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OPTIMIZATION OF POWER TRANSMISSION CAPABILITY OF UNDERGROUND CABLE SYSTEMS USING THERMAL MONITORING

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REPORT OF CIGRE WG B1-02

Optimization of Power Transmission Capability of Underground Cable Systems using Thermal Monitoring

Prepared by CIGRE WG B1-02

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1 INTRODUCTION

The application of thermal monitoring of underground cables, as a means of safely maximizing the transmission capability of cable networks, is growing.

Historically, underground cable systems have not generally been loaded to their design ratings. This situation is changing and cable systems are likely to be more heavily loaded in the future as Utilities work their systems harder and make more use of their assets.

Although rare, there have been examples of failures within cable systems that have been operated above their maximum operating temperatures.

Increased congestion of services are having an impact on circuit ratings arising from closer proximity of other circuits and other heat sources. Changes in depth due to construction activities can also reduce ratings. Lack of understanding of the external thermal environment, including inadequate attention to the thermal backfills etc. present further risk to the performance of underground cables.

Continuous monitoring of cable temperatures can reduce or even eliminate this risk. As a consequence, temperature monitoring systems are being installed with new underground distribution and transmission cable systems. Retrofitting of such systems would also be of great interest but complete distributed monitoring is unfortunately not practical. Consideration should be given to discrete instrumentation at the locations of interest.

The output of such monitoring systems is now being used in conjunction with other parameters to forecast and provide guidance regarding the short term overload capability of cable circuits under emergency conditions.

At the CIGRE Study Committee 21(HV Underground Cables) meeting held in October 1999 it was agreed that a task force be established to review the need or otherwise to form a working group on the subject of 'Thermal Monitoring of Underground Cables' and to establish the terms of reference if appropriate.

Subsequently a Working Group was agreed and formed in August 2000.

Terms of Reference

- To review the existing and emerging technologies and applications of underground cable monitoring systems in order to provide a better understanding of the capabilities of the equipment and associated software to enable users to make a more informed selection.
- To make recommendations regarding the utilisation of temperature monitoring and dynamic rating capability.
- To make recommendations concerning any areas of uncertainty or risk (hardware, interfacing, accuracy etc.) in order to facilitate the continued utilisation.

- The scope of the WG would cover both MV and HV applications. Both temperature monitoring aspects and dynamic rating capability should be considered.

There are many potential benefits arising from the ability to measure the temperature of the cable route using cable thermal monitoring systems;

- Capital Expenditure deferral
- Safely maximise utilization of the circuit
- To make use of the cyclic and emergency rating capability
- To drive alarms and other systems such as cooling
- Detect hot spots and any changes to the environment

The actual position of the thermal constraint that limits the circuit rating can be located (e.g. close proximity of other circuits) allowing remedial action to be taken if appropriate. Any changes in the thermal environment effecting the rating can be monitored, such as increased burial depth resulting from the construction of a new road.

This report is aimed primarily at the User and reviews the technologies currently available. Results of a survey provide some indication regarding the current utilization of both cable temperature monitoring and dynamic cable rating systems. Some recommendations are proposed in connection with the application of these systems and identifies possible future development trends.

2 CURRENT TECHNOLOGIES

2.1 CABLE THERMAL MONITORING (CTM)

Temperature is one of the most important physical data to be monitored for real time rating of underground cables. In fact, the cable temperature should be known, with reasonable accuracy, at any moment in order to calculate the projected maximum current-carrying capacity, given the operating and ambient conditions. The best and most accurate thermal rating is based on monitoring directly the conductor temperature under voltage. This would eliminate any uncertainties related to the correlation between the measured temperature, if it is not that of the conductor, and the conductor temperature itself. Direct conductor temperature measurement is mainly used in research and testing facilities and is applied easily in oil-filled cables where the temperature sensor (thermocouple, optical fibre etc) is inserted inside the oil-channel. The wires exit the cable at the terminations where the data acquisition system is located. The signal is transmitted to the control room by infrared beams or by any other means outlined in this guide. Due to its limited application, this technique is not detailed in this guide. Only indirect conductor temperature measurement is considered, where the sensors are installed nearby or at the cable surface. In any cases, care should be taken to insure that the measurement is at the hot spot location, a position that often changes with time.

A thermal monitoring systems consists of two major components: the sensor that generates the signal and the peripheral equipment that conditions the signal and transmits it to the user in readable format. In the following, the most commonly used temperature sensors and their peripheral equipment are described with their advantages and limitations. Outlined also are the various methods of sensor attachment in new and retrofit installations, the discrete versus distributed temperature measurement and some of the precaution to be taken in temperature monitoring in general.

2.1.1 Discrete Temperature Monitoring

Temperature sensors could be classified in three distinct categories: those that measure temperature by mechanical or chemical effects; those that measure by electrical means and those using optical effects. The sensors of the first category operate on the basis of changes in mechanical dimension or in colour with changes in temperature. The liquid-in-glass thermometer is a classic example of such sensors. Their use in cable temperature monitoring is not recommended, for obvious reasons. Description of such sensors is not included in this guide.

Thermocouples

Thermocouples are the most frequently used temperature sensors. They are very rugged, inexpensive and could operate, with reasonable accuracy, over a wide temperature range. A thermocouple is created when 2 wires of dissimilar metals are joined together at one end. The contact point produces a small open-circuit voltage as a function of temperature. This thermoelectric voltage is known as Seebeck voltage, discovered by Seebeck in 1821. Temperature measurement by thermocouples requires some form of temperature referencing commonly called cold junction. The old practice consists in maintaining this junction at 0°C in an ice-water bath. Nowadays, electrical hardware and software embedded in the measuring instruments are used to create electronically this reference point. Thermocouples are designated by capital letters. Type T made from copper-constantan and type J (iron-constantan) are the most frequently used thermocouples in day to day applications and are quite suitable for cable temperature monitoring. In underground cables systems, the T-type is recommended to avoid corrosion problems that can occur with the J-type (iron oxidation gives bad contact and thus fault indication of the contact voltage).

Over voltage protection

The head of a thermocouple, being in the vicinity of an important voltage source, may cause an important potential rise at the data acquisition systems in case of cable failure, lightning or any other perturbation. The majority of acquisition systems are protected to withstand a certain level of voltage ranging from few volts up to several hundreds. A thermocouple transmitting higher voltage may lead to the failure of these costly equipments. A practical method to eliminate these hazards consists of installing non-linear resistances (Transient Voltage Limiter) on both leads of the thermocouple before connecting them to the measuring device. These resistances are usually installed in a junction box and properly grounded.
In the laboratory a disconnect switch may be inserted for additional protection.

Peripheral equipment

Any instrument capable of reading low DC voltages (on the order of millivolts) with 5 to 10 μV resolution is suitable for temperature measurement with thermocouples. The output voltage is highly non-linear and depends upon the difference between the measuring end and the reference end of the thermocouple. The Standards NBS-125 and IEC 60584-1 provides tables describing the correlation between voltage and temperature for various types of thermocouples. Data acquisition systems approximate the data in these tables by using power series polynomials.

Low-level thermocouple signals are very susceptible to noise corruption. The wires of the thermocouple act like an antenna and pick up unwanted noise from the environment. It is therefore important that the monitoring systems be designed to minimize outside noise. This disturbance could also be minimized by carefully shielding and twisting the wires and by adapting various configurations of guarding and filtering. Details of these precautions are found in the catalogues of various manufacturers . It should be noted that, with all the precautions and protection measures taken, the length of thermocouple wires rarely exceed 100 m in real life applications. It is recommended to keep the distance between the measuring head of thermocouple and the acquisition system as close as possible and to transmit the measured temperature data to the user by other means as outlined in the Data Communication Section of this guide.

Resistance Temperature Detectors (RTD)

These temperature sensors are made of fine wires or thin films metallic elements whose resistance increases with temperature. A small current (AC or DC) is circulated through

the sensor and its resistance is measured. The temperature of the sensors is then deduced using available tables or calibration equations specific to the type of RTD used.
Unlike thermocouple, an RTD is not self powered. The fact that a current must be passed through causes Joule (RI^2) heating within the RTD. This self-heating could corrupt the measurement and lead to errors.

RTD's are somewhat more expensive and more fragile than thermocouples. They are, however, more precise and more stable. In the field of cable temperature monitoring, these characteristics do not procure any substantial advantages over thermocouples. The reason is that a temperature resolution of more then ±1°C is rarely needed, a level of precision well within the reach of any type of thermocouples. Due to their fragility, RTD's are usually encased in steel tubing or potted in epoxy. The additional protection makes them less suitable to record transient events due to their increased time constant. Similar peripheral equipment is used to condition the signal like in the case of thermocouples, with the addition of an external power source to inject the necessary current through the RTD.

Thermistors

Thermistors are temperature-sensitive resistors made from semiconductors or metallic oxides, whose resistance varies inversely with temperature in a highly non-linear manner. They are used frequently where high accuracy is required (up to 0.001 °C). This is far too precise for cable monitoring needs. Thermistors are generally perceived as being fragile and more expensive than thermocouples. This is not necessarily the case and robust cost effective devices including appropriate data loggers can be found. They also require an external power source and some form of mechanical protection. They must be carefully mounted to avoid crushing or bond separation. Peripheral equipment identical to the RTD's is used to condition the signal and evaluate the corresponding temperature.

Optical sensors

These types of sensors are popular for temperature measurement in places where harsh environment with high electromagnetic interference (EMI) and radio-frequency interference (RFI) exist. They could also be used to monitor temperature under voltage. They are classified into 2 categories: single-point or discrete temperature measurement and distributed temperature measurement.

Discrete optical sensors

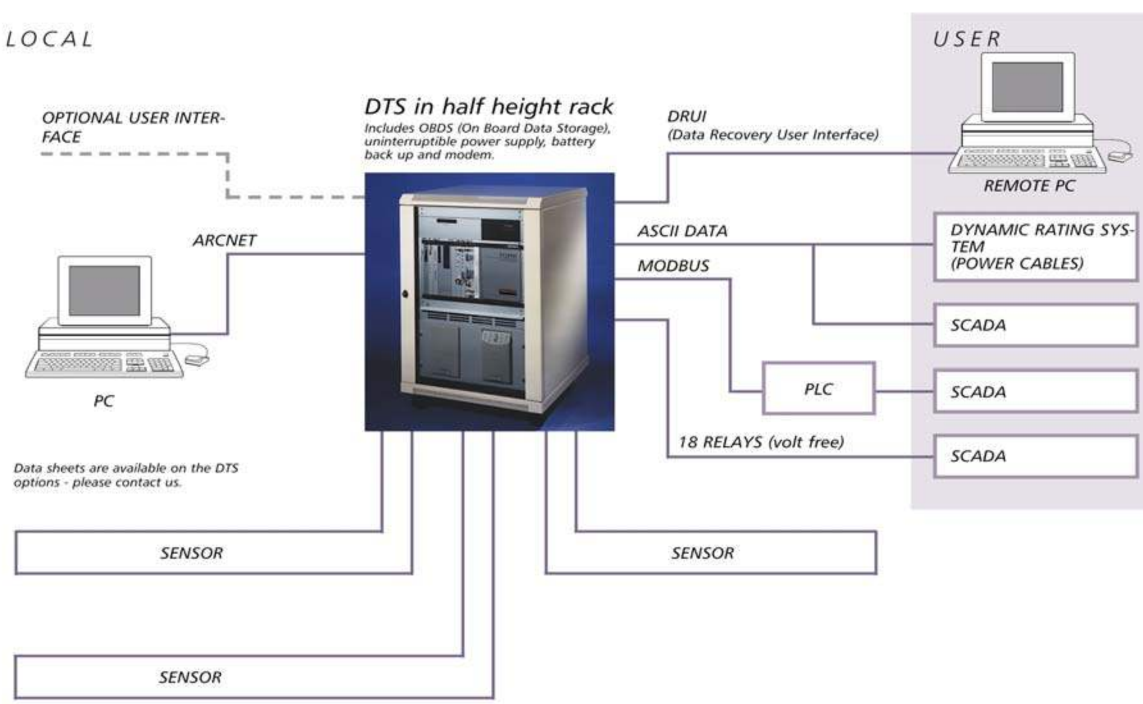
These sensors are made from an ordinary optical fibre with a semi-conductor crystal placed at the measuring end. The principle of operation is based on the light absorption by the crystal and its dependency on temperature, a phenomenon that is well understood and documented for various types of semi-conductors. They are becoming more and more popular for temperature monitoring of electrical equipment, especially for transformer top-oil and winding temperature. Their use in cable monitoring is on the increase due to their resistance to EMI and RFI and to their ability to measure the temperature at a location far away (up to 1 km) from the monitoring system.

Peripheral Equipment

The measurement device consist of an Electro-luminescent diode that injects light into the optical fibre coupled with an acquisition system that analyses the reflected wave from the measuring head and interprets it in the form of temperature. Thanks to the great advances achieved lately in optical science, these devices are now much smaller in size and cheaper than what they used to be few years ago.

2.1.2 Distributed Temperature Monitoring (DTM)

The Distributed Temperature Monitoring systems (DTM) or Distributed Temperature Sensing (DTS), represents the major trend in cable temperature monitoring nowadays due primarily to their abilities in identifying the critical hot spot locations along several km of cable route. The sensor in these systems is the fibre itself, which actually replaces thousands of individual discrete temperature measurements, spaced uniformly along the cable route, with the additional benefit of not having a data transmission device to link each one of them to the peripheral equipment. The principle of operation is generally based upon optical time-domain reflectometry or optical frequency domain reflectometry. Pulses of laser light are launched into the fibre at different time intervals (OTDR) or laser light is launched at variable frequency (OFDR). At each point along its length some scattering takes place, which varies with changes in local temperature. Part of these reflections (Raman back-scattered light) is analysed to produce the temperature profile that is continuously updated and displayed on the computer screen.



Schematic of DTM System

DTM system has 3 major components:

- Optical fibre
- Optical-electrical processing unit
- Controller

Optical fibre

Optical fibre is made of a silica glass with certain dopants added. This material could withstand extreme temperatures (below –100°C and above 500°C). The non-glass coatings that are required to preserve the fibre strength determine the actual temperature range limitation. Coating technology is available to cover a range from -100°C in case of acrylic to temperature as high as 460°C with metallic coating. In the case of underground cable monitoring a fibre with acrylic coating can be used allowing for a permissible temperature range from –20°C up to 75°C on the basis of continuous operation and up to 150°C for short time.

