Distributed Temperature Sensing using Fibre-Optics (DTS Systems)

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Abstract:

There is growing demand from the electricity supply industry for optical Distributed Temperature Sensing (DTS) systems to continuously measure temperature along the length of power cables, inside transformer windings and switchgear and around key substation equipment.

Thermal profiles obtained from DTS data are being used to facilitate more effective management of key assets, not only through avoidance of overheating failures but also by life prediction and real-time thermal rating. The economic benefits from fault minimisation and better asset utilisation significantly outweigh the marginal costs of installing optical sensing.

DTS systems make measurements by detecting and analysing Raman/Stokes backscatter within a fibre-optic cable when pulsed with a laser light source. The intensity of certain reflected frequencies is temperature dependent and time of flight for the returning signal equates to distance along the fibre. For power cables optical fibres can be either built in to the cable when manufactured or attached externally at the time of laying.

The paper describes DTS technology, hardware, software and applications with reference to installations at Integral Energy, NSW and United Energy, Victoria. Reference is also made to applications in New Zealand and overseas.

It includes details of fibre-optic sensing cables, installation techniques, data analysis storage and display, and SCADA interface.

Introduction

"In early 1998 a series of power failures occurred in the underground cables providing electricity to the central business district (CBD) of Auckland. As a consequence much of the CBD of Auckland was blacked out for a significant period. It is understood that the loss of power has had a significant impact on the economic activity of Auckland." Inquiry into the Auckland Power Supply Failure: Public Summary.[1]

This disastrous power failure in New Zealand, with consequential costs exceeding hundreds of millions of dollars, might have been avoided had a Distributed Temperature Sensor (DTS) been used to monitor for hot spots along the length of the cable. Integral Energy, who conducted the inquiry, stated that for an underground cable to perform to its optimum capacity a routine maintenance program should ideally include monitoring of cable, ambient and soil temperatures. They concluded that Mercury Energy's 110 kV cables *" ..had been operating at temperatures above their design limits from an early stage after their commissioning. ...In fact the rating of these cables was much lower due to the ground conditions in which they were buried. When they were loaded to more than half their nominal rating they would have started to overheat."*

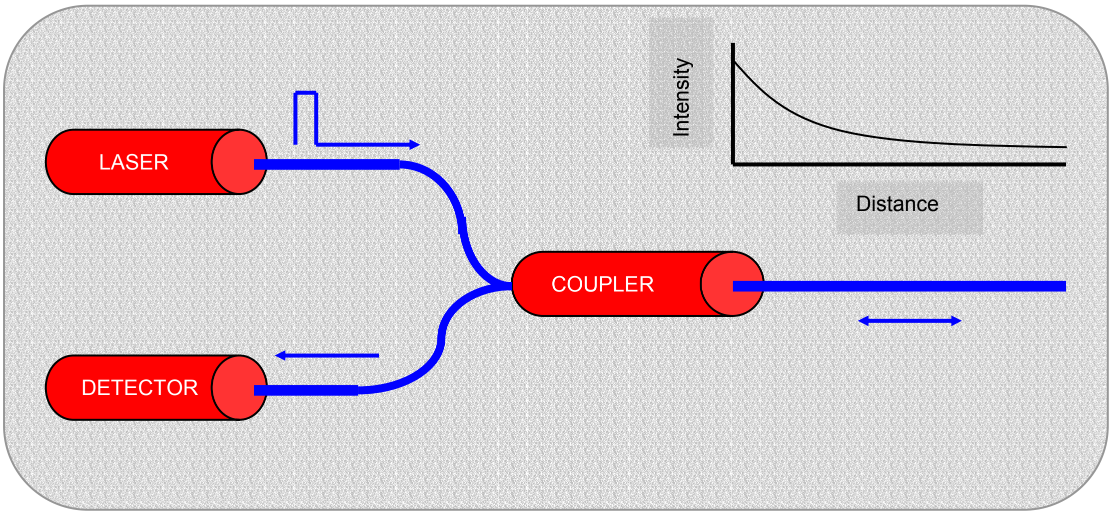
When the replacement cables were installed in December 1998 Olex Cables incorporated a DTS system and, as part of their contract, provide a monthly report on circuit performance to Vector Limited (Mercury's successor) using temperature data from the DTS sampled every two hours and load information from the power company. This continuous monitoring, with data available every 2 m along the cable, has shown that there are certain regions along the 9 km route that are warmer than the average. This may be due to other services crossing the cable route and is under investigation – Vector is not going to be caught twice!.[2]

Technology

Distributed Temperature Sensors, such as Tyree Optech's Sentor®101, make measurements by detecting and analysing Raman/Stokes backscatter within a fibre-optic cable when pulsed with a laser light source.

