UPDATE ON ACCELERATED AGEING OF MV XLPE

ABERDARE CABLES

Driven by Powertech

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1. Introduction

In October 2001 a paper was presented [1] at the 4th Southern Africa Regional Conference of Cigré in Somerset West detailing the state of accelerated ageing testing of MV XLPE in South Africa. At that stage although the tests were already defined SABS 1339 and SABS SM 1284-5 (later known as SANS 1339 and SANS 6284-5 respectively), there were no functional test rigs operating in South Africa. Since then some have been built and this paper describes both the good and the bad experiences of the Aberdare rigs at the Aberdare Test Centre in Port Elizabeth.

2. A brief description of MV XLPE and its challenges

What follows is a simplified view of a very complicated subject!

Crosslinked polyethylene (XLPE) as an insulation arrived on the scene around the 60's. Although its potential as a terrific electrical insulation was appreciated, the material was not fully understood and was found to have a failure mechanism, now generally referred to as water treeing, that had not been predicted. The trouble was that the mechanism took in excess of 5 years, typically from 8 to 12 years, to manifest itself. This compromised electrical MV networks around the world many years after XLPE cables had been installed. Understandably the technology acquired a bad name and much effort was put into understanding the problem, engineering it out of cables, and developing tests that demonstrated that the problem had been addressed.

Superficially, polyethylene is not a particularly complicated material. It consists of extremely long chains of carbon atoms joined by single bonds, with hydrogen atoms attached to the remaining two bonds on each carbon atom (… – CH_2 – CH_2 – CH_2 – …). A chain can contain up to 100 000 carbon atoms. Occasionally additional shorter polyethylene chains will attach to a chain at the site of one of the hydrogen atoms, and the distribution of such side chains will influence the material properties and density, giving us materials such as low density polyethylene (LDPE), medium density polyethylene (MDPE), and others. When this material is used as insulation we arrange for the chains to be bonded to each other at a few sites along each chain in a process known as cross linking, producing XLPE.

The failure mechanism that had not been understood, was a subtle change in the material at various specific points, that then progressed slowly through the material creating structures that are tree-like in appearance. Some would start at contaminants or voids within the material and grow in opposite directions looking like a bow tie, while others would start at contaminants or blemishes on the surface of the material. Although the material in these structures remained a good insulation, its insulation properties compared to healthy XLPE were somewhat reduced. The mechanism of creation and propagation is very complicated, and relies *inter alia* on the existence of mobile ions. As the mobility is usually provided by water, the structures became known as water trees. (See Figure 1.)

A cable infected with water trees will in all probability still function well under normal steady state circumstances. The problem comes when such a cable experiences a voltage spike that exceeds the breakdown strength of the water tree material, leading to the initiation of an electrical tree which will inevitably cause the cable to fail. As we all know, every MV distribution network is subjected to the occasional voltage spike.

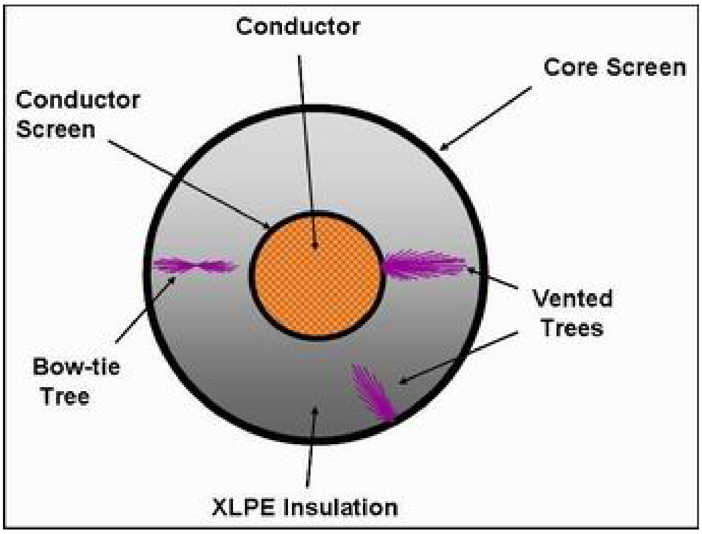


Figure 1: Types of water trees

3. Accelerated ageing of MV XLPE

The purpose of an accelerated MV XLPE ageing test is to realistically simulate about 10 years of cable use in the shortest time possible. The most accurate way of doing this would of course be to use the cable in service for 10 years, but waiting this long is somewhat problematic for both users and suppliers. Much work has been done on aspects that influence the speed of water tree growth and aspects that could prove useful are [2]:

- Ions — The presence of ions is essential.
- Electrical stress — Also essential as water trees will not develop in a cable that is not energised.
- Mechanical damage — These make good initiation points, particularly for vented trees, as they distort the electrical field and are exposed to an unlimited supply of ions from the environment.
- Contaminants — These make good initiation points as they can distort the electrical field as well as provide ions.
- Humidity — Water will provide the ions with mobility. It has been shown that water trees can grow if the humidity within the insulation is above 65%.
- Voids — These can initiate water trees by causing mechanical damage. They are also sites for partial discharges.