The optical fibre is the sensor that provides the data to constitute the temperature profile along the entire fibre length. We can distinguish the use of two types of fibres :

- The multimode type (standard CCITT G651)
- The single mode type (standard CCITT G652)

The single mode type is a standard long-distance telecom fibre. It has a very low attenuation enabling the system to monitor for longer distance. This is achieved to the detriment of spatial resolution and accuracy. Compared to multi-mode, the single-mode fiber has a very weak backscattered signal, which lowers the reflected power that can be measured. It provides noisier measurement, lower spatial and temperature resolution and requires longer measurement time. On the other hand, the multi-mode fibre could achieve a 1°C resolution and a 1 m spatial resolution to a distance up to maximum 10 km whereas, with single-mode fibre the average performance is in the order of 2°C and 10 m, to a distance of 30 km. (See also definition of spatial resolution in Glossary of Terms)

Fibre loss has an impact on the quality of the signal and on the effective range. The loss arises from the scattering and absorption of light within the fibre core and from outside sources, namely, the connectors and splices, the presence of tight bends and excessive heat or mechanical damage. Where possible, fusion splices rather than mechanical splices should be made to minimize losses. In practical situation, a cumulative loss of 20 dB in double ended measurement and 10 dB in single ended measurement is considered the limit to maintain temperature accuracy within acceptable measurement time limits.

The operating temperature of the system is limited by the connectors: - 40 to + 85°C
Typical value of attenuation in a DTM link at ambient temperature of 20°C are as follows:

Type of fibre	Wave length (nm) of the laser	Typical dB/km	dB/Splice	dB/Connector
Multimode	1064	1.00	0.05 dB	0.4
Single mode	1450 or 1550	0.22 or 0.32	0.05 dB	0.4

Specifications on Test Conditions: IEC 874-1

The Distributed Temperature Sensor, DTS, is based on monitoring the Raman backscatter component along an optical fibre. The intensity of the backscatter increases with temperature and with increasing germanium in the optical fibre core region. The anti-stokes component of the Raman scattering is sensitive to temperature and is used as a monitor. For short distance links, up to around 10 km, multimode standard graded index fibre is used and a spatial resolution of about one meter is possible in double or single ended operation. For longer lengths, where optical loss of the monitoring link becomes a problem, lower loss single mode fibre is used and up to 20 km, with a resolution of 5 meters, is possible with single end processing. Up to a 30 km link is possible but with only a 10 meter resolution. Resolution can be improved by reducing the input pulse-width and hence its power, so that only shorter distances can be monitored.

Single mode standard telecommunications silica fibre has a raised index core region doped with germanium. The minimum optical loss of telecom fibre can be improved by reducing the doping level of germanium in the core and decreasing the cladding region index, by doping with fluorine, to maintain the guide. Another reason to reduce the germanium doping levels in the core is to reduce non linear effects that occur at higher input power levels. These can cause interference between adjacent signals in a multi-wavelength, WDM, system and reduce the signal to noise ratio. There are many different types of fibre profile for different applications: non-zero dispersion shifted fibre, large core fibres to reduce non-linear effects by spreading the power over a wider area and segmented core fibres.

For the application of the DTS a standard telecommunications fibre is required with a constant mode field diameter and germanium content to provide reproducibility, to avoid splice loss at joints and artificial non-uniformities in the monitoring backscatter trace.

Special fibre coatings are not required for this application, the temperatures being below 75 C. Ageing of the fibre is not perceived as a problem provided that protection of the fibre against moisture and hence premature ageing is required and the fibre should be installed in such a manner to avoid mechanical strain.

Optical-electrical processing unit

This is the main component of a DTM system. It houses all the hardware and part of the software needed to generate, transmit and receive the light signal. The major parts are:

- The laser source, the detectors for returning signals and the optical switch if needed;
- A data acquisition system;

- A microprocessor and memory card to complete the signal processing into a temperature versus distance trace;
- A communication card to interface with the external controller.


DTS Cabinets

Controller

DTM system includes a built in or an external controller, usually a portable PC that is used to interface with the user and to generate DTM commands for the optical-electrical processing unit and to communicate with it. Its major role is:

- Provide an interface to select the parameters needed to drive the instrument;
- Receive and display alarm messages generated by the instrument;
- Create and transmit command sequences to the instrument;
- Display the temperature profile along the fibre length;
- Store pertinent data for later use (temperature profiles, max and min, alarm messages, etc.).

Performance and Limitation of a Distributed Cable Temperature Monitoring

The performance of a DCTM system is linked to the particular instrument used and to its opto-electronic characteristics. A part of this performance could be controlled by the user when designing and installing the system or when setting up the parameters. The major questions and issues that surface when performing temperature measurement with DTM are related to the maximum distance along which temperature measurement could be achieved satisfactorily, to the spatial resolution and to temperature accuracy and resolution.

Maximum distance

The maximum distance in distributed temperature sensing is limited by the losses and power budget in the fibre above which the temperature cannot be measured to a given resolution in a given time. Distance gives rise to a basic attenuation determined by the fibre quality and the presence of other optical accessories. It also limits the pulse repetition frequency of the pulses launched by the laser. While single-mode fibre allows for longer range compared with multi-mode fibre, the latter is more suited for resolution and accuracy. The majority of commercially available systems guarantee a spatial range of 30 km with single-mode, single ended fibre and up to 10 km in multi-mode, close loop fibre.

Spatial resolution

The spatial resolution of a DTM based on OTDR technology is governed by the pulse width of the laser source and by the type of fibre. Current multi-mode fibres have a larger bandwidth, which could maintain a spatial resolution of 1m over 10-km distance when using a narrow pulse in the order of 10 ns. Considering that extra processing do not improve the spatial resolution, it is still possible to refine the positioning of samples by means of two techniques: fibre coiling and measurement interleaving. Wrapping a fibre around an underground cable or coiling it along its surface could reduce the axial spatial resolution down to few centimetres. The other technique consists in increasing the sampling frequency by adjusting the sampling start time on successive measurements. Readings are recorded for positions along the fibre, which lie between the previous readings. 2-way interleaving could for example detect any hot spot to the nearest 0.5 m instead of 1 m by doubling the effective sampling frequency. A 4-way interleaving further improves the spatial resolution down to 0.25m.

Temperature accuracy and resolution

The fidelity of a temperature measurement is defined by 2 parameters, namely the temperature accuracy and the temperature resolution. The accuracy of the measurement is determined by the calibration accuracy of the system, by the linearity and reproducibility of the electronics and the robustness of the signal processing. In general, the measurement requires that the sensor fibre be measured from both ends. This "double-ended" approach allows the temperature computation algorithm to correct for intrinsic and induced losses in the fibre. This technique is the most robust in terms of achieving optimum temperature accuracy. A less rigorous and less accurate technique calls for single-ended measurement that allows the temperature measurement to be performed from one end of the fibre only.

Temperature resolution is defined as uncertainty in the temperature information resulting from noise inherent in the opto-electronics. Thus the temperature measured in steady-state condition at a given point in the fibre will vary between successive measurements and between adjacent point in the fibre that are at the same temperature. The temperature resolution of the system becomes worse as the return signal level decreases, as in the case for measurements in longer fibres or as a result of increased fibre loss due to bends or connectors. The signal-to-noise ratio, and thus the temperature resolution, could be improved by averaging a larger number of measured data traces. The penalty for improved temperature resolution by increased averaging is, of course, increased measurement time. Depending on the Thermal time Constant of the cable system, the measuring time should not normally exceed 30 minutes per circuit and where the number of circuits are measured concurrently the total time before repeating the measurement on the initial circuit should generally not exceed two hours.

Single and Double Ended Operation

Double-ended operation describes the condition where the loop of fibre is probed first from one end , the laser source is switched to the other end and a second measurement taken. The geometric mean of the two signals is calculated.
This operation has some advantages over the single ended technique in terms of improved accuracy (eliminates effect of fibre loss from the measurement) and resilience (enables measurement to be made along entire length of a break in the fibre).

2.1.3 Other issues related to cable temperature monitoring

This section deals with all other issues not related to the equipment itself or to the type of fibre used. It addresses the interpretation of measurement and the logistic and operational aspects, namely the sensors attachment and protection, system reliability, maintenance and calibration and cost versus performance of the various monitoring systems outlined in this guide.

Mounting of the temperature sensors

Principally, we can distinguish three categories of installation :

- ☞ Externally to the power cable
- ☞ Internally in the power cable construction
- ☞ Using existing Telecom cables

Externally to the power cable

In the majority of existing and new cable installations, the sensors can be installed nearby the cables. If the cable surface is accessible along the entire length (cable in tunnel for example, or cable installed in trough prior to backfilling), then the best scenario is to tape the fibre directly on the outside jacket or to attach it by attachment bands at regular intervals. The latter method provides better protection to the fibre during expansion and contraction of the cable due to cyclic operation. It is however less accurate because of the uncertainty in knowing what is being measured: the surface of the cable or the layer of air in its vicinity.

Cable in ducts can be monitored by installing the sensors in the air space between the cable and the retaining duct. This operation presents certain difficulties in retrofit installations but may be done in new installations by tying the fibre to the bundle of cables at the moment of installation. In duct bank, any empty duct could be used to house the temperature sensor. Keep in mind however, that farther the distance between the hottest conductor and the sensor, the more uncertainty is introduced in the correlation between what is being measured and the actual temperature of the conductor.

Internally to the power cable

The best choice from a thermal point of view is to install the sensor, during cable manufacturing. The calculation of the conductor temperature based on the measured temperature is straightforward in this case since the thermal characteristics of the cable materials are very well known.

The location to install the temperature sensor inside the conductor itself can only be used in laboratory applications. This method eliminates all the outside interference and any misinterpretation of the results.

Using existing Telecom cables

For existing cable links, it can be useful to examine the possibility of using the optical telecom cable as DCTM opportunity. Telecom fibres are from the single mode type, so the DCTM system must be compatible which such kind of fibres.

- ☞ Due to the single mode system and its specific spatial resolution, the exact temperature of a hotspot location can only be of a good accuracy, if the length of that hotspot is more than 10 meters.
- ☞ The distance between optical telecom cable and power cable will be the most important and critical factor. In practice, a maximum distance between axes of the power cable and the optical telecom cable of greater than 20 cm is not recommended. A good extrapolation between optical telecom cable length and power cable length is necessary.

Performance, Reliability and maintenance

Thermocouples are undoubtedly the discrete temperature sensors that have the best performance to cost ratio. They are rugged, reliable and reasonably accurate. The data acquisition system associated with thermocouples are also reliable and have been around for tens of years. They are also cheap, relative to other temperature monitoring equipment. For more accurate measurement (less than 0.5°C), RTD's and thermistors are the logical choice. They are however more fragile, more expensive and they require an external power source, adding some complexity to the system.
Nevertheless, such measurements are only to be used when localised temperature monitoring is considered.

For long cable route, where the hot spot location is unknown, the recommended monitoring system is the DTM. Unfortunately, this system is expensive and its reliability is yet to be proven. Maintenance and calibration have to be done on regular bases and usually at the manufacturer facility due to the complexity of the system. The response of the fibre could change also in time due to aging and mechanical stresses leading eventually to some errors in the measurement. The reliability of some key components such as the laser is of concern. Potentially the non pulsed mode of operation of the laser within the OFDR based equipment may offer some improved reliability over the pulsed type used within the OTDR based technology.

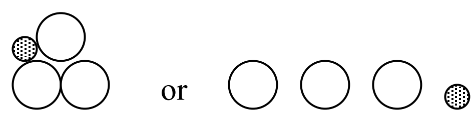
Despite all these problems, DTM systems are becoming more and more popular and are installed in great numbers at various utilities around the world.

Available Constructions

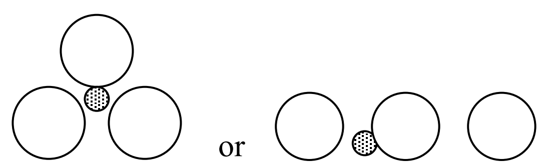
If we consider new cable systems, where thermal monitoring will be included:

☞ External optical fibre cable, as close as possible to the power cable system

- Outside of the three phases - system



- Inside (in the heart/centre) the three phases - system



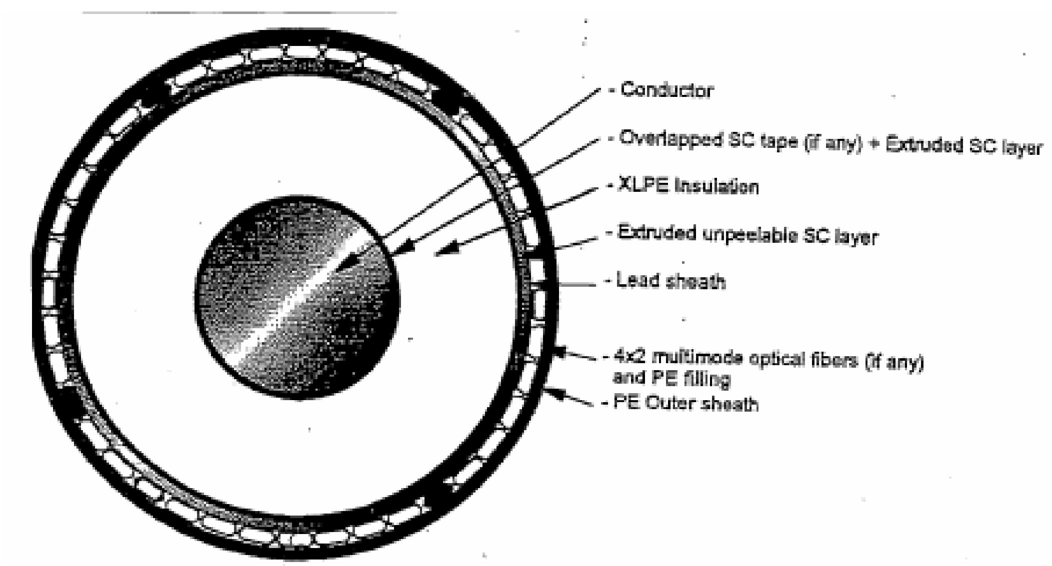
☞ Part of the power cable construction

- Directly under the metallic sheath (Type1)
- Directly under the outer jacket and above the metallic sheath (Type 2)
- Part of the screen wires assembly (Type 3)
- Inside the cable core (Type 4) : (only available in experimental form)

Integrated fibers of more than one type can be used .The conductor temperature is calculated from the fiber temperature taking into account the thermal resistances of the intermediate layers.

Examples of Type 3 is shown below.

Cable with Integral Fiber Optic



Schematic of Cable with Integral Fiber Optic

In all these constructions, the optical fibres are protected against mechanical damage and pulling tensions during the cable installation.

Examples of protection techniques are:

- Over length of the fibres with helical configuration
- Metallic or plastic tubes filled with lubricants
- Spacers between the different fibres
- Uses of gel for water ingress protection

Practical installation in the field

Due to the good current balance between phases in the HV links (above 30 kV), only one phase can be equipped with optical fibres, reducing the installing cost of the system. It's preferable to use the middle (in a flat system) or the upper (in a trefoil system) phase for DTM.

Connection boxes are installed along the cable route, the number depends on the maximum measuring length of the DTM system.
The splices can be made in on site boxes or directly part of the power cable joint construction. An advantage of such boxes is that they can be used for calibration purposes and to establish the fibre temperature response.
Where fibres are installed in cables, then joints in fibres may either be housed within the joint enclosure or in a jointing box which is fitted directly to the outside of the joint housing depending on the type of joint selected.

In order to further reduce costs, several fiber lengths from different cable circuits or phases can be looped together into a single monitoring channel.The signal can be mapped onto the fiber locations by means of sectionalising within the software.

