CABLE DIAGNOSTICS IN SOUTH AFRICA

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1.0 INTRODUCTION

M.V. Electrical Cables are the major arteries for electrical power. The higher the voltage the more critical and important they become. Being so important, why then is no maintenance or diagnostics done by the utilities? On transformers and Switchgear regular maintenance/diagnostics is done - oil filtration – gas analysis + dielectric strength of the oil. Cables are buried in the ground, hung down a mine shaft and left there to survive the elements and man. Today it is possible to do on-site cable diagnostics of all types of M.V. Cables. This paper will concentrate mainly on the M.V. PILC and XLPE cables.

2.0 BACKGROUND

In the factory Partial Discharge (PD) testing is done in a screened room (Faraday Cage). With the evolution of the computer, P.D. testing can now be done in the field.
Tan Delta (TD) is done on transformers, transformer bushings, motors, alternators and dielectric oil as an excellent indication of the quality of the insulation – it is now possible to do TD on cables and obtain an excellent indication of the reliability of these cables. The author has been involved with TD testing of MV cables since 1999 and PD testing since 2002.

When testing a M.V. cable, the main difficulty to overcome is the capacitance of the cable. A 95mm^2, 11kV XLPE cable capacitance is 300nF/km.
A 14kV maintenance test at 50Hz would therefore require a power pack of 20KVA or 82amps at 230V. It is understandable then why 50Hz testing of cables has not been a success.

D.C. Testing has, for years been the only form of “diagnostic” testing on PILC cables and oil filled cables. But then along came the solid dielectrics in the 1970s – so called PEX and now commonly called XLPE. At the same time the joints and terminations have become more convenient with the introduction of the Heat and Cold Solid dielectrics for both PILC, XLPE and VPR cables. The solid dielectrics are here to stay even though some of the pre 1980 XLPE cables have failed with catastrophic consequences. The modern XLPE cables manufactured in South Africa are of excellent quality and provided they are installed correctly and maintained, they should equal or better the life of the PILC cables: (This statement will start the tongues wagging)..

Damage the lead sheath of a PILC cable and it is a matter of time before the cable fails. Damage the coaxial copper tape and or semi conductor screen around the XLPE cable and it could be up to 10 years before the water trees manifest themselves. Once the outer sheath of the XLPE cable is damaged, the copper tape is eroded away and with the advent of a fault, arcing and burning occurs as the fault current struggles to find its way back. Once the semi conductor tape/screen is damaged, partial discharge (PD) starts to occur and together with the water ingress, (and 50Hz) water trees will result which can have disastrous consequences – which many Municipalities can vouch for. (Water trees have been extensively covered over the years in technical papers).
How then can the M.V. cable be maintained?

3.0 DIELECTRIC BREAKDOWN

Solid and PILC dielectric breakdown and dielectric deterioration is generally caused by:-

1. Partial discharge activity due to badly terminated or joined cables, surface damage to the semi conductive tape and due to impurities or cavities in the dielectric.
2. Thermal Breakdown, caused by overloading or from cables packed to close together and unable to dissipate the I^2R heat and dielectric losses. Hence the importance of Tan Delta – Why?
3. Electrical Conduction breakdown, where electrons are emitted into the insulation by electrical stress, caused by space charges or stress points.

The D.C. Voltage breakdown strength of XLPE is 60kV/mm.
The normal 11kV cable is 3mm, resulting a D.C. strength of 180kV.
D.C. voltage stress distribution is only resistive (R), whereas AC (both 0.1Hz and 50Hz) voltage stresses the impedance (admittance) where the R, L and C are stressed.

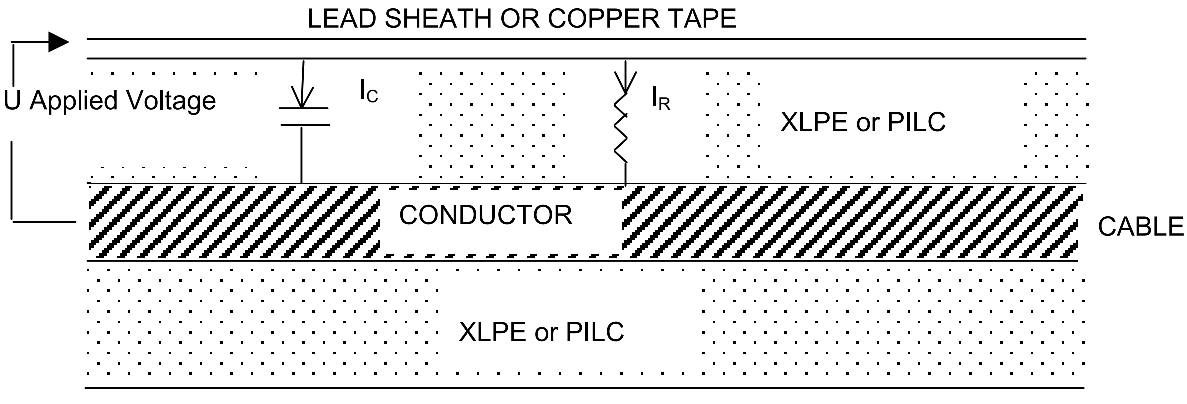
4.0 DIAGNOSTIC METHODS

At present there are the following diagnostic and maintenance methods available in South Africa.

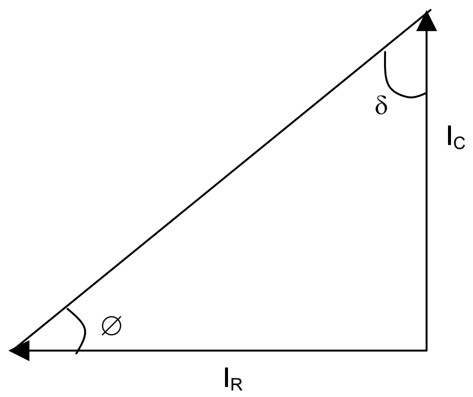
4.1 Tan Delta or Dielectric Loss Angle.
4.2 Partial Discharge
4.3 D.C. Leakage Current (PILC cables).
4.4 For outer sheath maintenance – the D.C. Sheath Test.
4.5 Joint P.D. discharge.
4.6 Termination P.D. discharge.

4.1 TAN DELTA

As the cable ages so the dielectric loss increases, and therefore dielectric loss is an important indication of the dielectric quality. The Tan Delta or dielectric loss angle is a measure of the dielectrics ability to withstand breakdown and a measure of the dielectrics losses.
Tan Delta is an AC Sinusoidal test to evaluate the quality of the dielectric. In theory the Tan Delta (at a fixed frequency) should remain constant as the voltage increases.



As mentioned above a cable is a large capacitor with a capacitive current Ic. The resistive component is very, very small. I_R.



