



# **Cable Condition Monitoring to Improve Reliability**

**by**

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## Abstract

The electric cable industry is definitely in the mature product stage and while there are many incremental developments and improvements, the history and experience gathered enables us to approach issues of cable failure and cable life maintenance with ever improving tools.

The task ahead of us is to implement well established techniques of design and installation of electric cables that almost guarantee the proper and continuous function of this essential infrastructure asset.

A summary is provided of the causes of failure (damage, ageing, and electrical deterioration) and reduced cable life with the developing tools to predict and analyse such failures as part of a continuous process of monitoring the condition of the asset.

Preventative measures are well known and should be utilised at every instance. Some advances in the use of temperature monitoring and partial discharge detection, in combination with the preventative activities and training would provide for the achievement of the full cable life.

This paper discusses currently available technology, the shortcomings, and the trends for future development.

## Introduction

The higher demands by the Electricity Industry have created an increased focus on the need to limit installation and service costs and obtain higher performance, reliability, and asset life.

The traditional and more conservative approach to circuit loadings and emergency ratings has given way to the demands for the maximum use and efficiency of a cable asset without any deterioration or reduction in the long term performance.

Such expectations can only be achieved with continuous monitoring and analysis of the condition of the cable so that the owner and operator have full confidence when taking decisions concerning the available capacity of the cable.

Conditions that cause the degradation of the cable include the mechanical damage that may occur prior to the energising of the circuit, the overheating of the cable with resultant ageing and deterioration, and the electrical deterioration of the insulating components.

Existing voltage tests are used to detect mechanical damage during handling and installation. Additional techniques, systems, and instruments are being developed to monitor the cable operating characteristics that lead to failure, the most advanced being temperature monitoring and partial discharge detection.

With appropriate training and care, the mechanical damage of cables should be able to be avoided and by the addition of fibre optics for temperature measurements and accessories including partial discharge detectors, then the running condition of the cable and accessories can be continuously monitored and relayed to the operator. Thus, operational damage can also be avoided while the cable is used at its maximum capability and for the entire cable life.

## **Cable and System Design**

The subject of cable design and cable system design considers three elements within the cable and ‘the environment in which the cable is installed’ is the external factor to be considered.

The cable elements include the conductor for electric current, the insulation suitable for the voltage level, and a means of protection from external elements during installation and in service.

The real situation is that there are a large number of applications and range of service conditions, so that a number of different cable products with a wide variety of features can be generated. Apart from the varying electric current demands at a range of voltage levels, one must also consider the chemical compatibility of each of the materials selected combined with an understanding of the installation methods and the environment in which the cable will be installed.

An additional dimension which increasingly needs to be considered these days is the environmental assessment of the materials themselves, their effect on operating performance, and the impact of their ultimate disposal at the end of the cable’s useful working life.

Thus the whole subject of cable and system design is in fact quite complex, but always targeted to improve performance and cable life.

## **Why Do Cables Fail?**

Power cables can fail for a number of reasons, the most common causes being external interference or damage, overheating, moisture ingress, poor accessory installation, cable or accessory defects, all of which will result in electrical failure or breakdown of the primary insulation.

Identifying the real cause of a failure can be a difficult task as one form of damage may lead to another, and the root cause may not be plainly evident.

## **Mechanical Damage**

Mechanical damage is usually attributed to activities during or after installation, when the cable is most exposed to the possible damage, however experience shows that damage during manufacture, transport, and handling is also possible.

Testing of each cable length by the manufacturer of cable and care during manufacture results in a product without defect that can be expected to perform for the entire design cable life. Such confidence can only be assured by close adherence to proven design concepts, quality procedures during manufacture, and strict criteria during the testing phase.

Analysis of cable failures due to mechanical damage shows that damage that occurred during installation is often the direct cause of failure in service.

Severe mechanical damage (such as dig-ins) during service will result in immediate failure of the insulation and disruption of the supply of electricity. However, if the damage is not so severe as to cause such an instant reaction, it may go unnoticed and eventually lead to failure by one of the other main causes. For example, a civil contractor installing water pipes near a cable circuit slightly damages the cable sheath, and does not repair the damage. In time, moisture from the surrounding soil eventually corrodes the metallic sheath, permeates into the insulating layers and eventually causes electrical breakdown. Unfortunately, the energy released at the time of eventual failure will often burn away the evidence of the real cause.