2.1.4 Comparison between the different types and installation principles

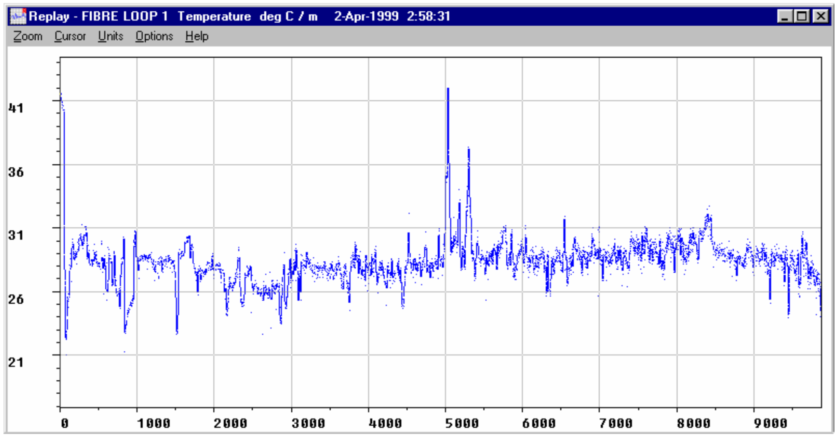
Object	External Fibre	Internal Fibre…. Part of Cable Construction		
		Type (1) and (3)	Type (2)	Type (4)
Ease of manufacture	Easy, separate cable	To include during cable manufacturing		
Number of fibres	No limit	Limited to cable diameter or number of copper wires needed for the screen		1 or 2 fibres in one stainless steel tube
Field installation	Independent from power cable and also usable for multiple power links (see trunks on MV)	Particular attention during pulling the cable in ducts if the fibre is not installed under the cable’s metallic sheath		Straight forward
Retro fitting	Possible	Impossible		
Protection against external damage	Same as for an optical fibre cable	Protection assumed by the power cable external PE-sheath		

Repairing of broken fibers	Easy (= fibre cable)	Power cable must be put out of service		
Jointing /splicing At joint position	Easy (= fibre cable)	Special adaptation of the screening part in the power cable joint	No special modification of the HV part of the power cable joint	Not applicable
Termination	Easy separate cable	Special adaptation of the screening part in the power cable joint	No special modification of the HV part of the power cable joint	Special applications
Connection to DCTM-system	No need of special cable connection	Additional optical fiber cable length from the power cable to the connection box for the DCTM system.		
Uncertainty of conductor temperature	Highest, (most remote)	Lower, (known distance from conductor)		Actual conductor temperature .

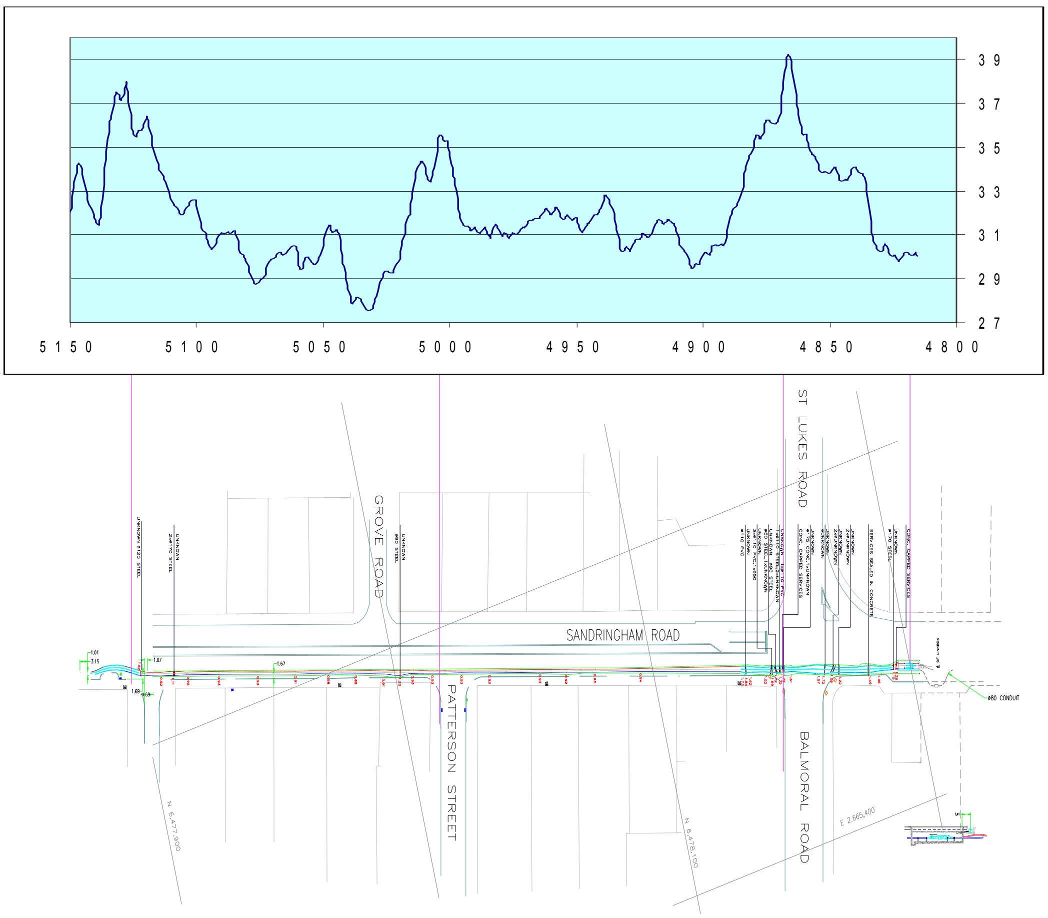
2.1.5 Thermal Hot Spots

One of the main short term benefits of DTM is being able to establish whether there are any Hot Spots or thermal bottlenecks along the cable route, that constrain the circuit rating.

The figures shows an example of the effect of and localisation of two hotspots on a 9km circuit. The first shows the temperature variations over the total length. The second illustration shows an expanded view in the area of the large temperature variation at the mid point position.(It should be noted that the latter DTS trace runs from right to left).



Overview of Temperature Profile



Detailed View of Hot Spots

The monitoring system can be used to both identify and locate these positions. The exact location can be determined by comparing the position of the hot spot on the DTM output trace (of temperature versus distance) with the physical position of a joint which can also be seen on the same trace (due to the local loss in the fibre splice). In the case of integral fibers the lay length of the fiber within the cable construction must be taken into account. Other techniques are available, for example applying cold water over the buried cables at a known location and calibrating this position against the hot spot location.

After locating the bottleneck, there are certain actions that can be taken to eliminate or alleviate the problem, such as

- Excavate and introduce a low resistivity thermal backfill around the cable
- Elimination of any heat source, such as a steam pipe
- Increase the cable spacing
- Introduction of localised cooling (heat pipe, water cooling etc)

2.1.6 General precautions in temperature monitoring

A sensor, being a thermocouple or a fibre, reports only what it "feels". This may or may not be the temperature of interest. The sensor in fact is influenced by its entire environment (cable, air, duct etc) and it will tend to attain thermal equilibrium with this environment. It is therefore important not to overlook any of the unusual, unexpected influence or interference.

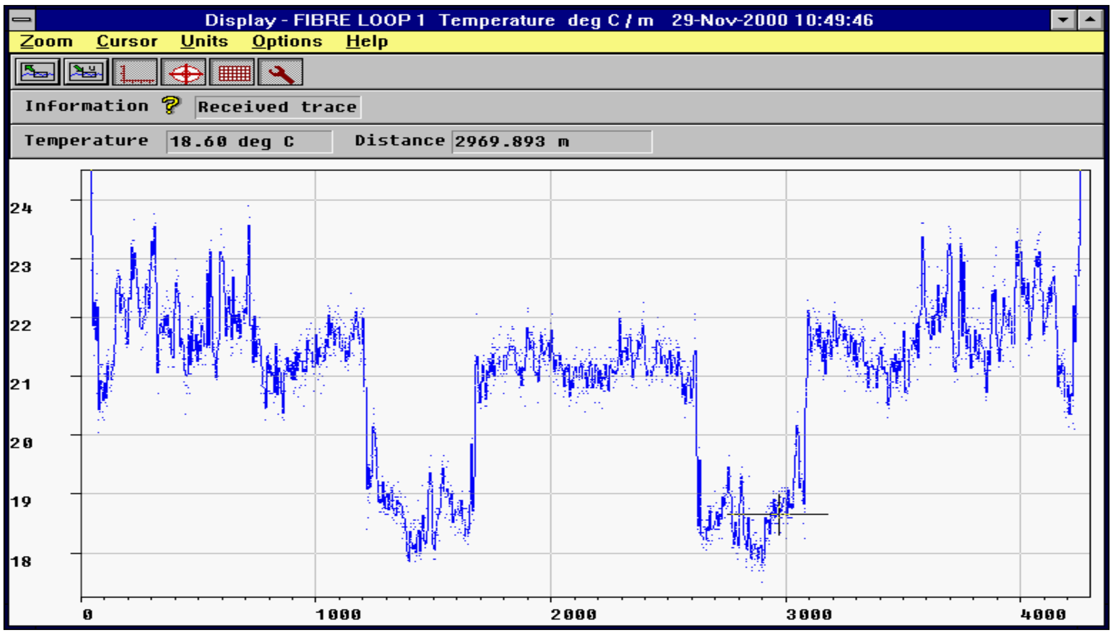
Sensor response to rapid temperature change depends on its size and on the type and thickness of the material surrounding it for mechanical protection. Greater the protection, slower is the response and larger is the attenuation in fast changing and fluctuating temperature measurement. A trade off is to be considered between increased mechanical protection and the fidelity of the measurement.

The temperature measurement by thermocouples is prone to noises (EMI and RFI interference). Care should be taken to reduce the influence of these outside disturbances on the signal by shielding and twisting the thermocouple wires and by filtering and guarding in the associated data acquisition systems. This problem is less severe in RTD's and thermistors because of higher signal output. However, the additional heating induced in these devices for measurement purpose could reduce the accuracy, if not properly evaluated.
Also the protection against over voltages coming from the network is necessary.

The optical fibre in cable DTM system has to withstand the extreme temperature range of its environment. Losses should be kept to minimum by avoiding excessive heat or mechanical damage and by minimizing the number of accessories (splices, connectors). It is recommended to install a few thermocouples along the fibre length to back check regularly on the cable DTM measurement and to monitor any drift in temperature accuracy and resolution in time.

In the case of multi mode fibres and possibly also in the case of mono mode fibres, there can be a variation in the temperature response of the fibres between manufacturing batches. Those problems can arise on important power cable lengths (more than 500m) with integrated fibres. For the moment, no special specification are available on the quality of temperature response for a given fibre construction (see batch number of production).

The figure gives an example of the effect of differences in response between fibers in different cables within the same cable circuit where four cables (containing a fiber optic sensor) are jointed together over a length greater than 4km.



This difference can result in important calibration problems. With a multimode fibre, such difference can reach up to 5 °C of offset between two adjacent lengths as can be seen in the figure which shows an apparent step change in measured temperature between adjacent cable lengths.
There is no information available for this phenomenon in single mode fibres.

In order to take care of the long life of the optical fibre cable the eventual degradation mechanisms of the fibres should be taken into account.

2.2 DYNAMIC CABLE RATING (DCR)

Temperature sensors provide raw-data about the thermal condition of a cable layer. If the temperature sensor is not embedded in the conductor, the measured temperature will be both different in magnitude and will have a time delay with respect to the true conductor temperature. As a direct measurement of the conductor temperature is technically difficult, the sensors are usually placed outside the insulation system. If possible, they are placed on a metallic layer to assure good thermal contact and that the measurements are taken on an isotherm surface.

The dynamic rating system, DCR, is to assure that the measured temperatures are translated into the conductor temperatures in real time.

In addition, DCR may also predict the conductor temperature at some future instant by calculating the transient temperature change as a result of a given current and/or given time and give alarm if the load on the cable may lead to transgression of the operating limits.

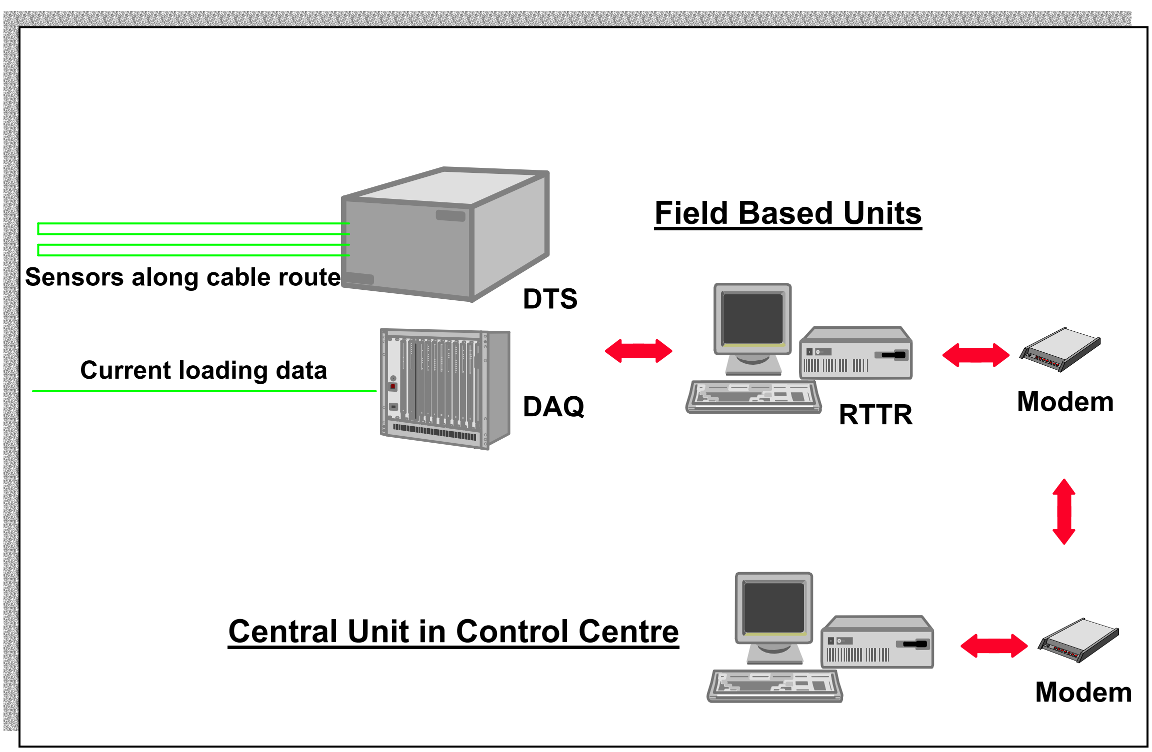
System description

The DCR system is a software package that calculates power transmission capability of a cable system. Calculation is based on maximum conductor temperature.
The required input data for the calculation are for example the following:

- cable parameters, including installation
- measured temperatures
- historic data
- cable current and voltage information

Depending on the system, the output from the DCR may be:

- present temperatures
- hot spots
- changes in cable environment parameters
- nominal transmission capacity
- maximum allowable transmission capacity either as function of current or time
- input to (Supervisory Control And Data Acquisition) SCADA system
- alarms



DTM System Hardware

Cable parameters

The calculations of the thermal parameters of cable and surroundings are based on the assumption that these parameters are independent of temperature. This assumption is correct for the most of the time. However, in case of drying out around the cable and in extreme case thermal runaway in the insulation the thermal parameters change.