- Frequency — This exerts some influence, although growth rate is certainly not proportional to frequency.

- Temperature — This also exerts some influence.

All accelerated aging tests make use of one or more of the above, with the exception of voids and internal contaminants which would be a function of the manufacturing process rather than a subsequent test.

4. Tests implemented in South Africa

As with most of the test methods developed in the world the South African methods follow three basic steps:

- Pre-conditioning — This removes the by-products of manufacture and thoroughly wets the cable sample, ensuring that all samples start in the same condition.

- Ageing — Simulate about 10 years of use by providing some of the aspects mentioned above that increase water tree growth rate.

- Assessing — This employs a Weibul statistical approach, causing rapid “wear and tear” by applying high voltages in a controlled manner, until each sample section is destroyed. The distribution of the breakdown voltages determines if the sample passes or fails.

In South Africa the preconditioning is carried out under water at a temperature of 50 ºC for 1 000 hours, or just under 42 days. The samples are then aged underwater at room temperature at 3 U_0, which for an 11 kV cable is 19,1 kV. There are two methods described in the SABS tests:

- 50 Hz — The sample is energised at mains frequency for 17 500 hours, which is 2 years. This is fairly simple to perform.

- 500 Hz — The sample is energised at 500 Hz, with a sinusoidal wave form, for 3 000 hours, which is 125 days. Producing a 19,1 kV 500 Hz sinusoidal voltage to energise a capacitive load is a big challenge, but the test provides results very quickly.

After ageing, 12 sample sections are then prepared and subjected to a voltage that increases in steps until the sample section fails. The sequence starts at 3 U_0, which is held for 5 minutes and then progresses in U_0 steps, with each voltage being held for 5 minutes. The voltage recorded is the last voltage held for 5 minutes. The pass criteria are:

- All 12 samples must pass a calculated maximum stress of 14 kV/mm.
- At least 9 samples must pass a calculated maximum stress of 18 kV/mm.
- At least 5 samples must pass a calculated maximum stress of 22 kV/mm.

The South African tests are similar to a test carried out in Europe, covered in Cenelec documents HD 620 and HD 605, excepting that the test parameters are slightly different. In the European test the final value recorded for each sample is the voltage at which the sample was destroyed, as opposed to the highest voltage held for 5 minutes. In order to pass, these voltages must have the same minimum criteria as those described above. The rigs at Aberdare are capable of performing the South African and European tests and some of the results given below relate to the latter.

(Note it would be incorrect to draw conclusions about the likely performance of a marginal sample to South African standards based on voltages recorded in a European test, and vice versa, as the preconditioning and ageing parameters are different and the distribution of breakdown voltages will not necessarily correspond.)

5. Aberdare's test rigs

Preconditioning is carried out at Aberdare in a single dedicated stainless steel tank. The samples are wound onto a stainless steel drum specifically designed for the test. We have found that for acceptable conductivity during the test, it is necessary that the samples are taped with a helical copper tape. The temperature of the water in the tank is controllable.

As the samples are each at least 150 m long our tank holds only one sample, and we are therefore limited to 8 tests a year. However, where space is available in the ageing tanks, and there is no temperature conflict, preconditioning can be done in an ageing tank as well.

As a standard, all the cores we test are for 11 kV cables, and the conductor size we choose is 185 mm².

Ageing at 50 Hz is relatively simple. We use a variac to supply power factor correction equipment and a step up transformer. With this arrangement the load of a single sample on the variac is less than 5 A. Ageing is done in a separate 50 Hz stainless steel tank large enough to hold three samples on their stainless steel drums. Once again the water temperature can be controlled.

At 500 Hz the test is far more of a challenge. This is because the waveform must be sinusoidal, and the reactive power rating of a sample at 500 Hz is 10 times higher than at 50 Hz. The energising supply is achieved using a pulse width modulator modulating an 11 kHz signal at 500 Hz. The result is fed through a 4th order band pass filter, which includes the step up transformer and allows for power factor correction. Much effort was required to get this to work! The control diagram is depicted in Figure 2.

