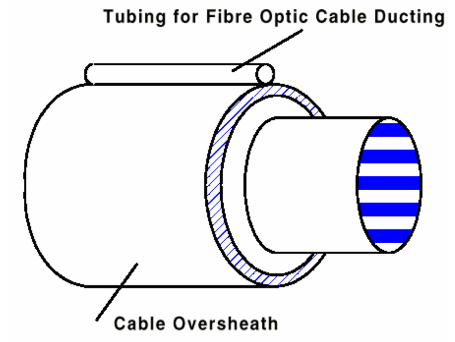

Fig. 3 : Schematic showing tube on the outside of the cable

2.2.3) The mathematical model

The monitored cables' status and thermal transient behaviour is continuously evaluated by means of an on-board mathematical model. The developed model is based on the IEC 60853 [3] and IEC 60287 [4] specifications where the algorithms have been upgraded and improved to take advantage of the real time capabilities and of the nature of that particular application.

The mathematical model is applied over the entire length of the power cable transmission link. Links are modelled by considering them as compositions of sequential lengths, described by common thermal behaviour. Each individual length's thermal behaviour is represented by a well-defined physical and mathematical model i.e. the model for tunnels is used where the cable runs through a tunnel. Worst case areas, commonly known as hot spots, on the monitored link, are used as load and boundary conditions for the sequential representation of the link, and for each one of the identified typical lengths.

To illustrate, consider a length of cable, between two adjacent joints that is buried in a constant characteristic soil. The worst operating condition in that part of the link, acquired in real-time and automatically identified by the system, is entered into the relevant mathematical model of that length to work out all evaluations. In parallel, a statistical analysis of the overall link is also performed. This method not only identifies the worst case but also any discrepancies in data received between each individual length of the link.

If too large a variation is monitored on the same part of the link then warnings and suggestions are issued to the user, in order to improve the knowledge on that particular part of the circuit. It is possible to generate a more precise analysis by adding "control" sections where large variations are present; this function can be performed while the system is running under normal operation.

As an example, this feature would be used when concentrated losses arise, possibly due to the appearance of a ferromagnetic object buried in close proximity to the cables, or a change in the environment due to a new building located close to the power cables. A localised discrepancy compared against average values, in that length, will be recognised by the system software. It is then possible to select a new length of section (dividing the actual existing length into multiple parts) in order to perform a more precise analysis in that particular length. The new analysis can be carried out using customised mathematical models that take into account the additional heat generated due to the increased localised cables losses or the modified cable environment. The system can therefore be easily adapted to changing operating conditions, unexpected events and post installation incidents.

2.2.4) The SCADA controller

The SCADA controller provides the interface to the system for both local and remote users. The controller is fully modular and upgradable to suit any particular installation. The system autonomously performs a wide range of functions that can be activated, disabled or upgraded, in real-time, according to various operator needs or requests or following changes in network operational policies.

Further to the already discussed data acquisition from the set of sensors, and the calculation by means of the mathematical models, the controller performs the following additional tasks:

- data validation and storing into the real-time database;
- alarm generation to highlight dangerous or above limit conditions;
- historical archiving of relevant trends;
- statistical analysis of historical data;
- data routing between different units and users;
- power transmission link control.

Fully automatic start-up and cold restart capabilities have been developed and embedded into the system as well as safekeeping procedures in order to improve overall reliability. Other activities which are possible during the normal course of operations include:

- remote connection into the system by mobile users;
- remote data visualisation;
- remote control of network operations.

2.2.5) The user interface

The man-machine interface (MMI) consists of a real time Graphical User Interface (GUI), an alarm server and historical data displays. The GUI is customised for the end-user's particular application and enables displays of the cable system capabilities.

As an example of the GUI, Figure 4 shows the screen containing the main data for four monitored cable systems. This monitoring system was the first commercially installed plant equipped with a thermal monitoring system [5,6]. The following data is displayed:

- the present load (measured current)
- the maximum admissible continuous load under present conditions (ground temperature and thermal resistivity)
- the admissible overload currents for 5h, 3h, 1h and 0.5h duration
- the calculated conductor temperature
- the time to achieved the admissible conductor temperature with the present load
- the maximum temperature within the optical-fibre.

The alarm server is capable of managing and generating graphical and visual alarms to warn the operator of dangerous or unusual conditions and of trends tending towards customer pre-set thresholds. All alarm statuses are stored on-board into a dedicated alarm historical archive for off-line analysis in terms of procedural control and contingency recovery.

The historical data displays enable the performance of on-line or off-line analyses of stored trends. Since all data access is performed on the client server, the user can request a connection through a dial-up remote connection and visualise, analyse and download any data required.