These changes are to some degree predictable if there is thorough previous knowledge about the thermal behaviour of the thermal properties for the length and taken into account. It should be noted that where there are other services adjacent to the cable , changes in the temperature of the soil could result. As an example gas leaks may cause microbiological activity in some soils leading to an increase in soil temperature.

If the transmission circuit is to be fully utilised, a cable thermal monitoring systems, CTM, and dynamic cable rating system, DCR, system should assure that:

- maximum continuous operating temperature of cable will not be exceeded
- temperature drop across the insulation of DC cables is acceptable
- external temperature of cable is low enough to avoid drying out of soil

Cable electrical parameters

The cable losses are dependent on the ohmic losses in metallic layers and on the dielectric losses in the insulation. The losses are calculated according to IEC 60287, and should be used during the system calibration.

Cable thermal parameters

The thermal parameters may be calculated according to IEC 60287 or may be measured on the actual cable. However, to find the thermal time constant, TTC, knowledge about the thermal capacity/specific thermal capacity of the cable parts is needed. This information may be found in IEC 60853. The TTC of metals is very short and may be disregarded. The TTC of insulation is between 1 and 3 hours, depending on type, conductor cross-section and voltage level. If possible the calculated thermal parameters should be checked through measurements.
It is noted that some Utilities allow for partial drying out of the soil.

Thermal parameters of surroundings

Usually the cables are buried or installed in ducts or pipes, which are buried. At one-meter depth the thermal time constant of the surrounding backfill is approximately one week, so that the steady state conditions may only be achieved in approx one month. The daily air temperature cycles becomes negligible at approximately 0.5m depth. So below 0.5 m the method of calculating thermal parameters according to IEC 60287 is adequate. For cables buried shallower than 0.5m more accurate systems, for example the finite element method or any other appropriate calculation method is needed. If not covered by IEC, as with the multiple parallel circuit impedances other numerical methods should be employed.

Cable network parameters

There may be restrictions from other parts of the transmission system that place additional restrictions on the transfer capacity, flexibility and the maximum load of transformers and other system components.

Measured temperatures

There are at least two temperatures that are essential, the cable temperature and the temperature of the surroundings. These temperatures may be acquired either by discrete sensors, continuous sensors or a mixture.

The cable temperature should be preferably measured on a metallic layer. If it is not feasible the sensor element should be installed so it is provided close and continuous thermal contact with the cable surface. Preferably the sensor is part of the cable design if FO element is employed.

The remote earth temperature should be measured as far as possible from the nearest cable, preferably 10 m away. If the FO element is utilised for this purpose, a length of at least four times the spatial resolution of the CTM system should be deployed at this location.

The measurement of air temperature should be along the rules practised by the meteorological institutes. If the FO element is utilised for this purpose, a length of it should be deployed at this location.

Historical and reference data

The calibration data should be kept on the hard disk or non-volatile storage medium, to validate the measurements at a new start up. The maximal allowable conductor temperature, eventual allowed over temperature and time is part of the reference data.

Cable current and voltage information

To be able to predict the maximum allowable power transfer rate, (MVA/MW), on the cable the actual current must be known and the voltage is also necessary for some applications. As this information is available at any sub-station the Dynamic Rating system (DRS) is usually located there. Otherwise, the information has to be transmitted to the DCR.

Dynamic Cable Rating System

The calculations of the temperatures resulting from transient load conditions are based on the CIGRE recommendations in Electra No. 87 and on IEC 60853-2 cl.2. Other methods calibrated by actual measurements are also applicable. This basis together with the system parameters, operating restrictions, required input and output and alarms are programmed in a generally available programming language, and installed on a PC. Before shipment the DRS should be subjected to a thorough system check in a simulated environment, as quality assurance.

It may also be directly implemented on the SCADA system but this requires a very close co-operation with the producer of that system.
As the time constants for cable systems is rather long, in the order of hours, the specifications for almost any CPU in a modern PC is adequate. It must be equipped with an industrial extension board to handle the protocol for the in/out signals. Also its specification should be such that it can function in the ambient electro-magnetic environment.

The size of the hard disk depends on the amount of historical data to be stored. It is usual during normal operation to store the highest temperature for each cable each ten minutes. In case of alarm it should store the complete previous 10 minutes data for analysis purposes. It should be possible to download the historical data for more permanent storage, as CD, if required.

The normal in/out devices for communication between PC and operator should be available.

The operation system should tolerate long time continuous operation. Also the start up and operation procedures should be as user friendly as possible.

If the PC is interfaced with the SCADA so it may directly influence the operation of the cable link, it should be possible to switch it between on-line and stand-alone modes and also security measures should be implemented.

The temperature monitoring system should be checked with calibrated sensors to verify the temperature monitoring system. If there is a transmission link between the temperature monitoring and the DRS it must be checked. The temperature values on the monitoring system as represented on the DRS should be compared and adjusted if necessary.

The next step is the verification of the load prediction system. The resulting transient temperature changes both in magnitude and in time delay should be compared to the predicted values. If discrepancy is found the cause of it should be found and changes made so the measured values and computed values are more in line. If the overload handling system is implemented it may be prudent to check this function, but usually the operating restrictions and/or load availability prohibits such test. The links with SCADA should be checked out in simulator mode, before implementation.

Operation

At start-up the reference data shall be loaded and the data acquisition started. The system shall typically have a start up period at least twice the insulation's time constant, if the temperature is measured at the cable surface. During this time the DCR acquires enough information on the state of the cable system and on the trend. After this initial period the DCR is ready for operation.

There may be a number of operational modes:
- showing the maximal temperatures along the cables
- computing the highest allowable transmitted power, normal operation

- computing the highest allowable transient power for given time and current, at maximum conductor temperature
- computing the highest allowable transient power for given time and current, at maximum overload conductor temperature, logging the time at overload, computing the maximum allowable load subsequent to the overload period
- optionally, implementing the computed transmission regime via SCADA and monitoring that the operating limits are kept, eventually if they are transgressed, sound alarm or shut down the system

There are also the normal house keeping duties as writing and/or transmitting reports at intervals and at alarm situations.

Output

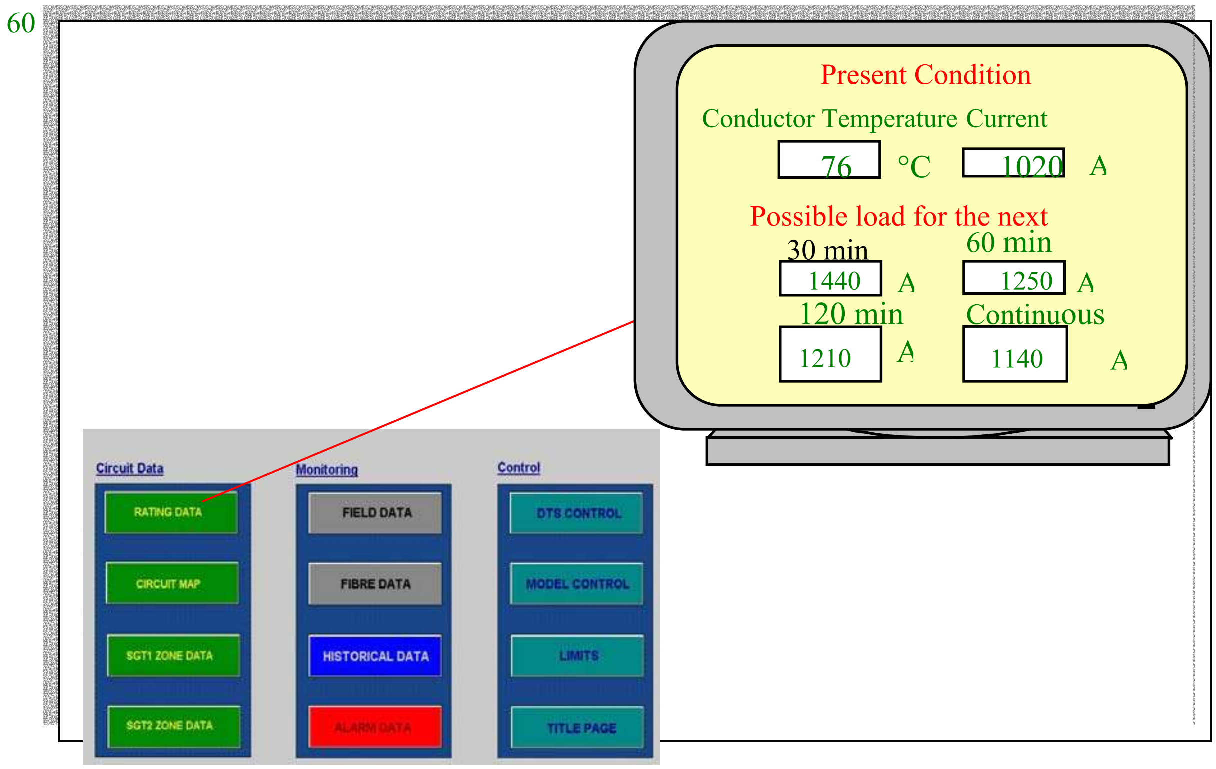
The output changes according to operational mode. The output may be a graph on screen or it may set the operational limits in the SCADA. The output may be characterised as operational data, logs and reports, alarms and if implemented, control signals.

However, the output requirements are strongly dependent on customer/operator requirements. The DCR must be flexible enough to meet the requirements of different Utilities without major modifications.

A more detailed discussion on this subject is given in User Interface.

Operational data

Operational data are a visual or written status of the present system parameters. It should give a comprehensive easily readable graphic overview of the present temperatures of the cable link and the existing limitations. It should also give possibility to the operator to ask load versus time or time versus load type of questions. The results should be presented in a graphic format on screen or printer.



Example of Utility-User Interface

Logs and reports

Depending on the operator requirement, the normal system operation is usually logged at some given interval for eventual analysis if more knowledge is needed on operation of the cable link. For example, the location and value of the maximum cable temperatures may be logged typically each 10 minutes to 30 minutes depending on the route length of the circuit and the temperature resolution required. After a while, it should be removed from the hard disk and stored on a CD.

At regular intervals report should be issued, stating the highlights in the period, any alarms and any changes made on the system.
In case of alarm the preceding registrations should be stored more permanently for later analysis and also displayed visually and in an alarm report.

All overload periods should be logged and reported.

Alarms

There are basically two kinds of alarms, one for information for example if one or more of the set limits are or will be transgressed, the other for alarms that are threatening the integrity of the link, for example, a steep local temperature increase.

In the first case the operator or the DRS should, depending of the alarm type go over to operate in a fail-safe mode, for example, by restricting the load to the normal operational maximum.

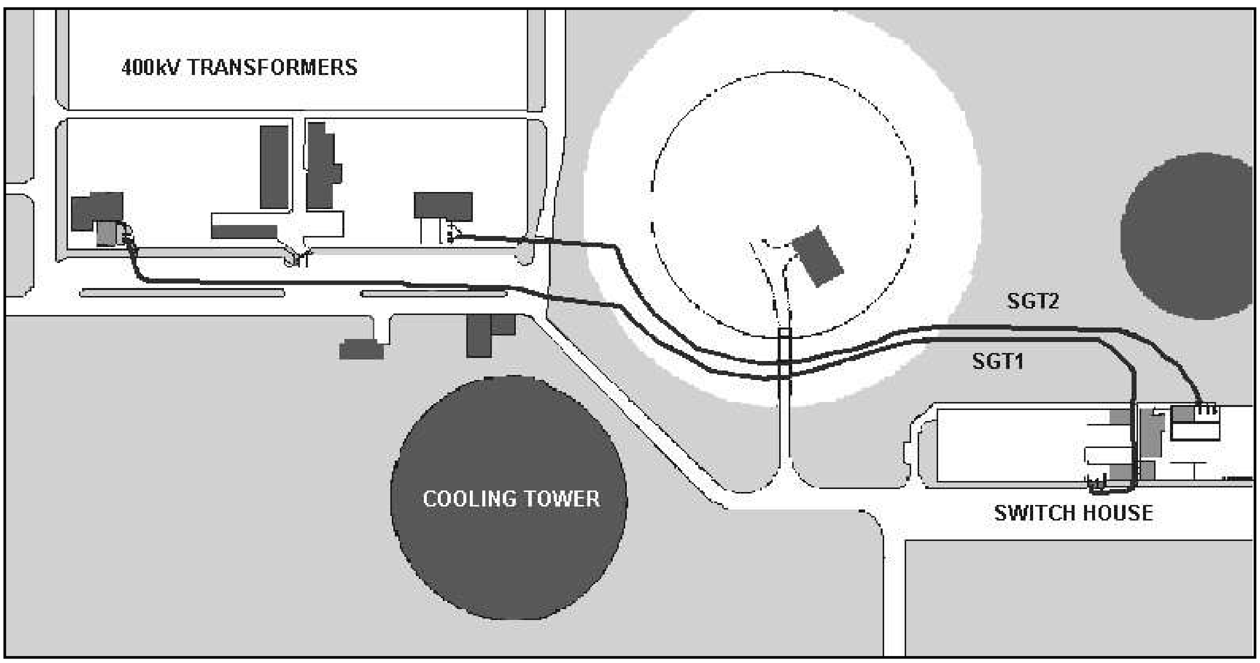
In case the second type of alarm is experienced, the DCR should issue a direct command to the operator to shut down the link until the cause of the alarm is determined.

An Example of Temperature Monitoring and Dynamic Cable Rating

Following the development and implementation of the DCR software the first application

on a UK utility's HV cable system was implemented in 1998. The installation involved a 132kV buried cable system as shown in the schematic in the figure.

Although the cable route was only 500m long it consisted of eighteen different thermal zones that were incorporated into the DCR program. The cable was installed in 1993 and had optical fiber cables attached to the outside to monitor cable temperature. The thermal zones included direct buried sections of cable, cable installed in surface troughs, flat and trefoil configurations and various road crossings. Each thermal zone was considered separately within the model. At initial start up the thermal resistivity (TR) of the environments within each thermal zone were assumed to be the standard values normally



Schematic of 132kV Cable Route with DCR System

applicable to the backfill materials being used. Using the difference between the measured cable sheath temperatures and the undisturbed ground temperatures the system was, after a short time, able to accurately establish the TR of each thermal zone and obtain a calculated value of the conductor temperature. The system was set into operation in this mode and it monitored and recalculated the parameters in real time giving both continuous and overload rating information that was easily accessible to the utility.