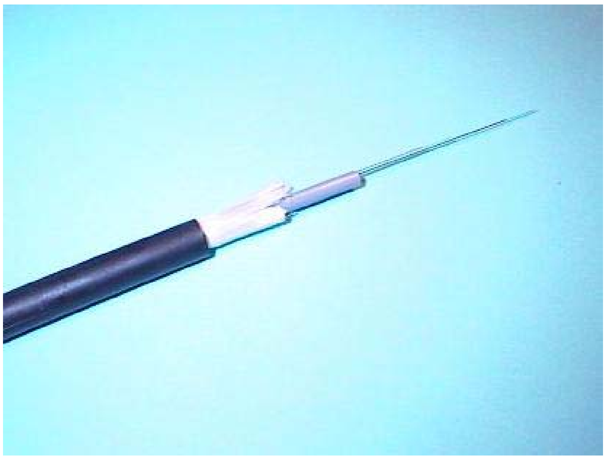
DTS systems work on very similar principles to RADAR and SONAR. In RADAR, a radio frequency probing pulse is launched into the air. In SONAR, sound waves are used under water. When the probing pulse encounters a reflective object, some energy is returned to a receiver. The period between the launch of the probing pulse and the detection of the reflected signal allow the object's distance to be deduced. The amplitude of the returned signal is partially due to the distance of the object away from the source and detector and partially due to reflective properties of the object, including its size.

In Distributed Temperature Sensors the probing pulse is a very short burst of laser light. After leaving the laser the light travels through an optical coupler and into the sensing fibre. As the light pulse travels along the sensing fibre it is attenuated. (One way to envisage this attenuation is to imagine the fibre as a glass window that can be several kilometres thick!) The attenuation process involves the probing pulse interacting relatively weakly with glass fibre molecules. The interaction causes light energy to be scattered from the molecules - some of this scattered light travelling back towards the launch end of the fibre. Thus, while most light energy is transmitted in the forward direction along the fibre, a very small fraction of it is sent backwards, towards the coupler where it is diverted to a light detector. By measuring the intensity of some of the returned light which is temperature dependent, together with its time of arrival, the system can deduce the temperature profile along the sensing fibre.



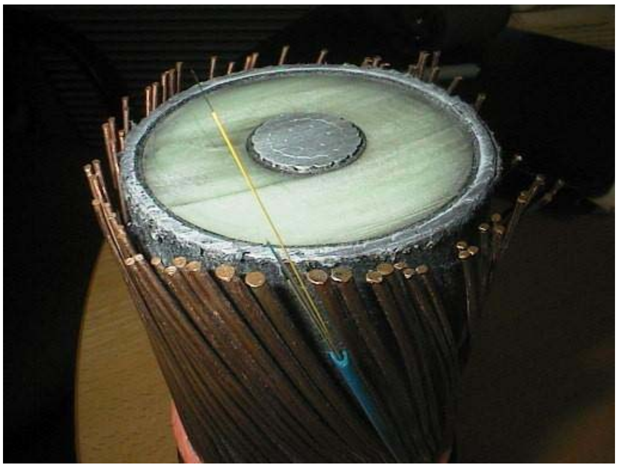
Fibre-Optic sensing cables

DTS systems employ standard communications grade optical glass fibre. Whilst some long-range systems use single-mode fibre, low to medium range systems up to 10km use multi-mode with core diameters of either 50 or 62.5 microns – about the thickness of a human hair. The core is typically contained in a glass/acrylate cladding, taking the diameter up to around 250 microns for so called "bare" fibre. Further claddings and sheathing provide rugged, waterproof cables, capable of direct burial alongside power cables.



The photo shows a standard outdoor sensing cable, comprising four colour coded 62.5/125/250 micron multi-mode fibres in a loose tube configuration, sheathed inside a gel-filled nylon tube. The outer sheath comprises a polyethylene cover over an aramid fibre strength member. Overall diameter is approximately 8mm.

An alternative to the external cable shown above is to incorporate the fibre-optic cores inside the power cable – see photo over-page. Such construction is available from several cable manufacturers and optical fibres have been used in this way for both DTS and communications purposes. The marginal cost of adding several fibres to a HV power cable is quite low and many utilities are adopting the practice of purchasing cables that are "DTS-ready" in anticipation of a future role for temperature sensing and dynamic thermal rating.



