Advanced Cable Monitoring Techniques For Earlier Failure Warning

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In the past two decades the power sector has steadily increased its investment in optical sensing technologies. At present, distributed fibre optic temperature sensing technologies are widely used by utilities to provide valuable operational ampacity data for safeguarding those critical assets. New advances in fibre optic sensing techniques are now offering better visibility of buried cable operation and earlier warning of cable degradation issues endemic in the underground cable environment.

This paper sets out how the power sector can capitalise on these advances after first considering the challenges and limitations of cable condition monitoring with existing technology.

The challenge of underground cable monitoring

Strengthening the resilience of networks against environmental factors and aging infrastructure is a primary concern. Undergrounding power lines avoids exposure to strong winds, limits the cost of damage, provides a more aesthetically pleasing vista in areas where valued, and offers lower fault rates compared to overhead lines. On the other hand, undergrounding is expensive and introduces new hazards such as flooding and tree root damage. Most obviously, cable systems are harder to access and introduce multiple potential failure points at joints which are challenging and costly to inspect manually or remote monitor comprehensively.

Condition monitoring limitations

Remote condition monitoring of a cable's structural integrity can be achieved through fibre optic-based distributed sensing technologies, and this has proved valuable based on global market adoption in recent years. The initial applications of distributed temperature sensing, using standard telecommunications fibre, have enabled utilities to monitor the temperature on critical cable links, pinpointing cable hotspots and providing utilities with valuable real time thermal ratings. More recently, distributed acoustic sensing technologies have been introduced, enabling utilities to monitor damage caused by third parties, such as nearby excavation works or anchor damage on subsea cables. But while these techniques are clearly helpful, they focus on the results of damage, rather than the underlying causes of that damage. Understanding and monitoring these causal factors would permit earlier failure warning.

As HV cable length increases, cross-bonding of metal sheath connections at cable joints are required to reduce power losses induced in the metal sheath, protecting the cable insulation. In addition, induced circulating current in the metal sheath limits the current ampacity of the power cables. During their service life, cables are exposed to adverse environmental conditions (accelerated ageing) and interventions (third-party damage, poor service work). The most vulnerable points therefore tend to be cable joints, terminations, and link boxes. Sheath system faults can occur, and may be the result of flooded cable joints, corrosion, third party damage, tree root damage, breakdown of insulating flanges in joints, or sheath voltage limiter (SVL) failure. Corrosion may lead to neutrals becoming disconnected, presenting a clear electrical safety hazard, and limiting the cable system's ability to conduct over-voltages and currents safely to earth. The industry recognises that severe service failure may be attributed to poor ground screen connection in transmission and distribution networks, and indeed a CIRED working group "Ground screen power cable connections" is currently reviewing test recommendations for ground screen connections. However, there are no existing qualification or standards for ground screens, and the true ampacity of the ground screen is generally not known or assessed.

DNV GL Energy (formerly KEMA) conducted root failure analysis over several years, on a mostly MV and HV cable population. They found that, of the reported failures, approximately two thirds involved cable joints and terminations. This implies that accessories and their installation techniques inherit the highest risk of failure. Figure 1. below summarises the cable failures by component, voltage, insulation, and root cause.