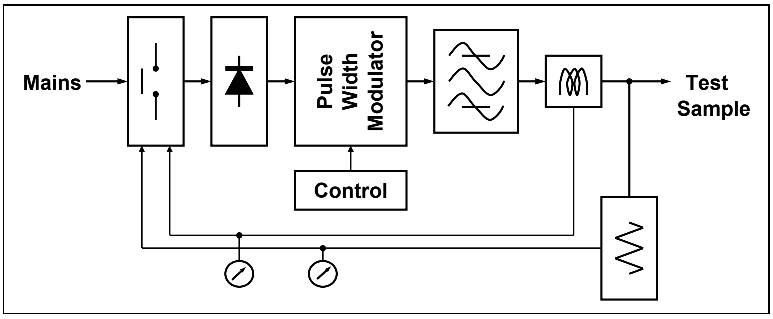


Figure 2: 500 Hz Generation

The breakdown assessing is achieved using a 300 kV 300 kVA transformer giving us a continuously variable voltage. The protection equipment used is very fast in order to limit the damage at the breakdown site, so that we can then examine the area for water trees. Given that a typical breakdown voltage will be around 90 kV, and all the way up to 150 kV, a normal termination will simply not work. For this reason we use reusable water terminations rated up to 350 kV.

6. Operating experience

Once we realised the advantage of installing the power factor correction equipment between the variac and the transformer on the 50 Hz rig, instead of on the supply side of the variac, we found operation of this equipment to be very easy.

In the case of the 500 Hz system we found that the equipment was very sensitive to temperature variations. After much analysis, we established that the reason for this is that the filter of necessity has a pole, where its impedance is very high and transfer voltage low, and a zero where the impedance disappears, very close to one another. The separation of the pole and the zero is a function of the step up transformer ratio and, as such, cannot be changed. As a result, including the modulator in a control loop was found to be almost impossible and the circuit was quite unstable. We are presently developing a control circuit that uses a variable capacitor in parallel with the sample, as this appears to give us a reasonably stable circuit.

The inverter consists of solid state components being driven reasonably hard. It is perhaps not too surprising that we have already blown up and replaced the equipment once.

Experience from Europe warned us of the possibility of Legionnaire's disease developing in our tanks. The disease is usually present naturally but the conditions in the tanks are conducive to it growing to a dangerous level. As a result we conduct regular tests and can confirm that the danger is real – we have had to shut down and disinfect a tank twice already.

7. Tests completed by Aberdare

We have so far completed 7 tests, with 5 more underway. Of the completed tests three failed, giving us valuable information on certain materials and processes. The materials tested to date are summarised in Table 1 below, with specific results being given in the graphs that follow. Comments on the specific materials are:

Material 1: This is a standard material, which we tested to the Cenelec requirements (Test 1) as the test commenced before the SABS tests were published.

Material 2: This was a material that we tried because it had a distinct price advantage. This was perhaps reflected in the result as the material failed significantly and was therefore not used.

Material 3: We have used this material as a standard and will soon have completed both 50 Hz and 500 Hz tests on identical samples (Tests 3 and 8), providing data on the similarity of the tests. We have also used this material as an indicator of a process (Tests 7 and 8).

Test 7 was carried out before we upgraded our material handling system and Test 8 was carried out after. Note that while each test was conducted on 12 samples sections, these were consecutive. In effect this means that for comparison purposes we have only one sample before the upgrade, and one after. While it is pleasing to see a significant improvement after the upgrade the sample sizes are too small to prove on their own that the upgrade was effective.

Material 4: This was development work on a new material and a new process. While the material has proved successful overseas, the test results showed that we would have to put considerable effort into the development of the process before it would produce successful cable.

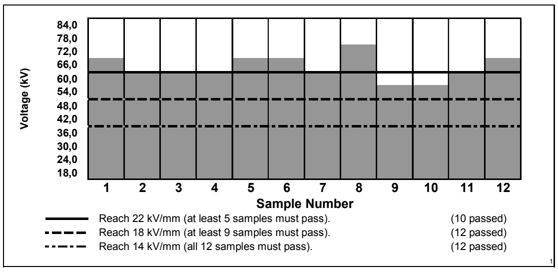
Material 5: This is an alternative material that is being investigated at present. We are testing it at both 50 Hz and 500 Hz, which will give us alternative data to the data acquired with Material 3.

Materials 6 and 7: These are also alternative materials currently under investigation.

