AN ACCELERATED WET AGEING TEST ON MEDUIM VOLTAGE XLPE CABLES

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The failure of medium voltage (MV) cables in North Queensland has led Ergon Energy to consider the relative economics of refurbishment or replacement. In order to provide data to inform decision making, an accelerated ageing program has been designed to investigate the ageing of new, field aged, and refurbished cables.
This paper describes the considerations affecting the design of the ageing experiment and reviews the features of the test rig in which ageing is accelerated by a combination of high voltage stress, load-cycling to high temperatures and water immersion. Research into cable condition diagnostics will also be discussed.

1 INTRODUCTION

In the past two years, Ergon Energy have experienced a number of failures in its 22 kV network in northern Queensland. A 10 km cable near Cairns had to be abandoned after 23 years because of multiple failures and a 5 km feeder cable has had to be replaced. The expected life of the cables was 40 years. Post failure forensic optical analysis has established the cause of failure to be water trees, and these failures have raised concern over the condition of many of kilometres of cable operating in a similar environment.

Water treed cable may be either replaced or refurbished. Replacement can be expensive and difficult, with the possibility for significant customer outages while the work is being performed. Alternatively, refurbishment requires little or no earthworks and can be performed on live cables. These advantages have made refurbishment a popular choice – especially in northern America.

Refurbishment is realized by injecting silicone fluid into the cable strands under pressure, the fluid filling the core and slowly impregnating the insulation, bonding with any water molecules and filling microvoids. Thus it heals water trees and is claimed to inhibit their further growth [1].

Even if Ergon were entirely confident about the refurbishment process, there remains great uncertainly in deciding which cables would benefit most from refurbishment, which should be replaced and the priority that should be ascribed to each cable in dealing with a potentially extensive problem with finite resources. Clearly there is a pressing need for some form of *in situ* condition assessment technique that can be applied in the field to give a reliable estimate of the condition of cables that have been infested by water trees.

2 FACTORS AFFECTING WATER TREE GROWTH

2.1 WATER TREE DEFINITION

In order to design a well balanced accelerated ageing test, it is necessary to consider the basic processes involved in water tree degradation of XLPE. Firstly, a definition of water trees is needed:

"Water trees are degradation structures in a polymer that are permanent, have grown due to at least humidity and an electric field, have a lower electrical strength than the original polymer when wet, but which are not a short circuit or local breakdown path, and are substantially more hydrophilic than the original polymer. A typical water content of wet water trees in polyethylene is ≥ 1%." [2]

2.2 INITIATION AND GROWTH MECHANISMS

Unlike most other breakdown mechanisms (eg partial discharge, electrical trees), water trees form at normal operational conditions. Their formation requires neither defects in the insulation, nor direct liquid contact (although the above will accelerate their formation).

It is known that water trees may breach the entire insulation without causing fault current to flow. As water trees grow, they lower the dielectric strength of the insulation, making conditions more favourable for the formation of electric trees – especially if voltage surges are incident on the cable. Once an electrical tree has been initiated, a cable may fail within hours [3].

Water trees are generally considered to form and grow by the following mechanism: first, a void (or microvoid) is formed, then water causes the void to increase in size, lowering the dielectric strength to the point where electrical tree initiation is imminent. There are several processes at work in the growth and formation of a water tree, and each plays a different role depending on the environmental conditions [4-6].

One means of growth of water trees is the expansion of micro cracks in the polymer by environmental stresses, electrostatic forces, or residual stresses from the extrusion process. This process is accelerated by tensile forces, the corollary is that water trees propagate and grow faster on the outward side of bent cable. A cable subjected to 30% tensile strength grows water trees approximately 100% faster, but increased stress past 30% has no discernible effect [7].

Electrostriction occurs when a dielectric liquid is subjected to electric stress which causes a pressure change within the liquid. In a time-varying electric field, there will be a continuous cycle of expansion and contraction of a dielectric liquid, causing fatigue and cracking [4]. Water filled voids or cracks tend to concentrate the electric field at their boundary, making the electrical field two to five times stronger than the applied field [8]. This can lead to zones of 'crazing' – a low density area with many microvoids, susceptible to increased water treeing.

In addition to the pressure change caused by expansion and contraction of the dielectric, it has been found that water droplets tend to deform under a high field, causing water filled voids to continually elongate and relax. This causes mechanical fatigue on the polymer surrounding the water, leading to the creation of microcracks, and increasing the size of the water tree. These processes suggests that water tree growth should vary linearly with the frequency of the supply. Increasing the supply voltage frequency is found to increase the ageing rate, but the relationship is logarithmic rather than linear [4].

Polymers within XLPE are not perfectly homogeneous and because of this there are locations of electrical field enhancement. Under impulse conditions, this field enhancement may cause excessive heating, leading to polymer deformation or damage [4].

Damage may also be caused to the polymer by chemical processes. There are always some NaCl (common salt) ions in a given sample of commercial XLPE, and research suggests that other ions such as Fe^{+} can pose a much greater threat to cable life [4, 9].