Ø is power factor angle (cosØ).
Whereas

$$TD = \text{Tan Delta } (\ ) = \frac{\text{True Power}}{\text{Capacitive Reactive Power}}$$

$$= \frac{U^2/R}{U^2 wC}$$

$$= \frac{1}{wCR}$$

In an XLPE cable at 0.1Hz the required Tan Delta is 1.2×10^{-3} which equates to an angle of ±0.068 degrees. This demonstrates how small the resistive component of the current is.
The resultant current of the vectors $I_R + I_C$ will lead the applied voltage by ±90° (mainly a capacitive load) and by measuring the zero crossings of the voltage wave and current wave the angle Delta can be determined and hence the Tan Delta or Dielectric Loss Angle. With the power of the PC, microprocessors and at 0.1hz (1 cycle every 10 seconds) this is easily achieved.
However Tan Delta can only be done with a truly sinusoidal waveform (not square or trapezoidal), and accuracies of 0.2×10^{-4} are required.

4.2 PARTIAL DISCHARGE

Partial Discharge or PD is exactly what is implied, a partial breakdown of the insulation, not a complete flashover: PD is more commonly recognised as Corona (seen on H.V. overhead line insulators on a misty night).
Partial Discharge can occur in air, in cable dielectric, in transformers, motors etc. The measurement of P.D. is normally in pC or pico-coulombs.
1 Micro amp for 1 Micro second. When XLPE cables are tested in the factory only 5pC is permitted at 1.7 x rated voltage. In paper cables PD is not even measured in the factory. Partial Discharge does progressively damage the insulation and it is just a matter of time before the insulation will fail.

P.D. is like a cancer, early diagnosis is critical.
Partial Discharges emit

- Electromagnetic energy
- Acoustic energy
- Gases

Today it is possible to energise the PILC or XLPE cable with a sinusoidal wave form to determine the location phase and magnitude of these partial discharges.

With the advent of digital noise rejection techniques and the computer. it is possible to do P.D testing on long MV cables (which behave as long “aerials” to noise). P.D Testing is particularly useful for detecting faulty cable accessories, joints and terminations.
One of the major disadvantages of P.D. testing is that the terminations may have to be removed in order to have sufficient clearance and to install corona shields.
During PD testing the following levels are recorded.

- Background noise of the site
- PD Inception
- PD at Uo (rated voltage)
- PD at 1.7 Uo
- PD extinction

PD inception should/may occur above Uo but PD extinction should not be below Uo (with the exception of PILC cables).

4.3 D.C. LEAKAGE CURRENT

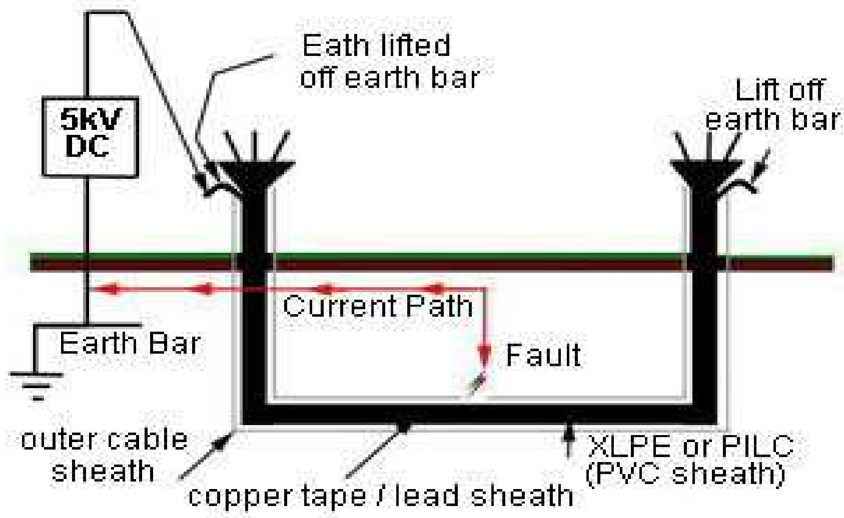
D.C. has been used for years and years to test PILC cables. As a diagnostic tool, D.C. testing is meaningless. Unless a fingerprint leakage current was recorded during acceptance testing, the test is really a fail / no fail result. As the oil in the PILC cable drains to one end of a cable the losses increase and the leakage current increases. Dry type terminations (heat shrink and cold shrink) are now used on PILC cables and D.C. testing is of little use.
D.C. Testing of XLPE cables is similarly meaningless and is destructive in aged water treed cables .

4.4 CABLE SHEATH TESTING

As the author highlighted in 2.0 above, the outer PVC or XLPE sheath of XLPE cables must be maintained. Water must be kept out of the cable jacket for two very good reasons.

- Erosion of the coaxial copper tape and earth fault path.
- To avoid the water seeping under the outer Semi conductor tape.

One very easy and simple methods is to do regular sheath tests. This test is described below where the earth tails are lifted from the earth bar. (not easy on PILC wiped terminations) and a 5kV D.C. cable sheath test is applied to test the integrity of the sheath. The 5kV test should be done for 2 minutes with a rough rule of thumb of 1mA per KM leakage current being acceptable. This test is applied between the armouring and mother earth (see below).
A sheath fault is easily indicated by the DC voltmeter and Ammeter (current increases and 5kV is not attainable)



These cable sheath faults can easily be located using a Sheath fault locator.
If a PILC cable has a outer PVC Sheath, the above sheath test can be applied. The normal jute covered PILC cable unfortunately does not allow the lead and steel wire armouring to be lifted from earth.

4.5 JOINT P.D. DETECTOR

A joint P.D. detector using an inductive or capacitive coupler is available on the market. The detector has had varying success and relies on the joint not being completely screened by an earth (braided) sock or tube. Traditional methods of P.D. Testing from the two ends will pick up P.D. Discharge travelling waves and is (in the author's opinion) a more effective manner of detecting faulty joints.

4.6 TERMINATION P.D. DETECTOR

At high P.D. levels, ultra sound energy is emitted and this can be detected with a tuned piezo crystal type detector.
A common problem found in terminations is where the termination's phases are crossed over in order to obtain the correct phasing. Unless this cross-over is done below the semi con/stress relieving point partial discharges will occur, and in time ultra sound and in the more severe cases even normal audio sound is heard. A typical tell-tale result is the white powder found at the heavy discharge points. It is just a matter of time before failure occurs.
Termination ultra sound detectors and P.D. discharge MV sticks are available on the market to test dry termination under operating conditions . These are relative detectors and do not record the P.D. levels. They are however a quick and easy test.
The normal 50Hz and 0.1Hz TD/PD detection systems can detect P.D. on terminations, but the cable has to be removed from service. These P.D. levels are traceable back to a standard and therefore more meaningful.

5.0 CABLE TEST AND TEST SYSTEMS

In the market today, the following overvoltage and diagnostic test methods are available:

1) 0.1 Hz Sinusoidal } 1 cycle
2) 0.1 Hz Cosinus trapezoid and or square wave. } every 10 s
3) Oscillating Wave
4) 50Hz Sinusoidal.
5) Relaxation and Recovery
6) D.C. – negative with respect to earth.

