AN INVESTIGATION INTO THE FEASIBILITY OF MIGRATING FROM PILC TO XLPE AS THE CABLE TECHNOLOGY OF CHOICE FOR MEDIUM VOLTAGE ELECTRICITY NETWORKS IN SOUTH AFRICA

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6 October 2011

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DECLARATION

I, **Morgan Lyle Ryan**, declare that:

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(ii) This dissertation has not been submitted for any degree or examination at any other university.

(iii) This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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As the candidate's Supervisor I agree/do not agree to the submission of this dissertation.

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DEDICATION

This dissertation is dedicated to my late wife Lisa,
who always believed in me and encouraged me,
and to my children James, Ana and Alex.

ACKNOWLEDGEMENTS

I would like to thank Professor Nelson Ijumba for his guidance and academic input. Without him, I doubt this dissertation would have been finished.

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Last but not least, a big thank you to my children, who put up with me during the writing of this dissertation – not an easy task for them and one which I appreciate immensely.

ABSTRACT

South African medium voltage underground electrical networks consist mainly of cables of paper insulated lead covered construction. This construction is still the standard used for most utilities in South Africa. While the in-service performance history of these cables has been excellent, global manufacture of this cable type is decreasing.

Internationally, the use of polymeric cables is increasing, resulting in the security of the supply chain for paper cable becoming an increasingly important issue. The most widely used polymeric construction is cross-linked polyethylene. Modern distribution switchgear, which is increasingly used in South Africa, is designed for the newer polymeric technology as this enables more compact construction and reduced equipment footprint. The reduced clearances present installation and operational issues when using modern switchgear with paper insulated cables.

Although a comprehensive literature review was conducted, not much academic work has been done on the process of migrating from one cable platform to another. Manufacturer data, academic reference sources, industry experts and software modelling tools are used to demonstrate that the use of polymeric technology is viable for South African utilities.

This dissertation focuses on the difference between paper and polymeric technologies, and explores the advantages and disadvantages of each. Integration issues are examined along with the methods used to overcome the challenges of hybrid or mixed dielectric networks. Economic comparisons between paper and polymeric cables with respect to purchase and operating costs (including the cost of losses) as well as steady state, cyclic, distribution and emergency current ratings are made.

The dissertation concludes that it makes economic and engineering sense for users of paper cable in South Africa to change to polymeric technology, taking the recommendations given into consideration in order to choose an optimised cable design and gain maximum benefit from the change.

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ABBREVIATIONS

A: Amperes

ABC: Aerial Bundled Conductor

AC: Alternating Current

AMEU: Association of Municipal Electrical Undertakings

AWA: Aluminium Wire Armour

BS: British Standard

CAS: Corrugated Aluminium Sheath

CENELEC: European Committee for Electrotechnical Standardisation

CIGRÉ: Conseil International des Grands Reseaux Electriques

CIRED: Conference Internationale des Reseaux Distribution

City Power: City Power Johannesburg (Pty) Ltd

CONSAC: Low voltage cable with paper insulation and aluminium sheath

CSA: Corrugated Seamless Aluminium

CTMM: City of Tshwane Metropolitan Municipality

CWA: Copper Wire Armour

CWS: Copper Wire Screen

DC: Direct Current

DNO: Distribution Network Operator

DSTA: Double Steel Tape Armour

EDI: Electricity Distribution Industry

EHV: Extra High Voltage

ELL: Economic Loading Limit

ENA: Electricity Networks Association

EPR: Ethylene Propylene Rubber

ESKOM: Electricity Supply Commission

ESLC: Electricity Suppliers Liaison Council

FR: Flame Retardant

FRPVC: Flame Retardant Polyvinyl Chloride

HDPE: High Density Polyethylene

HMWPE: High Molecular Weight Polyethylene

HTS: High Temperature Superconductivity

HV: High Voltage

IDMT: Inverse Definite Minimum Time

IEC: International Electrotechnical Committee

IEEE: Institute of Electrical and Electronics Engineers

LLDPE: Linear Low Density Polyethylene

LME: London Metal Exchange

LV: Low Voltage

MDPE: Medium Density Polyethylene

MIG: Manufacturers Interest Group

MIND: Mass Impregnated Non Draining

MV: Medium Voltage

NRS: National Rationalized Specification

OHS Act: Occupational Health and Safety Act of 1993 (Act 85 of 1993

PE: Polyethylene

PEG: Polyethylene Glycol

PEX: Generic term for early XLPE cable

PICAS: Paper Insulated Corrugated Aluminium Sheath

PILC: Paper Insulated Lead Covered

PVC: Polyvinyl Chloride

SA: South Africa

SANS: South African National Standard

StanSA: Standards South Africa

STP: Strategic Technology Programme

SWA: Steel Wire Armour

T&D: Transmission and Distribution

TC: Technical Committee

TR-XLPE: Tree Retardant Cross Linked Polyethylene

U: voltage between phases

U_0: voltage between phase and earth

UK: United Kingdom

U_m: rated voltage (maximum continuous voltage)

VLF: Very Low Frequency

WG: Working Group

WTR XLPE: Water Tree Retardant Cross Linked Polyethylene

XLPE: Cross-linked Polyethylene

CHAPTER 1: INTRODUCTION

RESEARCH QUESTION

"How can South African electric utilities effectively and efficiently manage the migration and integration of their MV cable system technology from PILC to XLPE?"

Since little research has been carried out with specific respect to integration of PILC and XLPE technologies in South Africa, it is envisaged that electric utilities in South Africa will be able to use this research as a sound basis for effective decision-making and risk analysis when contemplating the migration of their cable platform from paper to polymeric technologies.

HYPOTHESIS

Migration from PILC to XLPE as the cable technology of choice for medium voltage underground distribution networks is a sound technical and business decision for electricity utilities in terms of integration with modern cable-connected equipment, investment expenditure (both capital and operational), network performance and reliability.

1.1 BACKGROUND

Most electricity utilities in South Africa use PILC (Paper Insulated Lead Covered) MV (medium voltage) electric cables for their MV distribution networks. This is mainly as a result of historical or legacy factors i.e. since South Africa was originally a British colony, the electric standards implemented were based on the British system and technologies in place at the time.

PILC technology has served well but integration issues are increasingly coming to the fore. In particular, most MV switchgear is sourced from European companies, and in Europe polymeric cable construction is the predominant technology. Since polymeric cables typically make use of screened construction, the cable termination enclosures (cable boxes) are more compact and experience has shown that the failure rate of PILC terminations within these compact air-filled enclosures has increased when compared with previous-generation compound-filled enclosures. This naturally has negative implications in terms of Quality of Service and Quality of Supply.

South Africa has a compulsory specification (SANS 1339) covering MV XLPE (Cross-linked Polyethylene) cable. Eskom’s policy is to install XLPE in “greenfields” projects (i.e. in totally new installations where no infrastructure previously existed) but to continue the extension of PILC networks (for maintenance and so-called “brownfields” projects) with PILC technology. Most other utilities in South Africa tend to shun the use of XLPE and use PILC almost exclusively.

Globally, there has been a trend since the 1970s to move away from paper insulation to polymeric insulation for medium voltage distribution cables. This is partially due to the lower costs of cables constructed with polymeric insulation, but also as a result of the reduced skill set required for working with polymeric cable when compared to the traditional skills required for paper insulated cable [1].

Medium voltage power cables in South Africa are within the scope of VC 8077 [2], which makes compliance with SANS 97 [3] and SANS 1339 [4] compulsory for paper and polymeric medium voltage cables respectively. With cables covered by both SANS 97 and SANS 1339, the operating voltage (the power frequency voltage at which the cable is designed to operate) of the cables is expressed as the relationship U_0/U for screened cables, and U/U for belted cables. U_0 is the voltage between phase and earth and U is the voltage between phases.

In the context of this dissertation, the typical construction and application of three-core and single-core PILC and XLPE cables are considered. City Power and Eskom have made several strategic decisions in terms of NRS 013 [5] with respect to cable construction. NRS 013 outlines the requirements for PILC and XLPE cables and Annex C (which is informative rather than normative) details the preferred cables to be used in the Electricity Distribution Industry (EDI). As Eskom is a major driver and sponsor of the various NRS projects, it was natural that they should adopt the requirements of NRS 013. As a key member of the ESLC and AMEU, City Power decided, in the interests of alignment with NRS standards to adopt the preferred requirements which are (for paper cables) screened construction, copper conductors, and double steel tape armoured, and conductor sizes of 95 mm^2 and 185 mm^2 for three-core cables. XLPE cables have only recently been introduced due to resistance as a result of first generation XLPE (so-called "PEX") cables which have a dismal performance history. The poor service performance was partly due to incorrect manufacturing and partly due to an unacceptable test regime, which included (due to ignorance) the application of DC insulation resistance and high voltage tests to find faults, exacerbating the tree phenomena.

1.2 CHARACTERISTICS OF PILC CABLES

Paper insulated lead covered (PILC) cables have been around for many decades and have proven to be reliable in service, in many cases exceeding their expected service life [6]. There are many PILC cables that have been in service for 70 years or more. The paper insulation (which is applied helically with small gaps between successive turns to allow for bending of the cable without damage to the paper) [7] is mass-impregnated with a non-draining compound and hence the cables are known as MIND (Mass Impregnated Non Draining) cables [8]. The modern impregnant is usually a polyisobutylene compound that only melts at around 100°C and hence migration of the compound will not occur at the normal maximum operating temperature of 70°C. In earlier cables, the impregnant was rosin oil which tended to migrate (under the influence of gravity) when cables were installed on inclines or in vertical applications (such as in high-rise buildings) [9]. When dealing with PILC cables moisture testing is extremely important and to this end City Power and Eskom (among others) have developed detailed procedures dealing with the testing of PILC cables for moisture [10].

In general, when calculating short-circuit ratings for PILC cables, a maximum conductor temperature of 160°C for one second is used as the most common jointing and terminating technique used on these cables is sweating (or soldering). The maximum allowable temperature is 160°C because the solder will soften above this temperature, affecting the integrity of the joint or termination. If crimped connectors have been used, the allowable maximum temperature may be increased to 250°C [11]. However, considering the likelihood that older PILC cables were jointed using solder technology, it would be prudent to apply a conservative rating and assume solder technology wherever PILC cables are concerned. In any event, short circuit calculations for all cables are conservative in that adiabatic conditions are assumed i.e. it is assumed that no heat is lost or dissipated during the process.

The lead sheath, which serves to block radial moisture ingress as well as carry earth fault currents, is made from lead alloy E, as it is less susceptible to inter-crystalline fatigue fracture (from external vibration and thermal cycling) than pure lead and is also less injurious to the health of personnel handling it. Vibration sources may be nearby roads, rail lines or even being transported a long distance to site [12]. Due to the chemical composition of the lead it is susceptible to creep, or deformation, under stress such as that which will occur under thermal loading due to load cycling in the cable [13]. The actual composition of lead alloy E is given in Table 2 of SANS 97 [14]. Pure lead is dangerous – the Occupational Health and Safety Act [15] has an entire section devoted to it. Personnel exposed to lead through handling (and the fumes during soldering and plumbing operations) are required to have their blood lead levels tested at regular intervals. If the blood lead level is too high, they are required to be removed from the environment in which they receive exposure. All cable manufacturers have comprehensive programs to safeguard the health of workers exposed to lead during the manufacturing process.

In the United Kingdom, lead sheaths were replaced with aluminium sheaths in the 1970s for economic reasons (savings of 25% over traditional lead sheathed cable were achieved) and by the end of that decade most users had adopted the corrugated aluminium sheath, which allowed for easier handling due to its reduced stiffness when compared with the smooth version as well as lower mechanical stresses at joints resulting from aluminium's high coefficient of expansion [16].

The earth fault rating of the cable is dependent on the cross-sectional area of the lead sheath. The one second earth fault capacity of the cable is equal to the area of the lead sheath multiplied by a factor, K, which is a constant taking into account conductor properties and temperature limits, and for lead sheathed cables is 24 A/mm^2. It is possible to increase the fault rating by dividing the one second rating calculated above by the square root of the required clearance time [17]. It would be prudent to retain the one second rating given past protection mishaps and also to allow some leeway for grading of protection settings and mechanical delays in circuit breakers.

With respect to cable armouring, most users of three-core PILC cables tend to favour DSTA (double steel tape armour) although SWA (steel wire armour) is a more practical choice as it has lower impedance (it has a longer lay than the short lay of DSTA) and allows for higher mechanical forces during cable pulling. Both choices will provide mechanical protection but corrosion resistance varies [18]. It may seem that the earth fault rating of the three-core PILC cable is low in comparison with the single-core XLPE cables. The cable construction and configuration are different, and the contribution of the DSTA is ignored. Not only does the DSTA have a negligible contribution to the earth return resistance, but it is generally assumed that the armour tapes will corrode (in some cases completely) and hence cannot be relied on to carry any part of the earth fault current [19].

For PILC cables covered by SANS 97, the cables are designed to be operated at a continuous maximum conductor temperature of 70°C (for 6.35/11 kV cables and greater) and a maximum short-circuit conductor temperature of 160 or 250°C, as explained in further detail in Chapter 4 of this dissertation.

The cores may be screened with a metallised foil or paper tape, which is required to be non-magnetic. With this design, the tape is made with a matrix of closely spaced holes. The reason for the holes is to aid impregnation, as the core is insulated before the impregnation process. More recently, an alternating carbon tape/metallised tape layer has replaced the metallised foil and due to the construction, holes are no longer needed as this design does not impede impregnation. As is the case with XLPE cables, PILC cables are supplied with FRPVC (Flame Retardant Polyvinyl Chloride) bedding and sheath as standard, although SANS 97 makes allowance for alternative materials.

1.3 CHARACTERISTICS OF XLPE CABLES

Cross-linked polyethylene (XLPE) insulated cables are insulated using an extruded polymeric insulation, which can either be steam-cured or cured by means of the dry nitrogen process. Modern dry curing techniques are preferred to mitigate the risk of water trees, which will be discussed in Chapter 4.

XLPE insulation has the advantage of a higher sustained maximum operating temperature of 90°C. In addition, for emergency overload situations, the maximum temperature can be up rated to 130°C for a maximum period of 8 hours continuously, and an aggregate total of not more than 125 hours per annum at this temperature [20]. Although this seems like an advantage (and will indeed be such to a utility suffering from system failures and a desperate need to supply power while the faulted portion of the network is repaired and restored to service) this higher temperature rating is a double-edged sword with respect to moisture migration. This will be discussed in more detail in Chapter 4.

XLPE, being polymeric does not suffer from migration of internal compounds as it is thermosetting to a large extent following the cross-linking process [21]. The same concerns with respect to maximum conductor temperatures under fault conditions exist as for PILC cables; however XLPE is a newer technology and it is unlikely (although not inconceivable) that conductors would have been soldered. Certainly, in Eskom and City Power's networks, all XLPE cables have been connected by means of crimped connectors (compression connectors) or mechanical connectors.

Aluminium Wire Armour (AWA) rather than Steel Wire Armour (SWA) is used for the armour of single-core XLPE cables as it is non-magnetic and hence there is no need to take the effects of eddy currents and hysteresis into account. Aluminium is prone to corrosion, especially in ground or other situations where moisture is present. For this reason in the United Kingdom copper wire armour (CWA) is used in place of aluminium. If water penetrates the outer sheath of an AWA cable the armour will rapidly corrode and the earth fault capability of the cable will be reduced or lost entirely depending on the degree of corrosion [22].

Type A XLPE cables are designed to carry high earth fault currents, while Type B XLPE cables are designed to carry earth fault currents not exceeding 1,000 A [23]. City Power networks, for instance, are variously effectively and non-effectively earthed (depending on region) and the worst case scenario is always assumed in the interests of safety and network performance. To cater for the expected earth faults (which exceed 1,000 A in most cases) as well as providing mechanical protection for the cables as they are buried directly in the ground, Type A cables are often purchased as standard.

Annex B of SANS 1339 provides details on how to calculate earth fault ratings of XLPE cables. The earth fault rating of the cable is dependent on the maximum allowable temperature rise of the cable sheath. SANS 1339 defines type A single-core cables as cables for 3.8/6,6 kV to 19/33 kV with copper tape screen, aluminium wire armour and sheath. In the case of a single-core, aluminium wire armoured Type A cable with PVC sheath, Table B.1 of SANS 1339 [24] (for a PVC sheathed cable) gives the allowable temperature rise as 70 to 200°C. Table B.1 gives a k (constant) factor of 89 for a single core, aluminium wire armoured Type A cable. This value is multiplied by the minimum cross-sectional area of the armour (given in Table 10 of SANS 1339 for a 120 mm^2 cable, for example, as 160.2 mm^2) and hence the one second earth fault rating of the chosen cable is 14.258 kA. Again, it is possible to increase the fault rating by dividing the one second rating calculated above by the square root of the required clearance time. However, as stated for the PILC cables, it would be prudent however to retain the one second rating given past protection mishaps and also to allow some leeway for grading of protection settings and mechanical delays in circuit breakers.

It is interesting to compare this earth fault rating with the maximum symmetrical fault current-carrying capacity of the chosen 120 mm^2 cable of 16.2 kA for one second. As discussed above, if the time taken for the fault to be cleared is only 0.5 seconds, the fault rating can be increased to 22.9 kA and similarly decreased to 9.4 kA to obtain a three second rating, which is the standard time used for switchgear ratings.

For XLPE cables covered by SANS 1339, the cables are designed to be operated at a continuous maximum conductor temperature of 90°C and a maximum short-circuit conductor temperature of 250°C [25].

In South Africa, XLPE cables are usually triple extruded i.e. the conductor screen, XLPE insulation and core screen material are all extruded together. This process has the benefit in that moisture ingress or air voids in the construction are largely avoided.

SANS 1339 requires the bedding of Type A cables to be made of PVC type B1 to SANS 1411-2 [26]. The same document allows some discretion with respect to the sheath material; however, both major manufacturers in South Africa (Aberdare Cables and CBI Electric: African Cables) will supply flame retardant PVC as standard for bedding and sheath unless a polyethylene sheath (which is recommended for direct burial applications) or a sheath which will emit zero halogens is required and specifically requested. The term flame retardant implies that the material is self-extinguishing, and the material will not support combustion once the source is removed. To indicate that a cable has flame retardant properties, it is given the designation FR and is colour-coded with a red stripe in the sheath. Cables with flame retardant sheaths are recommended for use in outdoor free air applications.

A polyethylene sheath may be required where superior ageing performance and water imperviousness is required, and is the recommended option except for use in applications where the cable(s) may be exposed to fire, unless a special protective coating is applied. In practice, where a cable goes up a pole and may be exposed to grass fires or similar, the cable is enclosed in a metal conduit for a height of at least three metres from ground level. Cables installed in confined spaces such as cable tunnels may require a low smoke, zero halogen sheath so that a minimum of poisonous fumes are given off in the confined space when the cables are subjected to combustion processes [27].

1.4 UNSCREENED/BELTED CABLES

The belted design was the first cable design to be widely used on three phase systems but once system voltages began increasing it was discovered that its electrical performance left a lot to be desired at voltages of 33 kV and above. The belted design is generally applicable to cables with paper insulation [28].