There are also a number of other opportunities for mechanical damage to occur over the life of the cable, including insect and rodent attack, vibration, soil erosion, and corrosion.

Therefore having a cable with the best possible protection and good installation procedures is some of the best assurance for a reliable cable asset in service. Continued cable life is assisted by the monitoring and period checking of the cable and accessories.

## **Ageing and Overheating**

Ageing and overheating is a direct result of incorrect system design, inappropriate installation, or abuse of the cable by overloading.

Overheating of cables accelerates the ageing process and can lead to cable or core movement (due to thermal expansion) that was never designed or catered for in the system arrangement. If such movement is concentrated at one point (as is often the case, for example, at the accessory) damage and/or failure at that point (the accessory) will certainly result.

As paper insulated cables age due to overheating, they become quite fragile, and mechanical impact, or an attempted movement, may be sufficient to crack the increasingly delicate paper insulation layers and cause failure.

The newer XLPE insulated cables also suffer problems when overheated, initially seen as deformation of the insulation layer, but eventually resulting in a breakdown of the polymer chains, baking and carbonising of the insulation. With the insulation at any one of these stages

of deterioration, any additional stresses imposed by voltage peaks, impulses, and spikes will initiate the breakdown of the entire thickness of insulation.

Deterioration of the primary insulation is the most severe type of ageing damage, but the most common ageing damage occurs to the outer parts of the cable, as they are in contact with the external environment.

For the polymeric sheathing materials, such factors as UV radiation and chemical reactions, are the most significant, while for the metallic layers, corrosion and electrolytic action are a danger. The breakdown of the external cable protection then leads to damaging effects onto the primary insulation and cable eventual failure.

An example is the problem commonly seen with oil filled cables where either fatigued or corroded metallic sheaths release oil pressure, and result in primary insulation failure.

In very many cases it is not the cable that initiates the failure, but the accessory, by allowing the ingress of water at an aged or poorly installed interface or at a broken interface due to movement.

## **Electrical Deterioration**

Partial discharge is, as the name suggests, a “partial” discharge (or breakdown) within the insulation medium. It is generally initiated from a small defect or contaminant within the insulation or a void. These defects increase the electrical stress at that point to a level where discharge is possible even within solid materials.

The XLPE insulated cables are not tolerant of continual partial discharges and rapidly deteriorate and fail.

This phenomenon also occurs in paper insulated cables but is generally less destructive to them as they exhibit a unique “self-healing” property due to the mobile impregnating compound or pressurised oil.

Manufacturers of XLPE cables take great care during manufacture to ensure no sites for partial discharge activity exist, and during routine testing, all cables are energised well beyond their working voltage whilst PD levels are monitored. It is therefore unlikely for new cables to exhibit such problems for many years of service.

In the field however, these cables must be fitted with accessories suitable for jointing or termination, and unless the design and workmanship in fitting of these accessories is effective for the electrical stress levels involved, partial discharge can occur at the interface between cable and accessory.

XLPE can also suffer from the phenomenon of water treeing, where under the influence of electrical stress and moisture, “trees”, which are microscopic void channels can occur and propagate slowly through the insulation, causing increasing levels of electrical stress and leading to eventual electrical breakdown.

It is consequently extremely important that highly stressed XLPE insulations (such as in EHV cables) have an effective moisture barrier provided for their entire lifetime.

## **Prevention of overheating and ageing, prior to installation**

It is normal to monitor the current flowing in the cable and the limits passed on a circuit are based on the assumed maximum current that can be allowed to flow. However, at a more basic level, it is really the temperature of the cable that is being limited by the restrictions on the electric current. This correlation and relationship of current to temperature is critical.

Traditionally, the current rating of cables is based on thermal equations established many years ago and published as IEC documents, such as the IEC 60287 and IEC 60853 series. Whilst these have proven reliable, they are generally accepted as conservative and underestimating of the cable temperature. As mentioned earlier, there are pressures on the electricity supply industry to become more efficient, and this has focused attention on the thermal design and installation conditions (backfill) of new high and medium voltage insulated cable systems, to ensure the accurate rating of the cable with minimum investment outlay.

