The evolution of VLF Testing Technologies over the past two decades

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I. INTRODUCTION

Due to the regulation of the electricity market, the reliability of distribution networks become more and more important. Network operators are forced to maintain the distribution cable system carefully. Withstand testing after installation or after repair of failures reduces significantly the failure rate during normal operation.
This paper describes the evolution of the Very Low Frequency (VLF) testing technology over the past two decades. Since the introduction of the VLF technology not only the technology itself has changed. Because of the large number of systems in operation and the gathered field data/performed researches, also the application has received high attention from the asset management.

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II. WHY VLF TESTING?

The VLF technology was introduced in 1986; the main driver of this technology was the need for a new testing method for polymer insulated cables and the enormous problems with water treeing effects in XLPE cables of the 1st generation. Several researches [1, 2] have showed that the traditional DC-testing method on polymer insulated cables induced trapped space charges in the polymeric material. These space charges could be trapped for longer then 24h inside the amorphous regions of the polymeric insulation. If the cable will be re-energized before all space-charges are gone, a local overvoltage will appear which could induce an electrical tree and result in a breakdown shortly after putting the cable back into operation.
In most countries DC-testing is therefore not an allowed test-method anymore for testing of

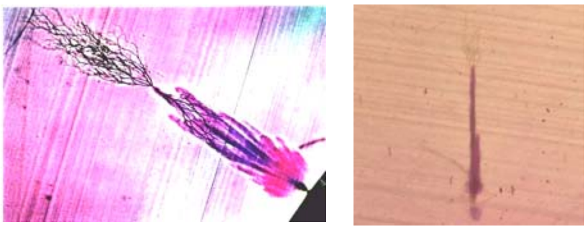
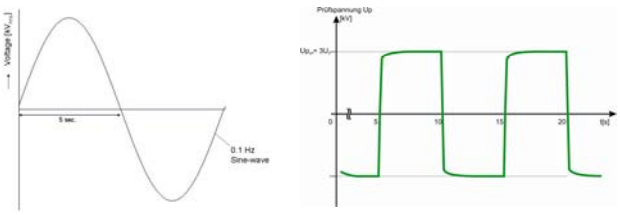


Fig.1: Water trees of critical length can effectively be tested out by using VLF-Test methods [3]

PE/ XLPE cables, also because of the other disadvantages of DC-testing like [2]:
- It is blind to certain types of defects, such as clean voids and cuts.
- It may not replicate the stress distribution existing with power frequency ac voltage. The stress distribution is sensitive to temperature and temperature distribution.
- Leakage current readings may have wide variations due to atmospheric conditions and lack of control of charges at termination lugs.

III. EXISTING VLF TECHNOLOGIES

The first VLF systems operated on the still existing and proven cosine-rectangular technology. In the early nineties the VLF sinusoidal technology was introduced. These two technologies are still widely used for commissioning testing of newly installed cables and also for maintenance testing of aged cables to eliminate critical weak spots e.g. soaked joints or water-trees with a critical length.
These two technologies differ itself in the wave-shape, see figure 2. Apart from the cosine-rectangular and sinusoidal wave-shape there are also systems available with a wave shape that resembles a sine wave.
The first two are the most common test methods which each having their own advantages and disadvantages.



a) b)

Fig.2: a) Sinusoidal voltage wave-shape
b) Cosine-Rectangular voltage wave-shape (polarity change resembles a cosine wave with a frequency close to 50Hz)

VLF COSINE RECTANGULAR TECHNOLOGY

The VLF Cosine-Rectangular technology was the first VLF technology available. The systems consisted of a dc-source, an inductance controlled via a rotor switch and a support capacitor. Because of the evolution in power electronics the rotor-switch has nowadays been replaced by a thyristor switch; resultantly leading to a smaller, lighter and more powerful system.

One of the significant advantages of the cosine-rectangular technology is the power recycling during polarity reversal which is based on the resonance principle. Therefore the power-consumption is relatively low and the capacitive load of these systems high. Currently there are systems available with a maximum capacitive load of 25µF at 60kV$_{rms}$.

The polarity reversal of the cosine-rectangular VLF-systems is cosine shaped and has a frequency close to 50Hz, see figure 3, thus the field stress is comparable to operating frequency.