The photo shows a section through a 132kV XLPE power cable which had been fitted with a multi-core fibre-optic loose tube cable located within the screen wire array

(Courtesy of Integral Energy)

Applications

To date the most common application of fibre-optic Distributed Temperature Sensing has been in conjunction with underground power cables. Because of the relatively high cost of DTS until recently the systems have been mainly limited to critical EHV cables. However, increased competition among manufacturers and technical developments have reduced prices significantly and made DTS available for economical application at lower voltages and in other thermal monitoring roles within the Electricity Supply Industry.

Other applications include monitoring of substation plant such as transformers, switchgear, packaged substations, bus systems, control and auxiliary cables and fire detection. For example, Integral Energy have installed a Sentor®101 DTS linking thermally rated plant at their Penrith Substation in western Sydney.

The photo shows a DTS installation at Integral Energy's Penrith substation. The equipment is mounted in a 19 inch rack and includes the Sentor®101 instrument, key board, monitor, uninterruptible power supply, alarm output relays to the SCADA and modem for remote control and data acquisition. The laptop computer is being used to commission the remote control function via a mobile phone.

Installation
Fitting of external fibre-optic temperature sensing cable to new underground power lines is quite straightforward. The sensing cable is pulled into in the trench after the power cable is laid and strapped to the top of the centre phase approximately every metre with cable ties. If the power cable is to be pulled through long ducts the sensing cable can alternatively be attached with spirally applied PVC tape.

The photo shows installation of fibre-optic sensing cable by strapping to the outside of 22 kV power cables at United Energy's Dandenong Valley Substation in Melbourne. The as yet unattached sensing cable can be seen in between the leftmost pair of phase cables.

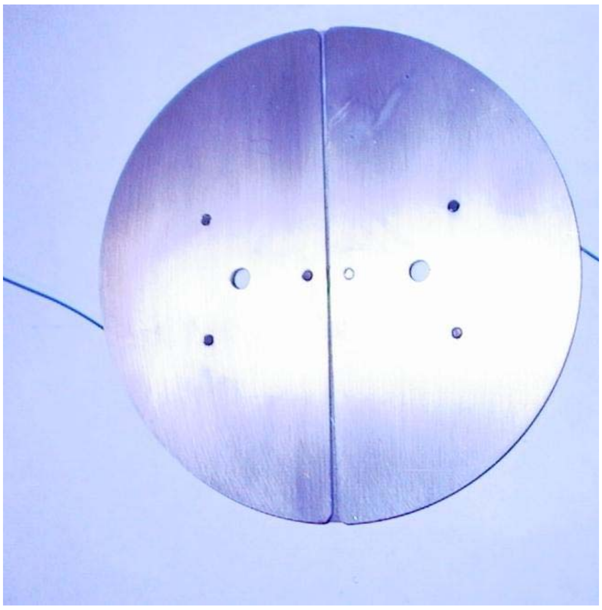
At the substation end the fibre-optic cable is terminated inside a junction box and a patch cord with optical connector spliced to the start of the fibre, for connection to the DTS instrument. Splicing of optical fibres requires a relatively expensive fusion splicer and trained operator, but can be carried out by communications contractors or DTS systems suppliers, if the utility does not have these facilities in-house. At the remote end of the fibre a waterproof heat-shrink boot is all that is needed to seal the cable end, although in some installations the opportunity has been taken to splice together pairs of fibre cores to provide a reading on the return path for comparison purposes.

HV cable with integrated fibre-optics requires fibre splices at each cable joint which adds to the complexity and cost of installation. It also makes it difficult to get a temperature reading in the vicinity of the joint, since the fibre zone for a short distance either side of the splice has to be excluded from the data analysis, to eliminate optical reflections which would otherwise cause spurious readings. Since cable joints are of special interest thermally, other techniques may need to be adopted such as splicing in a spool "concentrator" similar to that shown over-page.

The spool concentrator can also be used to provide a "spot" temperature because it offers better effective spacial resolution than a straight DTS sensing cable, which at the present limits of technology typically averages temperature every a one-and-a-half metres. This is achieved by spooling up several metres of fibre at each concentrator. The resultant node can be very clearly seen on the screen trace and can assist in identifying items of equipment.