0.1Hz testing was originally developed back in the 1950s to test large turbo alternators. The main reason for the 0.1Hz was to cope with the capacitance of these large alternators. Cables present a similar problem (see above) that is a large capacitive load. 0.1Hz is now incorporated in most cable standards. (SANS10198, IEEE400, IEC 6006-3 draft form). 0.1Hz will, in the future (and in the authors opinion) become the standard form of testing for alternators, motors, cables, transformers and switchgear. The electrical stress at 0.1Hz sinusoidal wave form is similar to that which will occur at 50Hz.

ADVANTAGES & DISADVANTAGES OF VARIOUS DIAGNOSTIC & OVERVOLTAGE TEST SETS.

5.1 0.1 Hz Sinusoidal Diagnostic & Overvoltage Test Set

ADVANTAGE	DISADVANTAGE
• Sinusoidal Waveform • Stresses both resistivity and impedance R, L and C • Higher breakdown strength than 50Hz • Tan Delta measurements - possible • Partial discharge measurements - possible • Symmetrical wave form • Stress lines similar to 50Hz on cable, terminations & joints. • Sinusoidal is symmetrical under any load (electronically generated)	Not 50Hz but 0.1Hz

5.2 0.1Hz Square, Cosinus or Tapezoid Wave Form.

ADVANTAGE	DISADVANTAGE
• Cheap to manufacture • Complies with Standards • RMS/Peak are same • SANS 10198 does not differential between peak & RMS for Square or sinusoidal	• No diagnostics possible • Leakage difficult to measure • Does not stress cable to same level as sinusoidal.

5.3 Oscillating Wave

ADVANTAGE	DISADVANTAGE
• PD possible • Cheap • Easy to operate • Frequency 100Hz – 1KHz	• D.C. charge • Frequency dependent on cable length • RMS voltage limited (at present) • TD is calculated value from damping of wave. (not real TD) • Minimum cable lengths • Variable frequency – cable length • Composite cables (PILC + XLPE) not possible • Resistive load not possible • Few systems in world (±6 off)

5.4 50Hz Sinusoidal

ADVANTAGE	DISADVANTAGE
• P.D. Diagnostics • 50Hz Diagnostics • series resonant set • Mainly in USA	• Weight and size • Expensive • No TD (at present) • High operator skill • Composite cables

5.5 Relaxation & Recovery Method

This is a low voltage method of diagnostic which is still in the development stage and not widely accepted.

5.6 D.C. Testing

Well known DC test sets

ADVANTAGE	DISADVANTAGE
• Cheap • Lightweight • Traditionally used on Paper Cables	• Only stresses resistivity – conductance leakage current. • Does not stress dry joints & terminations (where 75% of faults are). • No P.D. possible • No T.D. possible • Destructive in aged XLPE cables

6.0 PILC CABLES

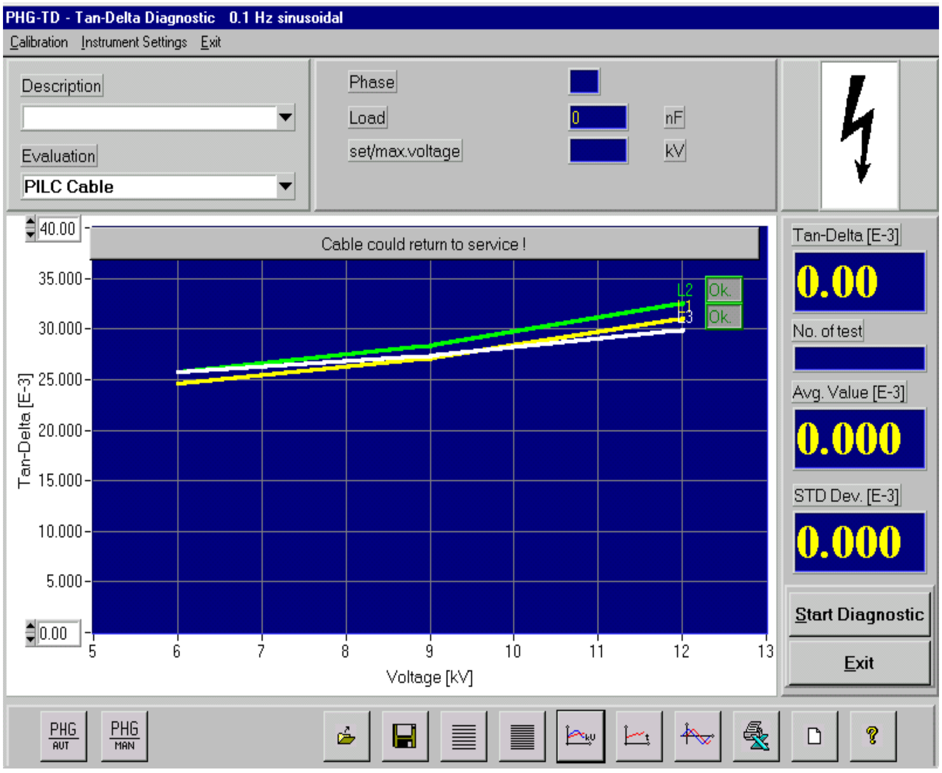
DC testing and the measurement of the final leakage current was the accepted method for testing and the only real test was if the cable failed during over voltage testing. (Yes/No Diagnostics). Crude but true. D.C. testing only requires the charging of the cable once (Capacitance current), and once the dipoles are polarised the leakage current is recorded. Unfortunately unless a finger print is taken during first commissioning, the result is meaningless – even then the leakage over the termination can play a large roll in the leakage current especially on short cables.

AC testing of PILC cables is regulated in the factory by SANS97 (4.3.3) which specifies for 22kV and 33kV (only) a type T.D. test where the TD is to be 6 x 10^{-3} to 14 x 10^{-3} from 0.5Uo to Uo (Uo is max. phase to neutral voltage, No PD is specified in SANS97 for PILC cables.