A limitation of the cosine-rectangular VLF systems is that this technology needs high efforts for the application with PD-diagnosis or Tan- delta measurement. The latter can be solved by making use of the Hamon approximation [4, 5].

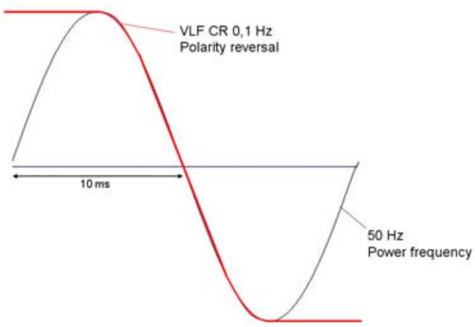


Fig.3: Polarity reversal of cosine-rectangular voltage

Because of the rectangular shaped voltage it is also possible to measure a leakage current; this leakage current is an indication for the quality of the insulation/ cable.

VLF SINUSOIDAL TECHNOLOGY

In the beginning of the nineties the VLF sinusoidal test systems where introduced. These systems already made use of power electronics from the beginning onwards. The evolution of the power electronics resulted in systems with a higher testing capacity, less weight and smaller in size. The principle of the systems is based on an AC-DC-AC convertor. Sinusoidal VLF test systems cannot re-use the power stored in the cable, this stored energy needs to be discharged and is transformed into heat in the discharging resistors. Therefore the capacitive load of sinusoidal systems is in general lower than cosine-rectangular systems. The advantage of using a pure sinusoidal wave-shape is that these systems can also be combined with diagnostics like e.g. a PD-diagnosis or a tanDelta measurement. However as the testing frequency differ 500 or 600 times with the operating frequency, the PD characteristics are not the same anymore. A direct correlation of important PD parameter with 50/ 60Hz power frequency has therefore not been given anymore. Moreover a recent research has concluded that the PD seems to die out at lower frequencies [6].

IV. INFLUENCE OF FREQUENCY

In Figure 4 the electrical tree growth for several wave-shapes and frequencies has been plotted against the test voltage [7]. This research clearly indicates that testing at lower frequencies e.g. 0.01Hz instead of 0.1Hz results in a smaller growth rate of the electrical trees. The difference in growth rate between 0.1Hz and 0.01Hz is roughly 10 times. If we reflect this to the testing time it means that if a test is performed at 0.01Hz the test time should be increased by a factor of 10. This implies for commissioning testing a test time of 10h at 3U0 instead of 1h at 3U0.

Moh [8] has confirmed this in his research about the effectiveness of VLF testing in detecting hidden faults. Tests that have been performed at lower frequencies because of the constraints on the capacity of the test set, had an after test failure rate that was more then 3 times higher when compared to tests that have been performed at 0.1Hz. Moreover this research indicates that a VLF test at 0.1Hz, 3U0 is more effective then an 50Hz AC test at 2U0.

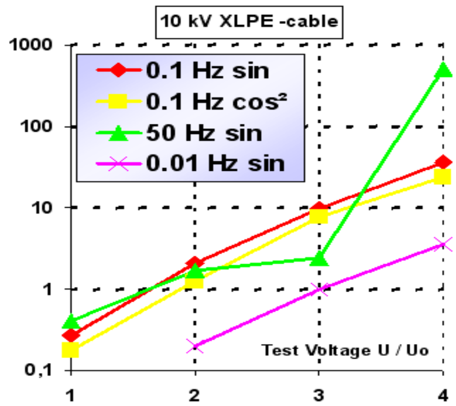


Fig.4: Electrical tree growth-rate as function of the voltage for several frequencies and wave shapes [7].

V. PRACTICAL EXPERIENCES

EXAMPLE CITY OF DORTMUND

The following example will describe the experiences of the city of Dortmund in VLF testing over a period of 10 years (1987 - 1998). In total more then 3000km of cable has been tested, see table 1. If we look to the number of breakdowns, then most of the breakdowns occurred in heavily aged polymeric cables, in average 4.2 per 100km of tested cable.

	Polymeric insulation	Paper insulation
Tested system length (km)	2149	999
Breakdowns	91	29
Breakdowns per 100km	4.2	2.9

Table 1: Number of breakdowns during testing [9].