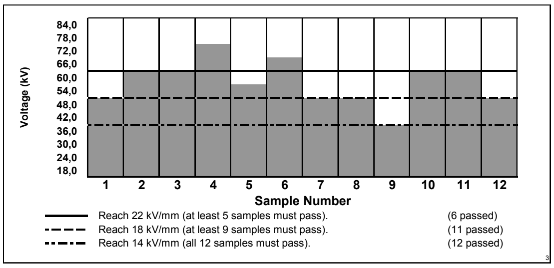
Test No	Insulation Material	Standard	Frequency Hz	Completion	Result
1	Material 1	Cenelec	50	09/05/04	Passed
2	Material 2	Cenelec	50	02/08/05	Continual failure, stopped at 12418 h.
3	Material 3	Cenelec	50	13/02/05	Passed
6	Material 3	SABS	50	-	In progress, 35% complete.
7	Material 3	SABS	500	17/02/04	Passed (before upgrade)
8	Material 3	SABS	500	28/12/04	Passed (after upgrade)
4	Material 4	Cenelec	50	25/04/05	Continual failure, stopped at 1148 h.
9	Material 4	SABS	500	07/06/05	Failed
5	Material 5	SABS	50	-	In progress, 30% complete.
10	Material 5	SABS	500	-	In progress - preconditioning
11	Material 6	SABS	500	-	In progress, 25% complete.
12	Material 7	SABS	500	-	In progress - preconditioning

Table 1: Summary of tests

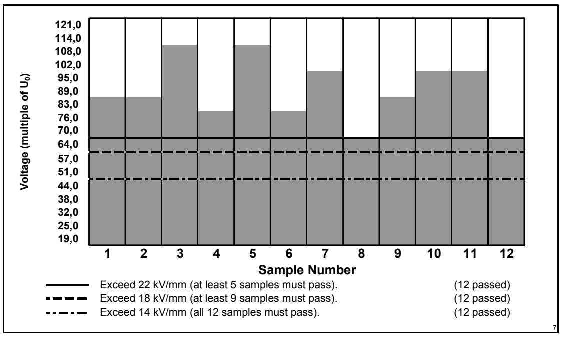
The results of the completed tests are presented on the following graphs:



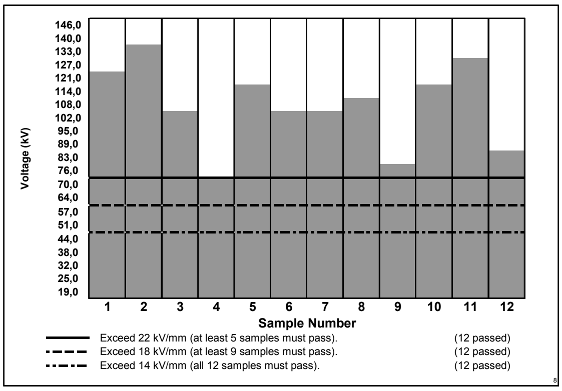
Test No 1: Material 1, Cenelec



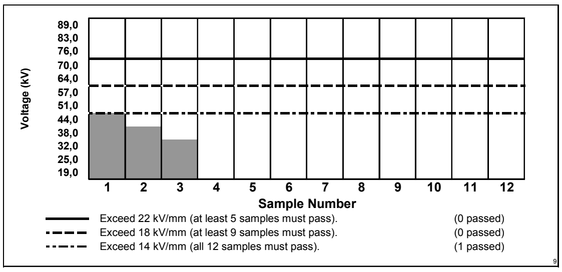
Test No 3: Material 3, Cenelec



Test No 7: Material 3, SABS



Test No 8: Material 3, SABS



Test No 9: Material 4, SABS

8. Conclusion

As the result of problems experienced by some users of MV XLPE, both in South Africa and abroad, it became necessary to design and manufacture cable that would be resistant to the water tree mechanism of failure. It became further necessary to find ways of demonstrating that cable which had supposedly been designed and manufactured specifically with such resistance, actually achieved this promise. In South Africa this meant including accelerated ageing tests in our national standards. As these standards are compulsory this to some extent should ensure that only cable that can pass the accelerated ageing type test will be sold and used in South Africa.

Including these tests on local standards has also encouraged us to build our own test rigs and as a result we have found that the number of new materials we can now investigate with confidence has risen dramatically.

References

[1] A Falconer, **Accelerated Ageing of MV XLPE Insulation**, Proceedings of Cigré Fourth Southern Africa Regional Conference.

[2] E F Steennis, **Water Treeing, the Behaviour of Water Trees in Extruded Cable Insulation**, ISBN 90-353-1022-5.