6.1 Tan Delta Diagnostic Testing

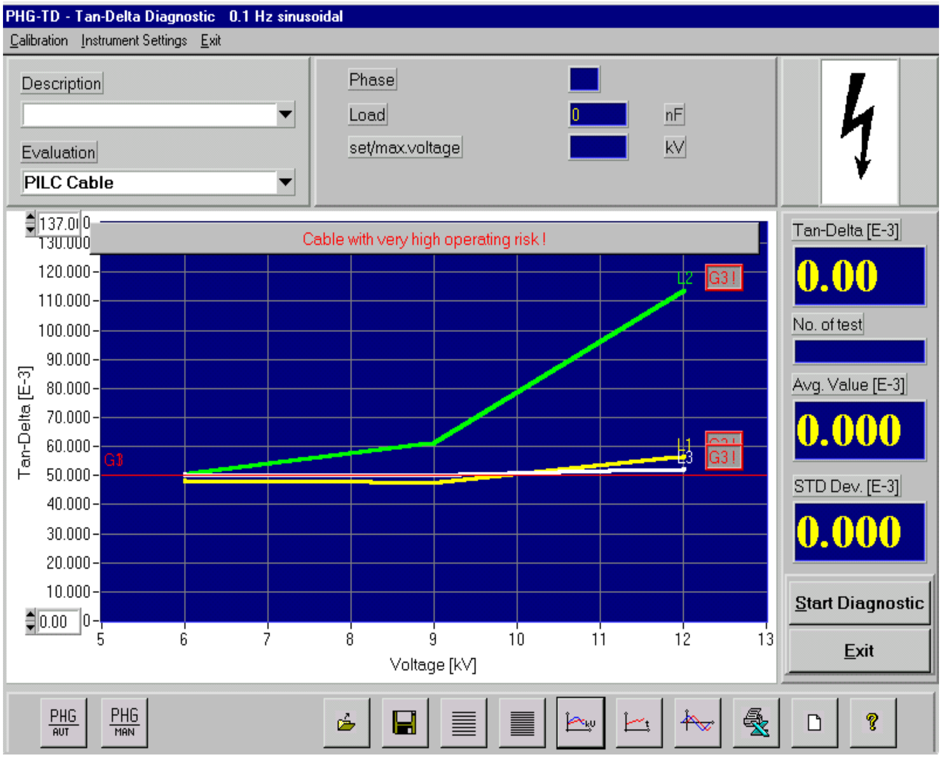
During on site testing at 0.1Hz Sinusoidal of numerous PILC cables it has been found that the Tan Delta of the insulation is an important factor. A cable with a Tan Delta of over 50 x 10^{-3} is considered to be a cable with high risk.

NORMAL TD



Like all other T.D. diagnostics, the T.D. Tip-up is equally of importance

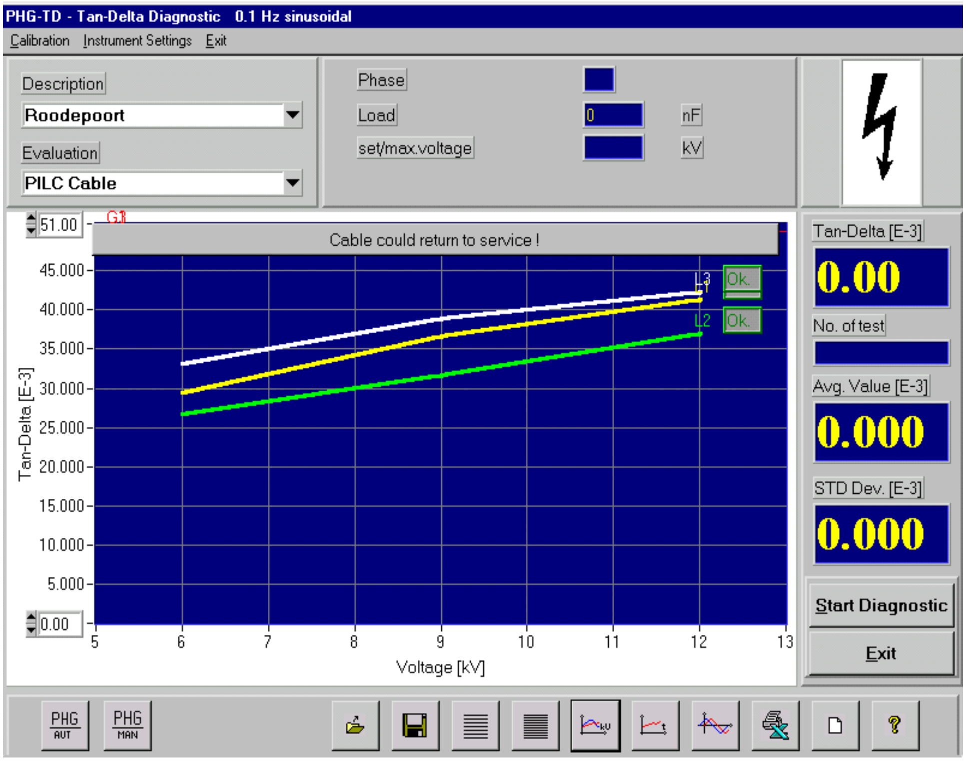
TD TIP-UP



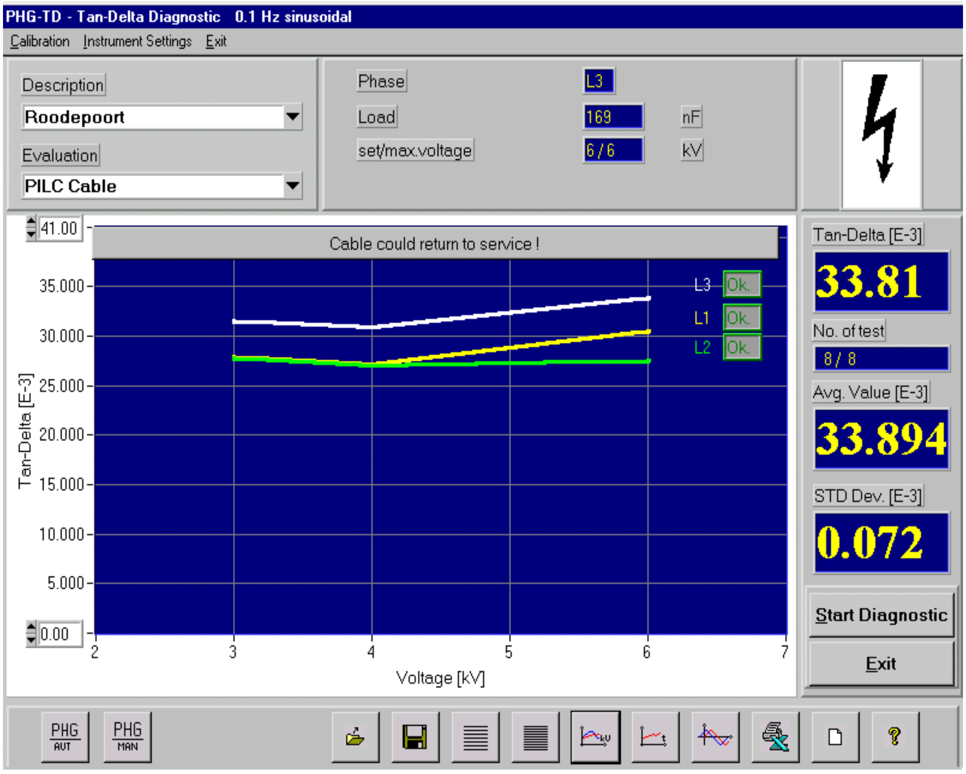
The Tan Delta test indicated that the one core was about to fail. A P.D. test was then done which identified a faulty joint. Real evidence that the tip up was caused by the P.D. activity in the joint.