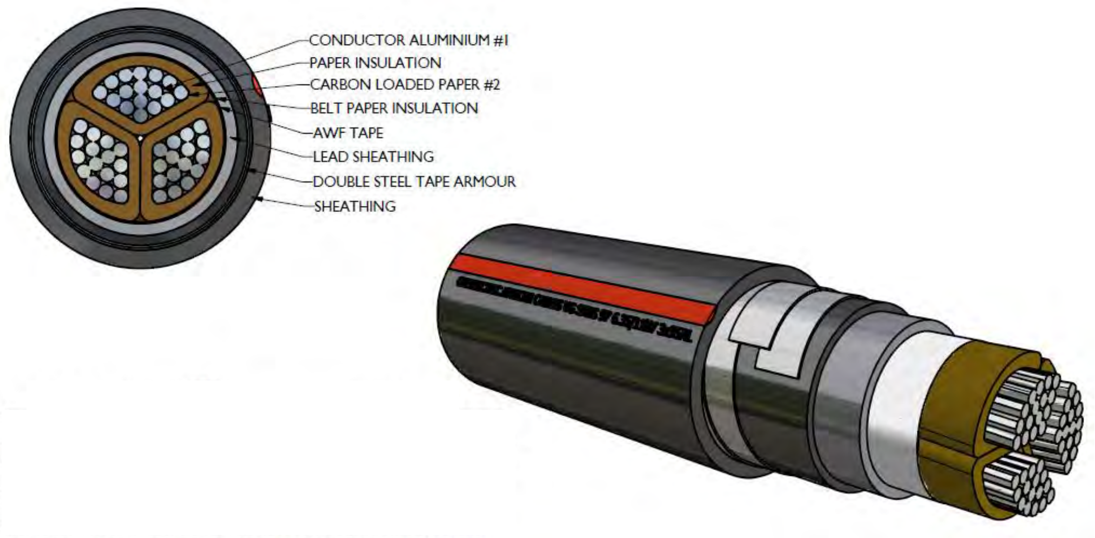

Figure 1-1: Three-core belted paper cable (© CBI Electric: African Cables)

The basic construction (as shown above in Figure 1-1) can be described as follows: the thickness of the paper insulation between any two conductors is twice the radial thickness of the insulation around one conductor. Also, the thickness of the paper insulation between any conductor and the earthed metallic sheath is equal to the radial thickness of the insulation around one conductor plus the thickness of the belt papers. The ratio of the thickness of the insulation between conductors to that of any conductor to the earthed metallic sheath is $\sqrt{3}$ i.e. the same ratio as U/U_0 [29].

The belt papers have an extruded lead sheath as described previously encasing them. In order to protect the lead sheath, a bedding of PVC is extruded over it. The armour (typically DSTA) is applied over the bedding, with a short lay and overlap, and an outer sheath of PVC is extruded over the armour.

This design may be used satisfactorily up to 22 kV or so, however in practice most cables in South Africa operating at above a rated voltage (U_m) of 12 kV will be screened. Since the design electrical strength increases as voltage increases (for both economic and construction reasons) the use of belted cables above 22 kV will not give satisfactory long term electrical performance [30].

Electrical stress distribution in a belted cable is complex and an example is shown in Figure 1-2. The electrical stress is greatest at the surface of the conductor and decreases with increasing distance from the conductor surface, and is dependent on the changing fields occurring during the voltage phase rotation. The diagram in Figure 1-2 is a snapshot of the flux distribution at a particular point in time, and is constantly changing [31].

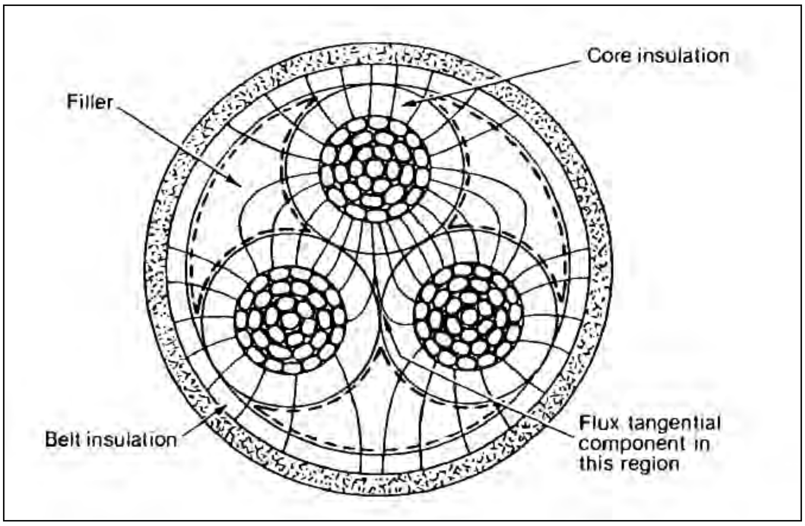

Figure 1-2: Stress distribution in a belted cable [32]

Since the field is constantly changing and not controlled, any voids or defects in the insulation may result in the inception of discharge activity that will lead, over time, to breakdown. With belted cables, this is particularly true if the cable is subject to heavy loading or faults [33]. The dynamic forces will cause the cores to try and move away from each other (core separation), and if gaps are allowed to open between the cores, the permittivity difference of air in comparison to the paper insulation will cause high stress and inception of discharge activity [34].

Belted cables do have the advantage that their impulse withstand values are generally higher than equivalent screened cables, and in applications where cables are used to connect sections of overhead lines, may be more suitable than screened cables [35].

1.5 SCREENED CABLES

In order to overcome the shortcomings of the belted cable with the increase in system voltage levels, a new type of cable design was developed. In this design, each core was surrounded by its own metallic layer, resulting in a substantially radial stress distribution. This metallic layer is known as a screen or Hochstadter layer, after the inventor Martin Hochstadter who patented this design in 1914. The screened design is sometimes also known as an H type design cable (although this is not common in South Africa) or a radial field cable [36, 37].

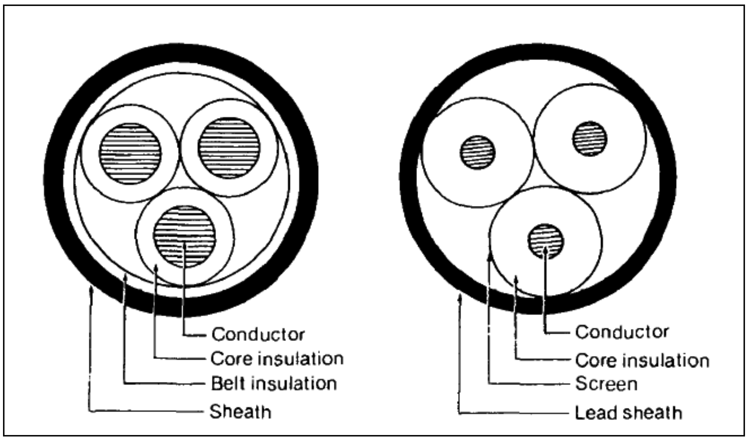

Fig 1-3: Comparison between belted (left) and screened (right) constructions [38]

The major advantage of screened cable is that the superior control of the electric field enables higher stresses to be achieved with consistent performance, and it is the preferred option in terms of NRS 013. The relative constructions of belted and screened cables are shown in Figure 1-3. With screened cables, the filling between the cores in a three-core cable is not critical as there are no electrical stresses involved, and for three-core screened cables the fillers are primarily to retain the cable shape rather than for electrical purposes [39]. Also, for three-core screened cables the three cores are bonded together, usually by means of an aluminium woven fabric tape for PILC or copper tape for XLPE. In South Africa, it is common for screened PILC cables to have sector-shaped conductors at 11 kV (with oval conductors at 33 kV) while XLPE cables always have round conductors [40, 41].

Since the conductors are stranded, a semi-conducting layer is applied over the conductors to smooth the electric field. Screening allows for operation at a higher temperature (typically 70°C for screened PILC vs. 65°C for belted paper cables) although there is a trade-off in that joints are more complex and costly as each core will need to be screened throughout the joint [42].

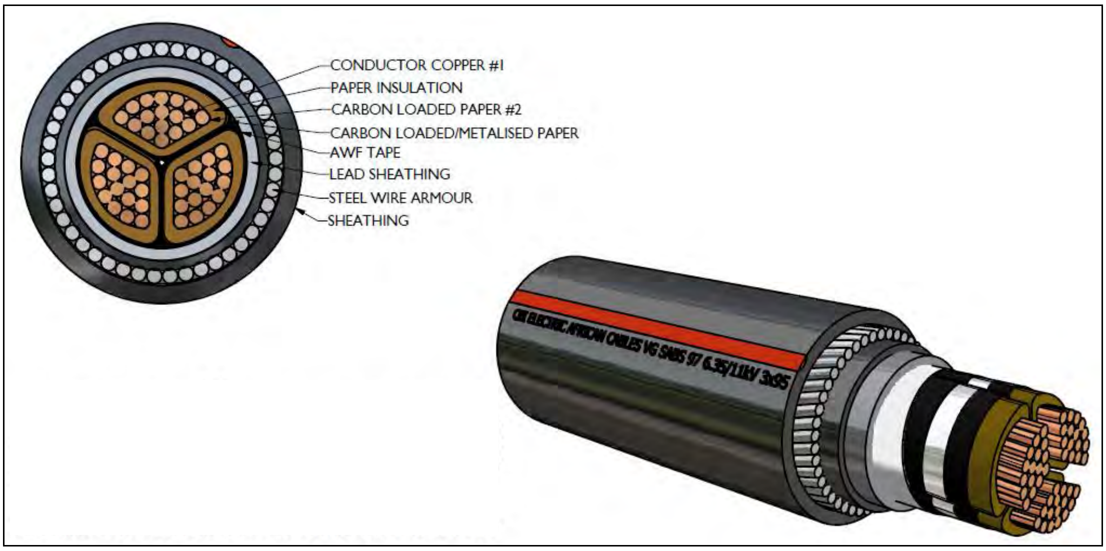

Figure 1-4: Three-core screened paper cable (© CBI Electric: African Cables)

The design of the screened cable differs from the belted cable in that the cores are individually and collectively screened. A semi-conductive layer is applied over the stranded conductor, the insulation is applied and then another semi-conductive layer is applied. For PILC cables this may take the form of carbon-loaded or metallised paper, for XLPE it will be semi-conductive polymeric material. The three screened cores are bonded by means of a tape with metallic thread woven into it. For PILC designs, a sheath will be extruded over the three cores, while this may not be the case for XLPE designs. For both a bedding will be applied, over which the armour (DSTA or SWA) is applied, and finally the cable sheath. A typical three-core screened PILC cable is shown in Figure 1-4.

1.6 SINGLE-CORE CABLES

Single-core cables are self-contained per phase and are not enclosed together with other cores in an external sheath. The typical construction of a single-core cable is shown in Figure 1-5 overleaf. Single-core cables are usually used for short interconnecting circuits or where very high load and fault levels are required [43].

Figure 1-5: Single-core screened polymeric cable (© CBI Electric: African Cables)

The preferred options in NRS 013 for single-core cables for armour is for paper cables to be unarmoured and for XLPE cables to be armoured. The preferred sizes for both are 300 mm^2 and 600 mm^2 [44].

Earthing arrangements for single-core cables can be quite complex depending on the actual configuration the cables are laid in, for instance, trefoil, or in flat formation with a spacing of twice the cable diameter between each core [45].

Single-core cables may also be laid up in a triplex configuration (as illustrated in Figure 1-6) in order to combine the benefits of single- and three-core technologies. This is widely employed in the United Kingdom. Apart from easier handling (jointing and termination) this construction negates the need for special and complicated earthing arrangements [46].

Figure 1-6: Drum of triplex 6.35/11 kV cable (© UK Power Networks)

1.7 THREE-CORE CABLES

In South Africa at medium voltage, this is the most common choice of configuration, and a typical configuration is illustrated in Figure 1-7. The nature of the construction simplifies laying and identification, as well as providing (where a metallic sheath is installed) excellent mechanical protection and protection against water ingress in the form of a radial water block [47].

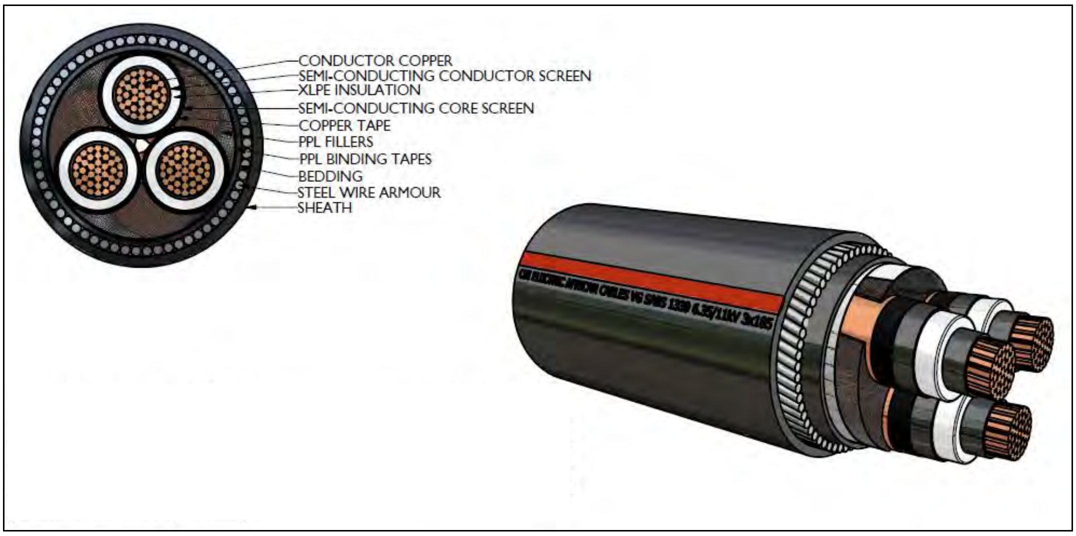

Figure 1-7: Three-core screened polymeric cable (© CBI Electric: African Cables)

The preferred sizes in NRS 013 for both three core paper and XLPE cables are 95 mm^2 and 185 mm^2 [48].

CHAPTER 2: LITERATURE SURVEY

There does not appear to have been much formal or academic work done in the field of changing technologies from paper to polymeric, but there is information available on the management of mixed circuits (i.e. circuits that comprise a mix of both paper and polymeric cables). Of course, there is also a wealth of material available on paper and polymeric cables individually. Some of this has relevance but most is not directly related to the research topic.

In order to obtain relevant information on cable systems used past and present, several experts in this field were consulted. These included subject matter experts both within the manufacturing industry as well as utility experts.

2.1 ELECTRIC CABLES HANDBOOK

The Electric Cables Handbook [49] is a recognised industry standard and a valuable source of reference for the cable engineer, and is widely referenced in this dissertation. It begins with the electrical theory relating to cables, through construction of the various types of cable, their use, testing methods, manufacture, performance and also covers specialist areas such as submarine cables and cables used for HTS (High Temperature Superconductivity).

Since it covers such a wide range of material, most of the focus with specific respect to review for this dissertation focussed on Parts 1 (Theory, Design and Principles Common to all Cable Types) and 3 (Supply Distribution Systems and Cables).

The relevant sections of Part 1 included electrical theory, materials (in the manufacture of cables, including conductors, insulation, armour and other protection), and ratings for normal and fault conditions.

In Part 3, the sections of most interest were generally those relating to manufacture and installation of the different types of cable, and in particular chapters 19 and 24 relating to paper insulated and polymeric insulated cables respectively.

The book is also a valuable source of information relating to past practices and the evolution in cable selection practices around the world, although with a specific emphasis on the United

Kingdom and its former colonies. Since this includes South Africa, a lot of the information in the book is directly relevant.

2.2 SANS 97

SANS 97 [50] is the South African national standard covering medium voltage paper insulated cables. VC 8077 [51] makes compliance with this standard compulsory in South Africa. SANS 97 describes the constructional requirements for the various types of medium voltage paper insulated metal sheathed cables, including maximum and minimum dimensions, thickness of cable components, and types and grades of materials to be used. Although several choices are given (for instance conductors may be either aluminium or copper, and sheaths may be aluminium or lead (or one of its alloys) it is rather prescriptive overall.

2.3 SANS 1339

SANS 1339 [52] is the South African national standard covering medium voltage cross-linked polyethylene insulated cables. VC 8077 makes compliance with this standard compulsory in South Africa. SANS 1339 describes the constructional requirements for the various types of medium voltage cross-linked polyethylene insulated cables, again including maximum and minimum dimensions, and types and grades of materials to be used. Although variations are allowed (aluminium or copper conductors, aluminium or copper wire armour) it is, like SANS 97, rather prescriptive overall. This is best illustrated by a letter [53] sent to the author while he was employed at City Power Johannesburg by a representative of one of the major cable manufacturers. At the request of City Power, the manufacturer had provided a proposal to manufacture and install a trial XLPE cable where, traditionally, a paper cable would have been used. The writer was at pains to point out that "... any cable not designed, manufactured and installed according to SANS 1339 is deemed to be illegal and users of cables outside this specification are liable to prosecution." The letter went on to suggest that "... the design proposal be put to the SABS and a concession be obtained for its design, manufacture and installation under the express understanding that the cable will be utilized for experimental purposes."

Although SANS 1339 was revised subsequent to this letter, SANS 1339 (and SANS 97) have direct relevance to this dissertation as any medium voltage cables in South Africa need to comply with them.

2.4 SANS 10198

SANS 10198 [54] is a "suite" or series of 14 documents covering the selection, handling and installation of medium voltage power cables. Parts 1 to 5 cover the selection aspects to be taken into account during the cable system design stage, while parts 6 through 14 cover handling and installation once the selection has taken place.

Although all the documents are important and an understanding of the subject matter of each part is crucial to obtain an understanding of cable systems overall, the design parts of most relevance to this dissertation were part 2 [55] covering selection, and part 4 [56] relating to current ratings.

In terms of the installation parts of the series, part 8 [57] covering actual laying and installation, and part 13 [58] dealing with testing, commissioning and fault location were the most relevant. In addition, parts 10 [59] and 11 [60] covering jointing and termination of paper insulated and polymeric insulated cables respectively, were directly relevant to this dissertation.

2.5 NRS 013

NRS 013 [61] was written to try and establish preferred common standard requirements for users in the electricity industry in South Africa in order to avoid the need for each user to develop their own unique specifications. Given the existence of the compulsory standards already referred to, the Working Group (comprising members from the major utilities as well as an MIG) documented the preferred construction of paper and polymeric insulated medium voltage cables. The document also include additional information that was required by the major users, but not compulsory in the SANS documents. Furthermore, following extensive discussion amongst the WG members, information relating to the consideration of the use of returnable cable drums in conjunction with a cable cutting operation was included, as was an (informative rather than normative) Annex A which provided rational explanations for the determination of the choice of screened vs. belted construction, copper vs. aluminium conductors, and preferred sizes and types of paper and XLPE cable.

2.6 SOME THOUGHTS ON MV CABLE ACCESSORIES

Derek Goulsbra's work (Some Thoughts on MV Cable Accessories) [62] contains valuable information on the technologies used in accessories for jointing cables of different construction.

The book begins with a theoretical discussion of breakdown in air and other dielectrics, and moves through stress distribution and cable preparation. There are separate chapters covering joints and terminations, as well as the effects of moisture. There are also sections covering earthing and type testing of accessories.

The main point that is emphasized is the correct preparation of the cable equipment as well as correct training. Too often faulty workmanship (through a lack of understanding of the principles involved) results in the failure of a joint or termination, resulting in a negative impact on the reliability of the cable system.

Goulsbra lists the nine main functions [63] of a joint as:

- The joining of conductors;
- The exclusion of air between high voltage and adjacent insulation;
- The provision of stress control;
- The replacement of primary insulation;
- The replacement of the earth screen;
- The replacement of the metal earthing system;
- The cross bonding of single-core cables;
- The exclusion of moisture; and
- The provision of mechanical strength.

The challenges and solutions regarding the jointing of hybrid (mixed dielectric) circuits will be discussed in more detail in Chapter 4.

2.7 SP POWER SYSTEMS CAB-05-019

A document produced by SP Power Systems (a United Kingdom DNO) in August 2001 entitled "CAB-05-013, Recommendation for Change from Paper Insulated to Polymeric Insulated Cable at 11kV" [64] was directly related to the topic being researched.