If we go more into detail and look to the distribution of the faults over time then we can see that 66% of the faults occurred in the first 10 minutes and 75% in the first 30 minutes, see figure 5. 25% of the faults occurred in the last half hour, this confirms that testing for the full hour is required as recommended by all standards. Same experiences are recorded at other power utilities too.

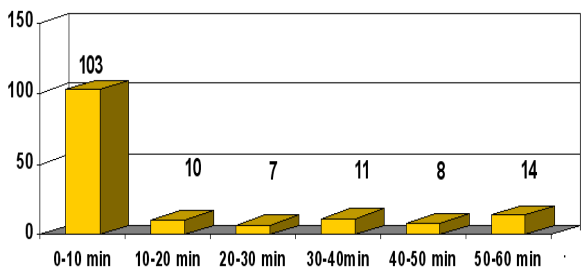


Fig.5: Breakdowns as function of the test time [9].

However, if we even go further into detail and look to where the fault occurred, we see that all joint faults occurred within the first 20 minutes, see figure 6. This implies for newly installed cables where the insulation of the cable itself is assumed to be new, a VLF test of 20 minutes will be sufficient.

The high number of faults in the XLPE insulation is caused by the poor manufacturing technology of the first generation of XLPE cables with graphitized outer semiconductor layer. Current generations of XLPE cables do not have these problems as the first generation anymore.

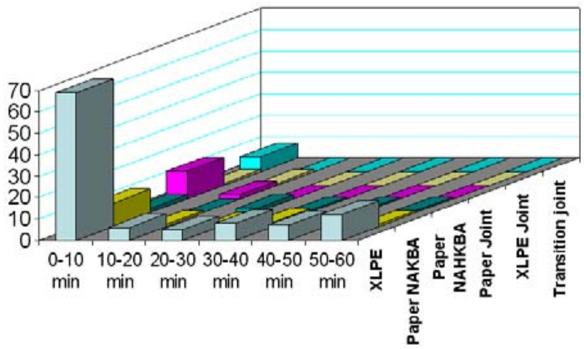


Fig.6: Breakdowns as function of the test time and fault position [9].

VI. OUTLOOK

Nowadays the VLF withstand test is more often combined with a PD-diagnosis. A Dutch power utility e.g. is having the following after-laying test procedure [10]:

1. Sheath test
2. VLF withstand test at 0.1Hz and 3U0
3. PD-diagnosis using damped AC-voltages (DAC)

The advantage of additionally performing a PD-diagnosis after the VLF withstand test is that significant workmanship failures, which were not recognised by the VLF test, will be detected and can be repaired on forehand. This

will further increase the reliability of the network and reduce costs for unplanned outages, non-delivered energy (e.g. when a wind park is disconnected) or penalty payments.
Significant workmanship failures could be e.g. un-complete shrinking of a heat-shrink joint, incorrect peeling of the outer semicon-layer or dirt inside joints. These workmanship failures will pass the VLF withstand test but will be detected by a PD-diagnosis. If these workmanship failures are not preventively maintained, joint failures for the next years are expected (depending on the type of failure).

a) b)

Fig.7:a) Incorrect peeling of the isolation with visible PD-tracking, joint close before failure
b) Remaining semi-conductive layers

Normally after successfully passing the after laying test, the next diagnosis is planned after 10-15 years. In other words, no problems are expected for this time period, unless because of external influences.

VII. CONCLUSIONS

The VLF Technology has proved its effectiveness over the past two decades for commissioning testing of newly installed cables and also for maintenance testing of aged cables to eliminate critical weak spots.
The evolution in power electronics resulted in maintenance free systems, and also resulted into a higher testing capacitance.
The effectiveness of this technology is only given when the frequency of 0.1Hz is used. When using lower frequencies the test time should be increased; this is from both practical and economical point of view not possible or too expensive.
Practical experiences have shown that most of the joint failures occur within in the first 20 minutes. If this practical experience is reflected on newly installed cables then the testing time could be reduced to 20 minutes instead of the recommended 60 minutes.
In addition to the VLF test nowadays also a PD diagnosis is recommended as part of a commissioning test. With help from PD-diagnostics also small workmanship failures can be found which will further increase the reliability of the network.

VIII. REFERENCES

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