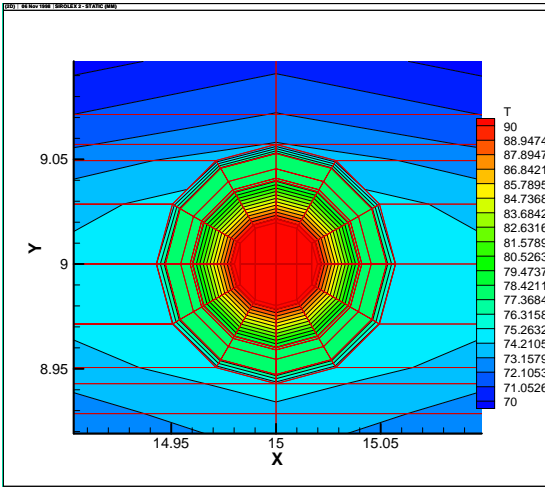
This situation stimulated Olex Australia to develop, through a contract with the CSIRO, a package of finite element computer programs, termed "SIROLEX", to address the accuracy of thermal design of insulated cable systems so that more accurate cable sizing and backfill properties can be specified.

## **Thermal Analysis with 'SIROLEX'**

A cable rating is purely determined by the heat balance equations that take into account the heat generated by the cable and its ability to dissipate that heat into the surroundings, particularly when there are other heat sources (other cables) nearby. A cable system design engineer, when involved in the thermal design of a circuit, must frequently address many different design configurations. There is thus a need to quickly generate different circuit configurations while retaining accurate and detailed representations of the geometry. In addition, both steady state and transient situations must be addressed. In fact cable systems are rarely, if ever, in a thermal steady state but are usually subject to load variations and a variety of diurnal and climatic changes leading to a complex transient thermal behaviour of the installed cable. Therefore some effort was invested in describing transient thermal situations.

Program operation involves building the finite element model, assigning the material properties and boundary conditions and solving for the temperatures. Circuit ratings must therefore be obtained from the resultant temperatures. In reality, because circuits are subject to load changes and variations in the environment, a circuit rating is a continuously varying quantity. The commonly used continuous or steady state rating is perhaps an abstraction never realised in practice.

Olex has linked this Sirolex software with the Olex IEC 60287 current rating program and this is proving a valuable tool for cable engineers in firstly assigning ratings, and then also interpreting results from systems such as DTS.



The above picture is an example of the output from the Sirolex package, showing the gradient of temperature from the conductor to the surrounding layers of cable components and soils. To obtain sensible results from any computer program, a detailed knowledge of the parameters that affect the results is necessary.

### Soil Thermal Resistivity

The importance of correct backfill properties has been appreciated almost since the first underground cables were installed, but the selection of appropriate materials to use as trench backfill was more dependent on local availability and experience in the selection of a “good” material. As an example, many installers considered sand to be a reasonably uniform material, so that it was also considered perfectly satisfactory just to add appropriate levels of cement or fly ash, as mentioned in cable handbooks, in order to achieve suitable stable backfill materials.

Nowadays, we understand the importance of achieving a low value of thermal resistivity together with a reliable compaction density, just as we now place greater importance on the assessment of the thermal properties of the native surrounding soils.

Soil thermal resistivity can now be readily and accurately measured in the field or in the laboratory using commercially available test equipment.

Installation of prototype sensors in the field, which continually monitor soil temperature and thermal resistivity are also yielding surprising details with regard to the variations of thermal resistivity with moisture content of the soil.

The conclusion we draw from all of this additional knowledge is that there is no “standard” installation condition, and that the environmental conditions over the length of even the shortest circuit may vary widely.

Ultimately then, as a cable will always fail at the weakest (or most overstressed) point, we need to be able to interrogate the entire length of cable to establish its condition and ability to continue to function.

## **Understanding cable thermal behaviour after installation**

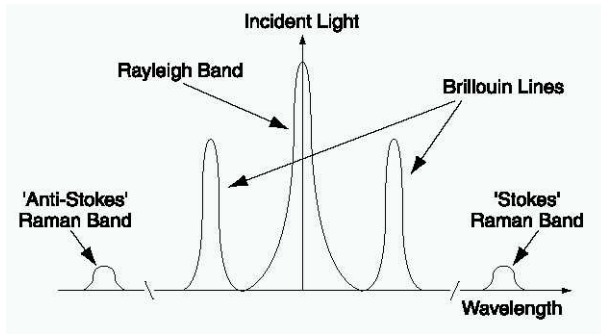
Once the design and installation are performed properly, it was normal human behaviour to consider the matter completed and to operate the cable by its assigned electric current rating for the remainder of the cable life. It was accepted that winter and summer ratings were appropriate in an improved attempt to correctly manage the cable temperature, but a greater number of ratings for more detailed subdivisions of operating conditions were not considered necessary nor acceptable.