The report detailed the historical reasons (both technical and commercial) for the preference for paper over polymeric cables. There was concern over failures of early polymeric designs in both North America and Europe as well as paper cable being commercially competitive when compared to polymeric alternatives. Importantly, it was noted that improvements in terms of design, manufacture, material handling and quality processes had addressed the earlier technical concerns.

The report highlighted similar concerns to the South African scenario, whereby cheaper imports threaten the dominant position of local manufacturers who resort to price cutting and commercial distortion to create a competitive advantage for their own products.

The report further identified escalating production costs and aging plant as a risk, and mentioned that plant breakdowns had already contributed to a failure to meet expected deliveries, causing a knock-on effect in work planning and project delivery.

Since the report was written from a technical and commercial perspective, it included reference to the fact that European polymeric cable could be obtained for less than the cost of locally produced paper cable, despite the fact that UK manufacturers had reduced the price of the PICAS cable as much as possible (artificial trade barriers do not exist in the UK due to European Union trade regulations, allowing users to purchase equipment from anywhere within the EU).

Of particular interest was the fact that 10 kilometres of polymeric cable had been installed in 1997 (on a trial basis) by Scottish Power and had remained fault-free since installation. Field feedback received indicated that jointers and installers had expressed a preference for the polymeric cable due to it being easier to handle and work with.

At the time of the report roughly one third of UK users had changed from paper to polymeric, a further third had committed to making the change and were in the planning or transition change, while the remaining third had not yet committed to the change.

The cost of change associated with changing cable platforms was noted, including one-off costs (training and familiarisation) and ongoing costs (accessory and strategic stockholding of paper cable and accessories). Legacy issues (compatibility of older plant designed for paper cable with newer polymeric cable) were identified and different scenarios evaluated.

The report concluded by recommending that SP Power Systems change from paper based to polymeric cable technology on the grounds of increased competition among suppliers, significant cost savings, concerns over ongoing quality and availability issues with respect to paper cable, experience with the trial installed polymeric cable and positive feedback from internal personnel and other users.

2.8 ESKOM REPORT

By the beginning of the century Eskom had done some work with a view to the future and produced a document of relevance to this study: MV Cable PILC vs. XLPE (Eskom reference SCSREAAC9) [65].

At the time of the report (May 2000), the MV cable technology of choice in Eskom was PILC. Factors that had informed this decision included similar pricing of the cable designs and consideration of the test equipment required for pre-commissioning and fault location. However, increasing competition caused by cheaper imported polymeric cables had resulted in a drop in the price of polymeric cable so that it was in the order of 15% cheaper than the paper alternative. This cost differential prompted a re-evaluation of the situation, and the report considered several scenarios: primarily standardisation on either of the two technologies. The scenarios were developed further by the consideration of different designs of XLPE cable, including the use of polyethylene sheaths, water swellable tapes and TR (tree retardant) XLPE.

The report went on to explore cost of ownership and standardisation alternatives, and predicted the failure rate of the two different cable technologies due to dielectric failure (excluding external factors such as mechanical damage). The results are given in Figure 2-1 below:

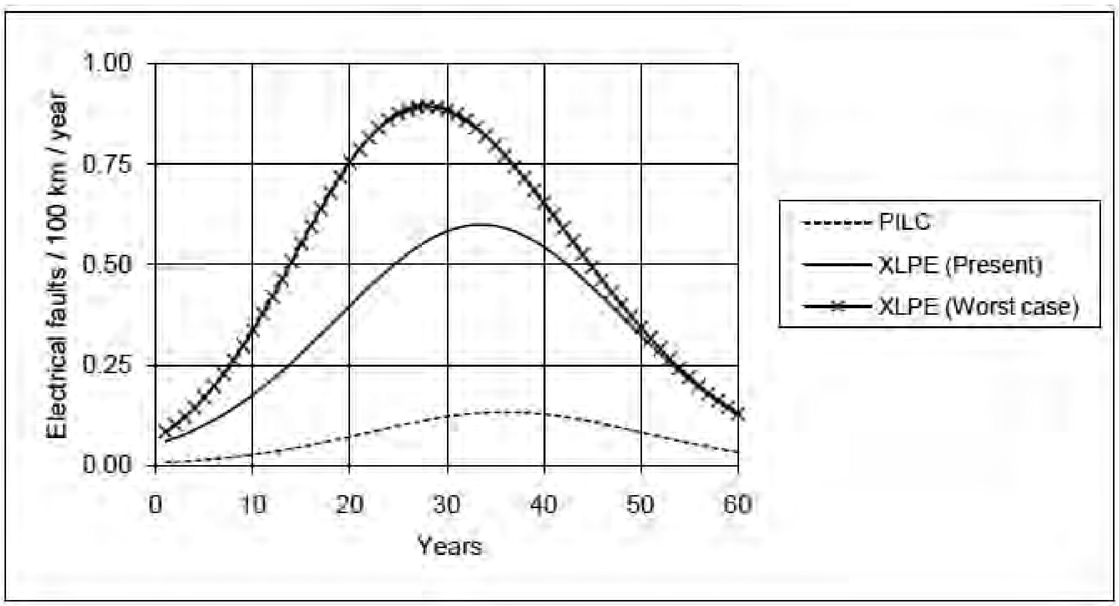

Figure 2-1: Electrical fault rate per 100 km per annum [66]

Eskom also obtained information that indicated that the mechanical failure rate was much greater than the electrical failure, at about 6 faults per 100 km of MV cable per annum, resulting in mechanical faults having a much greater influence on the total life cycle cost than electrical faults. Taking XLPE as the base (unit cost 1.00) the PILC was found to have a per unit cost of ownership of 1.13.

The report also identified that the use of a polyethylene sheath would minimise the risk of failure caused by water trees, leading to electrical trees. In conjunction with this, the report recommended that sealed joints with solid centre ferrules be used to limit migration of moisture in the cable if a damaged sheath allowed ingress.

The report recommended that XLPE cable be adopted as the standard for distribution at medium voltage, providing that the XLPE cable be rated normally for operation at 70°C (as with PILC cable) thus ensuring that conductor losses do not affect the total cost of ownership calculations. In addition, the 70°C rating offers an improved emergency rating margin.

2.9 TR-XLPE PAPER

In May 2006 a paper entitled "Global Trends and Motivation Toward the Adoption of TR-XLPE Cable" was presented at the IEEE T&D conference in Dallas, Texas [67]. The paper detailed the experience of the authors with respect to the service performance of XLPE, EPR, TR-XLPE and copolymer XLPE cables at medium voltage.

In North America, tree retardant XLPE (TR-XLPE) was designed as a solution to the problem of water trees experienced by XLPE and thermoplastic polyethylene insulated cables. In the 23 years since its introduction, it has become the predominant technology in medium voltage cable insulation. Evidence by the authors demonstrated that the performance of TR-XLPE with respect to water trees is superior to that of "normal" XLPE, and that the material retains its dielectric and loss characteristics.

The authors then examined developments in Europe, where a different approach was developed. "Emphasis was placed on cleanliness and retention of electrical breakdown test after aging in water. Researchers found that blends of the polyethylene resin used in XLPE with copolymers, based on ethylene alkyl acrylate copolymers, resulting in improved resistance to electrical breakdown after aging in water under electrical stress" [68]. The new product was called copolymer XLPE.

In both cases, the development of long term wet aging tests has confirmed the improved performance and characteristics of the enhanced XLPE. However, the authors went on to demonstrate that TR-XLPE is ultimately superior to copolymer XLPE as well. Figures 2-2 and 2-3 are reproduced from the paper.

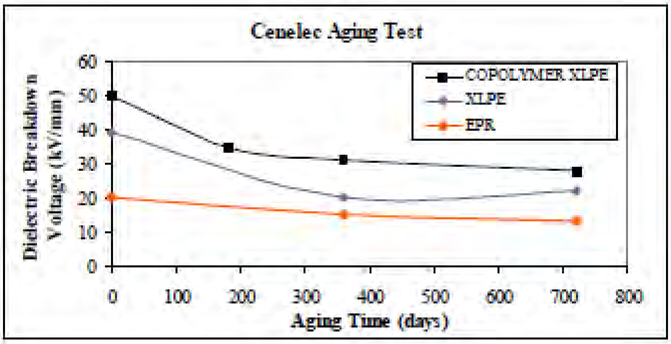

Figure 2-2: CENELEC Aging Test Results [69]

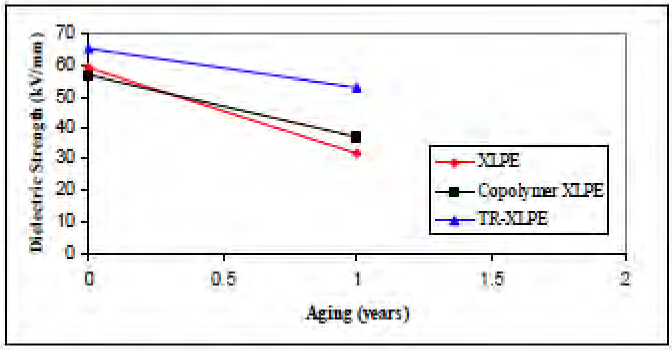

Figure 2-3: CENELEC Aging Comparison (one year) [70]

The paper also deals with the application of TR-XLPE technology in Asia, where historically little emphasis has been placed on performance specifications. As a result of large growth, utilities in the region, and specifically China, have realised the benefits of performance specifications and the proven history of TR-XLPE. It must be noted that the authors are all employed by The Dow Chemical Company (a supplier of raw materials used in the manufacture of XLPE). Although it might be expected that they would have a commercial interest in promoting the use of TR-XLPE their claims are supported by reference to, and citations of, independent work.

2.10 PRODUCT EVOLUTION IN THE UK

The information in this section was obtained by interactive discussions (interviews) held in August 2009 between Dr Darren Spiller of Prysmian Cables, Peter Calton (now retired) and the author [71]. It is of significance in that most former colonies inherited distribution systems designed to UK standards, and as a result face similar challenges to those already faced by UK utilities with respect to the maintenance, refurbishment, extension and replacement of these networks with standardised EU equipment.

As has been previously mentioned, PILC cables were universally used in the United Kingdom. LV and industrial cables moved from paper to PVC to XLPE insulation, and at higher voltages (33 kV upwards) utilities had moved to XLPE as well. Essentially the last bastion of paper insulation was at 11 kV.

Most UK utility companies used belted construction, although Midlands Electricity used screened construction, which appeared to be the preference of their cable engineers. In terms of manufacturing, a slight cost premium could be expected to be paid for screened construction. In any event, other methods were used to better control stress, principal of these being the use of oval conductors rather than sector-shaped conductors.

The cables were served with jute, and protected with bitumen. The cables were whitewashed in order to prevent the bitumen on adjacent coils (when drummed) sticking together. The later move to a PVC outer sheath would present earthing challenges, as over time the jute would absorb moisture, resulting in intimate electrical contact between the armour and the soil. This had the effect of a large distributed electrode. The PVC sheath prevented such effective contact, and the advantages of the distributed electrode were lost.

The armouring used was SWA rather than DSTA, since it was felt that the steel wires would provide better mechanical support to the cable in the event of it being undermined. The mechanical support would reduce creep and stress cracking of the lead sheath. Interestingly, Hiscock [72] noted that the "...service behaviour of a cable sheath may be almost completely defined and predicted by reference to two basic properties of lead termed 'creep' and 'fatigue'."

Prior to 1969, cable sizes were imperial and conductor cross-sectional areas were quoted in imperial sizes e.g. 0.1 in^2. In 1969, the changeover to metric system occurred and thereafter conductor sizes were quoted in metric terms i.e. mm^2. At the time there were about 10 manufacturers, who all used different manufacturing methods and made cables of copper and aluminium from 0.025 in^2 up to 1 in^2.

In the early 1970s, through industry collaboration and standardisation, one design was developed, with three different sizes. The cable was sheathed in aluminium and covered with a PVC outer sheath. As a result, operational efficiencies increased and overall cable cost decreased despite an increase in the raw material input costs. Furthermore, manufacturers had a vested interest in ensuring PILC was the preferred option since they could utilise existing plant (which had already paid for itself) rather than investing in the new plant required for cables of other technologies.

LV cable technology had already moved on, with a roughly equal split between the users of CONSAC and waveform. The cables featured longitudinal water blocking in the form of mastic. In Scotland, utility engineers specified copper wires due to corrosion concerns.

CONSAC, which has been in service for 30 years or so, has a very poor record with respect to corrosion. This is exacerbated by the application of this cable in LV distribution, where the cable is jointed every 5 to 20 metres in order to provide tee services to service connections.

The standardised MV cable construction consisted of stranded aluminium conductors, paper insulation, and an aluminium sheath. This new design was known as PICAS (Paper Insulated Corrugated Aluminium Sheath). Initially the sheath was straight (i.e. extruded as lead sheaths had previously been) but since aluminium is more rigid than lead, this led to complaints that it was difficult to lay. This resulted in the development of a corrugated aluminium sheath, with the corrugations being annular rather than helical in order to avoid any possible draining. This would appear unnecessary since the use of rosin oil (as an impregnant) was only used up until into the 1950s. After this time, MIND compound was used.

The PVC outer sheaths of PICAS cables were coloured red in order to signify that they were medium voltage cables. Training was necessary to reinforce that although red cables were MV, black cables could be either LV or MV, and that a black cable could not be simply assumed to be LV. On balance, it was felt that having red MV cables would enhance safety.

Conductor sizes had been standardised with the chosen range being 95, 185 and 300 mm^2. The advantages of the new design were that the cable was lighter and hence easier to install. The difficulties of soldering onto aluminium had been overcome with the relevant technology in the 1960s. EA 09-12 [73] was adopted by all electricity companies. The PICAS plant was used well in the 1970s and 1980s, with usage declining in the 1990s.

At 33 kV, the utilities had begun moving towards single-core XLPE insulated cable with extruded lead sheaths, for use within substation environments e.g. between primary transformers and switchgear. EA 09-17 [74] covers MV cables for use in substations. The current construction is XLPE insulation with copper wire screen matched to the system fault level (typically 50 mm^2), and MDPE sheath. Eventually this cable was used outside of substation environments, with occasional variation: sometimes using lead sheath, and sometimes using copper wire screen. It was accepted that the cable was (strictly speaking) unarmoured, but protected by its environment, due to the depth of burial and the fact that excavation would be carried out manually in the vicinity of the cables.

Industrial cable users had moved to three-core, XLPE insulated cables with copper tape screens and round conductors, string fillers, SWA and with PVC bedding and outer sheath, covered by BS 6622 [75].

At 11 kV, Eastern Electricity was the first to decide to use polymeric technology. The chosen design was triple extruded XLPE, sector-shaped (rounded) solid aluminium conductor, semi-conductive bedding, and copper wire in a waveform shape (due to existing plant set up). Eastern purchased and installed between 200 and 250 kilometres of this new cable. In terms of their network design philosophy, they had dropped their earth fault level to below 1,000 A. Conversely, London Electricity, MANWEB and Scottish Power had much higher earth fault levels. The cross-sectional area of the CAS was equivalent to 400 mm^2, which was more than adequate for the high earth fault levels of these utilities. For utilities with lower fault levels, the use of a foil laminate was considered. The South African concerns about its puncture resistance performance under lightning conditions were not seen as an issue, due to the lower number of storm days and the lower intensity and frequency of lightning experienced in the UK in general. The cables were sometimes installed below the supporting towers of overhead transmission lines and had been tested to withstand impulse values of up to 120 kV without negative consequences, and service data reinforced this perception.

The issue of cable thermal ratings came to be of importance. Prior to the 1970s, the maximum conductor temperature (for belted cable designs) was taken to be 65°C. Screened cable was tested at 70°C in order to provide product differentiation. This was commercially driven but technically proven i.e. the idea that screened cable could run at a higher temperature due to the lower migration of compound. The belted design was not retested at the higher rating. For the polymeric design (XLPE) the maximum conductor temperature rating was 90°C.

From round about 1985, the design moved to stranded sector-shaped (or round) aluminium, with a copper wire screen. Calculations carried out on a £/ampere basis revealed that as a choice of conductor material, aluminium was preferable (in 2009 the aluminium price was at £1,209 per ton compared with copper's £3,716 per ton). Since a large proportion of the cost of the cable is related to the conductor material, economic considerations drove the choice towards aluminium conductors.

In Europe, most countries had looked at moving to polymeric technology about 20 years earlier. Earth fault level influenced the choice of single- vs. three-core designs since the cross-sectional area of the earth wire is directly proportional to the earth fault current it is required to carry. In Europe, most networks have comparatively low earth fault levels and hence made use of 25, 35 or 50 mm^2 copper wire screens, for one second fault levels of 3.2, 4.5 and 6.4 kA respectively. In the UK (as is the case in South Africa), with a mix of solid and resistance earthed networks, worst-case fault levels tend to be higher. For a fault level of 13 kA, a copper wire screen of 102 mm^2 would be required for one second. In terms of cost/route kilometre, in a scenario with high fault levels it would make more economic sense to have a three-core cable with a large metallic sheath. However, utilities disagreed on this as they did on the matter of bonded vs. strippable screens. A lot of work had been done in terms of the design of the "strippable" screen. In general, strippable was provided on three-core designs with bonded on single-core. The argument in favour of bonded screens is that they force the jointer to use the correct tools and the construction is cheaper because it is thinner. Strippable screens are thicker to handle the mechanical forces involved in stripping and are thus more expensive. Some of the tools used for removal of the strippable screen were able to be used for the bonded screen design as well.

Further choices thrown up by the higher ratings of polymeric cables were the standard cable size considerations. Users had a choice of moving to smaller conductor sizes due to the increased current carrying capacity or staying with the standard cable sizes and possibly being constrained by the other equipment connected to the cables.

In the UK, for three-core construction, most DNOs have settled on solid circular aluminium conductors, although some take stranded conductors with water blocking. Both designs have copper wire screen, sized to suit their particular application with respect to earth fault levels. It is interesting to note that where possible, preference is given to copper wires with a diameter of at least one millimetre as experience has shown that due to arc dynamics, smaller wires will suffer from burn-back for a substantial distance away from the root of the fault, necessitating replacement of large sections of cable. In addition, there are an increasing number of designs incorporating copper equalising tape, due to concerns about jointer skill as well as a manufacturing aid. Two DNOs currently use three-core construction: SSE and Scottish Power.

With triplex construction, there are three single cores with a copper wire screen of 35 mm^2. The conductors may be solid or stranded aluminium or stranded copper. Utilities using triplex are UKPN, EON, United Utilities, CE Electric and Western Power. Western Power does not use XLPE but rather EPR (Ethylene Propylene Rubber). EPR is 20% more expensive and performs well in a wet environment, such as submarine links and underwater applications. However both EPR and XLPE pass the required tests and most users cannot justify paying a 20% premium for functionality they do not require.

Given the history of water trees in XLPE, water blocking was determined to be an important consideration in developing new designs of polymeric cable. Several variations are available:

1) No water blocking
2) Water swellable tape preventing longitudinal water migration under the copper wire screen
3) Water swellable tape over the copper screen wires which also serves the function of holding the screen wires together
4) Water swellable tape over and under the copper screen wires
5) As above with or without copper equalising tape

In terms of radial water blocking, the optimal solution is a metal sheath as it is totally impermeable to the ingress of moisture. The inclusion of a sheath gives rise to other issues such as handling, and in many cases a non-metallic sheath is used. The material used will affect the rate of moisture ingress: research by Fred Steennis at KEMA [76] shows that the time taken for diffusion of moisture through a MDPE (Medium Density Polyethylene) sheath is in the order of 115 years, dependant on material purity. For PVC, the time can be as little as a year as the fillers used tend to absorb moisture.

