LONG TERM SUSTAINABILITY OF CABLES

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ABSTRACT

The driving force of the electricity distribution industry is the transportation of power from point A to point B, requiring all parts of the system to perform to perfection over a very long period of time.

An integral part of this network is the underground link “cables”. The reliability and lifetime of this link is influenced by a number of different factors, some of which the network controls and some, which it doesn’t. But yet the networks will vary the demands on each part of this link in the hope that they achieve their objective, but each part has a definite effect on the end results.

Long Life Cable

Medium voltage XLPE cables have been in common use for several decades and since their inception many technological advances have taken place. This rate of advance has continued unabated as manufacturers strive to improve the reliability, performance and operating life expectancy of the cable.
Material Technology

Cable technology, by its very nature, is materials based. From the engineering point of view, cables are systems whose electrical behaviour is very much dependent upon the materials used within the cable construction. Since a cable system consists essentially of a metallic conductor surrounded by a dielectric, which is in turn wrapped in a metallic screen and protected from the environment, by a non-metallic sheath, the metallic and dielectric materials utilised in the construction thus largely determine its electrical characteristics.

The purpose of screening over the conductor boundary is twofold. Firstly, to provide a uniform voltage stress over the normally rough stranded conductor surface, so as to exclude any interspaced voids; and secondly, to provide close bonding between the conductor and the insulation.

In the last decade significant advances have been made in the technology used in manufacturing semi conductive carbon blacks. Recently, such technology has resulted in very pure carbon blacks with low ionic contamination levels. Such ions have the potential to migrate into the insulation layer, resulting in the potential for electrical stress initiation. These modern carbon blacks also have a very small and consistent particle size. Earlier carbon blacks suffered from having “rogue” oversized particles which could result in a “protrusion” at the conductor screen/insulation interface, creating an electrical stress point which could result in the development of “trees”.

The purpose of screening over the outside insulation boundary is again twofold. Firstly, with the outer screen grounded, the electrical field of the conductor is confined to the insulation itself for safety considerations; and secondly, it provides intimate contact between the outer screen and insulation.

For the purpose of this paper, we will only concentrate on the key aspects; conductor screen, insulation, insulation screen and protective coverings.

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The same carbon black technology has been applied to insulation screens resulting in fewer protrusions into the insulation layer. In recent years, considerable development has taken place in modifying the adhesive forces of the insulation screen in order to achieve easier “strippability”, while still achieving the minimum strip force necessary to prevent delamination.

**Cross-Linked Polyethylene (XLPE) Insulation**
The cross-linking process causes polyethylene to change from a thermoplastic to thermoset material, resulting in a marked improvement in the physical, electrical properties, and water treeing resistance. The main area of concern with the performance of XLPE insulated cables is a phenomenon called water treeing. This term refers to the crack propagation pattern of degraded insulation, which grows from local high stress points in the presence of moisture. Of vital importance to any insulating material is its cleanliness. Contamination of any type results in an electrical stress point, which can ultimately lead to cable failure. Of all the developments, which have taken place over the decades in XLPE, none is as significant as the effort and R & D expenditure directed at insulation improvements in the area of cleanliness and water tree retardant which has lead to the reduction in the concerns of water treeing.

![XLPE Insulation Timeline](image)

**Materials for Protective Coverings**
Various materials are used for cable non-metallic sheaths to provide protection for the insulation, insulation screen and from the external environment. Such protective coverings enclosing the cable structure may be metallic or non-metallic. The main function of the protective covering is to provide a mechanical outer protection and an impervious covering against moisture ingress. Exposed metallic sheaths and armours are subject to deterioration due to corrosion attack resulting from a number of possible causes:
- For cables buried directly, in ground corrosion may result from the chemical attack caused by
weak acid or alkaline waters;
- Galvanic currents generated between dissimilar metals in contact with the metallic sheath or armour;
- 50Hz current component between the earth and the cable;
- Stray direct currents.

In order to prevent corrosion of the metallic sheaths and armours, the latter must be shielded from the environment by non-metallic coverings.

**Life Expectancy**

The main area of concern in the life of XLPE cables is the phenomenon called water treeing. A great deal of work has been devoted to this phenomenon and a considerable amount of data has been published. The term "treeing" is used due to the apparent similarity in the branched tree to the structure found in the crack propagation pattern of degraded insulation. Water trees (occasionally also termed electrochemical trees) grow from local high stress points in the presence of moisture.

These water trees can be categorised into two main sub-types:

**Vented trees**
Initiated at the insulation surface or interface with a semi conductive shield where, having a continuous supply of water, growth is continual.