The inherent allowances and conservative approaches in the determination of the current ratings are no longer tolerable and the task of providing an accurate and maximised rating has led to the development of continuously monitored temperature by fibre optic techniques.

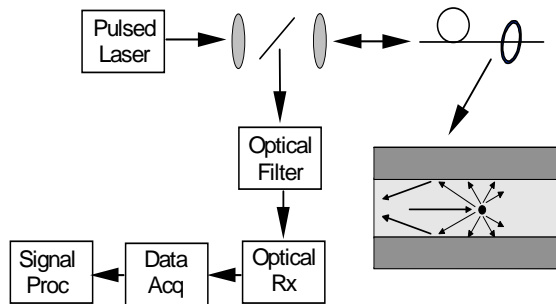
## **Distributed Temperature Sensing (DTS)**

In conventional temperature measurements, a sensor, such as a thermocouple or platinum resistance probe, is needed for each point of interest. For applications where large areas or long distances are involved, conventional systems therefore become over-complicated, bulky, unreliable, and costly to maintain. An effective alternative solution is a distributed sensing system.

The expression "distributed sensing" is used to describe a technique whereby one sensor can give data spatially distributed over many thousands of individual measurement points. A single optical fibre has the ability to act as a distributed temperature sensor with potentially many thousands of individual measurement points. Current Distributed Temperature Sensing technology (DTS) allows fibre lengths of up to 30 km in length with sampling every 2 metres to be used in this way. Optical fibre sensors for power asset monitoring have significant advantages because they are totally immune to EMC interference and can also be used in hazardous areas.

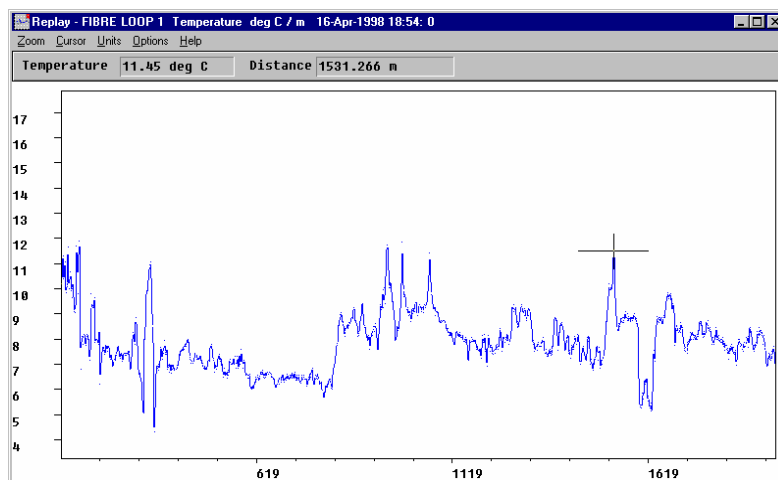


A DTS system is essentially a combination of two technologies, optical fibres and analysis of a complex physical effect. Temperature measurements are achieved by analysing the Raman back-scatter signals reflected back from laser pulses travelling down an optical fibre. The position of each measurement point is determined by its time-of-flight from laser emission and the temperature is related to back-scatter intensity. Complex electro-optical devices are required to detect the very small change in the optical signal.



The laser pulse is transmitted into the fibre via optical directional couplers which allows the returning back-scatter signals to be filtered into a highly sensitive dual-channel receiver where the Raman signals are detected and converted into a digitised format specifying temperature and position. The function of the signal processor is to provide a user-controllable level of signal averaging to obtain the desired level of temperature resolution.

The resultant temperature profile, shown below, enables cable owners to determine the size, location, and potential impact on rating performance by any hot spots caused by localised environmental conditions.