The type of material used in sheath construction varies – typically MDPE is valued because of its properties of abrasion resistance and mechanical strength. HDPE is very rigid (making handling more difficult) and is prone to stress cracking. SSE uses LLDPE, which is not as rigid or robust as MDPE, but these properties make handling easier.

The UK experience with first generation XLPE has not been as negative as in South Africa. A lot of first generation cable from the 1970s is still in service. Having said this, historically steam was used to cure (vulcanise) rubber, used in the manufacture of rubber cables. When XLPE required cross-linking, it was done using the same plant and hence steam was used. Water treeing occurred extensively in the USA and Germany, where dual extrusion methods were used with a fabric tape and polymeric sheath. In addition, it was found that contamination of the raw material had occurred and the material handling practices were questionable. By the time UK utilities moved to XLPE, the triple extrusion process was in use. Research had been carried out into the use of additives and retardants such as PEG (Polyethylene Glycol). Experience in UK facilities has shown that the best way to ensure quality cable insulation is to use clean materials from quality sources and employ best practice material handling.

In order to ensure that the required water blocking functional requirements have been met, BS 7870 Part 2 [77] covers water testing, while Part 4 [78] covers different designs. Harmonisation Document HD 620 [79] covers all European cable specifications.

With any network that employs a large percentage of paper cable, integration issues will arise when trying to introduce polymeric technology. Oil and compound have a deleterious effect on the XLPE polymer, so accessories used for jointing and termination need to include an oil barrier. Testing also presents issues, as the methods used for different constructions vary. There is little point in doing a partial discharge test on a mixed circuit, as the high partial discharge values in the paper insulation will mask any partial discharge activity in the XLPE. The use of DC in the testing of XLPE cables has resulted in a lot of discussion. However at MV no real space charge builds up and the application of DC to XLPE does not reveal anything meaningful. This does not apply at high voltage where DC should not be used; however this is outside the scope of this work.

An alternative method of dealing with performance is to evaluate circuit fault history. Initially, any faults would be recorded and repaired on a reactive basis. As the number of faults increase, consideration would need to be given to refurbishment or replacement. The higher the number of faults, the more weight would be given to a replacement decision, until eventually replacement becomes the only viable economic solution.

The dielectric loss of the cable is expressed by $2\pi fC.U_0^2.\theta$. For paper insulated cables with a U_0 value of less than 30 kV, and 45 kV in the case of XLPE cables, the effect is too small to have any effect on the cable rating and can therefore be disregarded.

For both PILC and XLPE cables, the DC resistance is identical for the same conductor cross-sectional area, and is measured at 20°C in all cases. For AC resistance, the values are given at maximum operating temperatures, which will result in differences since PICAS for instance can operate at 65°C and XLPE at 90°C. Clearly the XLPE temperature is higher and for a given cross-sectional area will require more current to reach the higher temperature. Using a 185 mm^2 conductor, the XLPE can carry 335 A vs. the 280 A of the PICAS equivalent. Also, at the higher temperature the conductor resistance will be higher because it has a positive temperature coefficient. If both current and resistance of the XLPE cable are higher, it follows that the I^2R losses will be higher too. If both cables are run at the same temperature the losses will be the same.

Anecdotal evidence suggests that polymeric cable performance is better than paper cable performance. This is partially due to the fact the paper cable fails very quickly after moisture ingress while polymeric cable can operate for many years after water ingress. Unfortunately this may allow the development of extensive treeing (water trees later developing into electrical trees) rather than causing just a local fault, long sections of water treed cable may have to be replaced. Also, while paper cable has a recorded in-service life of many decades, XLPE (being a newer technology) does not have the same in-service history.

CHAPTER 3: RESEARCH METHODOLOGY

As discussed in Chapter 2 there is not much published work available on the process of changing from PILC to XLPE (or indeed other polymeric) as the cable technology of choice. As a result this presents a challenge in making reference to existing or published works as the primary basis of support for the generated hypothesis.

Naturally a lot of work has been published individually with respect to the two different cable constructions, and a lot of the methodological approach consisted of evaluating the evidence to determine whether it added to, or detracted from, the validity of the hypothesis. Some of this evaluation may be subjective; however it is based on published literature.

A great deal of information was obtained from questionnaires and interaction (through discussion and interviews), with subject matter experts. The feedback thus gathered was critically evaluated (taking confidentiality requirements into account where appropriate) and analysed to determine its impact on the hypothesis.

3.1 QUESTIONNAIRE

In order to gauge the reactions and attitude of major users with respect to the potential migration to XLPE, opinions were sought in the form of a questionnaire. In order to try and elicit as full and honest response as possible, users were allowed to specify which (if any) included information they wished to remain confidential.

The questionnaire was sent to users at eThekwini Electricity, Cape Town Electricity, City Power, Eskom, and Tshwane Electricity (CTMM). These users were chosen due to their participation on previous NRS and StanSA Working Groups, as well as their current and historical cable selection policies. Cape Town Electricity, eThekwini Electricity and CTMM had previously used belted PILC cables while City Power had used screened PILC cables. Eskom had made use of screened PILC cables but had moved to XLPE for new projects. This represented a good cross-section of users as well as cable construction variations.

The questionnaire is included at the end of this dissertation as Annex A.

3.2 COMPARISON OF RATINGS

In order to quantify the benefits of like-for-like solutions, cable rating guidance and data sheets were compared to determine whether a significant benefit could be obtained by the choice of one platform over another. The source documents were obtained from South African and UK cable manufacturers (data sheets) and various utilities (rating guidance tables), and involved comparing similar types of cables with different construction (for instance comparing the rating of a 300 mm^2 three-core PILC cable with that of a 300 mm^2 three-core XLPE cable) as well as comparing the two cables on the basis of current carrying capacity (for example comparing a 300 mm^2 single-core PILC cable with a 240 mm^2 single-core XLPE cable).

Furthermore, some utilities have decided to retain a peak conductor temperature of 70°C even after migration to the XLPE platform, which will have the effect of lower current ratings compared to a maximum permissible conductor temperature of 90°C. The effect of the PILC and XLPE ratings under various conditions at the same temperature were compared, using the data tables of the utilities.

3.3 CRATER

STP3 (Strategic Technology Programme 3) is facilitated by EA Technology and is attended by many representatives from the various DNOs. STP3 is concerned with Cable Networks, and one of the outputs of that group has been a set of software modelling tools named CRATER (Cable Rater).

The advantage of CRATER over conventional software models for current ratings is that it caters for static and dynamic loads. The development of the tool was initially based on the ENA (Energy Networks Association) Engineering Recommendation P17 [80]. According to Le Poidevin *et al* [81], the concept of a distribution rating (with respect to a cable) is explained as follows: When the cable is operating under normal conditions, it is loaded in a continuous cycle, which repeats itself at regular intervals, as shown in Figure 3-1. The normal operation of the cable is shown in Figure 3-1 from -168 hours to -72 hours. At this point, the peak load is increased; however the shape of the load profile stays the same, as would be expected in the event of an increase in load due to a system emergency. After 72 hours of the increased peak load (taking the load profile into account) i.e. at 0 hours in Figure 3-1, the conductor reaches its maximum permissible temperature.

In this example, for the 11 kV belted PILC cable chosen in Figure 3-2, the maximum temperature is 65°C. Examination of the results of the CRATER output in Figure 3-2 shows that the distribution rating under the chosen conditions is 766 A. The duration of the increased loading chosen in this example was three days, and a utilisation factor of 50% was used. The utilisation factor is the percentage of the full distribution rating under normal operating conditions; therefore 50% would represent half the distribution rating before the load increase at -72 hours.

CRATER allows variation of the utilisation as well as the duration of the load increase.

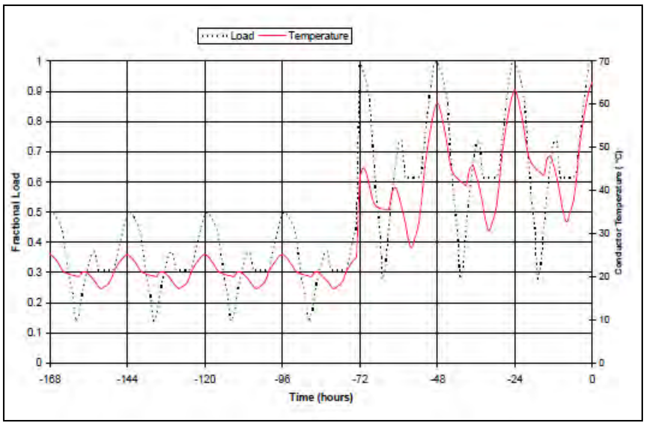

Figure 3-1: Typical load and temperature profiles before and after limited time excursion [82]

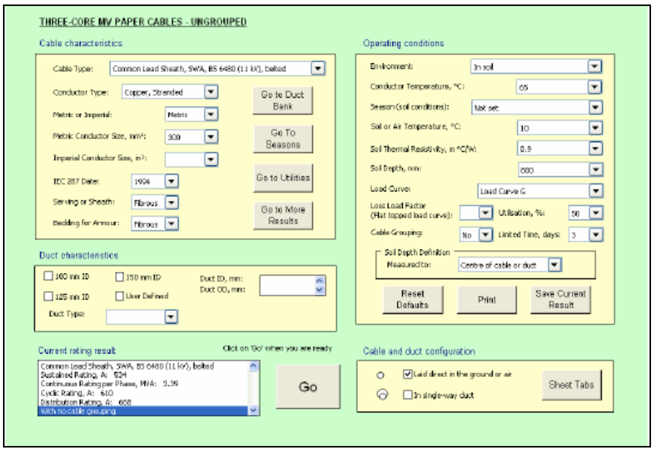

Figure 3-2: Screenshot from CRATER [83]

The CRATER functionality extends to the calculation of ratings for sustained and cyclic conditions, and caters for other conditions such as drying out of soil (with resultant increase in thermal resistivity), grouped circuits and banks of ducts.

Ongoing development of the CRATER software has also enabled functionality for paper, polymeric and mixed circuits. The tool can provide emergency and dynamic ratings, and has the facility for the user to generate load curves from SCADA. In addition, functionality enabling rating calculation for cable crossings and ventilated cable tunnels has been included, and comparison of the output of its iterative approach compares favourably with the P17 predictions that previously had to be carried out manually.

Since most of the parameters shown on the user interface are user-definable, it is possible to choose installation conditions such as soil thermal resistivity, circuit grouping, maximum temperature and load profile. For the purposes of comparison, the tool was used to compare current ratings and system losses for XLPE and PILC under similar installation conditions, using both the 70°C and 90°C maximum conductor temperatures, in order to provide economic comparisons for the different cable platforms.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INVESTIGATION AND COMPARISON

In order to evaluate the different constructions (screened vs. unscreened, and three-core vs. single-core), they were compared in terms of safety, economic performance and network performance, including installation issues.

The physical construction of the various cable types have already been discussed in some detail in Chapter 1. Medium voltage electric cables in South Africa are covered by compulsory specification VC 8077 [84]. Notification of this statutory requirement has been published in the Government Gazette and makes compliance with SANS 97 [85] (for paper cables) and SANS 1339 [86] (for XLPE cables) compulsory.

NRS 013 [87] details the preferred requirements for single- and three-core MIND PILC and XLPE cables with stranded aluminium or copper conductors. The Working Group given the task of revision of NRS 013 considered several factors when including advice on preferred cables in Annex A of the document. Screened construction was chosen as being preferable to belted construction for five reasons [88]:

- Superior field control due to the radial electric field being completely contained within each cable core (it was noted that screened designs are used almost exclusively at voltages above 11 kV);
- Since South African electric utilities use IDMT protection designed to operate in the event of an earth fault, a cable with insulation designed to operate continuously with one phase earthed is unnecessary, since such a situation is considered both abnormal and undesirable, and the protection systems are designed to operate to clear the situation as soon as possible;
- The increasing use of modern cable-connected plant imported from Europe favours screened cable systems as the plant is designed for these systems and is increasingly compact, making belted systems unsuitable for these applications (see Figure 1-2 for stress distribution in a belted cable);
- Improved personnel and equipment safety due to the superior field control within the cable termination enclosure, resulting in a reduced probability of failure and internal arc; and

- Improved fault performance with screened construction since any fault is likely to be a phase to earth fault rather than an inter-phase fault. Typically earth fault levels are lower than phase fault levels and hence less energy will be released, causing less damage. In a system that is non-effectively earthed (for instance a resistance earthed system) an earth fault will result in substantially less plant damage than an inter-phase fault, which could mean the difference between re-terminating a cable vs. changing the piece of equipment it is connected to.

The Electric Cables Handbook [89] states that the advantage of screened construction is improved electrical quality, resulting in a cable with a higher rating. At 11 kV, the disadvantage would be the extra cost and complexity of accessories for jointing when compared with belted cables. Also, for paper cable, the electric strength of impregnated paper insulation is stronger (by a factor of 15) in the radial direction than tangentially. The application of a conductor screen over stranded conductors will greatly facilitate smoothing and control of the electric field at the conductor/insulation interface.

Annex A of NRS 013 went on to recommend standard sizes and types of cables. For conductor sizes of 95 mm^2 and 185 mm^2 three-core cables were recommended, while single-core construction was recommended for 300 and 630 mm^2. The reasoning was based on easier handling (laying, terminating and jointing) of single-core variations of the larger sizes as well as the fact that usually the larger cables would be laid in more controlled environments such as substation yards where they would be less likely to be mechanically damaged. Three-core cables were felt to be able to withstand mechanical damage better than single-core cables as the three-core cables are constructed with steel armour (either double tapes or wire). Steel armouring is not included on single-core cables as the losses would be very large and non-ferrous armour (such as aluminium or copper) is used instead.

Clearly utilities preferred to have armoured three-core cables for general distribution. There was also an argument that laying a single three-core cable simplified the laying process in that users did not have to worry about cleating cables together (in trefoil formation) or ensuring that the necessary 2D spacing was maintained when laying cables in this (horizontal) formation. In addition, earthing and bonding arrangements are simpler with three-core cables than single-core cables.

What was not taken into account was the inherent protection provided to a cable by virtue of being buried (with or without additional protection) at the correct depth or the fact that there is no specific requirement for a cable to be armoured. Section 1.2 of SANS 1339 makes provision for both armoured and unarmoured cables. SANS 10198-8 [90] gives a normal depth of burial for an MV cable as 800 mm, measured from the ground surface to the centre of the cable or group of cables. Clause 4.5.2.1 of SANS 10198-2 [91] states, "*When* armouring is required on a single-core cable ..." (italics own). Clause 4.5.2.2 of the same document states "One or two layers of galvanized steel wire are *normally* used as mechanical protection for multicore cables..." and "A double layer of steel tape is *sometimes* used as mechanical protection" (italics own). SANS 1339 defines armouring as "mechanical protection for a cable, comprising a single layer of galvanized steel wires or, for a single-core cable, a layer of aluminium of copper wires" [92].

It follows that debate about whether copper (or aluminium) wires constitute a screen or armour is only relevant in the terms of assessment of the risk of damage to a buried cable (and possible injury to persons), and is not an absolute requirement.

SANS 10198-2 recommends installation of cables in such a way as to minimise the likelihood of damage and in clause 5.2.1 outlines a possible way to achieve this (through the use of concrete or suitable cover tiles). It further states that as "...an additional or alternative precaution, a brightly coloured plastic warning tape shall be laid above the cable at a depth of at least 200 mm below the ground surface".

This serves to illustrate that the choice of installation of three-core cables for medium voltage distribution is a preference of South African users rather than an absolute requirement. It may be that they have carried out comprehensive risk assessments and determined that three-core cables are the only suitable option with respect to their risk profile; however the author is not aware of any such assessments having been formally carried out.

It may be that the high ratio of mechanical faults to electrical faults experienced in South Africa [93, 94] provides an argument in favour of armoured cables, and three-core steel armoured cables definitely provide superior mechanical protection to AWA single-core cables.

For systems with higher fault levels, a three-core construction may make more economic sense. SP Power Systems and City Power Johannesburg chose three-core cable designs on the basis of the cost of the earth path – in a single-core system each core requires the armour/screen to carry the fault current. For an earth fault level of, say 13.1 kA, the physical amount of copper or aluminium required on each single-core cable would make the system cost higher than an equivalent three-core cable.

4.2 ADVANTAGES AND DISADVANTAGES

In order to compare the two cable technologies, an analysis of the advantages and disadvantages of the use of PILC vs. XLPE, with specific emphasis on fault performance and losses (dielectric and I^2R), was carried out.

4.2.1 PILC

PILC has a demonstrated performance history to the extent that it is accepted as the benchmark that other cable types are compared to [95]. The main cause of electrical breakdown is related to the ingress of moisture, which, if it gets under the lead sheath, can travel considerable distances from the point of ingress. Water ingress tends to produce relatively rapid failure in paper insulated cables, especially at 11 kV and above whereas water trees can exist for years in XLPE cable while the cable remains in service.

The Eskom report [96] demonstrated that the predicted number of electrical faults per 100 kilometres per year of PILC would always be lower than that of XLPE (see Figure 2-1), however the report did note that incorrect fault location techniques on XLPE cable (this is true for pure XLPE and mixed dielectric circuits) can result in further cable faults. Also, the curves shown in Figure 2-1 are biased somewhat in that XLPE (Worst Case) curve was scaled from data obtained from the Electric Cables Handbook. This data showed that XLPE cable installed in Europe in the 1970s had a failure rate of between 0.6 and 0.8 failures per 100 kilometres per year. This was then scaled to the higher figure (0.8) for XLPE cable at 20 years of age. The source data used includes first generation XLPE cables and thus for modern XLPE insulation, the actual figures should be much lower, perhaps even better than PILC.

Paper insulation is susceptible to breakdown due to ionisation and thermal breakdown, described in detail in chapter 2 of the Electric Cables Handbook [97]. Paper insulation is regarded as being self-healing under normal conditions in that discharge activity within any void in the insulation will cause local temperature increases, melting the compound which tends to fill the void and extinguish discharge activity. This is not a reliable characteristic of paper insulation and it is likely that breakdown by ionisation will occur under certain conditions, as described in the Electric Cables Handbook. An example of this is shown in Figure 4-1 overleaf.