**Bow tie trees**
Initiated from contaminant particles or voids contained within the insulation. They tend to be self-limiting in size and seldom lead to electrical failure.

Deterioration of XLPE cables in moisture-free environments is negligible during the cable’s service life. Cable designs are however varied. Present practice ranges from a high degree of protection against the ingress of water, to a low level of protection.

The following measures have reduced the likelihood of water treeing:
1. Conductor strand blocking.
2. Reduced level of contaminants in insulation.
3. Super clean insulation, conductor, and insulation shield material.
4. Longitudinal and radial water blocking tapes and powders.
5 Dry cure, triple extrusion.
6 Polyethylene sheaths.
7 Blocking of water ingress during cable installation.
8 Tree-retardant additives.

**Development of Water Tree Insulation**

Developments in water tree retardant material technology over the past decade have minimised this problem in XLPE cables. Life expectancies in excess of 50 years can be expected for cables utilising these technological advances. These advances in water tree retardant material technology have meant an increase life over the standard XLPE which should be taken into account when conducting an assessment of costs and risk analysis.

It is anticipated that customers will reap the benefits of this ongoing R & D effort, resulting in improved network performance, efficiency and a reduction in total system costs.

**Comparison of Field Aged Cables (XLPE vs TR-XLPE)**

Cable Design

The very rapid growth of underground power distribution in residential areas has led to extensive usage of polymeric insulated cables for medium voltage applications. The underground residential
distribution (URD) cable, because of its lower overall manufacturing and installation costs, has been well utilised. The two main advantages of underground versus overhead distribution are improvement in the appearance of the residential environment, and security from ice, wind and other natural hazards.

In the design, installation and use of power cables, the engineer must possess a sufficient background in cable construction materials to fully appreciate the limits of various cable constructions and systems.

**Design Considerations**

The purpose of a cable system is to convey power from the source of energy to the load. The amount of power is proportional to the product of the circuit voltage and conductor current (under given conditions of circuit length and load impedance). The designer must consider both the current rating (ampacity) as well as the voltage rating for any given circuit problem. The ampacity is determined largely by the service environment or installation conditions. The dielectric loss in medium voltage cables is normally very small compared to the $I^2R$ losses in the conductor, but should be considered when comparing insulation materials.

**Design Objectives**

Design requirements quite logically depend upon cable application. Low voltage cables do not require low-loss, high dielectric strength insulations because much of the insulation wall is there simply for physical robustness. Portable cables require special considerations for good flexibility and the physical protection of cut-resistant and impact-resistant coverings. Extra high voltage cables can employ only those insulations having low dielectric losses. The medium voltage cable used in modern distribution systems requires a reasonable balance of physical and electrical characteristics.

**Temperature Ratings**

XLPE insulations perform well at elevated temperatures so that a continuous conductor rating of 90°C has been established with emergency and short-circuit ratings of up to 130°C and 250°C respectively.

**Metallic Screens**

The design of the metallic screen has received much attention recently; with reference to short-circuit currents during a ground fault. The cross-sectional area of these screens should be such that the short circuit temperature rating is not exceeded during a ground fault and should not be greater than the conductor short circuit capability.

**Non-metallic sheath**

Over the last decade there has been a strong trend away from steel wire armour and PVC non-metallic sheaths towards unarmoured cables with non-metallic sheaths of High Density Polyethylene over PVC bedding. In the last few years a trend is starting to move away from the dual PVC/HDPE to
either a single layer of LLDPE or a dual PVC/MDPE with a much thicker MDPE layer due to installation issues with the dual PVC/HDPE sheath. The following points are a summary of some current world practices:

- 92% of USA utilities specify encapsulated LLDPE non-metallic sheaths based on cost effectiveness;
- LLDPE has superior water and ion migration resistance, which reduces neutral corrosion and the growth of insulation water trees;
- 90% of failures in direct buried cables are the result of mechanical damage or jointing;
- Polyethylene non-metallic sheaths have superior mechanical properties, which result in improved resistance to the rigours of installation practices;
- Polyethylene materials incorporating suitable levels of carbon black exhibit UV degradation resistance properties equal to that of PVC;
- The use of semiconducting LLDPE non-metallic sheaths is increasing, in order to negate neutral-to-ground impulse voltages. Such materials still exhibit the same physical and mechanical attributes as standard LLDPE.

Manufacturing

Medium voltage XLPE cables have been in common use for several decades and since their inception many technological advances have taken place in the manufacturing process. For the purpose of this paper, we will only concentrate on the key element of the manufacture of the Medium Voltage core operation.

