XLPE cable technical review

1.1 Recommendation

We recommend that proactive replacement of 1st generation XLPE cables be done as part of the deployment of the REFCL program.

Based on a review of the cable failures at Woodend (**WND**) zone substation, the cause was linked to the presence of water trees within the cable with premature failure due to water tree growth as a result of transient and sustained over voltages applied through the operation of the REFCL.

The Marxsen report identified XLPE cables as a category of asset that may fail depending on the date of manufacture of the cable.

Replacement of all first generation cables (i.e. those manufactured prior to 1989) will deliver the best reduction in risk. Newer cables use current standard cables and work practices that have produced a reliable performance over the last 10 years, as demonstrated by the performance of the cables at the Gisborne (**GSB**) zone substation that did not fail with the operation of the REFCL.

1.2 Background

This section describes XLPE cable and discusses the changes in their production over time.

1.2.1 Description of XLPE cable

XLPE is an acronym for cross linked polyethylene. XLPE is a thermosetting polymer meaning that the material (polyethylene (PE)) is cured under heat and in that process forms bonds in all directions forming a three dimensional matrix.

Within this XLPE matrix there is space between the individual molecules. Contaminants introduced at the initial manufacture or during the cable service life may infiltrate the XLPE matrix and degrade the overall insulation performance.

1.2.2 Changes in production of XLPE

HV underground cables were made of paper lead prior to the introduction of XLPE high voltage (**HV**) underground cable in the mid-1970s.

Due to advantages in cable installation and especially jointing, use of XLPE cables became widespread after introduction.

The earliest manufactured XLPE cable insulation worldwide used steam to apply heat to cure the XLPE. This process introduced moisture and other contaminants into the insulation resulting in water trees and premature failures.

The local experience with this cable has been much better than that in most other countries. For example, in North America much of the HV Underground Residential Distribution (**URD**) cable was replaced after 8-15 years of service life, as it was poorly manufactured single core unsheathed cable. The investigation into the cause of these failures uncovered of the phenomenon of water trees in the cable XLPE insulation.

The double sheathed cable construction employed by the State Electricity Commission of Victoria (**SECV**) together with the better local manufacture avoided most of the premature failure problems experienced overseas. However, the local experience is that these 1st generation cables have higher failure rates than later cables of different manufacturing types. Many of the 1st generation cables have already been replaced due to performance issues related to the XLPE insulation.

Direct Current (**DC**) testing previously employed to test paper lead cables was found to be a contributing factor in some early XLPE cable failures. As a result, Very Low Frequency (**VLF**) testing was adopted by the SECV to replace DC testing and it also better replicated the capacitive stress grading in the cable insulation of an AC system.

Steam curing of XLPE used in the manufacturing of cables was progressively replaced by other manufacturing processes (generally dry nitrogen curing) over the years up to 1998. In Victoria, the largest local manufacturer (Olex) converted their manufacturing process a few years earlier however other manufacturers that supplied HV cables into the Victorian market were completely converted to nitrogen curing by the end of 1998.

1.3 Technical issues

This section discusses the technical issues that arise in relation to XLPE cables, namely water trees, water ingress and insulation defects.

1.3.1 Water trees

XLPE dielectric has a relatively large molecule size and under high electric stress and in the presence of water, molecules of water are induced into the dielectric in the gaps between the larger XLPE molecules creating a water-filled vent. The vent will continue to grow at a rate largely dependent on the degree of electric stress and the availability of water.

In most “wet” medium voltage cable, trees are likely to number in the millions. Only a small number of these trees will threaten the operation of the cable with the remainder remaining benign, even after 35 years in service conditioning, because of their extremely slow rate of growth. Those that will become a threat are those that grow in a wet environment at locations of increased electric stress. The ionic status of the water is also believed to affect the rate of water tree development.

Water trees also grow by the application of electric stress (voltage) across the cable insulation. As REFCL operation results in voltages applied across cable insulation greater than normal system voltage, any pre-existing water trees will grow at a faster rate than for normal system operation. REFCL operation will age these cables at an elevated rate.

1.3.2 Water Ingress

Water can be introduced into a cable by:

- poor sealing of the cable ends or at joints during installation
- third party damage breaching the sheath
- the cable sheath being breached in an earlier cable fault; or
- permeation of water molecules through the plastic sheathing.

The cable construction has no water-blocking measures that would stop the water travelling along the cable, including the conductor strands, due to gravitational forces. This will generally result in water congregating in the low points along a cable route. Technology now enables water to be blocked at the point of entry into the conductor strands of the cable by use of “swell-able” powders but the water blocking of a 3 core cable construction to stop the movement of water along the cable interstices remains impractical.

Water can also be blocked from entry to the cable insulation by a metallic barrier. Ergon Energy adopted a sealed longitudinal aluminium tape (**LAT**) enclosing each phase core for application in a tropical climate.