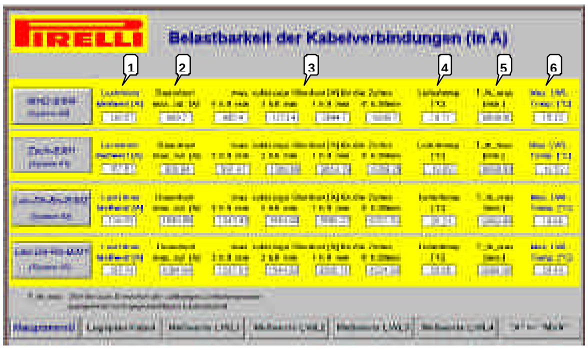

Fig. 4 : Main display of the MMI

3) OPERATIONAL EXPERIENCE

During more than 5 years of field operations, in five different locations, the system has demonstrated the capability to calculate the desired information with a high degree of accuracy.

Typically, conductor temperature is calculated to within 1°C of its value (measured in field trials by appropriate sensors) [1]. The experience gained has enabled the successful introduction and demonstration of RTTR in live HV cable systems and will gradually develop an understanding of real cable environments as compared to theoretical designs.
An example of the value of RTTR has been where the system clearly indicated that the bottleneck in a transmission link was never due to the cables but instead due to the transformers that supplied the cables. The transformers are to be up-rated and the overall link transport capability thereby increased by more than 60%.

As an additional example, Fig. 5 shows a typical working day demand and a possible increase in energy demand due to new customers or additional requirements. The main circuit feeding this area is working close to its limit according to the “worst case” design criteria. The basic daily energy demand is 3680 MWh, the extra demand is 360 MWh per day. It is a difficult decision to accept the extra demand under these conditions and the investment associated with a new circuit has too long a pay back period.

By monitoring the circuit and associated environmental conditions accurate predictions can be made based on circuit performance. The decision to accept the extra demand can therefore be taken with virtually no additional risks. In addition, as an example, assuming a net margin of R50/MWh, at an increase of 360MWh per day, an extra profit of R18 000 per day can be generated.

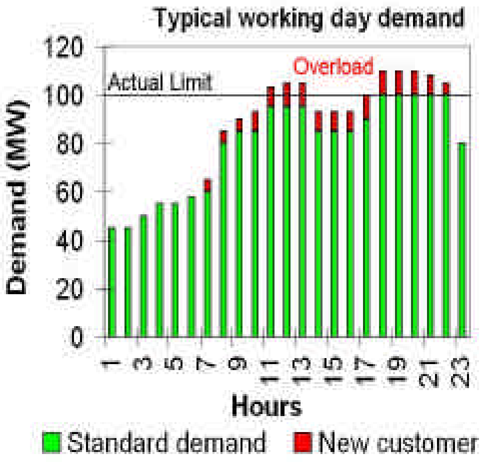

Fig. 5 : Additional energy demand

4) SOUTH AFRICAN EXPERIENCE

In South Africa several large municipalities and the major utility are considering the use of real time thermal monitoring in order to improve the performance of their assets and to increase their reliability. A complete system design including financial implications has been determined for local conditions. At the time that this paper was written, the first commercial installation of fibre optic in a stainless steel tube, strapped to the outside of a 132kV cable was proceeding. A 150m length of cable was chosen in order to perform the initial research.

In addition to the above, a preliminary study of fibre temperature measurement on installed cables, has been carried out on a cable in a tunnel. This involved application of an unclad multi-mode fibre to an 88kV cable. At the start of the tests the loading of the cable was however very low and the thermal profile did not significantly vary from the ambient temperature. Future testing is however planned.

5) CONCLUSIONS

The increasing requirements and specifications for a better utilisation of power transmission links, both existing and future, has in recent years led to a growing interest in advanced SCADA systems to analyse the status of and to control cable links.

An appropriate system has been developed with the capability to monitor cable and accessory temperatures, environment temperatures, cable load currents, voltages and other relevant parameters and thereby to effectively manage the operation of the cable circuit.

The developed system, after being successfully tested and validated in full scale, long term tests has been applied to several existing links employing a variety of laying conditions thereby demonstrating its applicability and advantages. The use of the monitoring system, apart from the obvious economical and reliability aspects in daily operations, enables the user to gain insight into the real time behaviour of monitored links.

The additional investment needed to install a RTTR system appears, after initial field experiences, to be acceptable and limited to a small percentage of the cost of the cable circuit. At the same time the demonstrated gains in daily rating, not considering the increased security obtainable with advanced monitored links, enables a very short pay back period.

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