Even with no voids or inclusions in the polymer, water vapour may condense between the polymer strands and exert a hydraulic pressure. A 2% supersaturation of the air will exert a hydraulic pressure of 2.5 MPa, close to the rupture point of the molecular bonds of XLPE [5]. Inclusions of water soluble ions also lower the vapour pressure of water, which will increase the rate of condensation, decreasing the time to inception of water trees. If the humidity of the air in the vicinity of the insulation is above 75%, then conditions become favourable for the condensation of water around NaCl inclusions. As NaCl inclusions in the insulation are a practical certainty, 75% is considered the 'critical' level of humidity for the initiation of water trees [10].

Thermodynamic theory states that water will condense preferentially in high field areas (eg voids). Thus the condensation of water into water trees is almost certain to occur.

Another growth process of water trees is the bond scission that occurs from electron injection or mechanical failure. The broken polymer chain ends allow for the release of free radicals that in turn cause more bond scissions. The by-products of oxidation are generally much more hydrophilic than the surrounding polymer matrix, and it has been suggested that oxidation plays a part in the growth of water trees. Evidence is not conclusive however, it has been shown that water tree initiation is not inhibited by an oxygen free environment, and studies have indicated that the level of oxidation in a water treed region is no greater than in the general polymer matrix [4].

Dielectrophoresis is the tendency of polar molecules to move from a low field area to a high field area. As a water tree is a concentration of water molecules, diffusion pushes molecules away from the water tree. Dielectrophoresis cancels the diffusive force, keeping water molecules at the site of the water tree, and drawing more molecules to the water tree [11].

If there is an anomaly in the insulation – whether it be a void, an inclusion or an intrusion – it will cause a field enhancement. Any water molecules that have diffused into the insulation will tend to move from the low field area to the high field area. This will cause hydrostatic pressure and give the water tree a larger reservoir to draw from.

3 CHOICE OF AGEING PARAMETERS AND TEST PROCEDURE

The aim of the accelerated ageing test is to increase the rate of inception and propagation of water trees without changing the processes that cause them to form and grow. Guidelines for accelerated ageing tests have been published by the IEEE [12] and this recommends test procedures and a range of values for the critical test parameters.

This was done in order to achieve better comparison of results from different laboratories. As recommended in the test procedure, ten short cable samples were immersed in a water bath. A current is to be applied to the samples to heat the conductor to a chosen temperature between 60°C and 90°C, and cycled in a 24 hour cycle – 8 hours on, 16 hours off. A 50 Hz supply voltage 2 to 4 times the rated cable voltage, U_o, is applied continuously. Cables were coiled into the minimum-bending radius. Preconditioning of the samples was carried out to remove any cross-linking products in the new cables.

3.1 VOLTAGE

Increasing the applied voltage will increase the electric field and the stress at impurities or defects at locations where water trees are likely to form. Thus an increased voltage is used to accelerate ageing of XLPE insulation.

Too high a voltage will generate large forces that initiate failure mechanisms that would not occur at lower stresses. For example a large force could cause a rupture of molecular bond rather than propagation along imperfections. In a review of accelerated ageing tests [18] a test protocol of $3U_0$ with a temperature of $75^{O}C$ and tank water controlled at $50^{O}C$ is recommended. Published data indicates that failure can be achieved in an average period of about six months [13] in XLPE cables for a voltage of $3U_0$ and temperature of $75^{o}C$. Although shorter failure times can be achieved at higher voltages, from examination of failed samples, there is a consensus that $4U_o$ is too high due to mechanisms that differ to those observed in service failures, while at $2U_0$ the ageing mechanism is too slow [13].

To test cable life the 'time to failure test' protocol or the 'retained breakdown' protocol can be used. The latter requires an AC breakdown test where the voltage is ramped up and failure under these conditions is not a true representation of field failure under constant stress. A time to failure protocol was selected as it is more representative of actual field conditions and will provide the opportunity to collect valuable information from non-destructive diagnostics in water treed cables.

3.2 THERMAL ENERGY

There are two aspects of heating that affect the water treeing process: The thermal gradient across the insulation, and the total thermal energy of the environment. Thermal energy increases the rate of chemical reactions (such as oxidation) and also increases the rate of diffusion of water both into and out of the insulation. Increasing the temperature by 15° from 60° to 75° shortens the cable life by about 30% [13]. A thermal gradient across the insulation will increase the rate of diffusion of water into the insulation. This decreases the time of inception of water trees, as any available voids and microcavities will fill with water more quickly. Additionally, the dielectrophoretic force and the osmotic pressure will be increased due to the presence of more water molecules. Conversely, a higher temperature will decrease the amount of water vapour that condenses into voids in the insulation, slowing down the process of saturation.

If the temperature is increased too much, the XLPE will start to soften and may deform. Softening will decrease the mechanical strength and will increase the rate of ageing due to processes that rely on mechanical force to break the polymer bonds. If the insulation deforms, the electric field will be distorted significantly. This will greatly accelerate the rate of water treeing due to mechanical processes, as there will be areas of very high electrical stress combined with low mechanical strength.