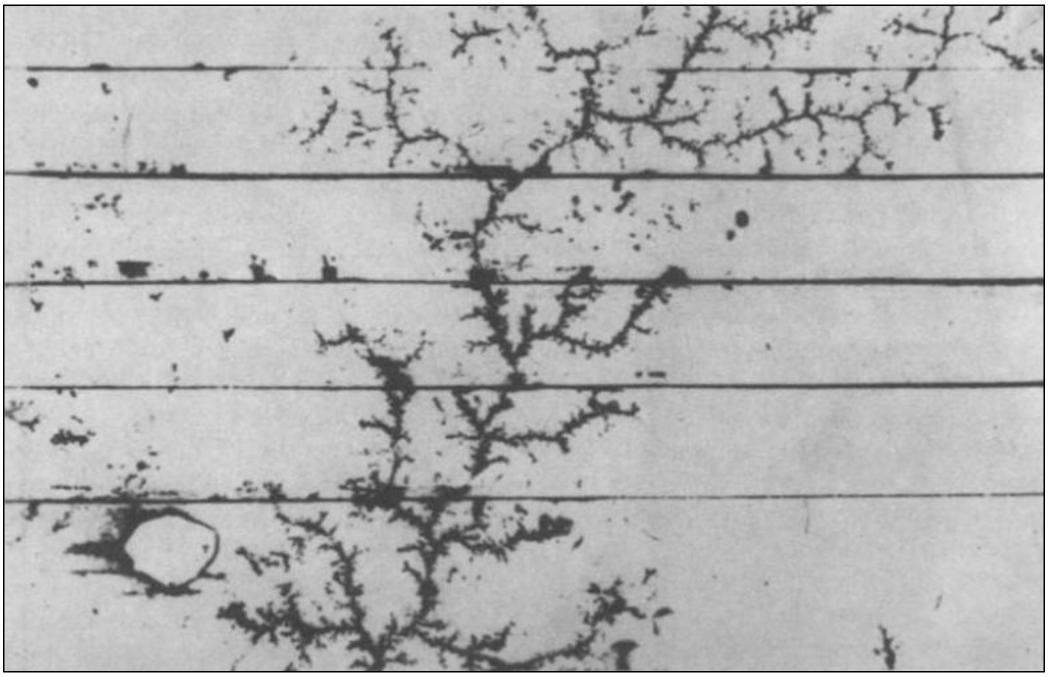

Figure 4-1: Paper insulation tapes showing carbon tracking [98]

Metallic sheaths are used on paper insulated cables to provide protection against the ingress of moisture as well as the provision of an earth path. Lead sheaths found on paper cables are typically smooth and are continuously extruded. In the UK this was replaced by a corrugated aluminium sheath (along with removal of separate armour) in the 1970s, as mentioned in Chapter 2. This development did not occur in South Africa for medium voltage cables and the lead sheath was retained until the present. Usually an alloy of lead is used (most commonly lead alloy E) as pure lead is susceptible to inter-crystalline fracture as a result of vibration or thermal cycling. Lead alloy E also has limitations. Even though its fatigue limit is twice that of pure lead, it has a diminishing extensibility characteristic and should only be used in applications where long term ductility is important if the grain size is fine enough [99].

Double steel tape armour (DSTA) is preferred by most users for three-core PILC cables but as mentioned previously it has a higher impedance due to the short lay length. It also has lower strength than steel wire armour (SWA) resulting in a lower permissible maximum pulling force during laying as well as insufficient longitudinal strength in the event of soil subsidence or undermining [100]. Perusal of manufacturers' data sheets will reveal that earth fault withstand ratings of DSTA cables are lower than those of SWA cables. In all cases, cables with corroded armour need to be treated with care as it is likely that most of the mechanical strength has been lost. In such an event, undermining, moving or interfering with the cable in any way should be avoided [101].

Globally, the security of sources of supply (for components and for complete cable) is of concern. The only known countries still manufacturing MIND PILC are South Africa, Russia, India and China. In their report [102], SP Power Systems raised concern over quality issues relating to PICAS cable, as well as machinery breakdowns of several weeks leading to significant delivery delays. Lack of investment in PILC manufacturing plant will exacerbate the situation.

It is also worth noting that the TC20 (Electric Cables) committee of the IEC is no longer actively maintaining IEC 60055-1 [103] or IEC 60055-2 [104] which are the IEC documents for paper insulated cables up to 18/30 kV.

4.2.2 XLPE

XLPE technology has improved since the initial "first generation" cables were produced. In the Netherlands, cables produced in the 1970s have all been replaced or treated with a proprietary silicone fluid. "Second generation" cables from the 1980s are less prone to water trees but require careful management. "Third generation" cables are not seen as problematic at all and have almost no issues with water trees (described later). This is attributed to increased material purity, improved water blocking (radial and longitudinal) and changes in the actual cross-linking process [105].

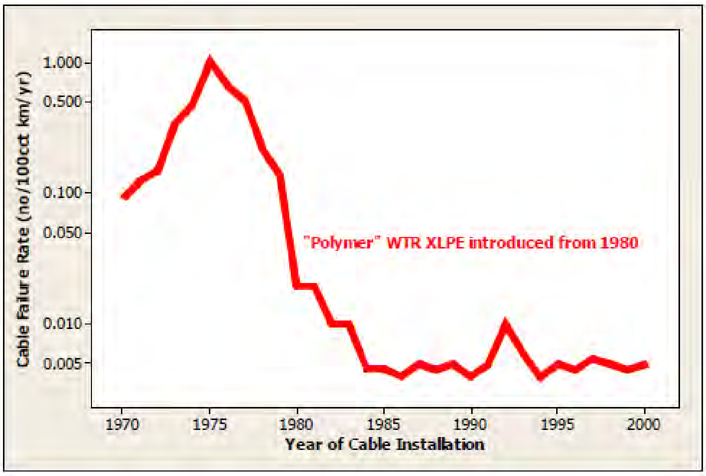

Figure 4-2: Cable failure rate as a function of year of installation in Germany [106]

In Europe in the early 1990s, the installed XLPE cable base at 10 kV was 59,000 km, with a failure rate of 0.21 faults/km/year. At 20 kV, 97,000 km had been installed with a failure rate of 0.61, and at 30 kV, 3,000 km had been installed with a failure rate of 0.76 [107]. Another source [108] gave the failure figures for XLPE installed in Europe during the period 1979 to 1994, for cables of 10, 20 and 30 kV as 0.2, 0.4 and 2.0 respectively (failure rate expressed in median failures per 100 circuit kilometres per year). Interestingly, the comparable figures for EPR were 2.3, 1.4 and 2.0. In the UK, where 11 kV is used as the primary distribution voltage rather than 10 kV, experience with XLPE cables has demonstrated good performance as well [109].

What is not really clear from Figure 4-2 is the effect on failure rates of the amount of cable installed. For instance, more circuit kilometres of cable were installed in 1995 than in 1985. A study carried out by North American utility TXU Electric provided the findings shown in Figure 4-3. For purposes of comparison, 30 failures occurred after 9,000 km years for the HMWPE (High Molecular Weight Polyethylene) cable. For XLPE, 30 failures occurred after 22,000 km years. Extrapolating the WTR XLPE data shows that it will take in excess of 100,000 km years to cause 30 failures [110]. This is consistent with the findings of Caronia *et al* [111] and provides a strong motivation to seriously consider the use of XLPE that is tree retardant.

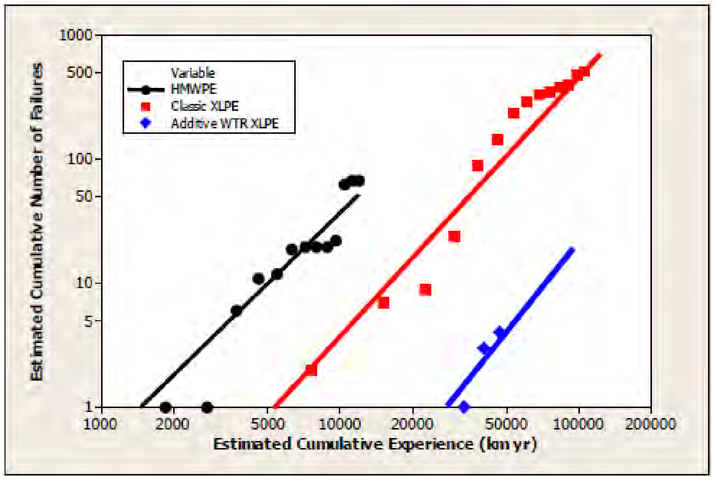

Figure 4-3: Cumulative failure data by cable type [112]

XLPE construction has advantages over PILC construction in that the absence of a metallic sheath makes the cable lighter and easier to handle, resulting in improved laying and jointing efficiency. The reduced bending radius assists installation, and the cleaner construction and greater mechanical strength are valuable, especially in locations where the scarce skills required for work with paper insulated cables are unavailable [113].

Notwithstanding the modern performance of polymeric cables, early designs were extremely susceptible to water trees and this was especially the case in North America, where by the end of 1983, 116,000 km of XLPE cable (and 60,000 of the thermoplastic PE) had been installed. Service performance was unsatisfactory, and the failure rate has been estimated at between 5 and 6 times that of the failure rate in Germany [114].

XLPE (indeed all polymeric insulation) is prone to a phenomenon known as water treeing. These water trees develop in the presence of water, ions and electrical stress. The inception and growth have been linked to several factors: ions, electrical stress, temperature, mechanical damage, contaminants, voids in the insulation, and to a lesser extent, frequency [115]. Water trees take some time to form, usually in excess of 5 years and typically from 8 to 12 years [116]. The service life expectancy of cables that have been in service have been estimated to have their service life expectancy reduced by up to 43% [117].

Water trees can be described as regions within the polymer insulation that have reduced insulation properties and lower breakdown strength than usual. Although they are inferior in terms of their insulation characteristics (when compared to the healthy insulation), they are not conductive. If the water tree is subjected to a high electrical stress, an electrical tree can form and this will lead to insulation failure and electrical breakdown. An example of a water tree with an electrical tree is shown in Figure 4-4. Electrical trees can also form independently of water trees at voids and interfaces within the insulation [118].

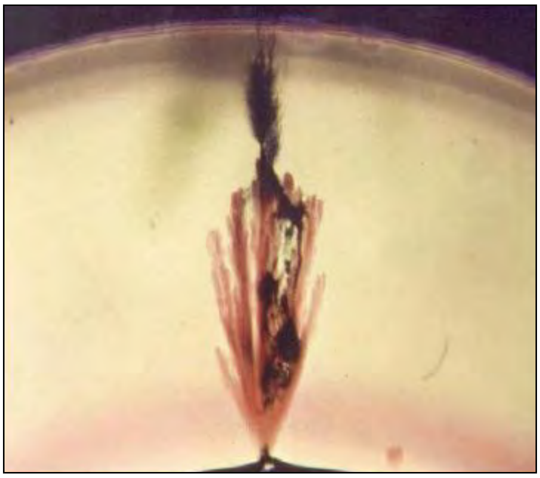

Figure 4-4: Water tree with electrical tree in MV XLPE insulation [119]

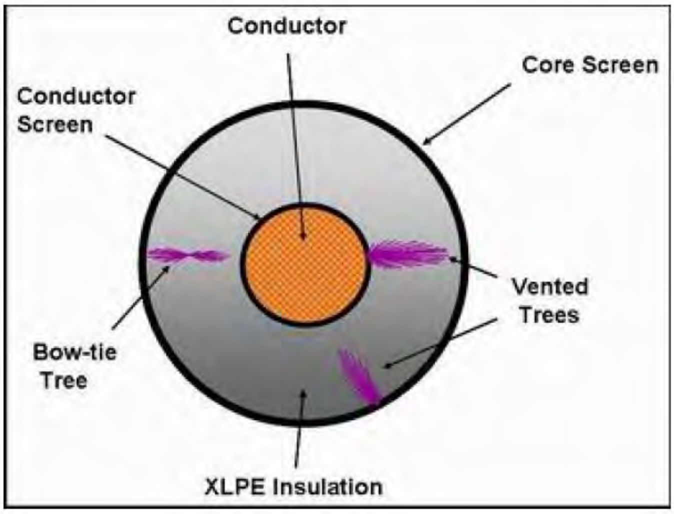

Figure 4-5: Types of water trees in XLPE insulation [120]

Research conducted by Geurts *et al* [121] demonstrates that inception and growth of water trees is minimal when the relative humidity is below 75%. The time taken to achieve this humidity level with outer sheaths of different materials, with or without water swellable tape respectively, was found to be 192 days/1 hour for PVC, 115 years/11 days for MDPE type 1, and 28 years/3 days for MDPE type 2.

This clearly demonstrates the necessity of using a PE sheath rather than a PVC sheath, and also provides a strong argument in favour of the use of water swellable tapes. Using such a construction will keep the humidity levels below those necessary for the inception and growth of water trees, thus enhancing the reliability and service performance of the XLPE cable installation.

Furthermore, the use of tree-retardant material (TR-XLPE) will provide increased performance and any trees that do form will grow at a significantly slower rate than would be the case in non TR-XLPE [122]. The different types of water trees that may develop are shown in Figure 4-5.

4.2.3 LOSSES

Power loss in AC cables can result from several factors: conductor losses, dielectric losses and sheath losses. Conductor losses are given by the Electric Cables Handbook [123] as:

$$n\, I^2 R_\theta \quad \text{(watt)}$$

where n = number of cores

I = current carried by the conductor (in amperes)

R_θ = ohmic a.c. resistance of the conductor at θ°C (in ohms)

Conductor losses will tend to increase with increasing current since the conductor material has a positive temperature coefficient i.e. its resistance increases as its temperature rises. Therefore when examining a manufacturer's cable data sheet, it is important to be aware that the quoted AC resistance values are given at the maximum operating temperature of the cable and hence will not be directly comparable. In general (and partially as a result of the different temperatures that the calculations are performed at), the AC resistance of XLPE cables is greater than the equivalent PILC cable, meaning that conductor losses in XLPE cables will be higher than for equivalent PILC cables. The DC resistance is given in the data sheets at a standard 20 °C and hence is directly comparable, and for the same material and cross-sectional area, equal.

Decreasing the cross-sectional area of any conductor increases its resistance (and hence its losses) and this is one argument against using the ability of XLPE to run at a higher temperature as a reason to reduce the conductor cross-sectional area.

Modern software can calculate the ratings required (taking varying AC resistance into account) and this will be discussed later.

Dielectric losses are proportional to the capacitance, frequency, phase voltage and power factor and are given by the Electric Cables Handbook [124] as:

$$D = n\ \omega\ C\ U_0^2 \tan\delta\ 10^{-6} \quad \text{(watt/km)}$$

where n = number of cores

$\omega = 2\pi f$

C = capacitance to neutral (in μF per kilometer)

U_0 = phase to neutral voltage (in volts)

Tanδ = dielectric power factor

XLPE has an advantage over paper in that it exhibits lower dielectric losses than paper insulation [125]. At medium voltage, the effect of dielectric losses is very small in comparison with conductor losses and it is usually ignored below 50 kV [126]. The Eskom planning guideline [127] only considers conductor losses when determining the economic loading limit and the total overall system cost of different cables. Dielectric losses are not taken into account. An example of the cost comparison of various cable conductor sizes (taking technical losses into account) is shown in Figure 4-6 below.

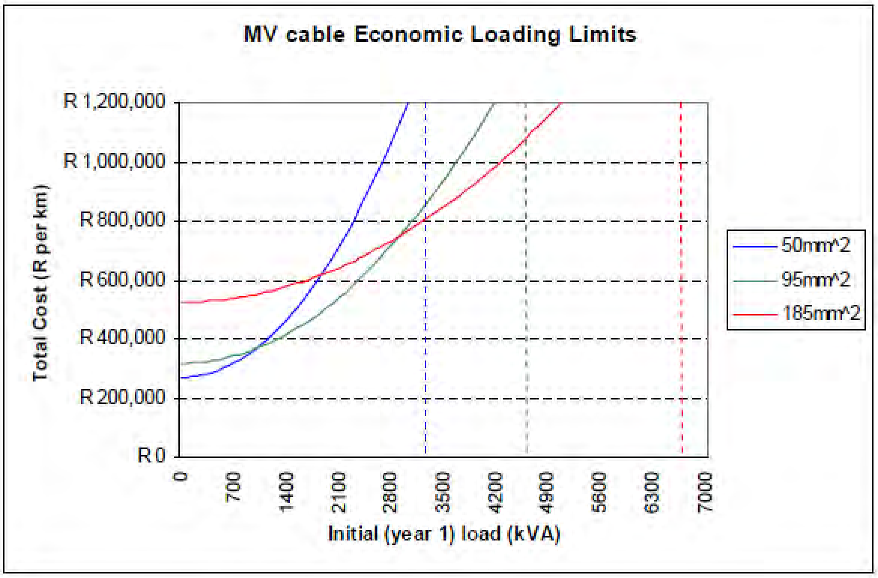

Figure 4-6: Economic loading limits for 11 kV cables [128]

4.3 COPPER VS. ALUMINIUM CONDUCTORS

Copper's mechanical and electrical properties make it an excellent material for a choice of conductor. Since it has better conductivity and lower resistance than aluminium, the cross-sectional area required to transmit a given amount of power is smaller than an equivalent aluminium conductor. Since less conductor material is required, less insulation, armour and sheathing material is required; and the overall cable diameter is smaller than it would be with aluminium conductors. Smaller conductors facilitate easier handling, and are more suited to modern switchgear, where dimensions have been reduced as improving switchgear technology allows ever more compact designs. However, economic factors play an important role in selection decisions and the copper price volatility combined with commodity price spikes has resulted in aluminium becoming a viable alternative [129].

Aluminium (particularly in stranded form) does not have the mechanical strength of copper but this may not be problematic depending on the application. In some cases, solid conductor is extruded. Furthermore, the conductivity of aluminium is only 61% of that of copper, with a density of 1/3 of copper. The properties of aluminium result in a mass of half that of copper for equal conductance, but with a cross-sectional area of 160% of the equivalent copper conductor.

When comparing aluminium and copper cables of identical cross-sectional areas, the current carrying capacity of the aluminium cable is typically in the range of 0.78 to 0.8 p.u. of the copper cable [130]. With a conventional PILC cable there is no significant mass advantage in using aluminium conductors but there is if the lead sheath is also replaced by an aluminium sheath, as is the case with PICAS (Paper Insulated Corrugated Aluminium Sheath) cable, as used in the United Kingdom [131].

Aluminium is prone to the rapid development of an oxide film, which serves a protective purpose against corrosion in above ground applications, but unfortunately has a high electrical resistance. Any work to be undertaken on aluminium cables needs to take this into consideration, and jointing or termination procedures need to be very carefully followed to ensure optimum electrical contact [132]. The use of modern accessories is covered later.

Standardising on either material will produce an economic benefit in terms of a smaller stockholding requirement with respect to the entire cable system (cable, lugs, ferrules and associated accessories). However, it must be borne in mind that crimping technology for copper is simple (typically using compression principles) and overcomes galvanic action (with associated corrosion) when connecting lugs to brass terminals of electrical equipment [133]. These issues can be easily overcome with modern technology (discussed later) but must be considered when determining a cable selection philosophy.

City Power and Eskom have standardised on copper conductors. This choice generated much debate but was based on several factors besides being preferred in terms of NRS 013, including increased ampacity for the same cross-sectional area as aluminium, and for a certain required load, a smaller copper cable could be installed than the equivalent (in terms of load rating) aluminium cable, enabling easier handling. The persistent argument of the higher cost of copper was found (at the time) to be without merit. When performing calculations on an equal comparison “Rand/ampere” basis, it was discovered that the costs were very similar and that slight variations occurred on a daily basis due to the fluctuations of the metal prices on the London Metal Exchange (LME) [134]. The cost differences tended to balance out over time and given the advantages of copper the decision was taken. This decision was taken several years ago and it may be time to review it again, in view of the sustained high commodity prices experienced over the last few years. The physical size of modern secondary switchgear was also taken into account: the compact construction meant that the largest three-core cable that could be realistically and correctly terminated within such an enclosure was deemed to be 185 mm^2 [135].

4.4 INTEGRATION ISSUES

Given that the two cable technologies under discussion are different in terms of construction and potential operation, it follows that integration issues will arise. Most users will have varying proportions of paper insulated cable on their existing networks, and a change to XLPE (i.e. a different technology) might well give rise to unforeseen issues.

Advances in modern technology and an understanding of previous problems can provide a deeper perspective into understanding these issues than was the case 20 years ago.

The first major issue that will be encountered is the physical integration of cables of different construction. The existing network may be three-core PILC, belted or screened, aluminium conductor, and armoured with SWA or DSTA. The new chosen cable platform may be single-core, copper conductor, and armoured with AWA. The jointing of cables of different technologies and construction may present difficulties, especially to personnel who may not have the traditional skills required.

Fortunately, modern accessories can overcome this part of the integration challenge, and this will be discussed later in this chapter.