The advantage of the 0.1Hz T.D. test is that the overvoltage and T.D. can be done at the same time. If there is any risk to the cable, the Tan Delta can be conducted below Uo (operating voltage) which will, even at the low voltage already indicate the quality of the paper/oil dielectric.

2Uo Test

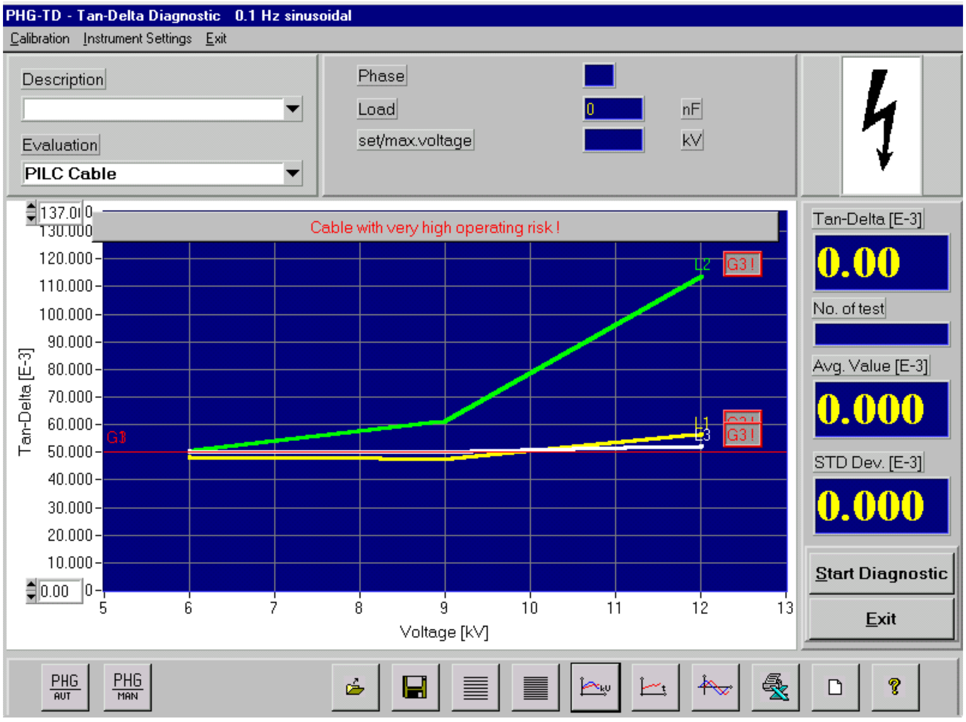


1Uo Test

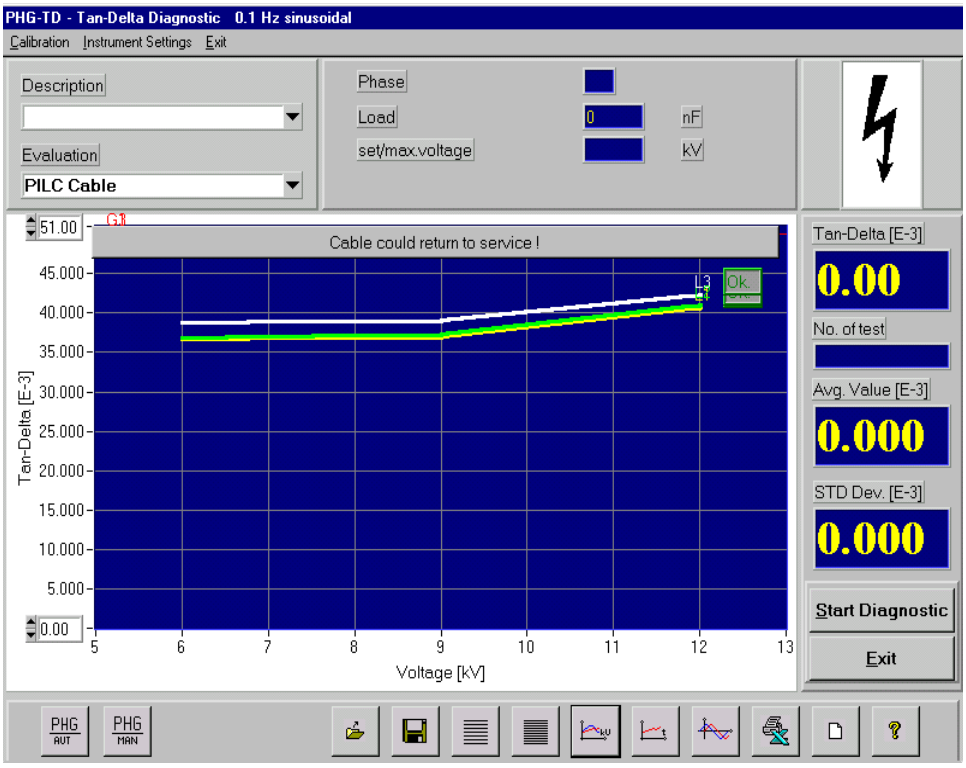


By careful diagnostic T.D. testing of the cable it is possible to cut out the bad sections and recover the good sections, thereby making substantial economic savings.