The results to date add considerable weight to the argument that cables currently installed in the UK are rated very conservatively and that by using an integrated program such as the DCR, higher ratings permit increase in transmission capacity without compromising the system integrity. One of the cable circuits in April 1999 was switched out for maintenance, which resulted in the other circuit running at 800 Amps. The calculated conductor temperature (in accordance with IEC 60287) at a current of 800Amps and using standard parameters of 10°C soil temperature and a TR of 1.2 °Km/W for the backfill material would have been 51°C. The DTM/DCR system using the measured temperature on the serving gave a conductor temperature of 38°C with ground temperature of 11°C and a TR of 0.4°Km/W.
The real time monitoring and cable loading evaluation systems described do remove the uncertainties over the changing thermal environment of a cable system. Monitoring takes advantage of distributed temperature measurement and therefore ensures that load assessment is based on the actual thermal constraints. They can be applied by utilities to facilitate more optimum loading of cables as well as insuring against unforeseen adverse thermal conditions.

A Simplified Approach to Dynamic Cable Rating

In the Netherlands and Belgium a great deal of experience has been gained with distributed temperature monitors by means of optical fibres integrated in or applied near MV and HV cables (see Appendix 2 para 1.1). In both countries cable density is high and there is already a great deal of underground electricity distribution and transmission. Various suppliers of MV and HV cables and accessories in both countries have designed, tested and installed a number of very robust constructions and designs. They have applied these cables in a large number of projects with Dutch and Belgian network companies.
There is a strong need amongst the liberalised Grid companies and the Asset Managers to use the experience gained to optimise the use both new and existing cable networks.

A Dutch working group has prepared a specification stating the requirements for MV and HV cable with integrated fibres (Dutch Pre-Standard NVN 36043-1). This document could be proposed for European standardisation (HD standards). The Belgian HV system operator has also introduced cables with integrated optical fibres .

A great deal of knowledge has been gained and a highly accurate picture has been obtained of the dynamic behaviour of all types of cables under their nominal, sometimes highly fluctuating, current conditions. The standard temperature images that are produced by these DTM instruments have been analysed, with a special focus on the hot spots occurring in virtually any connection. A temperature difference of 15 ºC between the hottest and the coldest spot in a single cable line is not unusual. This temperature difference is nearly always caused by the special situation of a cable, for example

- a bore hole that may or may not be filled with bentonite
- a crossing with a road or waterway
- a cable installed at great depth
- several cables lying close together in a single bed

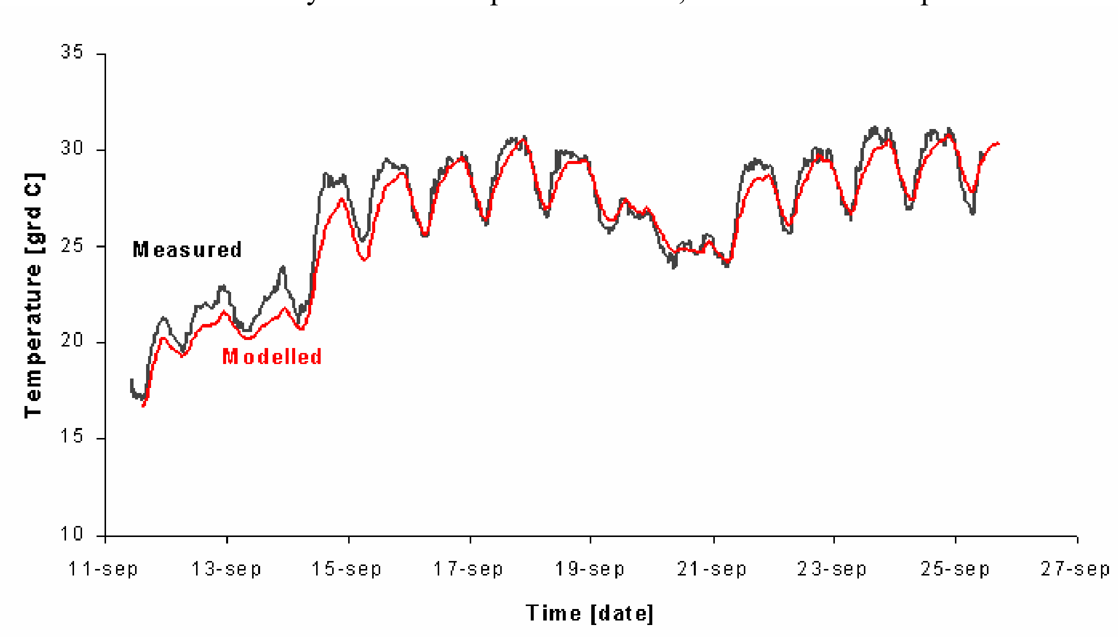
- cables crossing one another
- cables crossing with or lying parallel to external heat sources.

These special situations cannot always be adequately recognised in the engineering phase, also because they are not – or only partly – covered by the existing IEC and computation packages.

The General Approach

The first step is to subject all new cables containing a fibre to a no-load measurement with the DTM. This demonstrates that in this connection a distributed temperature measurement is possible at all times and/or that on-line monitoring is feasible. Moreover, a first impression is obtained of the cable line and it can be seen whether the measures implemented in the line by way of soil improvement etc. have been performed correctly. Subsequently, a load measurement is conducted at a nominal current. This measurement will be conducted for at least two to four weeks, during which the currents and other relevant parameters, e.g. temperature of the undisturbed soil, are also measured.

Analysing these temperature measurements and relating them to the load applied then makes it possible to pinpoint the potential hot spots under nominal conditions. Together with the user of the cable measured, the location conditions in some of these hot spots are subjected to closer inspection and the necessary specific information on these spots is collected. The actual location of hotspots requires establishing the precise location in relation to the length of fibre. In these hot spots, temperature and current applied are plotted as functions of time. The figure gives an example. This is a record of the thermal behaviour of the cable system in this special location, often the hottest spot.

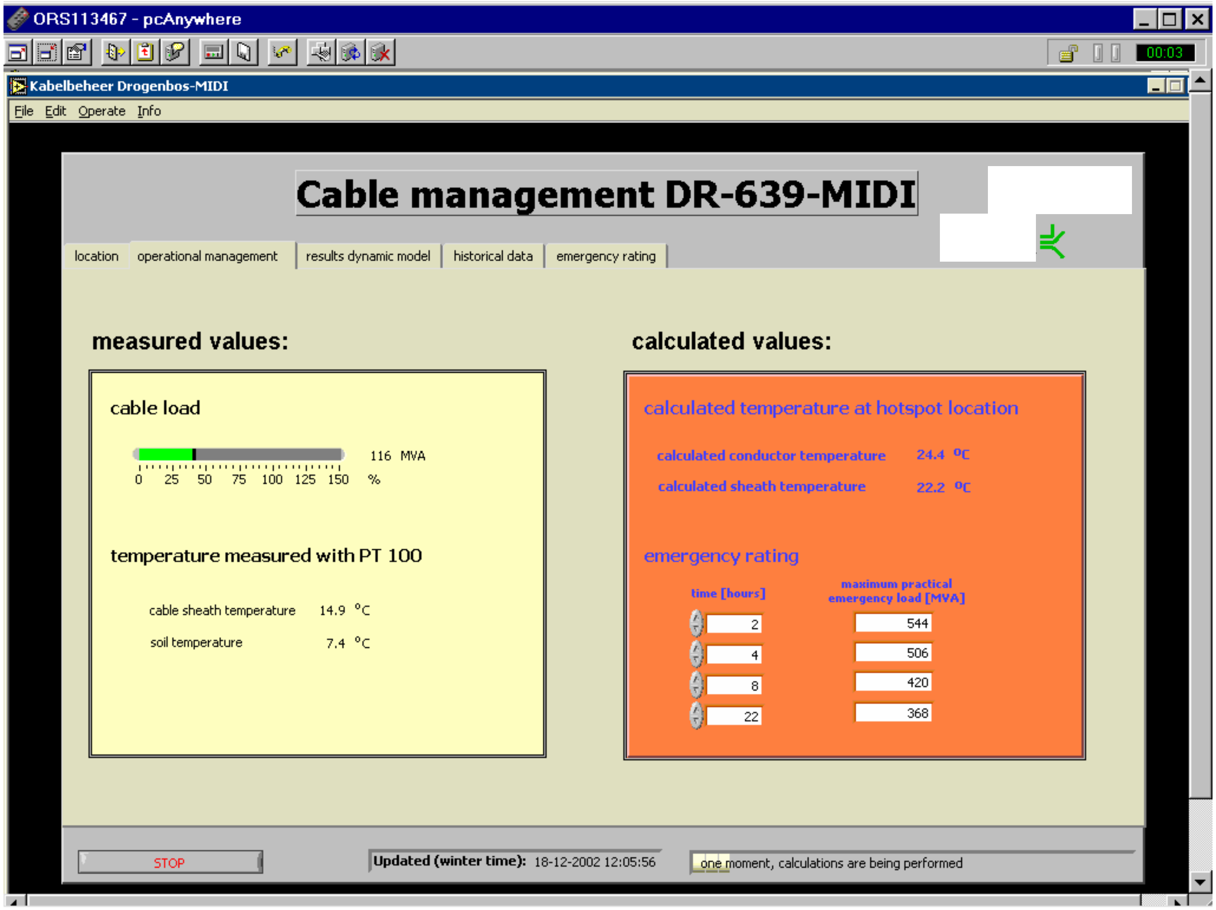


Cable Temperature / Time Profile

The thermal dynamic cable model developed can be used to model this defined and discrete situation, with all relevant parameters of the cable and cable environment being input. Comparison of the results of this model calculation with the measurement performed will give a good idea of whether the measurement and the modelling were performed correctly. This validates the model. The figure also plots the cable temperature and the temperature calculated by the model as functions of time. The correspondence between the values calculated and measured indicates that the model fits well. With this custom-made model the thermal behaviour of the weakest spot in the chain, the selected hot spot in the cable line, can be calculated at any given time.
The model is fed with the real-time currents, undisturbed soil temperatures and possibly a feedback check through a local temperature measurement of the outer cable sheath and results in the temperature of the cable conductor or sheath; especially the thermal history that has already heated up the cable is adequately processed with this model. This temperature is used by the cable owner for control purposes. Moreover, with this model it is possible at any given time, for instance when one of two circuits need to be taken out of service, to compute the temperatures to be expected due to the increased cable load on the other circuit.
This system is operational at the Belgian HV system operator on an XLPE cable without integrated optical fibres for temperature measurement. The on-line computation model gives an adequate prediction of the conductor temperature and is inspected twice a year by performance of a distributed temperature measurement and possibly adjusted if major changes have taken place in the cable line, creating for instance a new hot spot.

The approach differs from the previously described DCR system in which the rating calculation is carried out at all points along the cable route rather than at the one pre-selected location, ensuring that the hot spot location does not deviate.

The figure below gives an impression of the system and the information the end-user has at his disposal.



Example of User Iterface

Summary of the approach:

- Documentation of design, specification, exploration of cable line, soil improvement etc.
- performing calculations of special situations based on existing experiences and tools (stationary IEC 60287 and step response IEC 60853)
- preliminary temperature measurement and measurement at load approx. 1 month
- determination of hot spots and documentation of local information
- dynamic modelling at the hottest spot
- performing and validating calculations using the measurements
- installation of on-line cable management
- repeat measurement performance
- adjustment of the model.

When major changes occur in the cable line or in the cable loading, it is advisable to advance the repeat measurement. Based on experiences with older and newer cables, the 100 / 10 / 1 rule has been set.
This means that from 100 cable lines one has, about ten are eligible for further thermal measurement and calculation, and possibly only one of these 100 cables is eligible for an "expensive" on-line cable management system.

The following practical rules of experience are applied:
Calculations have been performed for the 100 cables in stationary condition. The thermal reserve capacity in relation to the actual, frequently fluctuating current and the manner in which the cable is dug in is often about 30%.

When the actual current and actual cable situation in the soil have been calculated in a custom-made model, the thermal reserve capacity still available has often fallen to <10%. This means that the model gives a far better prediction of reality, so that it is worth selecting these ten connections carefully and using all information available in the process.

Finally, one or two of the 100 cable lines will be eligible for on-line monitoring. If the approach outlines here is adopted, a temperature will be calculated that corresponds even better with reality; the error margin of this prediction is <5%.

This approach in phases provides the asset manager with a tool enabling him to give a reliable prediction of his cable network.

Conclusions and Recommendations:

Select a new cable link that has an important function in the grid and provide it with an internal or external glass fibre for temperature measurement.

Existing cable links can also be handled using the following:-.

- Installation of a thermocouple in the most critical location. This location will have to be modelled, in which the couple will be used to validate the model.
- Making use of a fibre-optics telecom cable installed nearby, pursuing the same goal as with an integrated optical fibre.

An alternative approach which the Belgian HV system operator intends to take is to model several critical links. The starting-point used for these models will be a nominal load curve that applies to that particular cable line and finally the actual current in the control centre can be input into the model. In that case the local temperature can be monitored using a mobile system.

N.B.: if the temperature is very high, especially with older cables that are examined in this manner, it is important also to determine the residual life of the cable based on the temperature to be expected and the dielectric condition of cables and accessories.

2.3 *USER INTERFACES*

Cable Thermal Monitoring:

The user interface of the CTM system is straightforward. The primary output is the measured cable temperature along the length of the cable circuit.
The CTM can be used either as a stand-alone temperature monitoring system or as an input into the Dynamic Cable Rating System.

The CTM is designed to operate "on line" or "off line" and provides information in graphical form to indicate "hot spots" and to verify the safe operation of the cable circuit.

Dynamic Cable Rating:

Attention must be paid to the user interface in order to provide all users with a predefined and user-friendly way to understand the status of the monitored cable circuits. In general the amount of data to be shown could be overwhelming or confusing in day-to-day operations.

Therefore, although all relevant information should and would be stored on board in order to be accessible for off-line analysis by trained and advanced users, the outputs should be consolidated into a small number of predefined values.

Moreover where direct control or sensitive information control is concerned, the outputs should be hidden or filtered to normal users and a different level of access should be implemented.

The primary output of the DCR system is the load capability versus time. The output can provide either the information or it can be used to control other parts of the overall system, such as a cooling system.

Data present on board

The considerable quantity of information present on board a monitoring / control system implies that the information has be adequately organized and presented.

In general both measured and calculated values will be stored:

- Measured data:

    1. Temperatures from point sensors; in general a limited number of point sensors (*e.g.* thermocouples) will be used. In case a large number of point

sensors are envisaged, a distributed measuring system could be advantageous both in term of cost and of system simplicity.

2. Temperatures from distributed sensors; the amount of information gathered from the distributed sensors is generally very large (*e.g.* with a spatial resolution of 1m, over a length of 10 km, 20000 values representing temperature and position would be necessary).
   XY scatter plots are the only feasible way to show such an amount of data, but it is not immediate to read values from an XY scatter plot in real time. Statistical information will, therefore be extracted and represented in tabular or schematic form (*e.g.* Maximum values, minimum values or averages).

3. Loads; the system loads are easily represented by either the circuits current or the transmitted MVA. Such values are also generally already available to the Utility; therefore they will be simply echoed locally in the system.