The effect of cable oil on polymeric insulation is detrimental in that the oil or impregnants used in a paper insulated cable may cause swelling of the polymeric insulation, particularly at the interface such as that which is found in a transition joint [136]. Initially so-called “stop joints” were employed to reduce the likelihood of oil migration within cable systems. Oil migration not only caused problems with softening and penetration, but in some cases lead to excessive hydraulic pressure resulting in cable system damage [137]. Although modern cables are mass-impregnated, it is possible that jointing onto an older rosin oil cable may be encountered in practice and when taking into account the effect of even modern impregnants on XLPE, it is advisable to use oil barriers in the accessories as well as solid centre ferrules.

CBI Electric: African Cables have also noted [138] that cable oil has an unfavourable effect on XLPE. In their test, the XLPE insulation swelled to several times its initial thickness after just four days at 90°C and the bulletin concluded that “every measure must be taken to avoid contact between cable oil and XLPE”.

Perhaps the most important topic in terms of ongoing commissioning, operation and maintenance of the network relates to testing.

Concern over the use of using traditional methods of testing for XLPE and mixed dielectric circuits was raised in a report by EA Technology in 1999 [139]. The report also highlighted concerns about the effectiveness of using proving techniques for three-core cables, on single-core cables.

The KEMA course on Power Cables (Testing Related to Service Operation) [140] gives the following reasons for not carrying out a DC test on HV XLPE cables:

- Certain defects can withstand high DC stresses (up to 7 times U_0) although will fail under AC conditions;
- DC testing can be harmful due to accessory design, causing dangerously high electrical stresses within the accessory; and
- XLPE insulation is more susceptible to space charges than paper insulation, due to the higher resistivity of XLPE. DC testing can result in space charges in the insulation, and these space charges are difficult to remove, resulting in very high electrical stresses (and risk of insulation damage) when the cable is re-energised.

In addition to the reasons given above, a source referenced as Kaminaga (1997) was quoted as saying “DC tests on XLPE cable systems have been shown to be very ineffective, far from representative and even dangerous for the circuit under test”.

Van Schaik [141] referred to a 1990 Cigré report which came to a similar conclusion. He further noted that 12 out of 15 countries “... abandoned DC testing because faults induced during installation were not detected, or faults were induced during DC testing because of the difference in stress control between AC and DC stress or because of possible space charges. They confirmed strongly the use of AC testing after installation.”

Guidelines issued during the course [142] were not to use DC at more than 1 to 2 U_0 for MV cables, and not to use DC for (E)HV cables at all. It was stated to be particularly harmful for healthy HV cables and water-treed MV cables.

In an article in *energize* [143], reference was made to a test on a 10 kV cable where a conductive needle was inserted into the cable, through the insulation and to a depth of 1 mm from the conductor. The test set did not pick up the fault, even at 100 kV.

Nyamupangedengu [144] states that "... solid dielectric cables should now be tested with high voltage of very low frequency (such as 0,1 Hz) to avoid insulation damage through space charge injection".

SANS 10198-13 [145] recommends the use of Very Low Frequency (VLF), Power frequency or Surge waveforms and cautions that the use of unsuitable methods of fault location can cause damage to the insulation of XLPE cables. DC overvoltage testing is specifically mentioned as being likely to cause irreversible damage to the insulation, along with the fact that this type of testing may fail to identify defects in the cable. If DC testing is absolutely necessary, reduced values of voltage and duration are specified and a soft discharge procedure is required.

In a 2007 article in *energize* [146], the author referred to a study by Chong where 15,000 MV circuits were tested by means of VLF over voltage testing. Any faults discovered were repaired and the circuit in question was retested until it withstood the VLF over voltage. The circuits tested represented 35.66% of the total and comprised PILC, XLPE and mixed dielectric circuits. These circuits subsequently contributed just 3.71% of the cable faults identified and recorded.

The cost of acquiring cable testing and fault location equipment was taken into account in the Eskom report [147] recommending that XLPE be used as the standard MV cable for Eskom Distribution. The cost of staff training was also taken into account. The report did note that as per SANS 10198-13, short lengths of XLPE cable may be tested with reduced DC levels, as AC commissioning tests are only strictly necessary for cable routes of significant length. Notwithstanding this allowance, in view of the overall tone of SANS 10198-13 (and other sources referenced above) with respect to DC testing of XLPE insulated cables; such testing should probably be avoided altogether if at all possible.

For users with a large installed base of paper insulated cable, and who are contemplating migration of their cable platforms to XLPE, the cost of training and acquisition of new equipment as detailed above, must be taken into account. The costs are one-off costs and are not ongoing.

4.5 USE OF MODERN ACCESSORIES

Any user of a cable system will have had to make decisions regarding termination and jointing of the cables used in that system. Historically, bitumen compound was used when terminating paper cables in compound filled cable enclosures. The modern trend of switchgear is toward more compact, air-filled enclosures designed for screened, single-core polymeric cables.

Modern accessories cater for a variety of installation constructions and conditions, and it is possible to terminate paper insulated cables into modern switchgear, within reason. The compact nature of modern switchgear places a limit on the maximum size of cable (especially three-core cable) that can be practically terminated within a compact enclosure [148].

Correct preparation is essential to the reliability of any accessory and details in this respect are provided throughout Goulsbra's book [149].

Of more interest with reference to this dissertation, is the subject of joints as this is where the difficulties and challenges associated with network integration are most obvious. For instance, accessories traditionally used for the jointing of belted paper cables cannot be used to join a belted paper cable to an XLPE cable. Furthermore, paper cables usually have sector-shaped cores, while XLPE has round conductors. To complicate matters more, conductors may be solid or stranded, and made from aluminium or copper, and be of different cross-sectional area. The physical construction of the two cable types is, of course, also very different.

The functions of a joint have already been listed in Chapter 2. The first function is the joining of conductors, and this may be achieved by means of crimped or mechanical (torque shear) connectors.

When crimping ferrules onto conductors, the ferrule must be chosen to correspond to the type and size of conductor being joined. Usually, copper connectors are crimped using the hexagonal method, whereas aluminium conductors are crimped with the deep indent method [150]. Both of these methods and constructions are shown in Figure 4-7 overleaf. The correct preparation of aluminium is particularly important to give good electrical contact due to the rapid formation of an oxide film on exposed aluminium. The disadvantages of crimping are that a range of ferrules must be held in stock, corresponding to the different sizes and types of conductor that may need to be joined. In the case of joining copper to aluminium conductors, special bi-metallic conductors need to be used, although SANS 10198 does not recommend their use [151]. Each crimp ferrule will require the use of a tool to provide the necessary pressure, as well as a unique set of dies designed to be used with a specific ferrule.

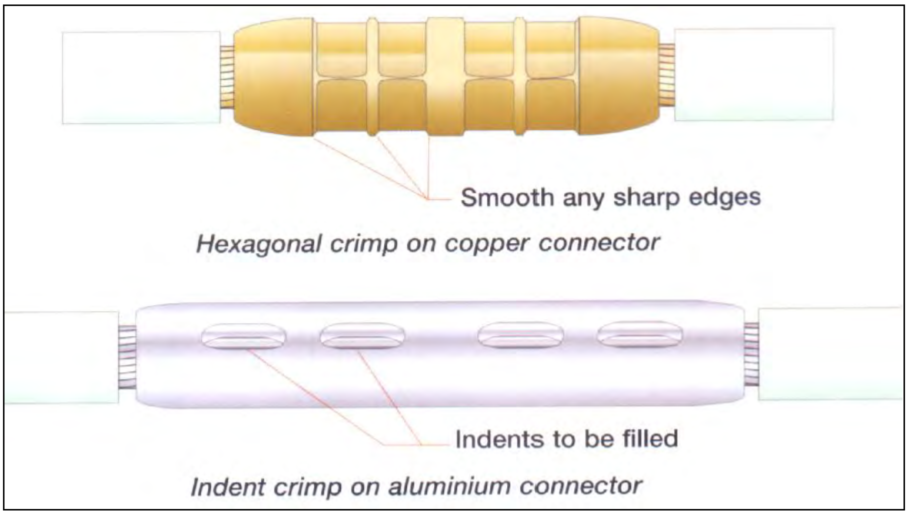

Figure 4-7: Crimping methods [152]

Mechanical connectors have the advantage that they are suitable for joining copper and aluminium conductors (they are inherently bi-metallic), sector-shaped or round conductors, solid or stranded. They are also range-taking. They can be water-blocked i.e. provided with a solid centre so that any water or oil present in a section of cable cannot continue to migrate down the cable. They are more expensive than crimp ferrules but have the advantage that no special tools and dies are required to install them. Their installation is simple in that the jointer tightens the hexagonal heads until they shear off at a pre-determined (by the manufacturer) torque, thus making sure correct installation is largely independent of the skill set of the jointer. In South Africa, NRS 075 [153] details the preferred requirements of the major users for these connectors. The preferred ranges are given [154] as 16 to 35mm^2, 25 to 70 mm^2, 50 to 95 mm^2, 120 to 240 mm^2 and 185 to 300 mm^2. The ranges have been chosen to overlap and thus provide maximum flexibility. Larger sizes are designed for circular conductors and are not range-taking. An example of a mechanical connector is shown below in Figure 4-8.

Figure 4-8: Mechanical Torque Shear Connector (© Tyco Electronics)

Having dealt with the physical connection of the actual conductors, the other joint functions need to be taken into account. The elimination of any air or voids from the joint, as well as stress control, are dealt with by stress relieving tape, or the Faraday cage principle [155]. With the former, layers of semi-conductive tape are wrapped around the ferrule and conductor interface in order to provide a smooth profile. With the Faraday cage principle, a conductive sleeve or accessory (either separate or integral to other parts of the joint) is installed over the interface. Care must be taken to ensure that the joint is dimensionally compatible and suitable and to this end it is advisable to purchase the joint as a system, rather than as discrete parts. The construction and stress distribution of a typical single-core polymeric joint are shown in Figure 4-9 below.

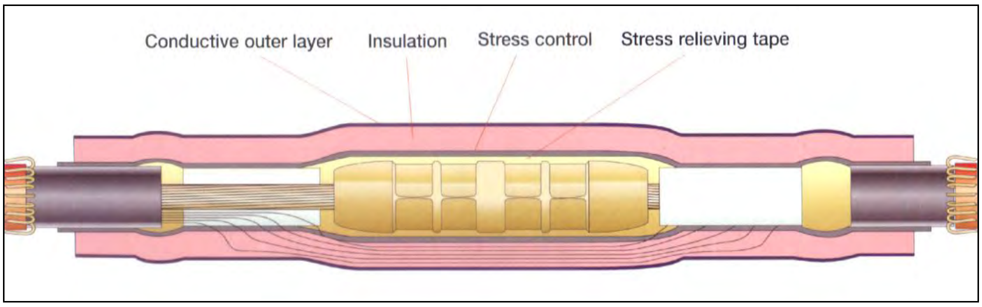

Figure 4-9: Joint with stress control [156]

Modern accessories may be cold applied (push on or cold shrink), heat shrink, or hybrid whereby more than one technology is employed [157]. In all cases they need to be designed to fulfil the functions required of them, with critical areas being sealing and mechanical strength.

For users considering the migration from a PILC to an XLPE cable platform, the accessory of most interest may be the transition joint. This is already employed by some large users who have experienced difficulties in terminating three-core PILC cable into modern compact cable termination enclosures. The solution has been to install a short length of single-core polymeric cable to facilitate easier termination within the switchgear, and then jointing these polymeric tails to the standard three-core PILC cable just outside the substation, or within the cable trench.

The use of transition joints is covered in SANS 10198-11 [158], and the recommended method is the resin-filled system. However, this document and part 10 date back to 1988 and are overdue for revision, as the reference to asbestos string [159], for instance, is out of step with the modern focus on health and safety.

4.6 ECONOMIC PARAMETERS

Most users will need to justify their decisions on an economic basis, or at least take the financial implications of their decisions into account. It is no different when determining the optimum cable platform to standardise on.

Since polymeric insulation in the form of XLPE can be operated at a higher temperature (90°C) than paper insulation (70°C), most rating sheets provided by manufacturers will give the maximum current which is at the maximum conductor temperature. However, there are several reasons why it may not be desirable to do so.

In order to compare the current ratings on a similar basis, installation conditions need to be standardised. All manufacturers provide rating factors for deviation from standard assumed installed conditions, and these relate to soil temperature, soil thermal resistivity, laying depth and cable grouping.

The standard installation conditions are assumed to be as per Table 4-1. The South African values are obtained from SANS 10198-4 [160]. The cable sizes chosen from the source documents are in line with the preferred cable sizes given in NRS 013, as mentioned at the beginning of Chapter 4.

Parameter	SA condition	UK condition
Depth of burial (m)	0.8	0.8
Soil thermal resistivity (Km/W)	1.2	1.2
Soil temperature (°C)	25	15
Air temperature (°C)	30	30

Table 4-1: Standard installation conditions

Eskom has chosen to limit the maximum temperature for both paper and XLPE cables to 70°C for a number of reasons, as given in the Planning Guideline [161], from where the ratings in Tables 4-2 and 4-3 are taken. These include prevention of soil drying resulting in increased soil thermal resistivity, reduction of conductor losses and provision for emergency operation.

Cable size (mm^2)	Construction	Maximum continuous current (A)		
		PILC (70°C)	XLPE (70°C)	XLPE (90°C)
95	3 core	240	249	294
185	3 core	340	352	415
300	3 core	440	447	527
630	1 core	696	636	750

Table 4-2: Current ratings of different 11 kV cables buried in ground

Cable size (mm^2)	Construction	Maximum continuous current (A)		
		PILC (70°C)	XLPE (70°C)	XLPE (90°C)
95	3 core	235	249	293
185	3 core	340	353	416
300	3 core	Not used at 22 kV		
630	1 core	690	636	750

Table 4-3: Current ratings of different 22 kV cables buried in ground

For the three-core cables there is a slight advantage to be gained by using XLPE instead of PILC when operating both at 70°C, while PILC has the advantage in the case of the single-core cables.

It is important to note that if cables that are buried directly in the ground and are operated at the maximum conductor temperature continuously (i.e. at a load factor of 100%), the heat generated by the cable is very likely to cause drying out of the surrounding soil. This drying out, also known as moisture migration, has a negative effect in that the soil thermal resistivity will increase. The process is explained in a paper by Millar and Lehtonen [162]. Once such moisture migration has occurred, the return of the soil to its previous state may take an extremely long time as the capillary bonds between water molecules in the soil have been broken. As the thermal resistivity of the soil rises, less heat is conducted away from the cable, causing a rise in temperature of the cable and its constituent components. Under such conditions thermal runaway and irreversible cable damage can occur. One method of overcoming the effect of moisture migration is to use thermally stabilised backfill. However, Millar and Lehtonen suggest that even under these conditions, it is safer to run cables well below their maximum operating temperature. In Helsinki (in Finland), conductor steady state temperatures are not allowed to exceed 65°C under normal conditions. This value ensures that the sheath temperature is kept below the critical temperature at which moisture migration commences, stated as being in the region of 55°C. De Wild gives a lower temperature of 45°C [163]. A major benefit of this philosophy is that a factor of safety is built in to take into account unfavourable route conditions which may be encountered. The disadvantage of course, from a purely financial perspective, is that maximum value or utilisation of the asset is not being realised although this argument can be countered to some extent by the extension of cable life as a direct result of this under-utilisation.

In practice, most loads are cyclical in nature (a typical utility load factor is in the region of 70%) and the surrounding soil conditions will be more favourable from a transient load curve resulting in a conductor peak temperature of 90°C than a steady state load resulting in the same maximum conductor temperature. Matti and Lehtonen found that the critical isotherm (55°C) is closer to the cable itself under transient conditions, whereas it extends further out and away from the surface of the cable under steady state conditions. Also, since the thermal resistivity is affected by the soil compaction (poor compaction results in an increase in soil thermal resistivity), it is important that the trench and backfill material are correctly compacted at the time of cable installation such that the thermal resistivity of the soil is unaffected by poor compaction.

In the Netherlands, which has a large installed base of PILC cables, only XLPE cables are now installed. In a paper presented at CIRED [164], the philosophy of Essent Netwerk B.V. (a Dutch utility) is explained with respect to maximum cable loading. Essent assumes that soil dehydration (with the resultant negative impact on the thermal properties of the soil) will occur when the cable sheath reaches a temperature of 45°C, and chooses cable ratings such that this temperature will not be exceeded. The distinction between static ratings in accordance with IEC 60287 [165] and dynamic ratings in accordance with IEC 60853 [166] is well understood by Essent and load profiles are taken into account for emergency operation. The utility takes advantage of the relatively long time constant of the cable, which results in the rise in temperature occurring some time after the load is increased. The paper concluded that "... it is possible to temporarily allow a higher current than the continuous rating without exceeding the maximum permissible cable temperature."

Interestingly, a similar philosophy is adopted by Eskom in South Africa, but with a different implementation. The Planning Guideline [167] makes use of emergency ratings in accordance with IEC 60287-1-1 [168] using the higher temperature of 90°C (as given in Tables 4-1 and 4-2 above), rather than in accordance with IEC 60853-2 [169]. This is not a true dynamic rating but rather a step change in the continuous rating, again using the thermal time constant of the cable. Eskom does not allow operation of the cable at the emergency rating for more than 24 hours in order to prevent drying out of the surrounding soil.

The Planning Guideline [170] also makes an argument for considering using larger conductor sizes, or not reducing them as a result of moving to XLPE. The benefits of this will be lower losses due to the larger conductor size, as well as catering for future load growth. The philosophy of economic loading limits is illustrated in Figure 4-6.

In SP Power Systems, one of the reasons for choosing the maximum conductor temperature of 70°C for XLPE and paper was that if the ability of XLPE to operate at a higher temperature was used to reduce the cross-sectional area of the (new) cable, the load causing the XLPE portion of the cable to operate at the higher temperature would transfer through joints by conduction and damage paper insulation in the older section of the circuit [171].

Temperature perhaps plays a more critical role than is generally realised. Haripersad [172] states (with reference to XLPE cables) that "... a 10°C increase in temperature from the normal 90°C operating temperature can reduce the cable service-life expectancy by about 50%."

When comparing the results from cable manufacturers' cable data sheets, it must be remembered that the maximum continuous (steady state) ratings are given. The ratings are therefore provided at a maximum conductor temperature of 70°C for PILC and 90°C for XLPE. The ratings given in Tables 4-4 and 4-5 below are extracted from cable data sheets provided by CBI Electric: African Cables. The three-core PILC construction chosen was SWA rather than DSTA to closer approximate the construction of the XLPE. In general, the SWA PILC cables have slightly higher ratings than the DSTA PILC cables, although the increase is marginal and only begins above cable sizes of 120 mm^2. AWA rather than CWA was chosen for the single-core construction as data sheets are not available for CWA, the option for which was only recently made available as a result of the revision of SANS 1339.

The comparatively lower symmetrical and earth fault ratings of the XLPE are partially as a result of the initial higher operating temperature of the XLPE cables (90°C as opposed to 70°C for the PILC cables).