Extrusion

The purpose of the extrusion process is to apply the polymer material to the conductor. The extrusion equipment basically consists of an electrically heated barrel, which contains a specially designed screw. The polymer, in a pelletised form, is fed into the hopper at the rear of the extruder. As the polymer passes along the screw it is melted, and mixed to a homogeneous state. At the end of the barrel is mounted the head and die, through which the melted polymer passes.

In the manufacture of medium voltage cables, the three layers of polymer are applied simultaneously. This is achieved by having three separate extruders that feed into a sophisticated triple extrusion head. Contained within the head is a complex series of dies, which allows the formation of the three layers of semi conductive, and insulation materials.

The diagram shows the three separate polymer flows converging at the front of the head, where they are applied to the conductor. Such a configuration is termed “true triple extrusion”.
Dimensional Control
Immediately following the head is a sophisticated dimension control device called an “Ex-Ray 800”. This device uses X-Rays, which are fired through the three layers of polymer to accurately measure the individual layer thickness to a precision of better than 0.01 mm. This system ensures that the dimensions of the three layers are absolutely constant and concentric throughout the entire length of the cable.

Installation Design

Factors to be considered when determining the current rating of the cable:

Depth of Burial
Variation of the depth of burial does not have a great influence on the maximum continuous current rating of a cable. A change from 1000mm to 800mm gives approximately a 2% change.

Proximity of Other Cables
Other load carrying cables or other heat sources in the proximity of a cable have a significant effect on the maximum continuous current rating of a cable. Spacings greater than two metres are usually required so as not to derate the current rating of the cable. This can be important at sub-stations or similar areas where the cables come together to enter switchgear, etc.

Ground Temperature
Ground temperature has a significant effect on the maximum continuous current rating of a cable.
Ground Thermal Resistivity
The ground thermal resistivity has a significant effect on the maximum continuous current rating of a cable. Cables under continuous heavy loadings can slowly dry out the surrounding ground and cause the ground thermal resistivity to increase. In the summer time, long hot dry spells can also cause drying out of the ground; hence heavy summer-time loads can have a more pronounced effect than may be expected.

![Graph](image)

Typical comparison of losses with variations in Ground Temperature, Soil Resistivity Conditions

Cable Support
Under fault conditions, single-core cables used as phase conductors in a multi-phase system may be subjected to large electromechanical forces, which tend to force them apart. Generally, properly designed cleats spaced at 1500mm intervals will provide adequate support to the cable under normal operating conditions. However this distance may need to be reduced for fault currents in excess of 15 kA.

Bending Radius
The safe bending radius for an electric cable is limited by the flexibility of the insulation and non-metallic sheathing material used. When a cable is being installed it may be pulled around several curves in different directions and subjected to dynamic stresses, which could cause damage. Consequently the bending radius around which a cable may be pulled, is greater than that which it can be set into, in its final position.

Duct Sizes
Ducts are another important consideration affecting the pulling operation. Selection of the appropriate duct should be based on internal duct diameter, to suit a cable size, and wall thickness to prevent
deformation during duct installation. The internal finish of the installed ducting should be smooth to prevent cable non-metallic sheath damage during installation. During cable installation, the use of graphite or other commercially available approved pulling lubricants can also prevent non-metallic sheath damage and reduce pulling tensions.

**Pulling Tension**

Where a cable is to be pulled in using a winch and steel wire rope, the maximum tension, which may be used, is limited by the tensile strength of the conductors or armour wires, or by the gripping capability of the cable stocking, depending on the method used.

**Installation**

**Moisture**

Underground cables need a proper burial, they may come back to haunt you. Cables are manufactured in conditions that exclude moisture and it is important that precautions are taken during installation to ensure that moisture is not permitted to enter the cable.

- Cut ends or opened areas must be protected from moisture at all times, including during pulling in;
- Cables, after cutting must be re-sealed for storage, by an effective method such as a heat shrinkable cable cap;
- When using a pulling stocking, any cable end seal must be checked for integrity before and after the pull, and replaced when broken, torn, or the seal is broken;
- When using pulling eyes attached to the conductor, the pulling eye must be sealed to the cable non-metallic sheath to prevent the entry of moisture;
- Cable with cut ends, damaged end caps or opened non-metallic sheath must never be dropped into water.

**General Drum Handling**

Before commencing installation, the cable drums should be checked to determine that they have been received in good order and condition. The end caps should also be checked for integrity to ensure that moisture has not entered the cable.