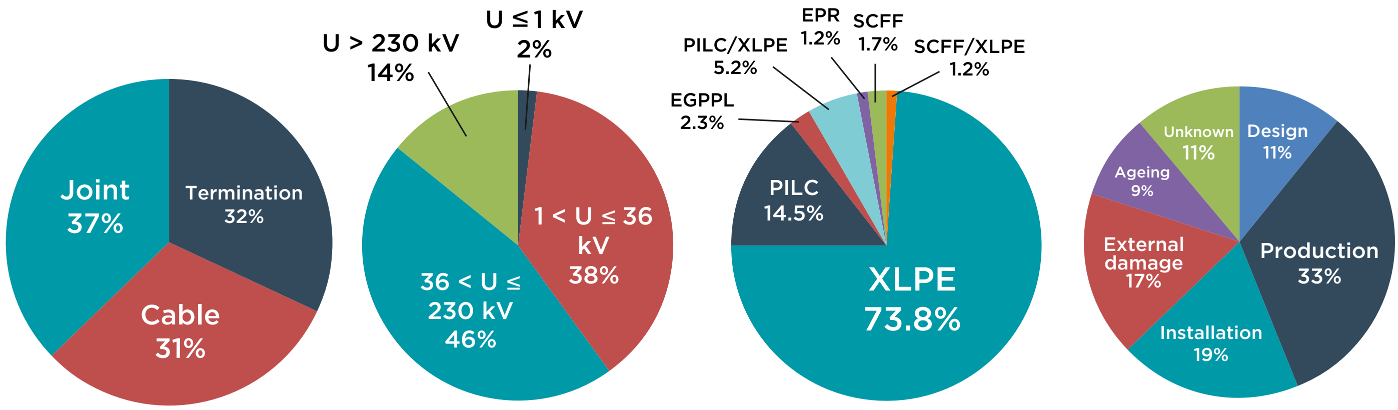


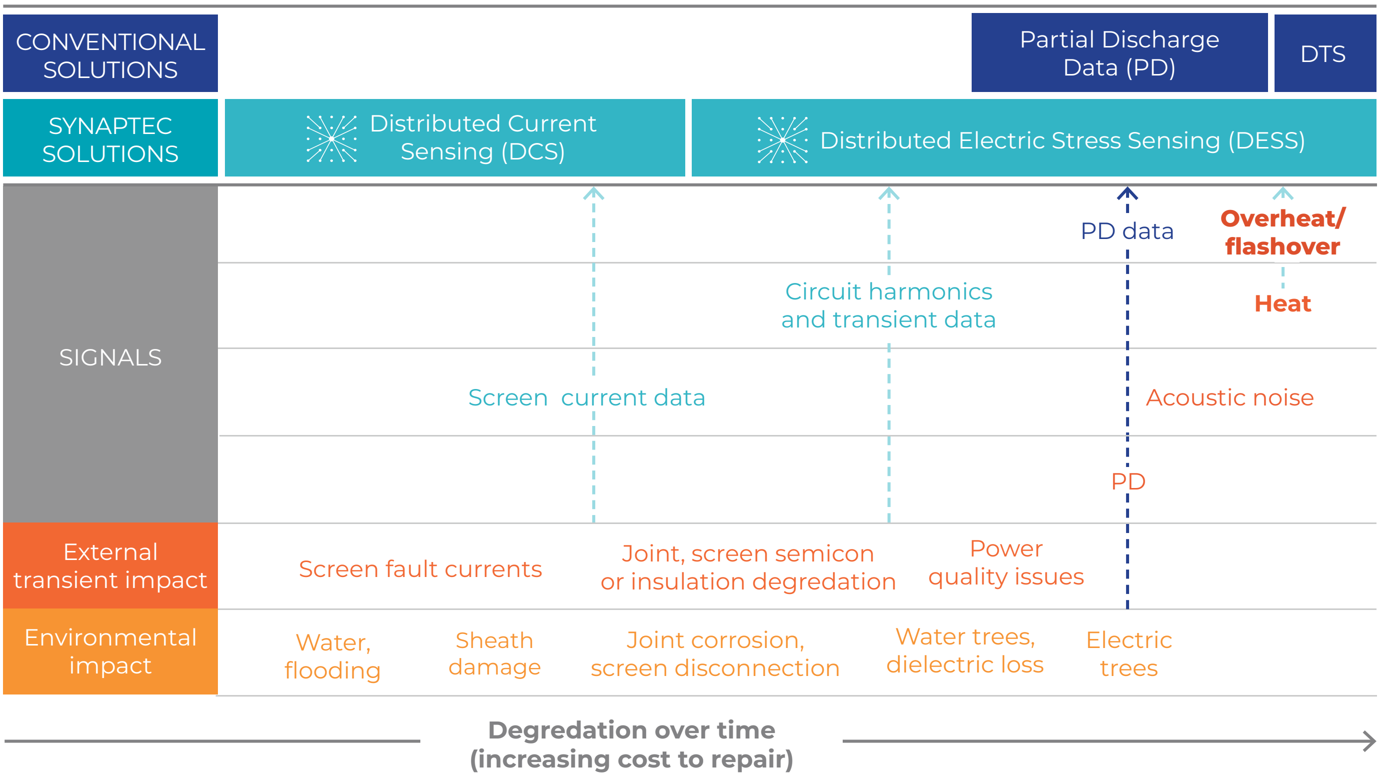
Figure 1. Cable failure data sample[1]

On-site fitting, high electrical fields, mechanical forces on accessories, and site cleanliness all contribute to failures. The use of pre-moulded sleeves for HV cable joints assists in reducing failures as they can be factory tested. As sleeves are fitted, they must exert sufficient interfacial pressure to prevent partial discharges occurring in the interface region. However, exposure to external contaminants and even the tiniest of scratches on the various surfaces can lead to future rupture. The percentage of accessory failures related to design is like that of cables, at 13%. DNV-GL also found that the use of grease, when sleeving the joint, may temporarily reduce the effects of scratches, making them difficult to detect at commissioning, only to become a failure (electrical tree failure) months or years later.

The rate of the aging process is influenced by stresses induced by mechanical, electrical, thermal, and environmental influences over time. Two key external influences on the behaviour of the cable aging are water and transient currents. Water, near cables, can work its way into the cable sheath, and with the presence of significant voltage stress and ion impurities can lead to the formation of water trees that, over timescales measurable in years, damage the cable insulation. MV cables are more susceptible to this form of deterioration, as compared to HV cables, mainly due to their manufacturing materials and processes or installation methods. Additionally, nearby water can induce thermo-mechanical stresses on the cable and eventually introduce water to the screen or semiconducting layers, leading to the development of corrosion. This, in turn, can lead to screen current anomalies which can be flagged as a fault by an appropriate monitoring solution. The fault condition is dependent upon the relationship between circuit load current and the current in the cable sheath, and therefore any sheath current monitoring system must also have a measure of the real time circuit load current as a reference point.