Cable size	PILC (SWA)			XLPE (Type A - SWA)		
	In Ground (A)	Symmetrical (kA)	Earth Fault (kA)	In Ground (A)	Symmetrical (kA)	Earth Fault (kA)
95 mm^2	240	13.8	19.5	279	12.9	19.8
150 mm^2	305	21.5	26.6	350	20.0	27.2
185 mm^2	345	26.9	28.8	393	25.1	28.6
240 mm^2	395	35.3	32.2	450	32.9	30.9
300 mm^2	445	44.3	35.1	503	41.3	33.2

Table 4-4: Maximum ratings of three-core copper PILC and XLPE cables

Cable size	PILC (AWA)			XLPE (Type A – AWA)		
	In Ground (A)	Symmetrical (kA)	Earth Fault (kA)	In Ground (A)	Symmetrical (kA)	Earth Fault (kA)
95 mm^2	Not available in this size			297	12.9	10.3
150 mm^2	310	21.5	18.6	370	20.0	14.2
185 mm^2	350	26.9	19.7	412	25.1	15.0
240 mm^2	395	35.3	21.5	470	32.9	15.8
300 mm^2	425	44.3	28.1	520	41.3	17.1
630 mm^2	550	94.1	36.3	672	88.0	28.3

Table 4-5: Maximum ratings of single-core copper PILC and XLPE cables

Review of Tables 4-4 and 4-5 shows that purchasers may take advantage of the higher current ratings of the XLPE cables (in theory) to install a smaller cable. For instance, for single-core and three-core cables with copper conductors (and the situation is similar with aluminium conductors), a 150 mm^2 XLPE cable can replace a 185 mm^2 PILC cable, and a 185 mm^2 XLPE cable can replace a 240 mm^2 PILC cable. Also, a 300 mm^2 PILC cable can be replaced by 240 mm^2 XLPE cable. Doing this will result in a cost saving on the initial purchase price of the cable but at the expense of increased losses (and higher operating costs) as well as the risk of moisture migration as already discussed.

The situation is somewhat more complicated in Europe than South Africa since European and UK utilities have summer and winter loadings which take the differences in average seasonal temperatures into account. Nevertheless, using the CRATER software referred to in Chapter 3, most of the variables are user-defined and hence a standard load profile may be chosen to form the basis of a “like-for-like” comparison of different cable constructions. Importantly, installation conditions can also be defined to more closely approximate South African standard conditions rather than those based on the lower average ambient temperatures found in the UK.

CRATER uses cables based on BS requirements rather than SANS specifications, and there are slight differences in construction between the two. However, it serves as a useful basis for comparison if the evaluation parameters are adjusted, which was done in this case. A screenshot of the CRATER interface selection screen for the cable characteristics, operating conditions and grouping is shown in Figure 4-10 below. In this instance, cable grouping was not taken into account.

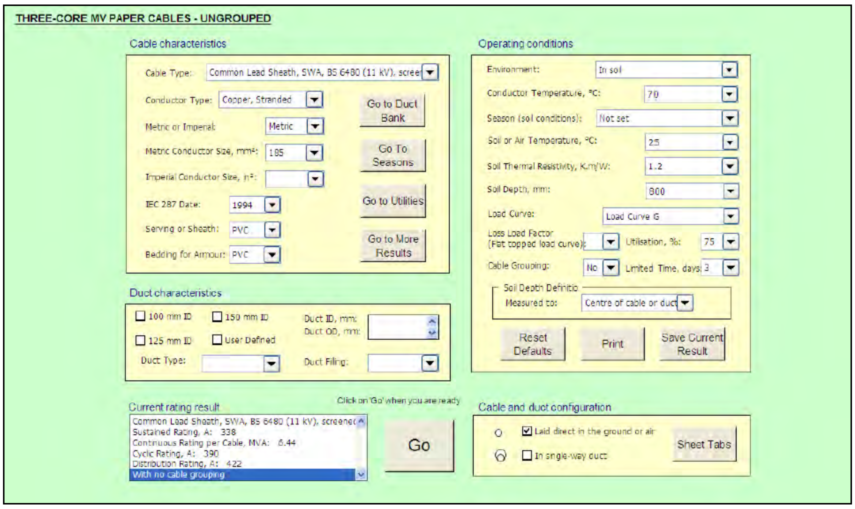

Figure 4-10: Ungrouped selection screen on CRATER

The sustained rating is the rating most commonly quoted by cable manufacturers, at full load. The cyclic rating is based on cable utilisation: to cover South African conditions with varying load factors this was chosen as 75%. The distribution rating is based on the selected load profile. Since load profiles vary enormously depending on the class of customer, and in many cases are mixed, the standard load profile was used (Load Curve G), as shown in Figure 4-11 overleaf. In any event, the actual profile is not as important as ensuring that the same profile is used in all calculations, so that the results may be directly compared.

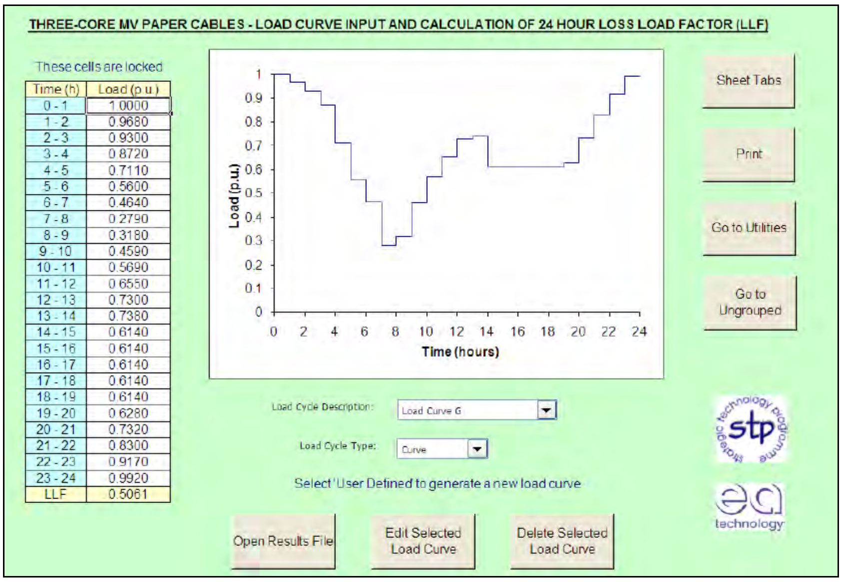

Figure 4-11: Load profile G selected for basis of comparison

CRATER also provides functionality that allows for derating as a result of cables being grouped together. There are numerous permutations that can be chosen to reflect real life scenarios but for the purposes of comparison, three cables spaced at 150 mm centres were chosen, as shown in Figure 4-12 and shown in Tables 4-6 to 4-9 as the "Grouped" rating.

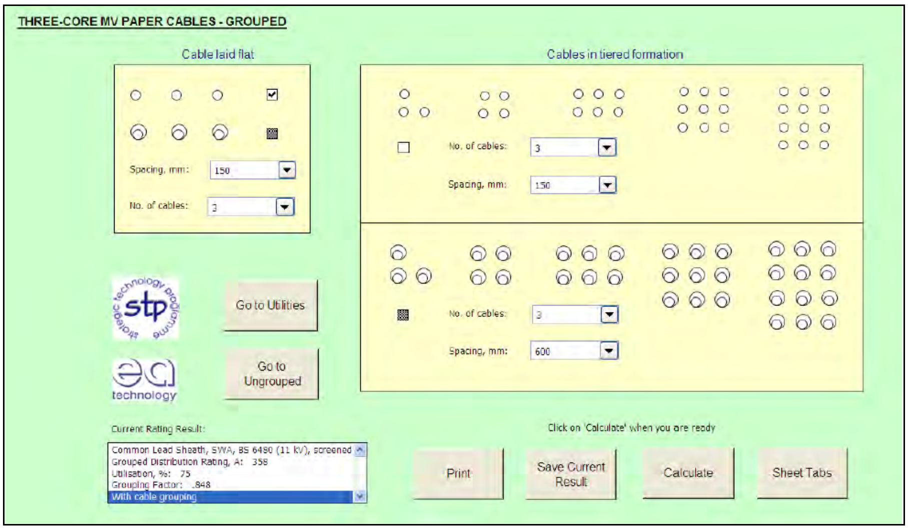

Figure 4-12: Cable grouping configuration

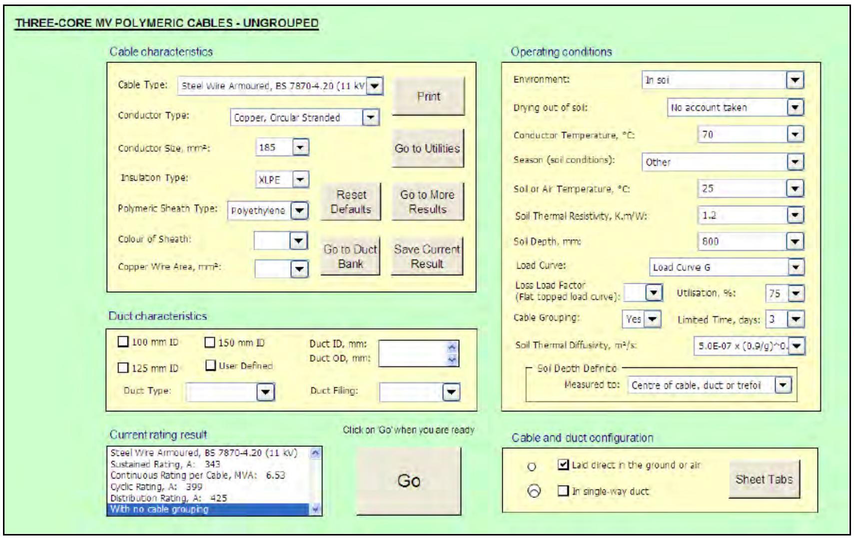

Figure 4-13: Three-core XLPE cable parameters

A wider range of cable sizes was chosen in order to cater for South African users (e.g. CTMM and eThekwini) who do not use the recommended sizes given in NRS 013. The ratings for three-core cables are shown in Table 4-6 (for cables with copper conductors) and Table 4-7 (for cables with aluminium conductors). The PILC cable chosen was of screened construction with SWA, and the XLPE cable chosen did not have a metallic sheath and was provided with SWA. As can be seen in Figure 4-13, the maximum conductor temperature for the XLPE cable was chosen as 70°C.

Size	**PILC**				**XLPE**			
(mm^2)	**Sustained (A)**	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**	**Sustained (A)**	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**
95	237	270	291	255	241	277	293	252
150	300	345	373	320	305	353	376	320
185	338	390	422	358	343	399	425	360
240	390	453	491	411	390	456	487	410
300	435	508	554	458	435	512	548	458

Table 4-6: CRATER current ratings for three-core copper cables

Size (mm²)	PILC				XLPE			
	Sustained (A)	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**	**Sustained (A)**	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**
95	184	210	226	198	188	215	228	196
150	234	269	290	249	238	276	293	250
185	265	305	330	280	269	313	333	250
240	306	356	386	323	309	361	385	324
300	344	402	437	362	347	408	436	365

Table 4-7: CRATER current ratings for three-core aluminium cables

Similar simulations were created for the single-core cables, except that the load factor was changed to 50% as the CRATER version for single-core paper cables (version 3) does not have the functionality of later versions (version 5) and can only be used with a utilisation of 50%. In order to make a meaningful comparison, the XLPE load factor for the single-core cables was chosen to be 50% as well. Both cable types were chosen as being solidly bonded, and laid in trefoil. The grouping configuration was the same as for the three-core simulations i.e. three bundles at 150 mm spacing.

The CRATER ratings for the single-core cables are shown in Table 4-8 (for cables with copper conductors) and Table 4-9 (for cables with aluminium conductors). The XLPE cable variation chosen in both cases was CWS. The maximum conductor temperature for the XLPE cable was again chosen as 70°C. In addition, the preferred (in terms of NRS 013) single-core cable size of 630 mm^2 was included.

Size (mm²)	PILC				XLPE			
	Sustained (A)	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**	**Sustained (A)**	**Cyclic (A)**	**Distribution (A)**	**Grouped (A)**
95	255	292	325	299	256	295	329	303
150	325	375	419	383	324	376	422	385
185	367	425	476	433	365	425	477	434
240	425	495	556	504	419	491	552	501
300	478	560	630	569	470	553	623	563
630	672	800	907	809	663	793	902	804

Table 4-8: CRATER current ratings for single-core copper cables

Size (mm²)	PILC				XLPE			
	Sustained (A)	Cyclic (A)	Distribution (A)	Grouped (A)	Sustained (A)	Cyclic (A)	Distribution (A)	Grouped (A)
95	198	227	252	232	199	230	256	236
150	253	292	326	298	253	294	329	301
185	286	332	371	338	286	334	374	341
240	333	388	435	395	330	387	435	394
300	376	441	496	448	372	437	493	445
630	548	651	738	658	547	653	743	663

Table 4-9: CRATER current ratings for single-core aluminium cables

Review of the figures in the tables above will reveal that in each case, the ratings for polymeric cables are slightly higher than for paper cables, when operated at the same temperature and under the same conditions.

In order to compare the actual losses in the various cables, further simulations were conducted. The cables were not grouped for the purposes of the simulation as the objective was to determine the relative losses for different operating temperatures. In order to model South African conditions, the installation parameters were set in accordance with Table 4-1. A utilisation of 50% was chosen across all models, with trefoil or triplex laying configuration.

The losses in Table 4-10 include conductor losses as well as screen, sheath and armour losses where applicable. SWA and screened construction was chosen for three-core cables and CWA with a cross-sectional area of 35 mm^2 for single-core cables. All cables were modelled with stranded copper conductors.

Cable size	Three-core (losses in W/m)			Single-core (losses in W/m)		
	PILC (70°C)	XLPE (70°C)	XLPE (90°C)	PILC (70°C)	XLPE (70°C)	XLPE (90°C)
95 mm^2	39.51	41.28	59.59	44.50	46.66	67.37
150 mm^2	41.51	43.53	62.81	46.89	48.92	70.62
185 mm^2	42.60	44.74	64.53	48.05	50.13	72.38
240 mm^2	44.16	46.29	66.73	49.76	51.50	74.33
300 mm^2	45.77	47.95	69.09	51.19	52.94	76.42
630 mm^2	Not available in three-core			55.87	58.53	84.48

Table 4-10: CRATER losses for copper cables at different operating temperatures

In all cases the XLPE cables have slightly higher losses than the PILC cables when operated at 70°C but this is offset by the slightly higher ratings of the XLPE cables at this temperature. With the single-core and three-core cables, losses are increased by approximately 44% when operating the cables at 90°C.

Furthermore, operating the XLPE cables at the higher temperature will result in a much higher sheath temperature: in the case of three-core cables the sheath temperature will exceed 70°C and for the single-core cables, the sheath temperature is in the region of 80°C. These temperatures increase the risk of moisture migration as already discussed. Fortunately these temperatures are only reached under peak steady-state conditions which are not found often in practice.

The actual construction of the cables chosen will depend to a large extent on the network conditions into which the cable will be installed. Both SP Power Systems and City Power chose three-core cables over single-core due to their high system earth fault levels. Economically, providing a single earth path to handle the fault current is cheaper than providing three separate paths as needs to be done in the case of single-core cables [173, 174].

The required earth fault levels will determine the construction for single- and three-core cables, as will the requirement for a metallic sheath. When choosing between CWS or AWA (for single-core), the user would do well to bear in mind the notes already made with respect to the latter's susceptibility to corrosion in the ground. Particularly in the case of corrosive or aggressive soils, users need to be aware of the expected life of the cable. The author had personal experience of this in Johannesburg. Historic practice was to lay 70mm^2 bare copper in the trench with all MV cables. This had a beneficial effect on overall system earth resistance as the copper wire was effectively a large distributed earth electrode. However, with the rising price of copper and the value of the metal in scrap terms, it was stolen as quickly as it could be laid. In order to try and avoid the problem of theft, yet retain the benefit of a distributed electrode, a decision was taken to lay galvanised stay wire in the ground with the cables. Since stay wire is characteristically difficult to handle and has almost no scrap value, it was not stolen. However, it was discovered than in some cases, in as little as two to three years, the stay wire corroded away due to the aggressive nature of the soil. The same was true for buried cables with aluminium wire armour where the cable outer sheath had been damaged.

Most purchasers of cable systems will be interested in the cost of buying the cable and related components. Eskom had already established in 2000 [175] that the cost of standardising on

XLPE would result in a overall saving of between 10 and 12% in comparison with remaining with PILC as a cable platform.

At the 2010 Doble conference, a paper presented by Papayya and Dhrochand [176] provided details on the experience of eThekwini Electricity with respect to cable costs. The figures given for the various cables showed that a saving of between 4.5 and 11% could be achieved by purchasing XLPE cable instead of PILC cable. Updated figures provided in 2011 [177] confirmed this and showed an even greater saving, with a general trend of increasing the savings achieved as the cable cross-sectional area increased. The overall prices were lower too but this is to be expected since the conductor construction is aluminium vs. the copper cables referred to in the 2010 paper.

The cost of accessories was taken into account by Papayya and Dhrochand and their findings are presented in Table 4-11 overleaf. The cost of the complete kits includes mechanical torque shear connectors.

Belted PILC Joint	**Price/kit (R)**	**XLPE Joint**	**Price/kit (R)**
95 mm^2 to 150 mm^2	1436	95 mm^2 to 150 mm^2	1418
185 mm^2 to 300 mm^2	1611	185 mm^2 to 300 mm^2	1644
Belted PILC Termination	**Price/kit (R)**	**XLPE Termination**	**Price/kit (R)**
95 mm^2 to 150 mm^2 for indoor switchgear	907	95 mm^2 to 150 mm^2 for indoor switchgear	1235
185 mm^2 to 300 mm^2 for indoor switchgear	1050	185 mm^2 to 300 mm^2 for indoor switchgear	1331
95 mm^2 to 150 mm^2 for outdoor equipment	1235	95 mm^2 to 150 mm^2 for outdoor equipment	770
185 mm^2 to 300 mm^2 for outdoor equipment	1331	185 mm^2 to 300 mm^2 for outdoor equipment	880
PILC to XLPE Transition Joint	**Price/kit (R)**		
185 mm^2 aluminium to 240 mm^2 aluminium	2181		

Table 4-11: Cost of cable accessories [178]

There is not much difference in the cost of the straight joints i.e. PILC to PILC and XLPE to XLPE. The PILC indoor terminations are cheaper, while the XLPE outdoor terminations are cheaper. It should be noted that the cost of the indoor XLPE terminations is for fully screened accessories, which is not the case for the paper terminations. The philosophy of eThekwini Electricity is to employ fully screened systems as they are believed to perform better under the environmental conditions encountered in eThekwini Electricity's area of supply [179]. Using the figures provided, the savings achieved by the purchase of just 14 metres of 95 mm^2 XLPE cable instead of PILC cable, will offset the higher cost of the indoor XLPE termination kit.

City Power provided information [180] that the cost difference between XLPE and PILC was between 10 and 15% in favour of XLPE.

Tshwane Electricity indicated [181] that they had no intention of changing from their standard belted PILC cable, and had not investigated the potential savings to be achieved, due to a perceived lack of incentive to do so.

Some utilities have specified a different colour sheath to differentiate between MV and LV cables. In the UK, most utilities specify red sheaths for MV cables. This is only cost-effective if all users (or a majority) specify it. In the 1980s and 1990s, the then Johannesburg Electricity Department had an orange sheath for MV cables to help personnel distinguish them from LV cables. At the beginning of the 21st century however, it was found that City Power was paying a premium for the non-standard sheath and the practice was abandoned, and the standard black sheath reinstated on new cables.

The practice of using coloured sheaths is a double-edged sword from a safety perspective. While there is no doubt that a jointer coming across a red (or orange) cable will understand that it is a medium voltage circuit, there may be a risk that personnel will assume that all black cables are LV, and this is definitely not the case. In the UK, DSTA was traditionally used for LV cables and SWA for MV cables [182] to help jointers identify the cable they were working on. Naturally, this would not be the case in South Africa and hence jointers and other personnel need to be trained to identify cables without reference to the colour of the sheath alone.

4.7 TRAINING AND CERTIFICATION

As far back as 1946, the skill of jointers was a topic of interest. The Dussek publication "Electrical Knowledge as an Aid to Craftsmanship in Cable Jointing" [183] states that "Much of that assurance is in the hands of the cable jointer. Careless work may not show failure of Supply immediately, but may continue to weaken the functioning (working) of the cable joint or apparatus, until, finally, after several months, or even years, the destructive action of the faulty work results in failure of the Supply."