The permeation of water vapour through the sheath/s is a two way street and driven by partial pressures. The cables in question have a HDPE outer sheath which has a low permeability to the ingress of water vapour (used as water pipe). Nevertheless these cables have been in service for 35 years and the extent to which this has contributed to the water in the cables is uncertain and also dependent on other factors including the load cycling experienced by a cables.

The presence of free water inside the cable sheath or along the conductor provides a source of water to be driven into the XLPE lattice structure by applied voltage stresses. If water is not present in the cable then this process cannot progress. For this reason wet cables are at greater risk of premature failure. First generation XLPE cables did not have water blocking to prevent the migration of free water or additives to the XLPE to make it less permeable to water. Later formulations of XLPE (introduced in the late 1990s) were termed “tree retardant” meaning the XLPE was chemically altered to resist the formation and growth of water trees and associated water induced defects.

First generation XLPE cables were not “tree retardant” and hence have a greater risk of forming new and growing existing water trees from the presence of free water within the cable.

1.3.3 Insulation defects

Defects in the cable insulation are a reflection of the quality of manufacture of the time. When XLPE was an emerging cable technology, the degree of cleanliness in the handling and storage of the dielectric material together with the precise control required over all facets of the manufacturing process were not fully understood nor appreciated. This resulted in:

- irregularities and discontinuities on the surfaces of the extruded semi-conductive insulation and conductor screen
- foreign inclusions and voids in the dielectric
- insulation thickness defects due to XLPE extrusion issues

All of the above give rise to points of heightened electric stress in the cable insulation.

Significant advances have been made over time in the manufacturing process to mitigate these risks as they were identified. These included:

- gas curing replacing steam curing
- vertical extrusion replacing inclined plane
- the sophistication of controls in the extrusion heads.

Defects in the cable insulation can also result from damage caused during the installation of the cable.

Defects as above which were prevalent in the first generation XLPE cables resulted in areas of the insulation with higher electrical stress. Those localised areas of higher electrical stress lead to accelerated ageing of the insulation and increased risk of failure.

1.4 Failures of XLPE cable

Failures of XLPE cable occurred at the Woodend (**WND**) zone substation during commissioning of the REFCLs. However, no failures occurred at the Gisborne zone substation. The failure and relevant testing is discussed below.

1.4.1 Gisborne zone substation

No failures were experienced at Gisborne zone substation following the hardening and commissioning tests being carried.

The cables at Gisborne have been in service less than 10 years and water trees are unlikely to have grown to a size that would cause an electrical discharge in the cable insulation with operations of the REFCL, regardless of whether the cables sheaths have been breached and water has entered the cable interstices.

1.4.2 Woodend cable failures

Three feeder exit cables failed following the hardening test and commissioning tests and two of these suffered further failures following repair and return to service.

The cables had been in service for 34 years and test results show that the sheath integrity of all the failed cables had been breached, possibly since the time of installation. Given the period of manufacture and in the presence of water, it is likely that water trees of a significant size had developed.

These cables were all first generation type without water blocking or tree retardant formulation of the XLPE.

The installation of REFCL may impact on cables seriously compromised by water trees. This has been borne out in the different outcomes experienced at Gisborne zone substation and Woodend zone substation with the installation of a REFCL system.

1.4.3 Marxsen report

A report prepared by Dr Tony Marxsen for Energy Safe Victoria identified the high risk of cable asset failures in its assessment of factors that may create potential safety risks when high voltage (**HV**) customer sites are supplied by Rapid Earth Fault Current Limiter (**REFCL**) protected networks.

The report reviewed cable assets at twelve customer sites. Based on the review, the report listed the age profile of the XLPE cable and the associated level of cable failure risk. It identified that XLPE cable installed before 1980 had a high risk of failure and the default action should be to replace the cable. Furthermore, it identified that cables manufactured between 1980 and 2000 should be tested and those that fail should be replaced.

Figure 1Marxsen report estimated failure risk of customer XLPE cable assets and appropriate mitigation action

Number of cables	Total length	Manufacture	Risk	Default action
34	5.3 kilometres	Post 2000	Low	Nil
46	6.7 kilometres	1990s	Low[18]	Test
24	7.0 kilometres	1987	Medium	Test
2	30 metres	Pre-1980	High	Replace

Source: Marxsen Consulting Pty Ltd, Customer Assets Directly Connected to REFCL networks: a preliminary risk survey, 20 June 2017, p. 16.

The report referred to studies in Europe and North America. It stated that the customer owned XLPE cable in Victoria's REFCL protected networks should suffer one failure every 4.2 years. North American data would suggest one failure every six months. The report then noted that given the cables reviewed in the report had all been in service for a long period in non-REFCL networks, the North American figures may be more relevant. That is, high failure rates should be expected.