The simplest sensing topology employs a single continuous length of fibre-optic cable linking items of equipment to be monitored. Connectors and, to a lesser extent, splices, introduce attenuation which can limit performance, and should therefore be kept to a minimum.

In substations with radial feeders it makes sense to consider multiplexing of a single DTS instrument across several cables and at least one manufacturer offers an opto-mechanical switch.



The photo shows a stainless steel spool concentrator, approximately 150 mm dia, on which is wound several metres of PVC clad optical fibre. This device can be used to provide "spot" temperature measurements within a run of sensing cable.

Performance

Performance claims vary between manufacturers and models but there is fairly general agreement that DTS systems must be tuned to suit specific applications as the physics of currently available optical devices dictates some trade-off between measurement parameters. Typical accuracies of plus/minus 1 deg.C are possible, with spatial resolution of around 1.5 metres, although the theoretical limit is perhaps 250 mm or less. The trade offs are either range and/or acquisition time. Ranges up to several kilometres are the most common but some systems can handle over 30 km. Acquisition time varies from seconds to hours depending on the application – a fire detection system needs a quick response but temperature accuracy is less important than in a system providing real-time thermal rating for equipment with a long time constant, such as a transformer.

Software and Data Analysis

With DTS hardware typically generating 10,000 laser pulses per second there is a lot of data to collect, analyse, store and display in order to produce a useful thermal profile along the sensing cable. Operating software is therefore a key element of any DTS system. This is now well developed and in the Sentor® system offers digital as well as graphical display, multiple zoned alarms for absolute and rate of rise of temperature, different storage modes for short and long term data, and optional models for post-processing of raw data (such as variable space averaging of displayed data). Features such as automatic correction for splices and connectors, external as well as internal calibration, are also available

As well as a sophisticated operating system, DTS application software is being developed to provide for a variety of SCADA interfaces and for Real Time Thermal Rating of temperature dependent assets, such as power cables and transformers. Sentor® uses a Microsoft Windows platform, which facilitates the addition of third-party programs for application specific data analysis and display.

International Interest
Power companies around the world have realised the benefits of optical Distributed Temperature Sensing for enhanced circuit protection, but more importantly, for real-time load management. The US Electric Power Research Institute (EPRI) estimates that many transmission lines have significantly greater load capacity (20–30%) than their static ratings suggest. DTS is the only safe and effective way to exploit full circuit capacity.

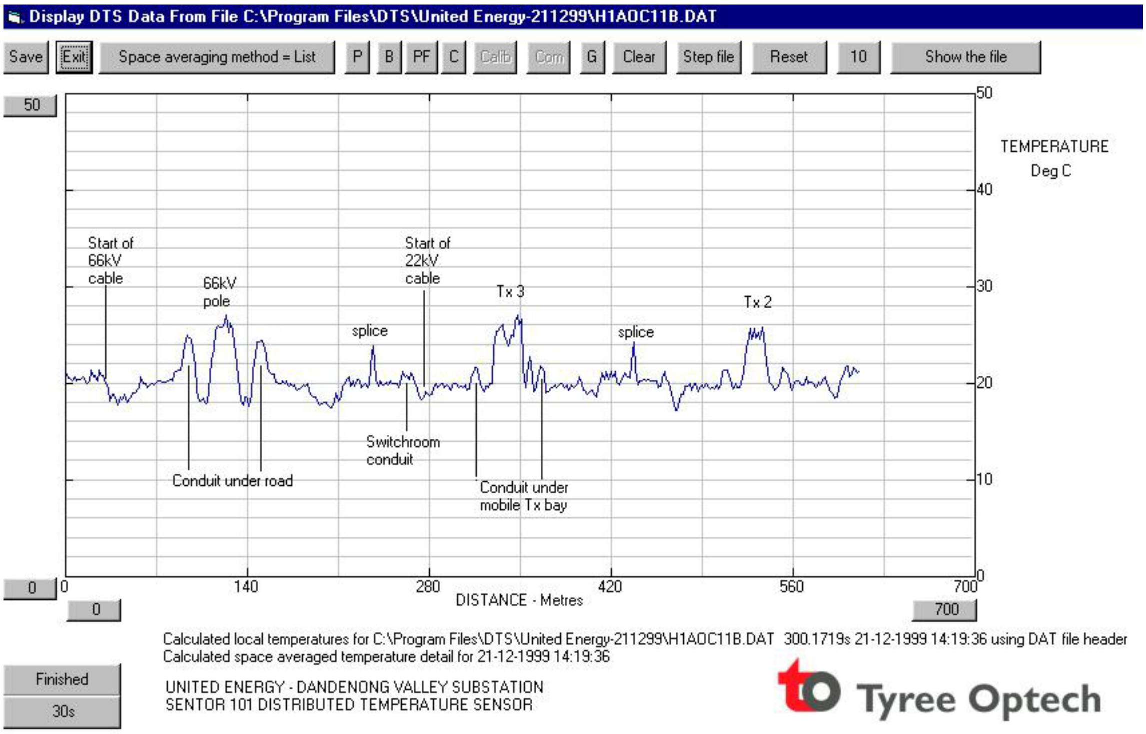
In the UK The National Grid Company has been using DTS systems on selected new EHV cable circuits since 1992. In the USA, Commonwealth Edison are adopting fibre-optic temperature sensing for all new 138kV in-duct underground cables in Chicago and Northern Illinois. *"DTS systems will give us precise real-time, measured data and allow us to avoid all the variables such as surface temperature, soil moisture and thermal influences."* - Linda Manning, ComEd's Asset Management and Planning Vice President.[3] ComEd are also looking at retrofit options for existing key circuits. Other key overseas users of DTS systems for power cable monitoring include Hydro Quebec in Canada and Tokyo Electric in Japan.