[1] F. De Wild et al, "Failures in underground power cables - return of experience", Jicable Proceedings D9.2, June 2015

Water trees, if left to develop, can eventually lead to electric trees due to extreme local electric fields around the problem area. The field strength can become significant enough to permit partial electrical conduction within the space. This process is repetitive, and one that accelerates towards a fault condition. This type of partial discharge (PD) event is the target of PD monitoring technologies. The PD event occurs within a background wall of noise and can be quite difficult to detect and locate its origin. While PD signals can travel within the cable, the distance over which PD activity is detectable is limited by the PD energy, the defect type, the cable age, and the earthing quality. Currently, installing PD detection equipment at every cable joint to ensure sufficient monitoring coverage is prohibitively expensive, requiring additional expenditure on maintaining the processing electronics and power supplies, and the equipment footprint is excessive relative to the available space.



Much success is attributed to condition monitoring through existing methods of monitoring partial discharge (PD), insulation resistance (IR) and dielectric loss (DL). These offline solutions are tools to enable detailed examination of potentially damaged cable assets. However, utilities tend not to use PD testing alone for analysis purposes, often using alternative diagnostic methods[2]. The reasons for this are multiple. Firstly, PD tests are complicated, and data is difficult to interpret. Secondly, tests on components at production can yield different results to those in the field. Thirdly, there is no clear metric of severity and, as such, sensitivity may be reduced to minimise false positives. Lastly, in terms of time scale, PD occurs close to the point of failure, providing utilities with little time to react to the impending failure.

[2] Hampton N., Perkel J.,"PD Testing – some perspective from users", IEEE PES Insulated Conductors Committee, Apr 2016

Capturing transients for earlier failure warning

The role played by different forms of transients, and how to measure them and evaluate their impact on cables, is a relatively new area of discussion and understanding in the industry. In addition to lightning strike and other sources of conventional high impact switching transients, high frequency behaviour associated with DERs have become a significant new source of transients and higher harmonic components. The CIRED report[3] concludes that the proliferation of distributed generation and the associated power electronics are having significant detrimental impact on power systems operation. Switching transients occur when operating inductive or capacitive loads, such as a motor or capacitor bank, or from Silicon Controlled Rectifiers (SCR), commonly used in DER rectifiers and inverters. Repeated low amplitude transients can slowly degrade insulation, eventually leading to localised overheating and short circuit currents. A transient with a primary frequency component of less than 5 kHz, and a duration from 0.3 to 50 ms, is considered a low-frequency transient. This category of phenomena is frequently encountered on utility sub-transmission and distribution systems and is caused by many types of events – for example: arcing, static discharge, tap changing, or loose connections. On the other hand, impulsive transients (e.g., lightning) tend to have much higher frequency content. They are generally not conducted far from the source of where they enter the power system, although they may, in some cases, be conducted for quite some distance along utility lines.

The Eagle Pass interconnector failure between Texas and Mexico is explored in some detail by ABB[4]. Calculations using 40% of power frequency voltage amplitude also showed very high losses in the stress grading layer at 12.4 kHz – a medium frequency transient. Back-to-back capacitor energization, and cable switching, results in oscillatory transient currents in the same frequency range.

Based on what the industry has learned to date about the impact of transients and harmonics on cable health, it is reasonable to conclude that cables designed according to present standards may fail if subjected to these relatively new electrical stresses which were not considered in the design.

The case for more comprehensive cable monitoring

Comprehensive monitoring of causal factors such as transients, harmonics, and electro-mechanical stresses at the cable's critical failure points is preferable to monitoring only their consequences, which are observed through distributed temperature sensing or PD monitoring. Synaptec's breakthrough passive electrical sensor technology makes this viable by avoiding the need for power supplies, active electronics, data networks including cellular networks, local servers, and time sources at the measurement locations. Centralised and permanent measurement of voltage, phase current, sheath current, strain, and temperature is easily achieved and then correlated to provide early detection of water damage, sheath damage, screen damage, transients, and oscillations – all of which initiate joint or screen degradation, overheating, trees, PD, and eventual catastrophic failure.

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[3] CIRED.C4.24, "Power Quality and EMC issues with future electricity networks", CIGRE TB719, Mar 2018
[4] CBengtsson, Tord et al, "Repetitive Fast Voltage Stresses-Causes and Effects", IEEE Electrical Insulation Magazine, Sep 2009

Distributed Current Sensing (DCS)

Permanent, continuous, and synchronous measurement of all screen currents enables:

- Power cable loss assessment
- Cable screen disconnection
- Earth continuity conductor disconnection
- Sheath damage
- Flood detection
- Minor cable section fault identification
- Screen ampacity calculations

The addition of passive temperature sensors further enhances the solution by providing:

- Cable joint and termination precision temperature monitoring
- SVL status monitoring

Distributed power Quality Monitoring (DQS)

The addition of phase currents and voltage measurement at critical locations enables:

- Power quality analysis
- Transient monitoring

Synaptec is providing, for the first time, a truly passive, zero-maintenance instrumentation solution that delivers all the above parameters permanently and synchronously, as a result, outages will be avoided or at least reduced, and vital cable assets can achieve their maximum operational life.

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