- The arrow painted on the side of the drum indicates the direction for rolling. If the drum is rolled in the opposite direction then the layers of cable will become loose;
- Rolling of the cable drum should be avoided as much as possible;
- Lifting of cable drums should be carried out carefully by cranes or forklifts;
- Cable drums should not be dropped as damage can occur to the cable and/or the drum.
Drum Positioning
All drum moving or lifting should be carried out in a safe manner in accordance with the requirements of the Occupational Safety and Health regulations. Drum pay off stands must be capable of carrying the full weight of the drum of cable and withstanding the additional forces when the cable is being pulled off.
- Drums are normally mounted so that the cable is pulled from the top of the drum;
- When paying off the drum rotates in the opposite direction to the arrow on the side of the drum;
- During paying off, the cable inner end moves backwards and slack turns can develop within the cable drum. Unless the cable end is checked and re-secured at frequent intervals during the paying off, the slack may develop into kinks in the cable;
- Drums should preferably be mounted at the start of a reasonably long straight section of the cable trench;
- A method of braking the cable drum during paying off must be provided to control the pay off and prevent over running.

Trench Preparation
All trench excavation must be carried out in accordance with the local authority regulations and Occupational Safety and Health regulations.
- The cable trench should be prepared with cable rollers spaced every 2 to 3 metres in the straight sections;
- The spacing of the rollers should be frequent enough to prevent the cable touching the ground during pulling;
- Any corners should be made as large as practical and corner rollers provided at any bend in the route. Spacings of the rollers on corners or bends will need to be more frequent than for the straight sections;
- Long rollers may be required between the drum payoff position and the start of the trench to allow for the cable reeling off across the width of the drum.

Duct Preparation
- Ducts should be clean and smooth and fitted with a bellmouth at the entry point;
- The duct exit point should also be fitted with a bellmouth if the end of the duct is followed by a bend;
- There should be a depression in the bottom of the trench at the entry to a duct to allow gravel and other objects to fall off the cable and not get dragged into the duct with the cable.

Cable Laying and Pulling
When installing any cable, irrespective of the type of insulation (i.e. paper, EPR, XLPE, etc), it should be handled with due care otherwise damage may occur to the non-metallic sheath. All cable laying and pulling cable off drums should be carried out in a safe manner in accordance with the requirements of the Occupational Safety and Health regulations.
- To attach the pulling rope to the leading end of the cable, a cable pulling stocking is normally used, but cable pulling eyes are available that can be fitted to the conductor(s);
- A swivel should be fitted between the pulling eye and the winch cable to prevent torsional loads being transferred to the cable during pulling.
- It must be emphasised to staff laying the cable that the cable is a high-value commodity and is very sensitive to damage;
- In order to prevent damage to the corrosion protection and insulation properties of the cable non-metallic sheath, the cable must not be dragged over sharp objects and must not be bent too sharply;
- Attention is drawn to the fact that as the temperature decreases PVC compounds become increasingly stiff and brittle, with the result that if the cable is bent too quickly to too small a radius or is struck sharply at temperatures in the region of 0°C or lower, there is a risk of shattering the PVC components;
- Cables with PVC components should not be laid when the cable temperature or the ambient temperature has been below 5°C during the previous 24 hours;
- The cable should preferably be pulled into position in one continuous pull;
- When pulled by winch, the winch operator must observe the dynamometer or tension measuring device to avoid the cable pulling tension from being exceeded;
- After each length of cable is placed in position, the end caps should be checked for damage to ensure that moisture can not enter the cable. Any suspect end caps should be replaced;
- When lengths of cable are being cut from a drum or when the drum is not emptied completely, the ends of any cut length should be sealed with an end cap, such as a heat shrink end cap, to prevent the ingress of moisture;
- When installing heat shrink end caps, the surface of the cable non-metallic sheath where the end cap is to fit should be cleaned and roughened by sanding with coarse sandpaper to provide a key;
- If a length of cable is being left on a drum for use in the future, the cable ends must be sealed and the tail tied off. The tying off of the tail may be carried out by attaching a heavy cord to the cable behind the end cap, pulling up any slack cable, and then anchoring the cord to the drum flange with a staple. The bottom end should also be checked as it may also need to be re-secured, particularly if the cable has “worked back”;
- Care must be taken to ensure that the end cap is secure and not likely to be stripped off by the cord. It is also important to ensure that the cord is not likely to slip off the cable and allow the cable end to flick back and cause injury;
- Nails should not be driven through the non-metallic sheath to secure the cable, as this will allow moisture to penetrate into the cable.