4. Environmental data; the amount of environmental data (*e.g.* air or ground temperatures, cooling fluids flow rates) will, in general be very small and will not impact too heavily on the data presentation. Moreover such information is NOT fundamental to understand the status of the system, but could be considered a second level set of information.

- Calculated values:

  Generally speaking different values will be calculated in the following scenarios:

  Discrete Sensors: one value of each type for each section of the monitored links where sensors are installed

  Distributed Sensors: one value of each type for each section of the monitored links where the thermal behavior changes significantly.

  Therefore, in general, the amount of calculated values depends on the complexity of each particular installation.

5. Conductor temperatures: this information is fundamental to understand the actual status/ behavior of the monitored links.

6. Admissible loads: the evaluation of admissible loads is extremely useful to real time management of the monitored links, in particular, based on actual status and short term history of loads it is possible to evaluate the admissible safe loads to be carried by the monitored links both in transient (short, mid and long term) or in steady state.

7. Time to reach Maximum Admissible Temperature; the evaluation of the time to reach Maximum Admissible Temperature is extremely useful to real time management of the monitored links, in particular, based on actual status and the history of loads it is possible to evaluate the time to reach, while exhausting the thermal transients to maximum admissible temperature. This value will be used to warn operators in advance of impending threshold crossings or of approaching dangerous situations.

8. System Information Data
   All set of information regarding the system configuration, the actual status, the system activities and processes should, generally be available to users for system control and remote survey of all activities and processing.

Data access from users

The data present on-board will be shown to with different level of access.
The first step is to distinguish between data relevant to real time activity of the monitoring system and data useful for off-line system analysis and control.

It is then necessary to define which data are sensitive and must be accessed restrictively, then the level of access to relevant and sensitive data for different Users or Users type.

Real Time Operation Data

Real Time Operation Data are all information/Values necessary to fully and easily understand the status and dynamic behavior of the monitored system.
The amount of data any user can be made aware in real-time and in continuous operations is a limited one, therefore statistically relevant data would preferably be selected and shown in an emphasized graphical way.
In particular, besides tabular representation of selected values, synoptic will be used to represent graphically the system in its current status, more detailed information will be made available to the user on request by keyboard or mouse operation.

Main Graphical panel

The main graphical panel would show, as an example of fundamental data to be shown on the main panel for all monitored links:

- Max calculated temperature of the conductor;
- Max admissible loads for:
  - Short duration Overload;
  - Mid Term Overload;
  - Long duration Overload;
  - Steady State Admissible Load

Said loads will be shown either in terms of admissible ratings(Amps) or in terms of loads (MVA or MW in case of DC circuits).

- Calculated Time to Over Temperature of the conductor;

Optionally, on the same main panel the following shall be shown too:

- Max Measured Temperature of the Circuit;
- Actual Load on the Circuit (either in terms of admissible Ampacities or in terms of loads (MVA or MW in case of DC circuits)).

On the main panel the values shall be refreshed at a rate suitable to enable an easy comprehension of the visible data, moreover dynamic colouring shall be applied in order to highlight those values / conditions representing out of limits or dangerous conditions.

Additional panels

In additional panels the user/s would find all relevant information to gather more details about the System.
In particular several Classes of panels could be envisaged:

Synoptic

Synoptic presents data and status in a graphical format.
In general all synoptic represent graphically circuits' and system's situation in real time: the cross section of the installation in a part selected by the user, the critical condition of an I/O module automatically activated and selected by the Alarming system….

As an example the reader can consider the circuit map, where all circuits cables are represented on a map, when the calculated Conductor temperature crossed the preset limits, the colour of the lines in the relevant part of the circuit changes colour according to the settings.

Visualised strings can, in some instances, change accordingly to system statuses, in order to show the user all relevant and specific information too.

Tabular windows

In tabular windows data are presented in tabular form, i.e. in an organized and numerical format so that users can easily and immediately read the exact value of the relevant field in the Real Time Database.

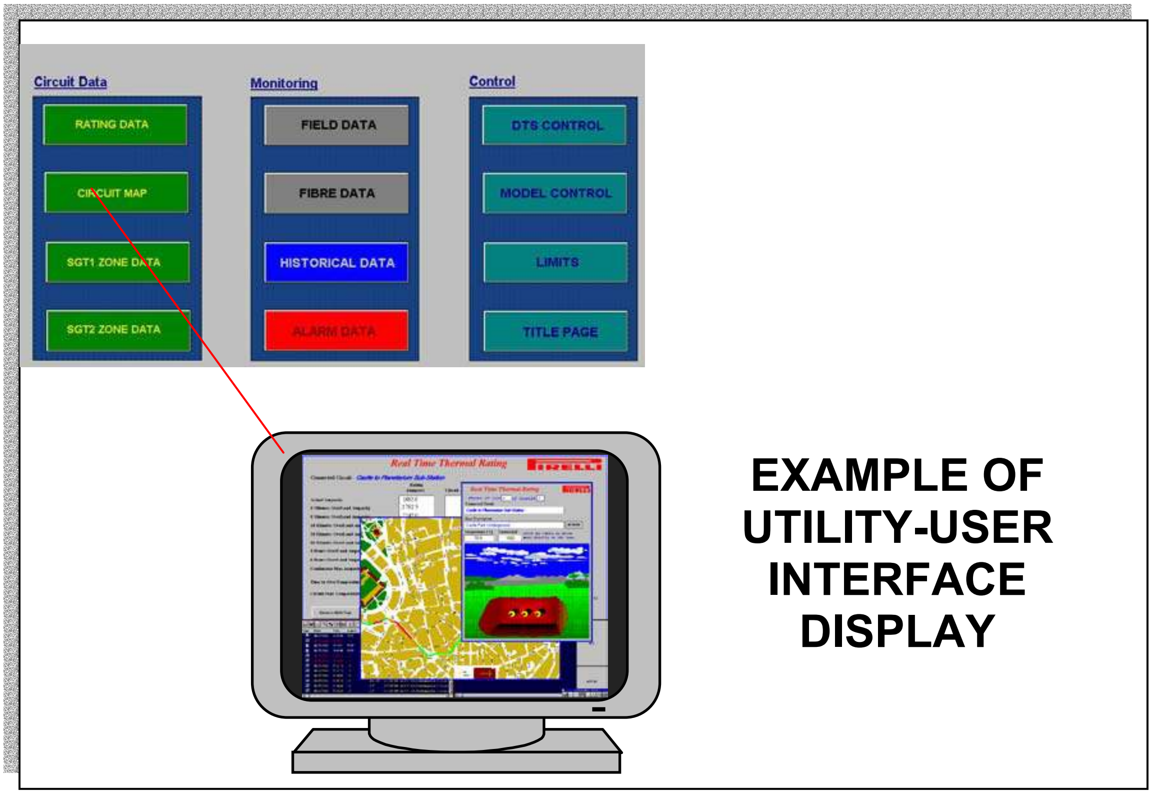
As in the case of the Synoptic windows, some relevant alphanumeric values can change according to the shown/actual values and to system status, in order to show the user all relevant and specific information too.

Maximum Number of Panels

As an ideal standard setting NO more than 10 screens/windows can be loaded or opened at the same time.

Circuit Map

In this panel a schematised overview of the circuit is presented to the user.
The lines on screen represent the circuit's path relative to streets and buildings. By clicking on that part additional more detailed maps are shown.



Fibre Zones Data

These panels show in tabular form the temperatures measured by the Distributed sensors instruments on the fibre of the system.
Additionally the panel gives an indication of the selected fibre status: the position of eventual breaks and the overall fibre attenuation.
For each monitored fibre the measured data are shown and refreshed in Real-Time (i.e. as soon as they are made available by the DTM instrument).

Single Circuit Panel [A or MVA]

The information regarding a specific Circuit are shown and refreshed in Real-Time.

CTM Control

From within this panel the users can control the performances and activity of the CTM.
By appropriate actions the user can send a command to the CTM.

Discrete Input / Outputs

In this panel the status of the Input / Output modules can be monitored and verified.

System Status

This panel shows the general status of the Monitoring system.

Historical Data

The System historical data are shown in trends, the user must have the possibility to:

- Scale on values,
- Scroll backward and forward in time,
- Export data,
- Create new trends,
- Perform statistical analysis on the selected data.

Traces display the trend of the points configured in the Historical Archive. For the sake of clarity every trend window can contain at most 8 traces.

The User can activate more than one historical window at a time.

Alarms Management

The alarms are displayed in a table containing some or all of the following fields, depending on the window type:

Field	Description
Type	Alarm type. The following types are available: • User alarms • System alarms • Controller alarms • External Application Alarms
Date	Date when the alarm status has changed
Time	Time when the alarm status has changed
Source	Name of the Unit or application that generated the alarm
Acknowledgement	Whether or not the alarm has been acknowledged
Status	Alarm status
Event	Type of event registered in the alarm archive (ON, OFF, ACK). This information is displayed only in History and Alarm Printer windows.
Message	Message string to appropriately identify the event generating the Alarm

The “Active” window

The Active window is used to view the active alarms, i.e. the messages indicating a dangerous or abnormal situation in the System.

When an alarm display window is opened, all user and external application alarms are automatically loaded.

Alarms can be sorted by time, priority or type.
Once these windows have been configured, they can be saved and recalled at a later date.

The “History” window

In the **History** window, the User can read the historical archive of the alarms, i.e. view all the alarm events stored on-board, in chronological order.

2.4 DATA COMMUNICATIONS

Any monitoring and control system to be implemented should be connected to other intelligent equipment in order to ensure optimum performance.

Data transmission between apparatus shall then be governed by existing standards for monitoring and tele-control.

Documents/standards that are generally applicable to the particular application of supervisory control of energy transport/distribution links are discussed.

Documents have been published within IEC TC57 "POWER SYSTEM CONTROL AND ASSOCIATED COMMUNICATIONS". The scope is the preparation of international standards for power system control equipment and systems including EMS (Energy Management Systems), SCADA (Supervisory Control And Data Acquisition), distribution automation, tele-protection and associated communications that are used in the planning, operation and maintenance of electric power systems.
Power systems control comprises control within control centres, RTU's (Remote Terminal Units) and substations including tele-control and interfaces to equipment, systems and databases outside the scope of TC 57.
The IEC TC 57 operates in co-operation with CIGRE (CIGRE/SC D2) - ITU-T – UCPTE.

It should be noted that the use of SCADA systems within Utilities is very significant. It is important that the DCR system interfaces with the appropriate SCADA system. However there is no SCADA standard currently available and as a consequence there is no standardization of hardware or software.

The relevant documents that currently exist are given in Appendix 3 .

3 CURRENT EXPERIENCE

3.1 Summary of replies to questionnaire

In order to establish the experience of the use of Cable Thermal Monitoring and Dynamic Cable Rating, a questionnaire was circulated to Utilities. A copy of this questionnaire can be found in Appendix 1.

The collation of comments can be found in Appendix 2.

The response to the questionnaire was good with the majority of countries providing responses, with a few notable exceptions. The replies were a measure of the experience at the end of 2001.It was noted that there are many examples of additional installations since that date.

3.2 Conclusions

The service experience can be summarized as follows:

Cable Thermal Monitoring:

- Temperature measurement using multi mode fiber is the most widely used distributed thermal monitoring system although single mode fiber and thermocouples are also utilized.

- Distributed temperature measurements based on fiber housed within a stainless steel tube, forming part of the wire earth screen appears to be the most widely used arrangement. Where the fiber is protected by the metallic sheath of the power cable the optical fibers may be housed within a non metallic tube.

- Generally only one of the three single phase cables is instrumented

- Raman backscattering and OTDR is the predominant technology for fiber temperature monitoring.

- Single ended and double ended techniques are used, in similar proportions

- The main reasons for use are given as hot spot location and monitoring, to compare installation conditions, to control cooling systems, to determine circuit rating criteria, to manage overload operation and to maximize power capacity.

- Use is mainly periodical rather than continuous.

- Spatial resolution of the systems are equally divided between 'less than 1 to 2m' and 'less than 10m' except for the Netherlands (a significant user) which employs systems based on 'less than 10m' .

Dynamic Cable Rating:

- The majority (64%) of thermal monitoring systems are used in conjunction with dynamic rating systems based on IEC60287 and 60853.

- The main parameters for deriving the rating capabilities are common (load current, ground temperature, installation detail, cable detail, cable surround thermal resistivity and cable temperature).

- Most DCR systems are 'stand alone' and not integrated into the load management system.

- Outputs include, cable temperatures (conductor and jacket), permissible current for a specified duration, the maximum allowable cable temperature and the maximum overload.

- The output data is used to detect any changes within the cable system, to operate the cable circuit closer to the maximum rating and to manage overloads.

- Two types of system are being used; the first uses inputs in real time making calculations that continually assess the changes in the thermal environment, the other considers a previously defined but stable thermal environment.

The Benefits of Thermal Monitoring to the user are seen to be:

- Maximum utilization of the cable circuit
- Hot spot detection, changes in environment
- To drive cooling systems and fire alarm systems
- To provide an overload management capability
- To make use of cyclic rating capability
- Capital expenditure deferral

The Disadvantages are:

- Initial capital cost
- Maintenance costs
- Inadequate data analysis capabilities
- Deterioration and reliability of hardware (laser, optical switch, hard drives, calibration)
- Software bugs, difficulty in maintaining obsolete software, lack of upgrading to new operating systems
- Poor level of after sales support
- Measurement irregularities on same length of fiber
- Data congestion and loss of data
- Bad fiber splicing giving false information

Perceived Future Developments / Opportunities

- Lower cost cable systems
- Re-rate cable circuits
- Selectively monitor circuits as required
- Upgrade CTM to DCR and integrate into SCADA
- Sensitivity analysis for varying soil TR over the length of the feeder.

There are several systems already installed and as a consequence significant experience does exist.

The most effective way to utilize the systems is unclear to the majority of users.

There have been some problems associated with the performance of hardware and the resilience of the software. Delays in rectifying the issues can lead to delays in commissioning the systems and provide opportunities for improvements in the future.

There was no reported experience with High Pressure Pipe Type cable systems but was limited to SCCFF and Extruded cable systems.

It might be useful to update the survey in the future, perhaps after 4 to 5 years.

4 RECOMMENDATIONS

- Utilities should strongly consider installing a distributed temperature measurement sensor (fiber) on any new cable installation at both distribution and transmission voltages.

- In some countries, it can be argued that distribution cables could benefit to a greater extent than transmission voltage cables, as a result of less engineering input at the installation stage and are frequently more heavily loaded.

- Install the fiber as close as possible to the cable (within or outside the cable) and at least on one phase.

- In order to avoid possible problems with the non uniformity of performance of different manufacturing batches of fibre, it is recommended that fibre from the same manufacturing batch be used in conjunction with the manufacture of all the power cable supplied on a particular cable link.

- Multimode fiber is preferred in order to provide better spatial resolution to recognize “hot-spots”. Double ended operation provides better accuracy and resilience.

- Although OTDR based technology has been the predominant approach in practice, OFDR based systems are now also available and could offer some advantages.