1 Core with High TD

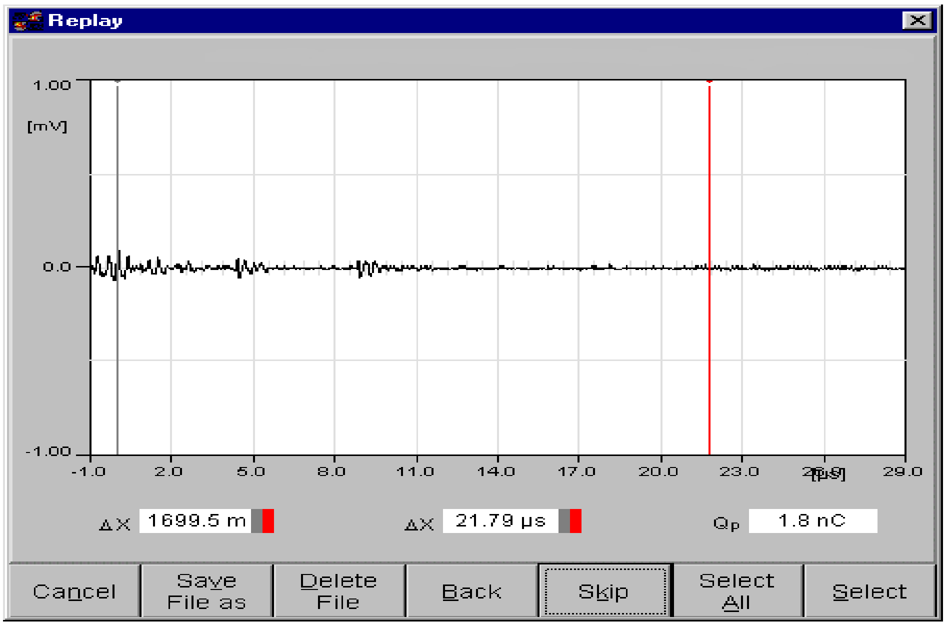


Normal TD



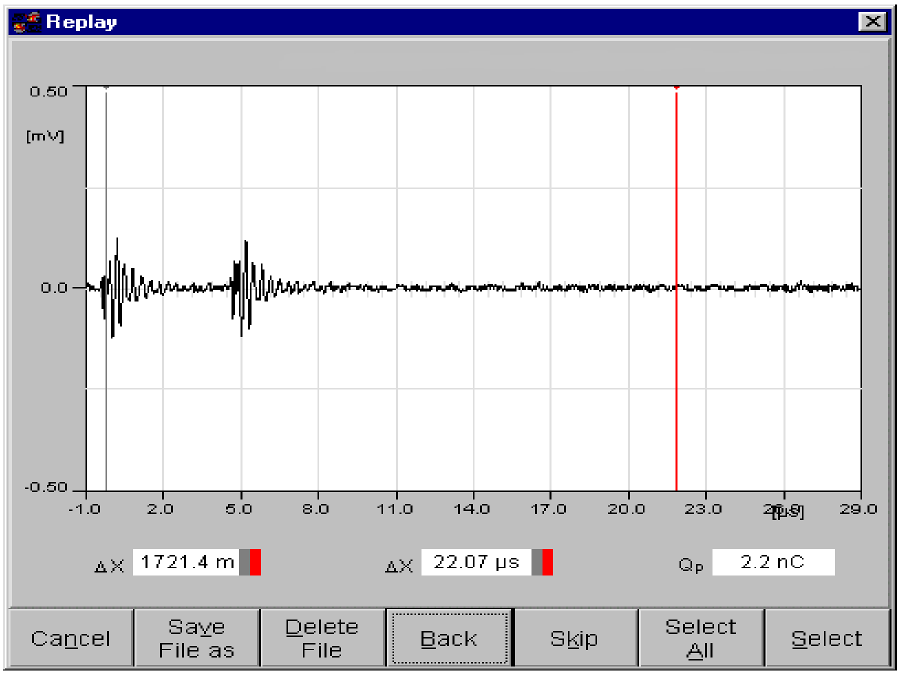
6.2 PARTIAL DISCHARGE IN PILC CABLES

Partial Discharge occurs in a 11kV PILC cable as low as 3-4kV where levels of up to 50pc are easily seen at these low levels and after each PD discharge the cable "heals" itself using the impregnated oil/paper.



The discharge points are seen to normally move along the length of the cable and are not constant at on point.

Where the PD activity at a point is seen to be consistent and above 1000pc (1.73Uo) (at 0.1Hz) level, then this point should be investigated. A good example was where a PILC cable was diagnosed as having discharges at a specific point and this was found to be there was a sharp bend in the cable or in the case below, at a joint.



Faulty joint at 300m - Cable Length 1721.4m

P.D. in a PILC is useful where:

1. The cable oil has drained to the one end and the paper insulation is no longer impregnated with oil.
2. Abnormal bending of the cable.
3. Terminations and Joints which are badly made off. Dry terminations and joints with PD activity above 1000pC (1.73Uo) are cause for concern.

It should be noted that PD must be carried out with a Sinusoidal waveform.
Partial Discharge is just one more added diagnostic tools available on PILC cables where levels of more than 1000pC are possible (when one compares this to XLPE where >5pC is considered unacceptable in the cable dielectric).

7.0 XLPE CABLES

In the factory great emphasis is placed on the overvoltage test and PD test (max 5pC at 1.73Uo) and no T.D. is specified by SANS 1339. In IEC 60840, Table 3 specifies a
TD for XLPE of 1×10^{-3} (max)
PD for XLPE of 5pC (1.5Uo) (max)

On site testing of XLPE has confirmed that TD and PD are important diagnostic tools.

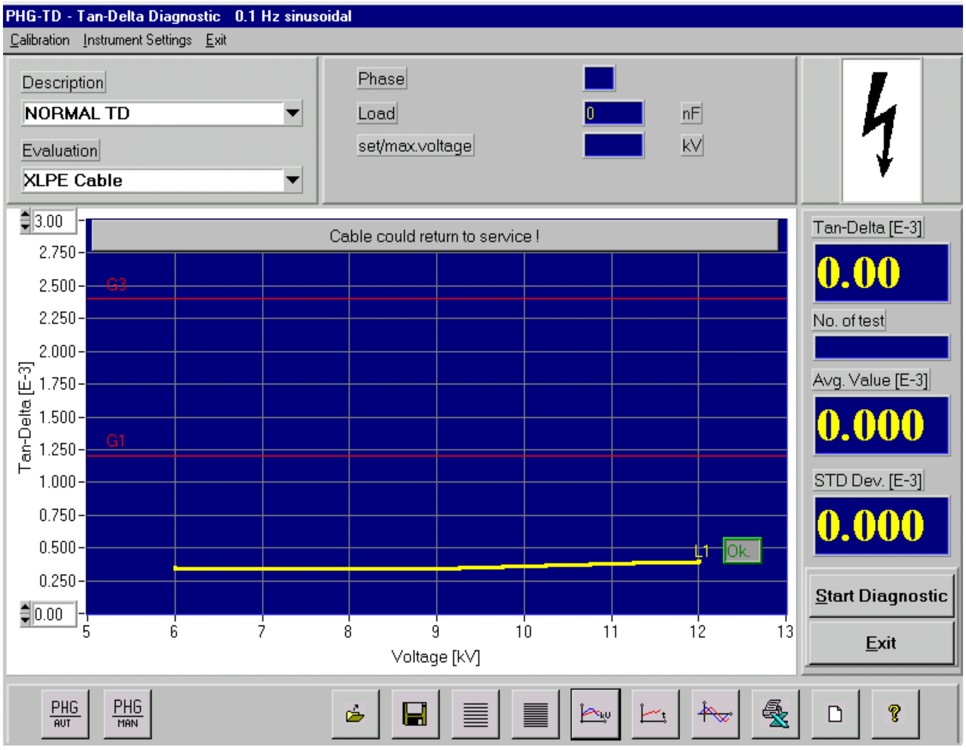
7.1 TAN DELTA DIAGNOSTICS

There are numerous technical papers on the development of the water trees in XLPE cables. A good recipe is water ingress and 50Hz.

Water Trees can easily be detected using the TD whereas P.D. cannot detect Water Trees per se.
P.D. is only possible once the Water Tree has converted to an electrical tree, at which point the cable then fails, which makes P.D. testing impossible.