1.4.4 Tests conducted

Powercor has historically carried out testing on the 22kV feeder exit cables. The following tests have been performed:

- sheath integrity
- polarisation index
- very low frequency (**VLF**) withstand at 23kV for 15 minutes

The results of the tests are discussed below, together with assessments following the cable failure.

There are a range of tests that can be conducted on XLPE cables, however there is no test that will pinpoint the location of a water tree of dangerous size. This is further discussed in Appendix A. It is noted that a review of the testing program in 2016 identified that there was no correlation between test results and the incidences of cable failure, and as such no future testing is planned.

Sheath integrity test

Sheath integrity testing will be one measure of the water tightness of a cable sheaths but this will not show up water introduced by bad practice during installation or during manufacture.

The results confirmed that the sheaths on WND13, WND14 and WND23 as well as WND12 had been breached and water had access to the interstices of the cables. This is consistent with the evidence of water found in the failed cables during the investigation.

The results also show that the sheaths on WND12 had been breached and the cable is at risk of having water in the cable interstices and consequently the further risks associated with water.

The integrity of the sheaths on the remaining four feeders appeared to be intact and should only be exposed to water resulting from permeation through the plastic sheaths.

Polarisation index

When a DC voltage is applied to an open ended screened cable there will initially be a current flow comprised of:

- a capacitive charging current
- a resistive current through the insulation and
- a polarising current to align the molecules with the electric field.

The polarisation index (**PI**) is the ratio of the insulation resistance (**IR**) reading after one minute to the IR reading taken after ten minutes with an insulation resistance tester at 5kV.

The capacitive charging is finished before one minute, the resistive current is constant, the polarising current diminishes over the ten minute period and the ratio reflects the effect of the polarising current on the IR reading. Historically PI has been used for rotating machines but does not appear to have been extensively used for determining cable condition.

Analysis of the Powercor test results does not reveal any correlation between the failures and the PI measured. The two cables with the poorest PI results both remained in service after the REFCL commissioning process, while WND13 and WND14 both failed, despite recording acceptable PI values at the last scheduled test.

It is believed that this test has not provided any indication of the likelihood of cable failure.

VLF (very Low Frequency) withstand test

This test subjects the cable to elevated voltage (up to 23kV) at very low frequencies (in the order of 0.1Hz). Failure of the cable is evidenced by breakdown or excessive leakage current. This test ensures that the cable, joints and terminations are serviceable for rated voltage.

1.5 Causes of failure

Failures are usually associated with system disturbances such as:

- lighting impulses
- switching surges
- inappropriate testing regimes.

The introduction of REFCL introduced additional over voltage excursions (beyond the originally specified normal operating voltage) and consequently will be likely to bring on additional failures in cables more seriously affected by significant size water trees.

During a hardening test[1] the electrical stress at the extremity of all water trees in a cable will be further increased. At the location of a large water tree the dielectric strength of the cable has already been compromised by the size of the water tree. The added stress of the hardening test can initiate an electrical discharge in the insulation at the extremity of the tree. The discharge will continue to grow while the overvoltage is maintained and when the overvoltage is removed the discharge will extinguish, provided there is sufficient unaffected insulation remaining.

Regardless, there will have been permanent damage caused to the cable insulation and this damage will continue to accumulate with further discharges caused by overvoltage excursions. Once the accumulated damage causes the extinguishing voltage to fall below the operating voltage the discharge will not extinguish. When the discharge becomes sustained the developing electric tree will result in the cable failing. The time to failure could be anything from seconds through to days.

For the large majority of cables the size of water trees will not result in discharges in the cable dielectric when subjected to over voltages and consequently they will not be accumulating damage. However some failures can be expected with cables known to have been affected by water and of early manufacture.

Once a failure has occurred in a badly water treed cable, it is common that it is followed by a sequence of failures, rendering the cable un-serviceable. Commonly referred as the “popcorn” effect, it is not well understood, but may be related to the transients created by a fault and probably the presence of other large water trees. This was observed to some extent at WND and United Energy has confirmed this phenomenon with XLPE cables on their network installed in the mid 1980s.

1.6 Addressing the risks

It needs to be recognised that cables from the earliest period of XLPE manufacture are now approaching 40 years of service life and will become increasingly susceptible to overvoltage as their latent defects including water trees develop with the passage of time.

The risk applies not only to REFCL operations but also the other causes of overvoltage excursions on the network. Of course, REFCL operations are likely to shorten the service life of age conditioned cables.

The possible controls for that additional risk across the population of first generation cables include:

- proactive replacement
- refurbishment
- reactive replacement
- testing and replacement prioritised by condition.

These are discussed in turn below.