- It is important to calibrate the DTS system in order to verify actual temperatures for example against a thermocouple

- In the case of a “hot spot” being identified it will be necessary to introduce some additional measuring equipment in order to verify the actual cable temperature and hence rating

- Support from the equipment supplier is essential with this emerging technology in order to avoid problems arising from obsolete software and life expectancy of components, remembering that the power cable system would be expected to last around 40 years. The life of the laser is of particular concern.

- In the case of application to old and existing circuits, hot spots can be established by careful examination of route records. In some cases there is experience of using existing communication optical fiber cables. Discrete temperature measuring equipment can be added.

- Cost comparisons must be evaluated on a case by case basis, taking into account not only the initial cost but also the on-going costs which may include internal support and maintenance staff

5 FUTURE DEVELOPMENTS

The future will depend largely on the economic evolution of the technology which in turn will be governed by the economic justification and benefits to the end user….the Utility. This is extremely difficult to predict.

Currently the cost of the equipment is rather significant at the lower voltage levels and less significant when supplied as part of an EHV transmission system. This provides an opportunity to develop a more cost effective solution for MV applications.

There is a need to further improve the composite power/optical fiber cable and to optimize and improve the installation and attachment of the separate optical fibre to the power cable.

Although it is now common practice to install the optical fiber cable with the power cable on new installations, the deployment of the CTM and DCR packages are less common. This seems to be a result of the uncertainty on how best to use these facilities and the difficulty in ascertaining the potential benefits.

Application to all cable circuits is and will be difficult to justify. The deployment will be limited to those circuits that are being more fully loaded, maybe in excess of 70% of rated load also recognizing unusual seasonal conditions and changing load patterns. At this level some additional monitoring can be justified.

Availability, cost and after sales support from the suppliers will all be key factors in the introduction of this technology.

It is suggested that a “portable” package comprising the optical-electrical processing unit and the controller that can be connected to a number of different circuits to provide periodic rather than continuous monitoring, could be the way forward in the short term. Complete hardware units to provide a continuous monitoring on all circuits, being available in the longer term.

In terms of technology development, the CTM systems in use today are based on RAMAN scattering. Development based on BRILLOUIN measurement is in progress but not yet commercial. This technique can be used to measure temperature and mechanical strain using single mode fiber over long distances with improved resolution (e.g. in terms of temperature, 20km with a resolution of 2m)

Although there have been a few examples of the real risks associated with overloading cable systems that have lead to the failure of the supply to consumers, these risks are not always appreciated. Once the risk is recognized temperature monitoring can provide a way of managing the risk. Further recognition will lead to greater use of the technology.
Other drivers for greater implementation will include the need to demonstrate improved network management to the Industry Regulation Bodies to improve the Quality of supply and to be seen to be making use of modern technology.

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7 GLOSSARY OF TERMS

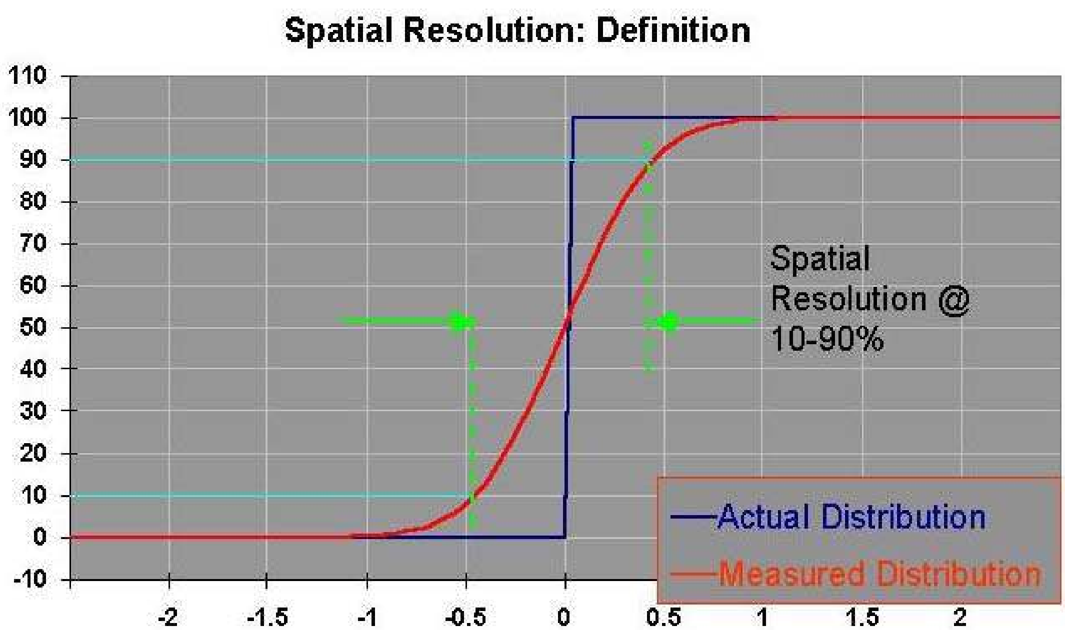
Cable Temperature Monitoring (CTM)
The direct measurement of the temperature of the cable using either discrete or distributed measurement techniques

Dynamic Cable Rating (DCR)
The calculation of the cable rating in real time based on the actual measured cable temperature.

Dynamic Rating System (DRS)
An estimation of the rating capability of electrical plant in real time based on thermal measurement

Spatial Resolution
When a step temperature change (T) is introduced at a point in the sensor fibre, the change measured by the temperature sensor is blurred over a length of the fibre.

The ***spatial resolution*** is defined as the actual distance between the 10% and 90% points of the step temperature change T.



Temperature Resolution

The temperature resolution is defined as the standard deviation of the temperature measured over a section of the fibre held at a uniform temperature.

Sampling Resolution

The sampling resolution is defined as the virtual length of each distributed measurement location (of which the average temperature is provided).It Is the ability to resolve the position of the temperature feature.

Note: The sampling resolution determines the total number of measurements on a fibre loop. Sampling at intervals smaller than the specified spatial resolution (interleaving) enables the position of a hot spot to be identified more accurately. The amount of fiber required to provide the true hot spot temperature measurement is approx two times the sampling resolution of the system

Positional Resolution

The positional resolution is defined as the minimum distance increment that can be detected for the location of a measurement feature.

Note: This resolution is inextricably linked to the sampling resolution.

Accuracy (Temperature)

Temperature accuracy is defined as the residual error in the calculation of temperature assuming the signal has no uncertainty contribution from random noise sources.

Note: In other words, if temperature uncertainty due to signal noise were removed (e.g. by very long averaging cycles) the residual error in temperature would define the accuracy of the system.

Hot Spot

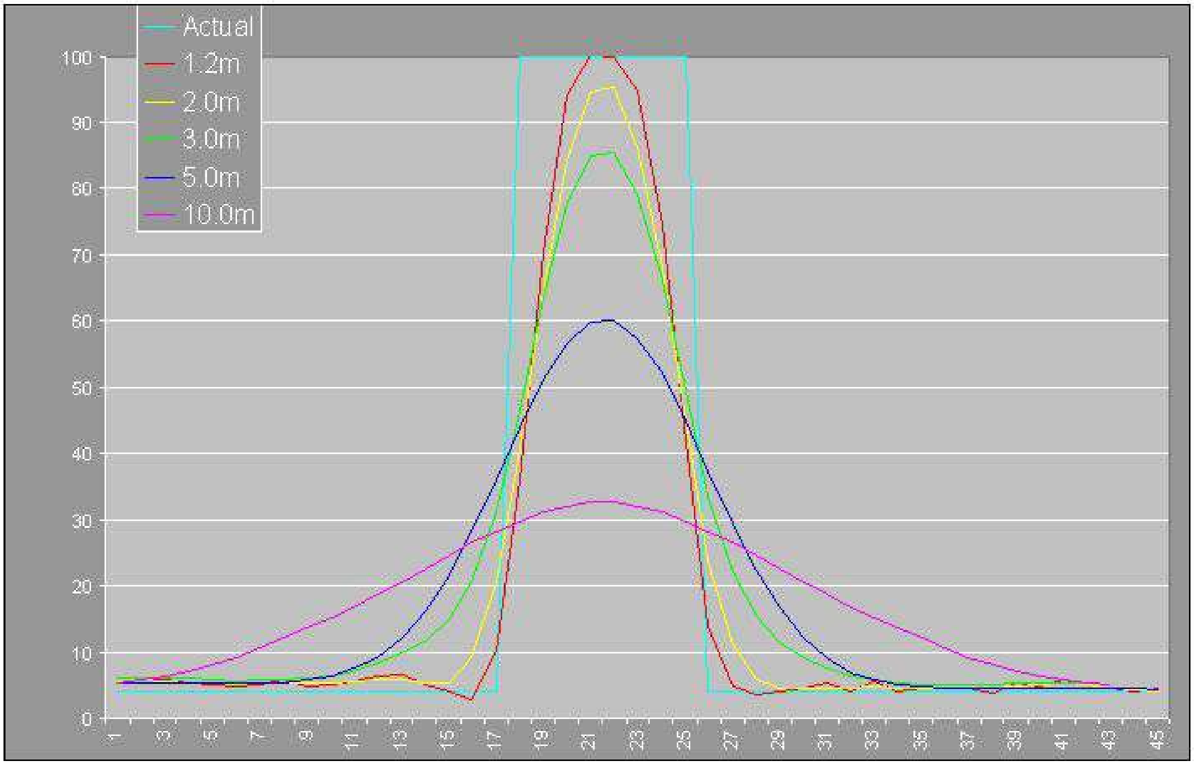
A hot spot in a power cable is defined as a location in the cable where a step change in temperature occurs in an upwards direction followed by a step change in a downwards direction.

Note: For purposes of analysis of monitoring equipment performance, a hot spot is often taken as a perfect impulse function.

Hot Spot Detection

Hot spot detection is defined as the ability of a monitoring system to detect a defined hot spot.

Note: A hot spot is characterised by the maximum temperature of the hot spot and the width of the hot spot. When the actual width of a 'hot-spot' is less than the spatial resolution of the DTS, then the resultant measured temperature will be lower than the actual value by approximately the ratio of hot-spot width to spatial resolution. In applications where the hot spot width is known then a correction factor can be estimated.



The diagram shows the "actual" response as compared to the response given by systems having a spatial resolution of 1.2 to 10 m.

Some Acronyms

RTD	Resistance Temperature Detector
OTDR	Optical Time Domain Reflectometry
OFDR	Optical Frequency Domain Reflectometry
CTM	Cable Thermal Monitoring
DCR	Dynamic Cable Rating
DRS	Dynamic Rating System
DTS	Distributed Temperature Sensing
DTM	Distributed Temperature Monitoring
SCFF	Self Contained Fluid Filled
HPPT	High Pressure Pipe Type
SCADA	Supervisory Control And Data Acquisition

APPENDIX 1 : USE OF THERMAL MONITORING ON CABLES

The following questionnaire consists of questions related to the current practice on, and experience gained with, thermal monitoring systems. The appropriate boxes need to be clearly marked. Where more than one answer is appropriate all the relevant boxes should be checked. If an option does not appear as required please check the "OTHER" box and specify in the space provided.

Particulars of user

Company name ____

Country in which system is installed ________________________________

1) Measuring Equipment

1.1) What type of measurement sensor is employed for thermal monitoring?

Single mode fibre ☐ Multi- mode fibre ☐ Thermocouple ☐

Other ☐ Please specify ____________________________________

____

____

1.2) Where is the measurement sensor positioned?

Inside the cable conductor ☐

Part of the screen wires in a separate tube ☐

Between the metallic sheath and the external serving ☐

Strapped to the outside of the cable in a stainless steel tube ☐

Strapped to the outside of the cable in a thermoplastic tube ☐

Other ☐ Please specify ____________________________________

____

1.3) How many phases of the cable circuit are equipped with the system

One ☐ Two ☐ Three ☐

1.4) On what thermal measurement theory is the equipment based?

Temperature measurement using Raman back-scatter signals ☐

Other ☐ Please specify ____

1.5) What type of measurement protocol is utilised?

Single ended measurement ☐ Double ended measurement ☐

Other ☐ Please specify ____

1.6) How is the sensor treated at joints?

Strapped to the outside of the joint casing ☐

Positioned inside the joint casing ☐ Please give details ________________

____

____

2) Installation Details

Circuit	1	2	3	4	5	6
Discrete/Distributed Measurement						
System voltage						
Circuit length						
Monitored length of circuit *						
Length of longest section being monitored*						
Installation - Direct burial - In ducts - In air						
Date of thermal monitoring equipment installation						

* Not applicable to discrete temperature measurement

3) Criteria for use of Thermal Monitoring

3.1) What is the reason for using a thermal monitoring system in this application?
(Examples : Security of supply, dynamic rating, overload management)

____

____

____

____

3.2) What is the utilisation of the thermal monitoring system?

Continuous monitoring ☐ Periodic monitoring ☐

3.3) What is the spatial resolution of the system?

What is spatial resolution? ☐ < 1 meter ☐

>1 meter, < 10 meters ☐ > 10 meters ☐

4) Dynamic Rating

4.1) Is a dynamic rating system used in conjunction with thermal monitoring?

Yes ☐ No ☐

If YES what is the basis of the thermal model?

IEC 60287 and IEC 60853 ☐ Finite element analysis ☐

Other ☐ Please specify ____

____

4.2) What parameters are required for the rating capability?

Remote ground temperature ☐ Installation detail ☐ Cable detail ☐

Current ☐ Thermal resistivity ☐ Cable temperature ☐

☐

Other Please specify ____

____

4.3) How is the system configured?

Stand alone system ☐ Integrated with SCADA system ☐

Other ☐ Please specify ____

____

4.4) What outputs are provided?

Jacket temp. ☐ Conductor temp. ☐ Permissible current ☐

Time, at present load, to reach maximum permissible conductor temp. ☐

Allowable load, for a specified time, under normal running conditions to reach maximum conductor temp. ☐

Allowable load, for a specified time, under overload conditions to reach maximum conductor temp. ☐

Other ☐ Please specify ____

____

____

4.5) How is the recorded information used?

Analysed to detect any change in system parameters over time ☐

Used to drive feeder closer to the maximum rating ☐

Used during overload conditions ☐

Other ☐ Please specify____

____

____

5) General

5.1) What are the benefits of having a thermal monitoring system to the utility/user?

5.2) What are the disadvantages of having such a system?

5.3) What problems have been experienced with the system? (If possible , give some description of the problem).

☐ Hardware of the system

☐ Software of the system

☐

Measurement irregularities on the same length of fibre optic

☐ Impossible to measure due to a high attenuation of the back scattered signal

☐ Other problems/issues of concern

5.4) What future developments, with regard the thermal monitoring system, will be taking place?

5.5) Is there any additional information, based on thermal monitoring, that would be of interest?

APPENDIX 2 : COLLATION OF REPLIES TO QUESTIONNAIRE – CIGRE WG 21-02 as of DECEMBER 2001

Breakdown of replies received:

Country	*No. of replies received*
Netherlands	7
Brazil	1
Japan	5
Germany	1
Israel	2
New Zealand	4
Belgium	1
Canada	3
Australia	2
UK	3
Denmark	1
Norway	1
Egypt	1
Jordan	1
Total	**33***

- Questionnaire also received from Ireland but no systems are currently installed so not taken into account in the collation.