The Local Scene
In Australia and New Zealand several Electricity Supply Companies are now specifying fibre-optic sensing cables to be incorporated in new installations. Western Power have adopted the Sentor®101 DTS with externally applied sensing cable for a new 132 kV cable in East Perth and are specifying internal optical-fibre cores for DTS on other underground cables. Energy Australia have specified the option of fibre-optic temperature sensing for a new 33 kV cable in Sydney.

Transend Networks have installed Sentor® external temperature sensing on a 22 kV XLPE cable upgrade at Norwood 2 x 50MVA substation in northern Tasmania. One of the old PILC transformer feeder cables had failed, having been subjected to regular overloading during single unit outages. Transend's CEO, Richard Bevan, says, *"…DTS is one of the most exciting opportunities for better management of assets that our industry has seen for a long time, for both lines and subs."*

In New Zealand interest is high. As well as the Vector installation, Orion are installing optical fibres in new 66 kV cables in Christchurch and WEL Energy in Hamilton are implementing DTS for a 33 kV underground application. Given the simplicity of adding a sensing cable at the time of installation, and realistic pricing now available for mid range DTS instruments, an increasing number of power cable specifications are calling for fibre-optic sensing down to 11 kV. For instance, Powerco Limited have fitted external fibre-optic sensing to 11kV ducted cables in New Plymouth.

Tyree Optech have installed external sensing cable on 22 and 66 kV underground cables at United Energy's new Dandenong Valley Substation in Melbourne. The effectiveness of this method of temperature sensing can be seen in the annotated screen view from the Sentor®101 instrument during commissioning tests – over-page. Although the cables were very lightly loaded there are very noticeable changes in temperature where they passed through conduits, compared with direct burial in controlled backfill.



The Future

What is the future for DTS systems in the Electricity Supply Industry? It is clear that fibre-optic sensing cables will be installed in growing numbers as asset managers seek to drive power systems harder and still enjoy a good night's sleep. Real Time Thermal Rating (RTTR) linked to SCADA systems will enable accurate measurement, prediction and control of load on temperature-critical circuit elements. As well as cables, transformers and switchgear will have embedded fibre-optic sensors for both distributed and point temperature monitoring. Other substation equipment will be linked by a network of optical fibre. Overhead lines will also have embedded fibre-optic temperature sensing in their phase conductors using similar techniques to optical ground wires (OPGW).. Fire detection is another emerging DTS application.

Perhaps one of the most persuasive arguments for adopting Distributed Temperature Sensing is its significant potential to impact positively on insurance premiums and minimise the increasing risk of class action, as well as other types of litigation, arising from failure of supply.

It seems fitting to close with two quotes from Powerco's 1999 Annual Report:

"Effective network management depends on accurate information. It drives our ability to reduce capital and maintenance costs, offer new value added services and improve asset value."

"The better we understand the life expectancy of our assets, the better we can manage them to achieve improvements in our company's value."

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[1] http://www.moc.gov.nz/inquiry/publicsummary.html
[2] "Critical Circuits – DTS Imperative", Barber et al, D2000 Proceedings, 1999
[3] http://ucm.com/news/display.asp?a+ComEd&rec_id=334