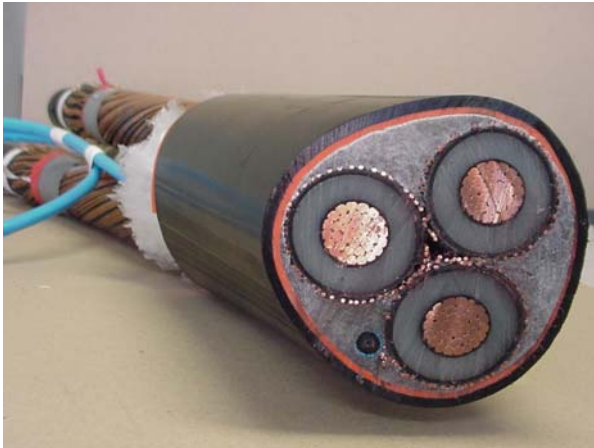
Just as a doctor has to interpret the results from an ECG machine, the interpretation of the results from the DTS equipment needs some special cable engineering skills. However, by combining the use of appropriate cable rating software, it is possible to establish a predictive rating assessment. Such a situation in a real time mode will enable system operators to maximise the cable capacity without any danger of overload and deterioration of the circuit.

It is clear that DTS validates design configurations while allowing optimal use of cable circuits and the elimination of the risk of damaging the cable unknowingly.

**Features that allow DTS to work**

The DTS system is operated after installation, but the fibre optic features needs to be specified and applied at the design stage. Already we are finding many existing circuits with the demand for more accurate knowledge of the cable temperature, but those existing circuits have no optical fibre in place, and no opportunity to attach such a fibre to the cable circuit.

Experience and development has shown that the inclusion of fibre within the cable is feasible and a small additional expense and available for both single core and multicore cables.



**Causes of Electrical Deterioration**

A perfectly manufactured insulation would tolerate expected operating conditions indefinitely, provided external factors did not affect that insulation adversely.

Partial discharges at accessory interfaces will degrade the insulation of the power cable. As mentioned earlier in this document, the paper insulated cable has the capability to accept some discharge, whereas the XLPE insulation suffers from such discharges so that break down may occur quite rapidly.

Water treeing, the phenomenon of water penetration into the XLPE under voltage stress, resembling a growing tree, tends to develop into a site for an electrical tree and eventual partial discharge, and hence eventually leads to electrical failure of the insulation.

Partial discharge testing of all cables as part of final testing after manufacture has been in place for more than 25 years. The detection and monitoring of partial discharges in service, under field conditions, is now becoming ever more important.

## **Partial Discharge**

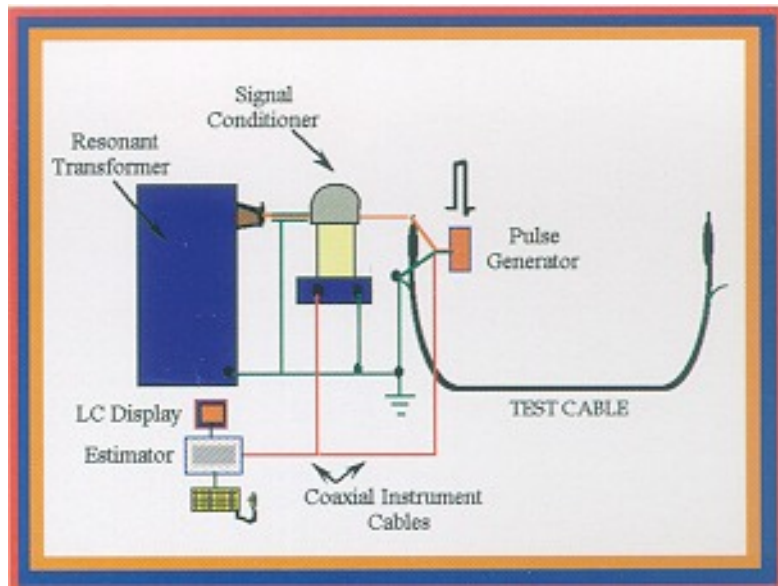
It is now possible to measure changes in partial discharge on a complete circuit and from the data, extract information, and obtain an indication of the location of such discharges. It should be recognised that actually being able to measure PD outside of a special screened room environment without a special PD free voltage source is a major technological achievement. A comprehensive study of all the various methods is given in a CIGRE WG 21-16 report. However, it should be pointed out that there are currently two schools of thought in relation to PD monitoring on cable systems.