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[1] Where higher than normal operating voltage are applied to selected assets in order to simulate REFCL operation

Proactive replacement effectively removes the additional risk associated with this early type of XLPE cable. This control is fully effective in terms of achieving the risk reduction and would deliver an optimum risk reduction profile over time.

Refurbishment can be achieved by rejuvenating cables with injecting proprietary fluids into cables. The aim of this method is to block defect tree growth and fill existing voids within the cable XLPE insulation. Various methods are commercially available for this process.

Water tree impaired cables can be treated with silicon based fluids. The fluids are injected under pressure down the conductor strands and permeate through the cable insulation. In doing so they chemically convert the water tree to an insulating compound, restoring much of the dielectric breakdown strength to the cable.

The fluid can take six months to move through the insulation and fully restore the dielectric strength. This process is not recommended for cables that have experienced a dielectric failure in the previous 3 months.

Further, in practical terms, this process requires cable termination and/or joints to be exposed and replaced with fittings that are then able to be used to inject the rejuvenation fluids. The joints along the length of the cable may also have to be replaced with ‘flow through’ type joints to allow the fluid to migrate along the cable length. At the end of the injection process, the terminations and joints have to be replaced with standard fittings.

Powercor trialled a rejuvenation process approximately 15 years ago, however, the result could not be quantified in terms of life extension.

Reactive replacement seeks to replace cables following failure. Additional risk remains until all of the target cables are replaced.

Testing and replacement prioritised by condition is not considered to be an efficient strategy. This is because there is no conclusive testing regime that can effectively condition assess water treed or aged first generation cables.

1.7 Summary

On the basis of the above, we recommend that first generation XLPE cables be proactively replaced as part of the program to harden the network prior to commissioning of the REFCLs.

These first generation XLPE cables need to be replaced for the following reasons

- manufacturing defects and contamination leading to the presence of and growth of water trees
- premature failures due to water tree growth as a result of transient and sustained over voltages
- existing elevated risk of failure (relative to later types of XLPE cables) due to overvoltage applied during REFCL operation.

These issues represent a higher risk of failure (and disruption of supply to customers) than the later XLPE cables.

Appendix A – XLPE cable testing methods

Since the initial failures in the 1970-80s resulting from water trees there has been extensive investigation and research into tests to identify cables with significant water trees nearing failure. However, there has been no silver bullet found; currently there is no test that will pinpoint the location of a water tree of dangerous size.

Most of the test methods currently used assess the condition of a cable as a whole. As cables are likely to contain water trees in combinations of differing numbers and sizes, this leaves uncertainty around the margins between which cables are likely to fail and which are not, particularly when subjected to overvoltage excursions. Most of the test methods currently being used are more a means of prioritising the ranking of cables for replacement or refurbishment. Replacement and refurbishment remains an ongoing process in North America and parts of Europe to address the poor performance of cable networks.

Available test methods are summarised below.

Time Domain Spectroscopy (TDS)

Time Domain Spectroscopy measures the polarisation and depolarisation currents in the cable dielectric to interpret the condition of the cable. There has been a lot of academic interest in polarisation and depolarisation currents for determining the condition of polymeric cables.

TDS has also been used in Canada. The National Research Council together with Hydro Ottawa have commercialised a testing program that measures depolarisation currents of “in service” cables and uses that in comparison to that of new cables to rank the condition of a cables.

Frequency Domain Spectroscopy

Used in conjunction with a VLF test set. This method measures the dielectric loss angle at various voltages and frequencies then interprets characteristic patterns**.** There has also been a lot of academic interest this technology for determining the condition of polymeric cables but the pattern recognition processes are complex and interpretation difficult.

One operator has been found in Australia, but they remain unconvinced about the ability to interpret results reliably at this point of time.

Partial discharge

Partial discharge is often used and is successful in finding discharges in the network. However, water trees are silent at operating voltages. Consequently decisions will need to be made regarding the test voltage level and if a discharge is initiated, what level of discharge will be acceptable. The test equipment must also be capable of distinguishing between the noise in the cable and that coming from accessories which is normally much louder.

There is also a risk that the discharge may not extinguish on return to the normal operating voltage. While it can be argued that this may not be a bad thing for this situation, there has not been enough quantitative work done in this regard to risk destroying serviceable cables.

Dielectric Loss Angle (Tan Delta)

This test will measure the operational ageing of an XLPE cable as a whole, but it cannot decipher or differentiate the number or various sizes of water trees and consequently will not see or locate dangerous water trees or their location. It remains a useful test as a means of plotting the operational ageing of XLPE cable and is recommended for zone substation exits but is not definitive enough to predict potential failures.

Water Tree Staining

This is generally an “after the event” test to confirm the presence of water trees. It often does not identify any large trees amongst the large number of smaller begin trees, but in this case with multiple failures, the presence of water and 35 years of service conditioning, is recommended in an endeavour to confirm the presence of water trees and their relative size.