1) Measuring Equipment

1.1) What type of measurement sensor is employed for thermal monitoring?

Country	Single-mode	Multi-mode	Thermocouple
Netherlands (Note 1)	24	15	6
Brazil			1
Japan	1	3	1
Germany		1	
Israel	2	1	2
New Zealand		3	1
Belgium		1	
Canada		2	3

Australia		2	1
UK	1	2	
Denmark		1	
Norway			1
Egypt		1	
Jordan		1	
% of Total	**36**	**43**	**21**

Note 1;
The experience in the Netherlands results from a large programme being undertaken between the Utilities and KEMA in which many circuits have been instrumented but measurements are taken periodically rather than continuously. More information is given in the report (end of para 2.2……Simplified Approach to DRS).

1.2) Where is the measurement sensor positioned?

Country	Strapped onto the cable surface	Part of screen wires	Between sheath and serving	Stainless steel tube	Plastic tube
Netherlands	1	38		33	5
Brazil	1				
Japan	1				4
Germany					1
Israel				1	2
New Zealand	2	1			3
Belgium			1		
Canada	2			1	1
Australia					2
UK				1	2
Denmark	1				
Norway	1				
Egypt	1				
Jordan	1				
% of Total	**10**	**36**	**1**	**34**	**19**

1.3) How many phases of the cable circuit are equipped with the system?

Country	One	Two	Three
Netherlands	30		9
Brazil		1	
Japan			
Germany	1		
Israel	1		2
New Zealand	3		3
Belgium	1		
Canada	2		1
Australia	1	1	
UK	3		
Denmark			1
Norway			1
Egypt			1
Jordan			1
% of Total	**67**	**3**	**30**

1.4) On what thermal measurement theory is the equipment based?

Country	**Raman backscatter signals**	**Not applicable**
Netherlands	39	4
Brazil		1
Japan	4	1
Germany	1	
Israel	2	
New Zealand	3	1
Belgium	1	
Canada	2	1
Australia	2	
UK	3	
Denmark	1	
Norway		1
Egypt	1	
Jordan	1	
% of Total	**87**	**13**

1.5) What type of measurement protocol is utilised?

Country	Single ended	Double ended	N/A	Other
Netherlands	24	15		
Brazil				1
Japan	3	1	1	1
Germany		1		
Israel	1			
New Zealand	2	3	1	
Belgium		1		
Canada			1	
Australia	1	2		
UK	2	2		
Denmark		1		
Norway			1	
Egypt		1		
Jordan		1		
% of Total	49	42	6	3

1.6) How is the sensor treated at joints?

Strapped to the outside of the joint casing in all cases where there are joints in the section. Exception is Brazil where they have their discrete devices inside the joint casing.

2) Installation Details

Country	**Discrete or Distributed**	**Voltage (kV)**	**Total cable length (m)**	**Monitored length (m)**	**Longest section (m)**	**Installed (Buried; Air or Ducts)**	**Date**
Netherlands	Distributed Discrete	10;150	464 000	464 000	22 900	A;B:C	1993/ 2001
Brazil	Discrete	345	15 000			B	1999
Japan	Discrete Distributed	275;500 66;275	189 200 87 988	N/A 85 130	N/A 12 000	A (Tunnel) A;D	1979/91 1993/ 2001
Germany	Distributed	110	8 700	8 700		B;D	2000
Israel	Distributed	161	7 000	5 000	500	B	2001/02

New Zealand	Discrete Distributed	33 11;22;33;110	4 200 59 100	N/A 59 100	N/A 9 900	B B;D;A	2000 2000/01
Belgium	Distributed	150	50 294	50 294	4410 (Multi-mode) 10 514 (Single mode)	B	1996
Canada	Discrete Distributed	120;115 69;120; 150;230; 500dc	30 000 16 300	N/A 16 300	N/A 4 000	B B;D	1998-2000 1991-2000
Australia	Distributed Discrete	132;110; 33	20 470	2 660		B;D;A	2000/02
UK	Distributed	132; 275; 400	82 842	32 722	4 500	B;D	1988-2000
Denmark	Distributed	250/350	360 000	360	120	B	1994
Norway	Discrete	250/350		300	100	B;D	1994
Egypt	Distributed	400	52 000	2 000	500	B	1997
Jordan	Distributed	400		1 200	300	B	1997

3) Criteria for use of Thermal Monitoring

3.1) What is the reason for using thermal monitoring in the application?

Country	Security	DRS	Overload	Other
Netherlands		31	8	Hotspot monitoring; comparison of different laying conditions; KEMA model verification
Brazil	1	1		
Japan	2	1	2	Control of water cooling system; Comparison of different laying conditions
Germany	1	1	1	
Israel	1	1	1	
New Zealand		1	2	Experimental; Theory vs measurement
Belgium		1	1	Hot spot location
Canada	1	2	1	Hot spot location
Australia				Determine circuit rating criteria; overload management; hot spot detection
UK		1	1	Hot spot location; Standard procedure to install fibres on HV cables, used only when deemed necessary
Denmark			1	Max transmission capacity
Norway			1	Max transmission capacity
Egypt			1	Max transmission capacity; Change of

				surrounding thermal properties
Jordan			1	Max transmission capacity; Change of surrounding thermal properties
% of Total	**8**	**51**	**26**	**15**

3.2) What is the utilisation of the thermal monitoring system?

Country	*Continuous*	**Periodic**
Netherlands	3	36
Brazil	1	
Japan	5	
Germany	1	
Israel		1
New Zealand	2	2
Belgium		1
Canada	2	1
Australia	1	2
UK	2	2
Denmark	1	
Norway	1	
Egypt	1	
Jordan	1	
% of Total	**32**	**68**

3.3) What is the spatial resolution of the system?

Country	**<1m**	**>1<10m**
Netherlands		39
Brazil		
Japan	3	2
Germany	1	
Israel	1	1
New Zealand		3
Belgium		1

Canada	3	
Australia		2
UK		3
Denmark	1	
Norway	1	
Egypt	1	
Jordan	1	
% of Total	**19**	**81**

4) Dynamic Rating

4.1) Is a dynamic rating system used in conjunction with thermal monitoring?

Country	**Yes**	**No**	**Basis for the DRS**	
			IEC 60287 and 60853	**FEM**
Netherlands	4		4	
Brazil	1		1	
Japan	1	4	1	
Germany	1		1	
Israel		2		
New Zealand	2	2	1	1
Belgium	1		1	
Canada	2	1	2	
Australia	1	1	1	1
UK	2	1	1	
Denmark	1		1	
Norway	1		1	
Egypt	1		1	
Jordan	1		1	
% of Total	**39**	**22**	**35**	**4**

4.2) What parameters are required for the rating capability?

Country	**Load current**	**Remote ground temp.**	**Installation detail**	**Cable detail**	**Soil TR**	**Cable temp.**	**Other**
Netherlands	✓	✓	✓	✓	✓		✓
Brazil	✓	✓		✓	✓	✓	Sheath current
Japan	✓	✓	✓	✓	✓		

Germany	✓	✓	✓	✓	✓	✓	
Israel		✓	✓	✓	✓	✓	
New Zealand	✓	✓	✓	✓	✓	✓	
Belgium	✓		✓	✓	✓	✓	
Canada	✓	✓	✓	✓		✓	Air temp.
Australia	✓	✓	✓	✓	✓	✓	
UK	✓	✓	✓	✓	✓	✓	
Denmark	✓	✓	✓	✓		✓	
Norway	✓	✓	✓	✓		✓	
Egypt	✓	✓	✓	✓		✓	
Jordan	✓	✓	✓	✓		✓	
% of Total	**16**	**17**	**17**	**18**	**12**	**16**	**4**

4.3) How is the system configured?

Country	Stand alone	Integrated	Other
Netherlands	3		Tuned model using real time data, current and temperature
Brazil	1		
Japan	4		Integrated with water cooling system
Germany		1	
Israel	1		
New Zealand	2	2	Alarms only in one case & as a source for historical graphical data
Belgium	1		
Canada	1	2	
Australia	2		
UK	2		
Denmark	1		
Norway	1		
Egypt	1		
Jordan	1		
% of Total	**70**	**17**	**13**

4.4) What outputs are provided?

Country	Jacket temp.	Conductor temp.	Permissible current	Permissible time	Maximum temp.	Maximum overload
Netherlands	✓	✓	✓	✓	✓	✓
Brazil	✓	✓	✓		✓	
Japan	✓	✓	✓			
Germany		✓	✓	✓	✓	✓
Israel	✓					
New Zealand	✓	✓	✓	✓	✓	✓
Belgium	✓			✓	✓	✓
Canada	✓	✓	✓	✓	✓	✓
Australia	✓	✓	✓	✓	✓	✓
UK		✓	✓	✓	✓	✓
Denmark	✓	✓	✓	✓	✓	✓
Norway	✓	✓	✓	✓	✓	✓
Egypt	✓	✓	✓	✓	✓	✓
Jordan	✓	✓	✓	✓	✓	✓
% of Total	**17**	**17**	**17**	**17**	**17**	**15**

4.5) How is the recorded information used?

Country	Analysed to detect any change in system parameters over time	Used to drive feeder closer to the maximum rating	Used during overload conditions	Other
Netherlands	✓	✓	✓	
Brazil			✓	
Japan	✓		✓	Fire sensor Management of water cooling system

Germany	✓	✓	✓	
Israel	✓			
New Zealand	✓	✓	✓	
Belgium			✓	Analysis of cable load during emergency conditions
Canada	✓	✓	✓	
Australia	✓	✓	✓	
UK	✓	✓		Assess whether cable meets design criteria. Circuits can be uprated where thermal design exceeds specifications.
Denmark		✓	✓	
Norway		✓	✓	
Egypt		✓	✓	
Jordan		✓	✓	
% of Total	**23**	**29**	**34**	**14**

5) General

5.1) What are the benefits of having a thermal monitoring system to the utility/user?

Automatic control of a water cooling system; maximum utilisation of the cable circuit; fire sensing/detecting of hot spots; capital expenditure deferral; real time thermal rating; awareness of any change with time; overload control; determination of actual vs theoretical.

5.2) What are the disadvantages of having such a system?

Initial capital cost; installation and maintenance cost; the system produces large quantities of data which is time consuming and difficult to analyse.

For a discrete system the largest drawback is that the system is not distributed.

5.3) What problems have been experienced with the system? (If possible, give some description of the problem).

Deterioration of equipment with time i.e. laser pulse and optical switch; hard drive failures; DTS calibration; software bugs; measurement irregularities on the same length of fibre; data congestion leading to loss of data; bad splices showing up as false hot spots; DTS cannot be sited outdoors.

5.4) What future developments, with regard the thermal monitoring system, will be taking place?

Projects looking at cost reduction of the system; upgrading to DRS and integration into SCADA. Sensitivity analysis for varying soil TR over the length of the feeder.

5.5) Is there any additional information, based on thermal monitoring, that would be of interest?

Information on incorporating fibre optic in Corrugated Seamless Aluminium sheathed cables; utilisation of DTS data for fire alarm and ventilation control in tunnels. Moisture content levels of surrounding soil.

APPENDIX 3 : DATA COMMUNICATIONS REFERENCES

The relevant documents that currently exist are;

IEC/TR 60870-1-1 (1988-12)

Specifies classes for environmental conditions under which tele-control equipment has to operate. Gives an overall view of the functional elements contributing to basic structures and to the choice of tele-control system configurations. It deals with functions which are typical for any process to be monitored and controlled but emphasizes the specific problems which characterize geographically widespread processes, such as the dominant influence of telecommunications links with restricted bandwidth and often low signal-to-noise ratio. However, this report serves only as an introduction to the detailed standards and recommendations laid down in Parts 2-5 of IEC 60870.

IEC 60870-1-2 (1989-11)

Presents guidelines but not standards for establishing specifications for tele-control systems and equipment following the other IEC standards on tele-control systems and other relevant international standards and recommendations such as CCITT recommendations. Also facilitates the comparison of equipment produced by different manufacturers.

IEC/TR3 60870-1-4 (1994-07)

This technical report is intended as a brief tutorial on transmission techniques, equipment and protocols in view of their use in tele-control systems. It is thus intended as a guide to orient those using the standards defined in the series of IEC 60870-5 and 60870-6.

IEC/TR 60870-1-5 (2000-09)

Is a technical report which describes the influence of modem transmission procedures on the data integrity of transmission systems using the protocol IEC 60870-5.

IEC 60870-3 (1989-05)

Defines the interface conditions to be fulfilled when connecting together the various elements of equipment needed to constitute a tele-control system and enabling the user to manage such a system.

IEC 60870-4 (1990-04)

Deals with those characteristics which affect the performance of tele-control systems and relates the characteristics to the application and processing functions. Establishes a set of rules to assess and specify the performance requirements of tele-control systems; where feasible, performance classes have been specified for each of the properties covered.

IEC 60870-5-1 (1990-02)

Covers asynchronous data transmission with half duplex and duplex link protocols operating with window size one for message transfers. Specifies the basic requirements for services to be provided by the link plus physical layers, for telecontrol applications. In particular it specifies standards on coding, formatting and synchronizing data frames of variable and filed lengths which meet specified data integrity requirements.

IEC 60870-5-2 (1992-04)

Applies to telecontrol equipment and systems with coded bit serial data transmission for monitoring and controlling geographically widespread processes.

IEC 60870-5-3 (1992-09)

Applies to telecontrol equipment and systems with coded bit serial data transmission for monitoring and controlling geographically widespread processes; specifies rules for structuring application data units in transmission frames of tele-control systems.

IEC 60870-5-4 (1993-08)

Gives rules for defining information elements and presents a set of information elements, in particular of digital and analog process variables frequently used in tele-control applications.

IEC 60870-5-5 (1995-06)

Applies to tele-control equipment and systems with coded bit serial data transmission for monitoring and controlling geographically widespread processes. It defines a tele-control companion standard that enables interoperability among compatible tele-control equipment.

Another applicable set of standard are those prepared by IEC TC N° 65: INDUSTRIAL-PROCESS MEASUREMENT AND CONTROL whose scope is to prepare international standards for systems and elements used for industrial-process measurement and control concerning continuous and batch processes.

Of particular interest for the energy transport link survey are the publications by SC 65C: DIGITAL COMMUNICATIONS.

IEC 60625-1 (1993-10)

Applies to an interface system used to interconnect both programmable and non-programmable electronic measuring apparatus and accessories. Specifies device-independent requirements which need to be met in order to interconnect and communicate unambiguously. Permits apparatus with a wide range of capabilities to be connected to the system. Enables the interconnection of independently manufactured apparatus into a single functional system.

IEC 60625-1 (1993-10)

Applies to an interface system used to interconnect both programmable and non-programmable electronic measuring apparatus and accessories. Specifies device-independent requirements which need to be met in order to interconnect and communicate unambiguously. Permits apparatus with a wide range of capabilities to be connected to the system. Enables the interconnection of independently manufactured apparatus into a single functional system.