As such, we considered 75°C to be a good compromise between ageing acceleration and possible insulation damage (XLPE softens at 110°, but begins to lose mechanical strength at 90°).

3.3 FREQUENCY

There have been some studies conducted that show the morphology of the water trees grown under high frequency is different to that of those grown under power frequencies [14]. There have also been studies that suggest that high frequency ageing is a very effective tool of accelerating the ageing rate [15, 16].

Due to the high cost of a high frequency supply, and the ambiguity of the evidence regarding the benefit of high frequency ageing, ageing will occur at 50Hz; the frequency of the local supply.

3.4 WATER IMPURITIES

Many tests add salt to simulate the effect of salt in the environment. An analysis was performed on the groundwater of the field samples to guide decisions on the addition of salts to the water.

There is a thought among researchers that the type of ion is more important than its concentration. The energy of cation reduction seems to play a part in accelerating the growth of water trees [4]. With this in mind, the decision to add NaCl as an accelerant becomes a somewhat questionable practice, as the accelerating effect of other ions may be far in advance of Na^+ ions [9].

3.5 CYCLING

The effect of thermal cycling has not been discussed in the referred literature, even though it is a fairly standard practice [12]. This test will undergo thermal cycling, keeping in line with standard practices.

One way thermal cycling could increase the ageing rate is by increasing the amount of water vapour that condenses into the polymer. During the hot cycle, water will tend to evaporate from the outside and from the inside of the polymer. When the temperature inside the insulation decreases, humid air will be drawn into the insulation, the air will become saturated and water will condense inside the polymer matrix.

As stated above, only 2% super saturation is required for hydraulic forces to equal the yield strength of XLPE, and only a 75% relative humidity is required for condensation around NaCl inclusions. There is some anecdotal evidence that repeated wetting and drying of the cable may accelerate water tree growth (e.g. the failed cables come from a tidal region), but a conclusive study has not been found.

The cables in this test will be cycled on a 8/16 rotation as specified by IEEE standard 1407 [12].

3.6 IMPULSES

Although field cables are subjected to impulses fairly frequently, evidence as to the effectiveness of impulses in accelerating the ageing process is rather ambiguous [16]. There is evidence however, to support the theory that impulses aid in converting water trees to electrical trees [17]. This implies that applying impulses would decrease the time to failure, without necessarily increasing the growth rate of water trees. This ambiguity, combined with the practical difficulties of applying impulses, have guided us to decide against the application of impulses in this test.

4 DIAGNOSTIC TESTING

One of the opportunities an accelerated ageing test provides is the chance to evaluate and improve methods of non destructive diagnostic testing. There are many methods available for condition monitoring of XLPE cables. These are the methods being used in the proposed ageing test:

- Dielectric Loss Angle (DLA)
- Isothermal Relaxation Current (IRC)
- Return Voltage
- Polarisation Depolarisation Current
- Dielectric Spectroscopy

4.1 DIELECTRIC LOSS ANGLE

This test measures the amount of energy dissipated by the dielectric. Studies have shown that water trees increase the dielectric loss. Free water molecules inside the insulation also increase the loss, so this test is not conclusive evidence for the presence of water treeing.

Quite recently (2000), a study [18] was done that suggests that the dielectric loss angle may be used to detect water trees by varying the temperature. The assumption of the test seems to be that the key process for water treeing is dielectrophoresis and saturation. The published results support this method of varying the temperature to detect water treeing.

4.2 ISOTHERMAL RELAXATION CURRENT

This test measures the relaxation current of the insulation after an initial charging by a DC source. This has been used successfully as the basis of a condition monitoring program [19].

4.3 POLARISATION DEPOLARISATION CURRENTS AND RETURN VOLTAGE MEASUREMENT

These methods are quite similar in that they both deal with the time domain response of the dielectric.

The dielectric is charged with a DC source for a fixed time which polarises the insulation. When the power source is removed, the dipoles in the insulation start to relax to a more disordered state, this generates a measurable electric field.

The return voltage method measures the voltage induced by the electric field, while the polarisation depolarisation method measures the current created by the field.

The return voltage measurement is commonly used to asses the condition of transformer insulation. The application of this method to XLPE cables is relatively new [20], but has been used on XLPE cables for the detection of water trees with some success.

4.4 DIELECTRIC SPECTROSCOPY

The dielectric spectrometer measures the dielectric response of the insulation in the frequency domain. It applies a variable frequency field to the insulation (usually from .1Hz to about 1kHz) and measures the response of the dielectric. It is a relatively new method, so the interpretation of the results is still being thoroughly researched [21].

5 CONCLUSIONS

There are many factors that affect the design of an accelerated ageing test, the synergistic effects of which are not fully understood. Care must be taken to ensure the results are relevant to the situation at hand.

From one perspective, the accelerated ageing test is very simple – a simple ‘race’ comparison between cables will be largely unaffected by the processes used to accelerate the ageing. But if any inferences to the field life expectancy are to be drawn, detailing the exact processes and conditions is critical.

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