**Backfilling and Reinstatement**

Prior to backfilling, a visual inspection should be carried out and the following checked.
- The cables have a proper bedding;
- The spacing is correct if there is more than one cable in the trench;
- Pulling equipment is removed;
- Cables are suitably supported at duct entries and the ducts sealed to prevent entry of moisture and vermin;
- The cable is free of obvious damage caused by installation;
- The end caps should be checked for integrity to ensure that moisture can not enter the cable;
- The bedding and initial backfill must be stone free sand or soil to prevent damage to the cable non-metallic sheath.

The reinstatement should be carried out to comply with the local authority requirements.

Joints/Terminations

All jointing and terminating should be carried out as per the manufacturer’s detailed requirements, instruction manual, and the jointers competent for their employ task. The most important factor in the jointing and terminating is the cleanliness of the preparation area. Jointing is a skilled specialist trade and should be treated as such.

Testing

After installation is completed testing should be carried out:
(a) The test is to detect defects caused during installation.
(b) The test is applied to the cable and accessories.

The following tests are considered to be the minimum that should be carried out for commissioning purposes on Polymeric Medium Voltage Cables, Non-metallic Sheath Integrity, Insulation Resistance, and High Voltage A.C. Test.
Other options are;

- A 10 Minute Polarisation Index Test.
- A 5 Minute Step Voltage Test.
- Partial Discharge test

As the voltages used in these tests are potentially lethal, appropriate safety measures must be employed to ensure that the safety of all people involved in the testing process is not compromised.

**Documentation**

All the values obtained in the above tests should be recorded in a cable log so that they are available for comparison purposes in the future.

**Operation**

It is possible to use a transportation analogy with aspect to the operation and maintenance of cables; roads or intersections equate to cables or joints, cars/trucks equate to electricity. Do the networks have the same level of operation and maintenance as with transportation?

**Cable Management Opportunity**

Cable management systems are now in operation for XLPE cables that ensure the efficiency and reliability of electrical power systems. It is very important to monitor and supervise the operating conditions within the network. It is possible to integrate optical fibres into the power cable. Perhaps the most convenient place is in the copper wire screen, where a tube of the same diameter, containing a number of optical fibres can be placed. A distributed fibre optic measurement allows the monitoring of temperature along the entire length of the power cable. An example of this is that they can measure the temperature distribution up to 10 km within ± 1°C and 1 metre resolution. This technology is used in New Zealand in the new Vector CBD Tunnel; this technology can also be integrated into a three core Medium Voltage XLPE cable.

**Maintenance**

**General**

The end user of the cables must determine whether these tests are relevant for them, the frequency, and the additional associated costs to perform them. If any of the tests are envisaged as being used as Maintenance Tests, then they should also be performed as a Commissioning Test and the measurements recorded for later comparison. The methods of performing the tests on each installation should also be recorded so that the tests are performed in exactly the same way in the future.
Insulation Resistance
Most supply authorities would normally perform this test before livening the cables after installation or after any repair work, using an Insulation Resistance Tester with a voltage of up to 5,000 volts DC. The measured values obtained from an insulation resistance test on installed cables are influenced more by the temperature, humidity and accessories fitted to the cable, than by the cable itself. The Polarisation Index Test is tending to replace this test, as the measurement is less affected by climatic conditions.

Conductor Resistance and Screen Resistance
These can be useful in evaluating faulty connections in either the conductors or screen wires and corrosion or mechanical damage to the screen wires.

5 Minute Step Voltage Test
This test should use five equal steps up to the maximum test voltage of 2.5 kV for 1.9/3.3 kV cables or 5 kV for cables greater than 1.9/3.3 kV up to 19/33 kV. The total test time is 5 minutes, i.e., one minute per voltage step. This test is becoming increasingly used on cables of 6.35/11 kV and greater. A Step Voltage Test is useful to identify local weak spots because they react differently as electrical stress is increased.

Tan Delta Measurement using a VLF AC Voltage Test Set
From available literature a VLF AC Voltage Test Set used in conjunction with a Tan Delta Bridge has the ability to detect the overall deterioration of cable insulation, rather than local positions as with a Partial Discharge measurement. It looks at bulk insulation, so cannot differentiate between lots of small problems or and one big one. It is more sensitive to early or small changes in degradation of the insulation than a simple Insulation Resistance or Polarisation Index test. Tan Delta is easily measured with a VLF AC Test Set as Tan Delta increases with decreasing frequency. It is a good test to use to evaluate water treeing in the insulation.

Partial Discharge Test
Partial Discharge tests can be carried out on installed cables by several methods. Firstly with cables Off-Line and using a VLF AC Voltage Test Set, PD Testing can be performed on the cables or secondly the cables energised, termed On-Line PD Testing can be performed. Electrical interference can cause problems and the minium discharge detection level is normally well above the requirements for the routine cable test after manufacture carried out in the factory.