### **PD at Supply Voltage**

In the first case, it is recommended that PD can be measured on a complete cable circuit at the normal operating voltage using directional coupling, so that it is possible to locate whether the discharge is coming from an accessory or from some other location. Very low values of Partial Discharge in HV and EHV accessories can also be monitored directly, although not at this stage economically on a real time basis. But, it can be done at regular intervals during the life of the circuit. In most cases this monitoring is used in a manner similar to a DTS. That is, as a trend analysis, either by comparing the results taken at regular intervals, or on a continuous basis. Because the partial discharge is being measured at normal working voltage the signals (if any) are very small. Hence it may be argued that the by the time a discharge is of such a magnitude as to be observed or detected, the cable or accessory will be on the verge of failure, and hence there is little if any time in which to respond. To compensate for this some systems are developing very sophisticated trend change/recognition software.

### **PD at Test Voltages**

In the second case, because PD can usually only be detected at voltages above normal service voltage, the PD test is carried out by testing at regular intervals with specialised PD detection equipment at a voltage above the normal supply voltage. In this case it is claimed that any minor defect will be detected before failure in service so that appropriate maintenance can be affected before system failure.



The typical configuration of test equipment is given in the diagram above.

The major problem in the past has been that of being able to develop an AC test voltage in the field of a similar frequency to the normal supply voltage. However, suitable equipment has now been developed and is being used extensively in USA and Europe.

### Summary and Future Trends for new circuits

We are entering the era of the 'smart cables and systems' so that the inclusion of an optical fibre within a cable or directly attached to the cable is becoming an essential requirement for any new cable system. We see a trend continuing to include fibres in distribution circuits and substation cabling.

For EHV, we see that there will be a trend to the inclusion of PD detectors in accessories, which can be used for monitoring the circuit after installation and also later in service.

### Summary and Future Trends for existing Circuits

The retrofitting of Optical fibres for DTS and associated monitoring is generally not practical over the complete length of a circuit. The solution is the installation of Optical fibre over a known hot spot area or providing specific temperature and soil thermal analysis probes at selected key points to confirm empirical calculations and ensure the circuit is operated within design limits.

### The Future

There is no doubt we are entering an exciting new era in the Cable Industry where there will be significant advances in cable condition monitoring to improve overall reliability of

electricity supply, reduce investment and maintenance costs, and extend the life of new and existing cables.

## Biography

### **Hilary Marazzato**, Engineering Manager – Cable Design and Applications

Hilary is responsible for cable design and cable applications for all cables up to 33 kV including XLPE, PVC, or EPR insulated, for fixed and flexible applications.

Hilary is an Electrical Engineer with 25 years experience in the cable industry with substantial experience within the manufacturing and product development environment. Hilary has been involvement for over 20 years in the Standards process at Australian and International level and is the Australian representative within the IEC TC20 WG16. Additional, Hilary is regularly involved in the development of new applications and resolution of field difficulties to ensure that design criteria and performance are met.

### **Ken Barber**, General Manager – Engineering and International Sales

In his current role he is responsible to the Managing Director of Olex Holdings for co-ordinating the engineering activities of company and has a direct responsibility for the overall management of turnkey cable projects and International Sales.

Ken has been directly involved in the Cable Industry for more than 38 years, having worked in the UK, India, Malaysia and Australia. He joined the cable industry in UK in 1963 working on cable design, testing and development. He was Assistant Chief Engineer for a cable factory in India, Technical Officer Power Cables for Olympic Cables in Australia and Chief Engineer of a cable factory in Malaysia before returning to Australia in 1976. He has been responsible for Olex' development program over the past 25 years including EHV cable manufacture/installation and establishing technology links with key manufacturers.

### **Mark Gregory Jansen**, Applications Engineer

Mark has been employed at Olex Australia since 1997 after graduating as an Electrical Engineer. Mark has been involved in engineering roles both in design and application and have entailed considerable involvement in the condition monitoring aspects of cable installation, particularly Distributed Temperature Sensing (DTS). In this field Mark has now gained several years of experience in both the long term and short term monitoring of underground power cables using DTS technology.

### **Graeme Barnewall**, Engineering Manager - EHV Cables

Graeme is responsible for cable and system design and manufacturing support for High Voltage cables.

Graeme has over 22 years experience in the cable industry and regularly visits installation sites to assist with resolution of field difficulties and provide assurance that design criteria and performance are met.