The language may be somewhat archaic, but the principles remain valid. The Dussek authors believed that provision of electrical theory to jointers would ultimately result in improved quality in their workmanship. The book provided details on electrical breakdown and its causes, and some basic high voltage theory.

A 2002 EA Technology report [184] found that the number of cables that had been installed in the last decade of the 20th century among UK DNOs had a "higher number of joint faults than would be expected from the amount of cable installed during those ten years...", implying that "...joints installed in the 1990s may be particularly unreliable." The impetus for the project had been DNO concerns that joint-related faults in particular, and cable-related faults in general, had increased following privatisation and the resultant increase in use of contractors as opposed to in-house jointing personnel.

A 1998 report by EA Technology [185] investigated failures of dry-type terminations, and highlighted related network risk and safety concerns. Interestingly, the report concluded that several DNOs were of the opinion that "... the effects observed are related to the use of 'dry' terminations on paper cables."

The experience of eThekwini Electricity has been that many failures in the cable network are directly related to poor workmanship [186]. Failures include incorrect sealing leading to moisture ingress, incorrect application of stress control and carelessness during cable preparation. Notably, reflecting the earlier concerns of UK DNOs, poor supervision of contractors is given as a cause of poor workmanship (through the use of general workers rather than more expensive skilled labour performing jointing tasks).

City Power states that the only failures it has experienced on new XLPE have been related to workmanship resulting in failed joints and terminations [187]. Furthermore, the number of failures on PILC accessories is greater than on XLPE. The primary cause of PILC failure is moisture ingress, followed by poor workmanship. XLPE technology is preferred by new jointers, as it is cleaner and easier to work with.

Due to the increasing number of failures relating to workmanship, in 2005 City Power decided to introduce an accredited jointer training programme. The idea was that all personnel (whether internal or contractor) performing cable work on City Power's cable networks would require to be trained and accredited by the accessory manufacturers. This removed the burden of training from City Power and ensured that the onus of ensuring current training was placed on the service provider. At the time, the approved accessory providers were Raychem and TANK. Each supplier was tasked with developing a training programme which would be evaluated and approved by City Power. Eskom expressed interest in the scheme and were invited to attend the evaluation and approval sessions.

The two suppliers each produced a course which included electrical theory (as envisaged by Dussek in 1946) and practical sessions. The courses were evaluated and approved. Each jointer was required to be individually evaluated for joints and terminations, where after they would be issued a certificate and a photo card. In terms of the City Power procedures, any authorised person could stop at any site where cable work was being carried out, and demand to see the photo card of the person carrying out the work. Production of the certificate was not enough as this could be misused, by means of one certificate being used to cover several (non-trained) workers. Only the person who was authorised would be allowed to carry out the work (and the photo card would prove that the person doing the work was actually accredited) and non-production of the photo card would lead to work being stopped immediately on the site.

The scheme was initially unpopular (for obvious reasons) but has been successful in reducing the rate of failure due to poor workmanship, as per the feedback from City Power. It is important to note that the initial accreditation is only valid for a certain period i.e. two or three years. This is to ensure that (as with courses such as Emergency First Aid) knowledge remains current and any changes in technology are communicated to the jointers. Feedback received from the accredited suppliers indicated that many personnel arrived at the courses with the attitude that they could not possibly be taught anything as they had been jointing for many years; however after the course they were invariably pleased with the new knowledge they had acquired and in many cases had identified things they had been doing incorrectly for many years.

The Eskom experience with respect to accessory failures is that the failure rates of the two technologies are evenly matched [188]. However, anecdotal evidence suggested a slightly higher incidence with paper cables as a result of over-bending causing paper damage, damage near the crutch and moisture ingress. Most XLPE failures were related to inadequate sealing and incorrect core screen removal.

Within the eThekwini Electricity of supply, mechanical damage as a result of excavation is responsible for 80% of cable failures [189], leading them to consider protection against excavation in the form of concrete slabs for MV circuits. This is in line with the findings of Eskom [190]. It would make sense therefore to ensure that cables are provided with adequate mechanical protection in order to increase the reliability and performance of cable circuits, irrespective of choice of technology.

Reasons to operate XLPE cables at 70°C have already been discussed; however users who wish to maximise the potential advantages to be gained with respect to ratings, and operate the cables at 90°C, need to realise that they are reducing the contingency that otherwise might be available, as well as increasing the circuit losses. For the cables to operate satisfactorily at the higher temperature, it is absolutely imperative to ensure that the backfill material surrounding the cable has suitable characteristics for the intended operation. It may well be necessary to import backfill material for his purpose. Although not generally done in practice, it should also be ensured that the surrounding soil has good heat transfer properties as it has a large effect on the ampacity of the cables in the trench. Notwithstanding this, the thermal resistance of the backfill material surrounding the cables still has the greatest influence on cable ampacity [191].

SANS 10198-5 [192] provides further details of soil types, thermal resistivities and suitability (or otherwise) for use in bedding and backfilling applications. Backfill and bedding should have a fine grain, low porosity and be thermally conductive. The relationship of thermal resistivity to the moisture content of soil is inversely proportional (i.e. as the moisture content increases, the thermal resistivity decreases).

Soil types that are suitable for bedding include loam and sand/clay mixtures. The typical thermal resistivities of these soils range from 0.5 to 1.5 Km/W.

Soil types suitable for backfill are clay, loam, sand/clay, and ouklip (if mixed with loam or clay). The typical thermal resistivities of these soils range from 0.5 to 2.0 Km/W.

Soil types that are unsuitable in either application include chalk and peat, which have very high thermal resistivities (up to 4 Km/W) when dried out, and mine sand, which is corrosive. Made-up soil may be suitable, but if any doubt at all exists it should not be used. Naturally, the use of any material which could damage the cable is also unsuitable.

When the need for a thermally stable backfill or bedding material arises, SANS 10198-5 gives two suitable options [193], namely:

a) Cement-bound sand, using mixed sand and cement in a volume ratio of 14:1; or
b) a suitable sand/gravel mix, mixed in a volume ratio of 1:1. The sand must be man-made (quarried sand or crushed rock) and the gravel up to 10 mm in diameter.

Both options result in material with a thermal resistivity of 1.2 to 1.5 Km/W when fully dried out. To ensure effective heat dissipation, the bedding must be at least 150 mm thick, and the stabilised backfill surrounding the cables must cover them for at least another 150 mm. Although effective, the cost of such a scheme is high and the need for such a backfill should be established and weighed against other factors, such as the nature of the load, the possibility of installing a larger cable and running it at a lower load factor, etc.

CHAPTER 5: RECOMMENDATIONS AND CONCLUSION

The research question introduced in Chapter 1 was "How can South African electric utilities effectively and efficiently manage the migration and integration of their MV cable system technology from PILC to XLPE?"

The findings in Chapter 4 demonstrate that utilities contemplating the change in technology need to first establish several key parameters identified in this research in terms of their MV cable operating philosophy. If these parameters are identified and actively managed, in accordance with the recommendations made in this dissertation, migration and integration of their MV cable system technology is entirely feasible from both a technical and business perspective.

5.1 OPERATING TEMPERATURE

It is recommended that utilities standardise on a standard operating temperature of 70°C for the reasons discussed in Chapter 4. In most cases, current ratings will be comparable with the ratings of PILC cables operated at the same temperature (although for three core XLPE cables, the current ratings are slightly higher at the same temperature) and running the XLPE cables below their maximum temperature will result in reduced losses and provide a margin of contingency in the case of system emergencies.

In addition, the lower temperature will extend the service life of the XLPE cable (the relationship between temperature and service life was demonstrated by Haripersad [194]), as well as ensuring that the higher cable temperature does not damage paper insulation (by conduction) in mixed dielectric circuits.

Importantly, operating medium voltage cables at the lower temperature will reduce the likelihood of soil drying and thermal runaway as a result of the increase in soil thermal resistivity. During the CRATER simulations (discussed in Chapter 4), operating the three-core PILC and XLPE cables at a conductor temperature of 70°C resulted in a cable sheath temperature in the region of 57°C in both cases. This is slightly above the temperature of 55°C recommended in SANS 10198-5 [195].

Notwithstanding the recommendation above, in the case of users determined to utilise the maximum operating temperature of 90°C, it is absolutely critical that the recommendations of

SANS 10198-5 [196] with respect to types of soil for cable bedding and backfill are adhered to, in order to prevent thermal runaway and irreversible damage to the cable circuits. This is even more critical when more than one circuit is affected.

5.2 COPPER VS ALUMINIUM

Eskom and City Power have standardised on copper conductors for the reasons given in Chapter 4, mainly due to easier handling due to smaller physical cable size (as a result of copper's superior conductivity).

CTMM and eThekwini have chosen aluminium conductors, due to historical reasons and the lower cost of aluminium. Many UK DNOs have chosen aluminium as the continued high price of copper is not economically beneficial for cable construction. Having said this, most UK users do have copper options available for when circuit loading is an issue, and the higher conductor ratings of copper are required.

As discussed in Chapter 4, standardising on either construction will produce an economic benefit as a result of reduced stockholding, although the use of mechanical connectors with modern accessories negates this benefit somewhat since these accessories are suitable for use with a variety of cable constructions.

The choice of conductor material will very much be down to the individual user. Overall however, the use of aluminium conductor is currently more economically viable than copper, and has been for some time. It is unlikely that this will change in the near future.

5.3 SINGLE-CORE VS. THREE-CORE

All XLPE cables are screened by design and the advantages of screened designs over unscreened designs have already been noted in Chapter 1. At larger cable sizes, single-core construction is preferred by NRS 013 [197] and the compact nature of most modern switchgear precludes the use of large three-core cables.

The South African preference to date has been to use three-core cables for distribution. This has mainly been as a result of the traditional construction of paper (belted) cables. XLPE may be manufactured in single-core or three-core configuration, and the most popular design in the UK is called triplex. This arrangement uses three single cores laid up together (similar to MV ABC) and has several advantages. It can be laid in a single operation (as with three-core cable), it requires no special earthing and bonding arrangements that are usually required to be taken into account with single-core cables, and it is easy to joint and terminate into compact enclosures. It therefore has the advantages of both single- and three-core construction.

South African users may have concerns about the triplex design's perceived lack of armour, as understood in the traditional sense. However, this construction is widely used in the UK (with an onerous regulatory regime with respect to health and safety) without problems, and as discussed in Chapter 4 burial at the correct depth can be regarded as adequate protection against damage.

With modern cable connected equipment in South Africa being increasingly sourced from Europe (and designed for European conditions where single-core cable systems are mainly employed) it is recommended that users give serious consideration to the triplex design. In their letter to City Power [198], CBI Electric: African Cables offered this design as the first steps towards evaluating the use of XLPE within City Power. Eskom has indicated [199] that they are giving consideration to the use of single-core XLPE as a result of switchgear design and the fact that water blocking of the interstices between cores is difficult in a three-core cable (unless a metallic sheath is employed). EThekwini Electricity has already used single-core cables terminated into compact switchgear and then jointed the tails onto the three-core cables outside the substation. The use of triplex will overcome these difficulties.

In some cases, users with high earth fault levels may choose (for economic considerations) a three-core design. The cost of providing an earth path of sufficient cross-sectional area on each core in a single-core design may prove prohibitive. This should only be a consideration in networks that are effectively earthed. In such networks, the overall cost of a three-core design will be lower. City Power and SP Power Systems have chosen three-core designs for this reason.

5.4 ARMOUR

For single-core designs, the choice is between AWA and CWA. The latter is preferred as it is far more resistant to corrosion than aluminium, as discussed in Chapter 1. SANS 1339 [200] allows the use of CWA (or CWS depending on the view of the user, as some users do not recognise the function of the copper wires as armouring, but rather as screening) and Eskom is considering the use of copper wire rather than aluminium for their single-core design [201].

For three-core designs, most South African users have historically preferred DSTA. It is recommended to use SWA on three-core cables as it has lower electrical resistance, higher earth fault rating and improved mechanical strength compared to DSTA.

5.5 WATER BLOCKING

It is highly recommended to incorporate water blocking into any XLPE cable design. XLPE is susceptible to the formation of trees within the insulation, as discussed in Chapter 4, and the early experience of the poor performance history of XLPE was found to be related to water trees.

Measures to improve the reliability of XLPE cable designs include the provision of a polyethylene (PE) outer sheath, insistence on the use of TR-XLPE in the manufacture of the cable, and the provision of water swellable tapes or powders to provide radial and longitudinal water blocking, as discussed in more detail in Chapter 4. Interestingly, this is almost identical to the features noted by Eskom as being necessary to provide resilience to water tree related failures [202]. There does not appear to be merit in providing coloured sheaths on XLPE cables.

5.6 METALLIC SHEATH

The use of a metallic sheath is not recommended except for where local water tables are very high, and even then the use of metallic sheaths should be evaluated to determine whether they are really necessary. Health and safety concerns with respect to lead are increasing, and there has been speculation that it may be banned in Europe [203]. The addition of a metallic sheath increases cable cost and makes handling more difficult.

5.7 USE OF ACCESSORIES

The benefits of the use of modern accessories with mechanical torque shear connectors have been documented in detail in Chapter 4. Over the past decade, several large users (City Power, eThekwini and Eskom) have standardised on their use at medium voltage, and in some cases also at low voltage.

The use of mechanical torque shear connectors will reduce stock holding, and eliminates the need for special hydraulic tools and dies, as well as a large range of type specific lugs and ferrules. The mechanical connectors are simple to install and are largely independent of the skill of the installer.

Modern joints and terminations are designed to provide a method to join cables of different constructions and the use of centre blocked connectors in the joints will prevent migration of water and/or cable compounds.

It is recommended that regardless of the technology employed, that jointing personnel attend accredited training in accordance with the guidance given at the end of Chapter 4. This will ensure that cable failures related to workmanship are reduced, if not eliminated.

5.8 CABLE DAMAGE

Most cable damage in South Africa is caused by mechanical means, rather than electrical failure, and cable failures contribute the most failures in terms of the total number of faults occurring on the distribution network [204]. In comparison, a study conducted by Dutch utility REMU (now Eneco) [205] in 2001, found that just 17% of network faults were related to excavation, with 59% related to cable failure (made up of cable, joint and termination failure).

With the costs of unplanned outages (in terms of repair as well as unserved energy), regulatory penalties and the loss of customer goodwill [206], it would make economic sense for utilities to evaluate methods of preventing unnecessary damage to their cable circuits (perhaps by mechanical means such as the installation of concrete slabs), especially in areas of high excavation activity [207].

5.9 CABLE CUTTING OPERATION

It is recommended that users consider the implementation of a cable cutting operation, as contemplated in NRS 013 [208]. The benefits of this are having the manufacturer supply a large drum with long lengths of cable (up to 5,000 m) and cut it to length at the user's cable yard. The cable can be cut to the exact length required, and placed onto a smaller (returnable) steel drum. The use of steel drums ensures that they will be returned (rather than used for firewood) and also eliminates the need to use and dispose of treated wood. Furthermore, the use of corrosion resistant drums is advisable where cables are to be stored for long periods of time, especially where indoor storage facilities are unavailable or not economically viable.

Since the cable is the exact length required (snaking of cables must be taken into account during the measurement of the length required), wastage is eliminated and more importantly, the number of joints required can be reduced. Since joint failures contribute to overall failures and joints are electrically weaker and less reliable than the cable, elimination or reduction in the number of joints will improve the reliability of the cable circuit [209].

5.10 TEST REGIME

Migration from PILC to XLPE will involve the purchase of additional test equipment, and the training of personnel on the new equipment. This is a one-off cost but a very necessary one, as the use of test equipment traditionally employed for paper cables is not recommended for use on XLPE cables, due to the possibility of damage to the XLPE insulation when using DC test equipment, as discussed in Chapter 4. The ongoing enhanced reliability of the polymeric cables will outweigh the initial purchase cost of the new equipment.

5.11 ECONOMICS

In all cases, the cost of XLPE cable, on a like-for-like basis, is between 5 and 15% cheaper than the equivalent PILC cable. Operating the XLPE cable at 70°C and not reducing the cable size to take advantage of the ability of the XLPE cable to operate at a higher temperature will result in similar losses to the PILC cable, with similar operating costs.

Security of supply is becoming a concern with very few global sources of supply of paper cable remaining. Lack of investment in plant is resulting in concerns over reliability and possible delays in the supply chain in the event of a breakdown. The cost associated with this risk needs to be factored in to any decisions by users to remain with paper cable technology.

Globally, modern XLPE is proving its reliability and in South Africa, eThekwini has been installing MV ABC (with XLPE insulation) since 1987, with good service history [210].

Replacement of PILC with XLPE will produce an economic benefit in that a modern technology can be utilised, designed for use as a system with modern switchgear and cable accessories, for a lower capital cost and with similar operating costs. As more users migrate to the newer technology, costs will decrease as a result of increasing market competition, allowing global suppliers to compete in an open market place.

5.12 CONCLUSION

Implementation of the recommendations above will result in a robust system, with better performance and at a lower overall cost. Therefore migration from PILC to XLPE as the cable technology of choice for medium voltage underground distribution networks is a sound technical and business decision for electricity utilities in terms of integration with modern cable-connected equipment, investment expenditure (both capital and operational), network performance and reliability.

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ANNEX A: MEDIUM VOLTAGE CABLE QUESTIONNAIRE

Thank you for taking the time to read and complete this questionnaire. The aim of this questionnaire is to establish trends with respect to usage of different medium voltage cable technologies in South Africa. In particular, this questionnaire aims to establish the attitude (and progress, if applicable) towards replacement of PILC technology by polymeric (XLPE) technology as the technology of choice among users of MV cable. I am researching this topic for my dissertation. Your assistance is much appreciated.

Further information on this subject may be obtained from Morgan Ryan (Asset Engineer) on +44 7875 110 012 or e-mail morgan.ryan@ukpowernetworks.co.uk. If you wish any of this information to be confidential please highlight it in red or write the word "CONFIDENTIAL" next to your answer.

Your name:

Your organisation:

SECTION A: GENERAL

1. What is your current preferred medium voltage cable technology?

   Paper based (please go to Question 2) ☐

   Polymeric based (please go to Question 5) ☐

SECTION B: PAPER USERS

2. Do you specify belted or screened designs?

   Belted ☐

   Screened ☐

3. Are you considering moving to polymeric? Whether yes or no, please provide a reason(s).

   Yes ☐

   No ☐

   Reason(s):

4. Do you have any statistics as to the MV circuit performance of your PILC networks e.g. faults/circuit km/year? If so, please include.

SECTION C: POLYMERIC USERS

5. If you currently use polymeric technology in your cable systems, do you specify three core or single core, or both?

   Single core ☐

   Three core ☐

   Both ☐

6. What motivated your decision to choose the construction(s) in Question 5 above?

7. Do you have any statistics as to the MV circuit performance of XLPE e.g. faults/circuit km/year? If so, please include.

SECTION D: PAPER AND POLYMERIC USERS

8. What is the current cost difference to you as a user between equivalent PILC and XLPE cables (cable cost only)? If you do not wish to give actual values, please provide a percentage difference with an indication of which technology is cheaper for you?

9. Do you have any information on accessory faults i.e. do you experience more faults on paper joints and terminations, or polymeric joints and terminations? If so, please include.

10. Do you have any statistics as to the MV circuit performance of XLPE vs. PILC e.g. faults/circuit km/year? If so, please include.

11. Have you had any feedback from the field regarding installation issues of XLPE compared with PILC?

12. Is there any other information of interest you may wish to include? (If the space is insufficient or the file is large, please attach separately).