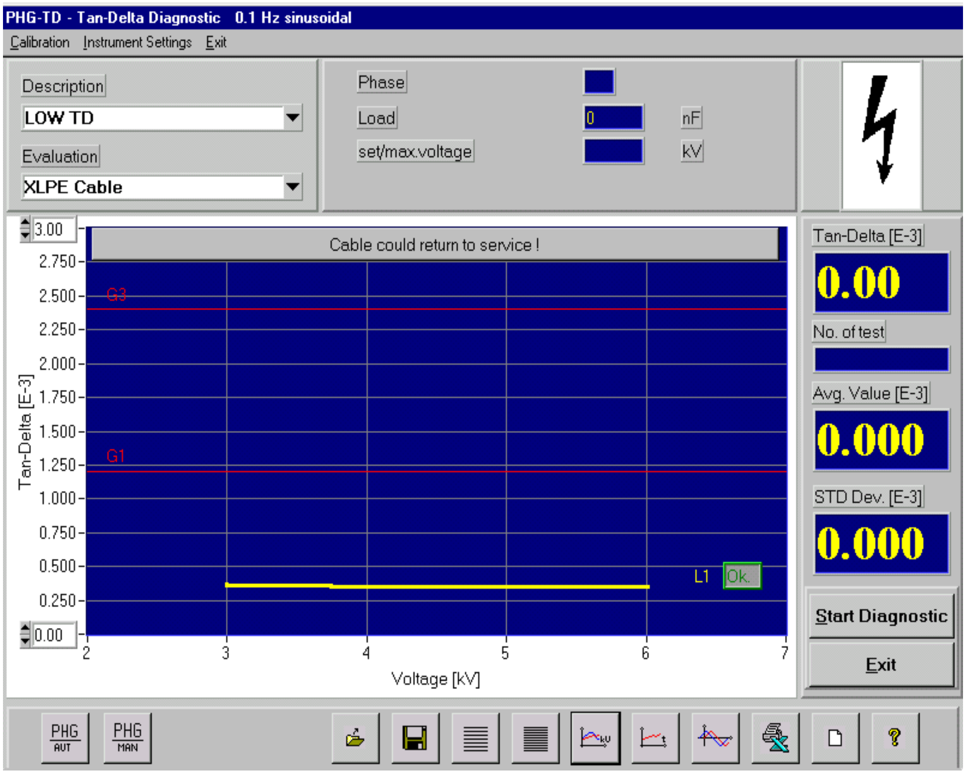
Tan Delta is an extremely important on site diagnostic tool for XLPE cables. Here the TD level is much lower than PILC cables. Cables are considered high risk when testing at 0.1Hz and:
TD $\geq 3 \times 10^{-3}$ at 2Uo (twice phase voltage)
A further criteria is that the TD must not increase by more than 0.6×10^{-3} when increasing the voltage from 1Uo to 2Uo. Another indicator is the well known TD tip up.
Should a drastic tip up in the T.D. occur when testing the cable between 1Uo -> 2Uo failure could be imminent. (see PILC cable below as an example of such a Tip Up).

Normal T.D. (2Uo



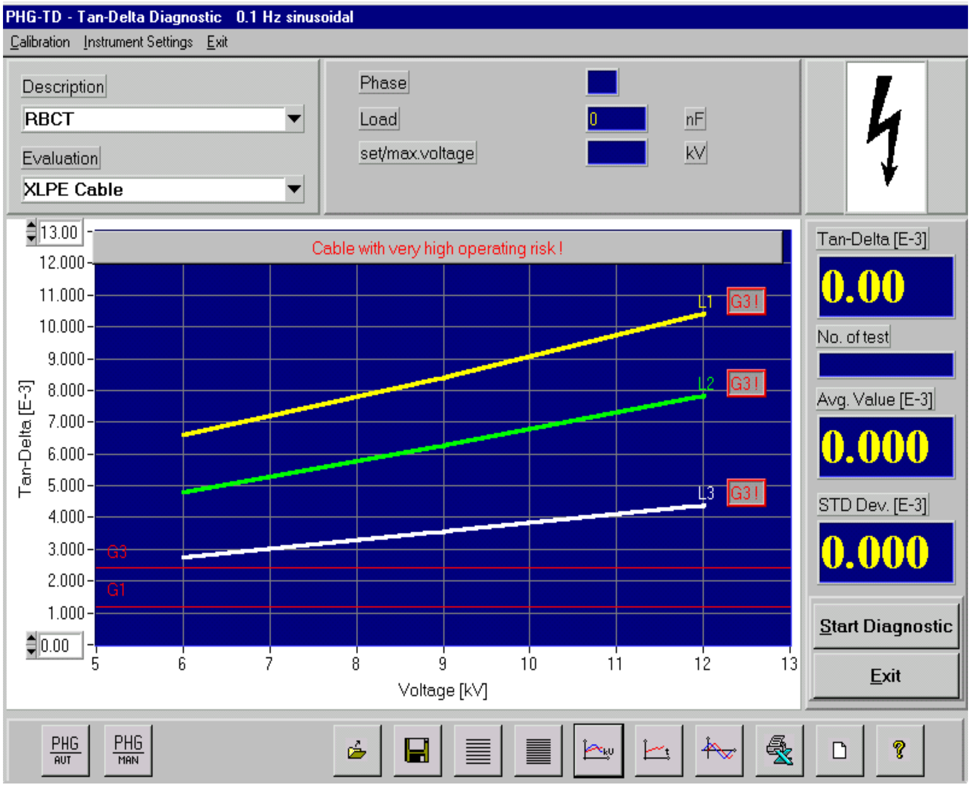
A T.D. taken at ½Uo will already indicate a high risk cable. Consequently cables which are considered critical or thought to have excessive water treeing can be tested well below the operating voltage and obtain a meaningful result. (Non destructive test).

Normal T.D. (1Uo)

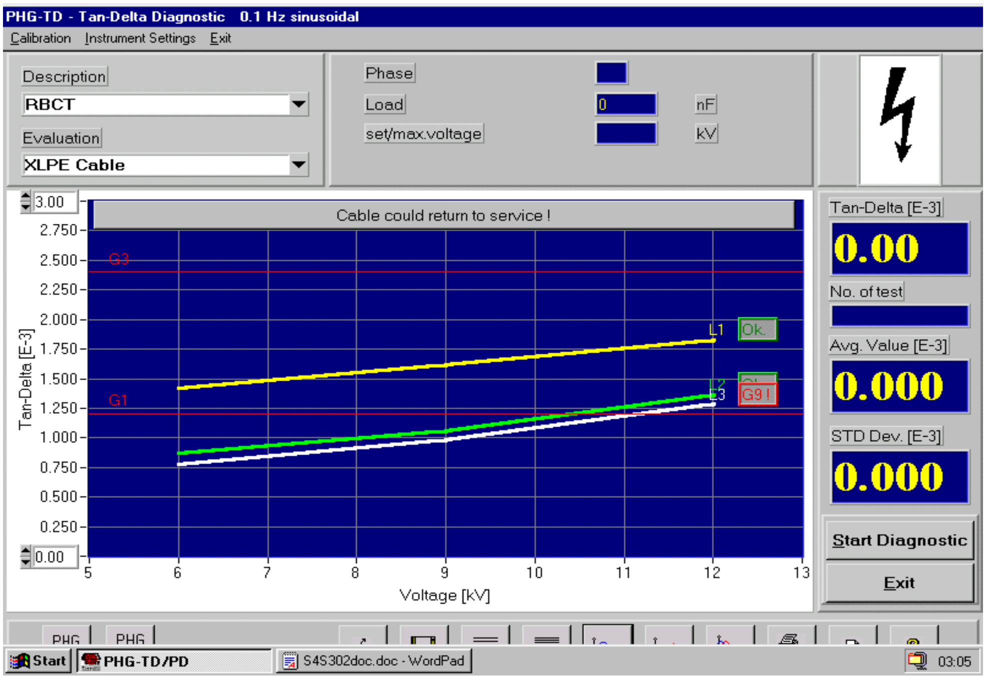


By using these TD and PD diagnostic tools it is now possible to detect bad sections of cable and make major savings in cable replacement – this applies to both PILC and XLPE cables.

High TD Levels



After Cut Back a Good TD was achieved



By cutting back ±20m of cable the Tan Delta reverted to a normal TD

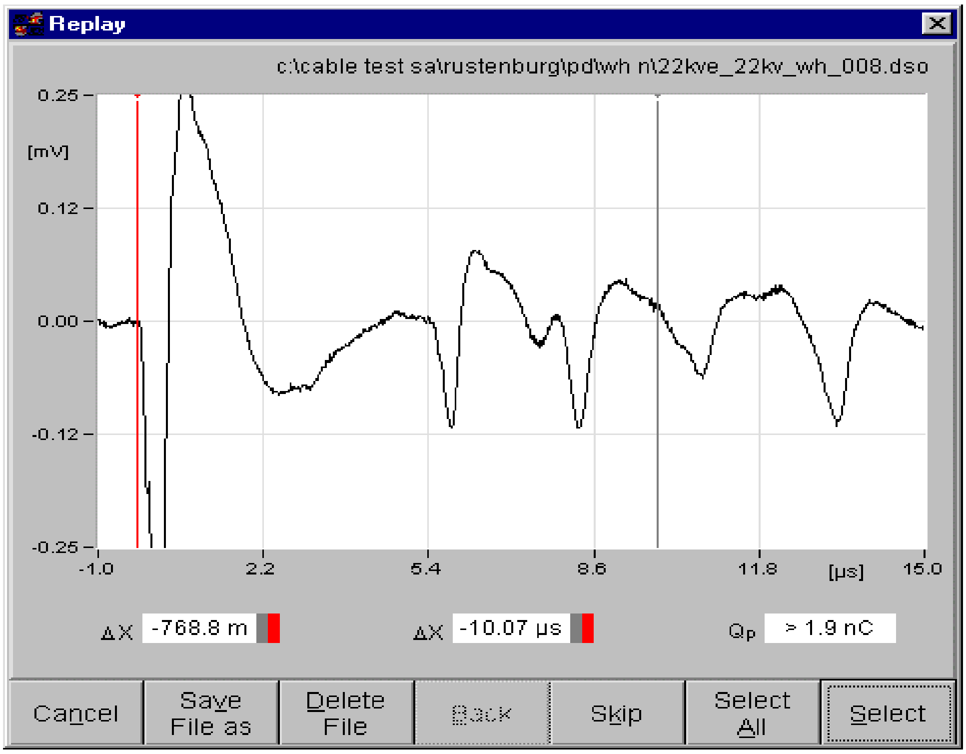
7.2 PARTIAL DISCHARGE DIAGNOSTICS XLPE

P.D. levels $\leq$ 5pC in the XLPE Dielectric are a factory requirement. This was reduced from 10pC a few years back. This extremely low level is indicative of the high quality standards called for by SANS1339.
A cable behaves as a long aerial and background noise during site P.D. measurements could be as high as 20pC. Therefore P.D. discharges in the XLPE dielectric could be difficult to detect, depending on the site conditions.

Between 60-80% of the cable faults (not physical damage) are joints or terminations. Heat shrink joints and terminations could have discharges as high as 2000pC and still operate for years.
This is the area where P.D. diagnostics of XLPE cables is extremely useful. These faulty accessories can be easily identified and located using the P.D. systems available today.

Another very important reason for P.D. Testing is to detect where the Semi-conductive screen has been damaged and discharging is occurring. The outer semi conductive screen can be damaged by:

- Incorrect earthing of the cables
- Circulating currents in the earth
- Water ingress into the outer jacket and the copper tape/wire has corroded away
- Physical damage to the outside of the cable.



Example of erosion of XLPE by PD and Copper tape interaction 33kV XLPE cable

CONCLUSION

Diagnostic Testing of PILC and XLPE cables is possible today with the power of the PC and modern microprocessors.
Tan Delta has proved to be a valuable measurement of the quality and the state of the insulating material whether oil impregnated paper or XLPE.

SUMMARIZING THE DIAGNOSTIC TESTING OF MV PILC & XLPE CABLES AT 0.1HZ.

1. **PILC Cables** (at 0.1Hz)

   Tan Delta $\geq$ 50 x 10^{-3} - high risk cable

   P.D. Activity Cable $\geq$ 2000pC - high risk cable
   Dry Terminations and Joints $\geq$ 2000pC – investigate
   - Will fail with time
   Cable Sheath Test 5kV 1min if outer sheath is of solid dielectric (PVC or XLPE).

2. **XLPE Cables** (at 0.1Hz)

   Tan Delta $\geq$ 3.0 x 10^{-3} - high risk cable
   From 1Uo - 2Uo TD $\leq$ 0.6 x 10^{-3} - High risk cable.

   P.D. Activity in XLPE dielectric - may not be possible because of noise.
   P.D. Activity on outer screen - possible.
   P.D. Dry terminations and joints $\geq$ 2000pC - investigate

Cable Sheath Test at 5kV DC 1min is of vital importance to avoid future problems on XLPE cables.

Cable Diagnostics will identify those cables that are about to fail. MV cables are normally damaged in a specific area or point and it is possible to cut back at a fault until the cable displays normal TD and PD values. It is normally not necessary to replace the whole cable. Reliability is improved and significant financial savings can be achieved.
In new cable installations it is right to assume that the cable was effectively tested at the factory.
However there are major mechanical stresses put on the cable during installation and joints and terminations are made with varying skills. It is therefore important and is strongly recommended to do Acceptance TD and PD testing and a cable sheath test (where applicable).

It is estimated that 60-80% of all cable electrical faults are cable joints or terminations. These joints and terminations don't fail immediately and may take 1-2 years to fail. A TD and PD test will detect these weakness and provide a valuable fingerprint for the future.

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