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Dielectric Spectroscopy for Diagnostics of Water Tree Deteriorated XLPE Cables

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ABSTRACT

A high voltage dielectric spectroscopy system has been developed for diagnostics of water tree deteriorated extruded medium voltage cables. The technique is based on the measurement of non-linear dielectric response in the frequency domain. Today’s commercially available system is capable of resolving low loss and small variation of permittivity as a function of frequency and voltage.

Experience from more than 200 field measurements was combined with laboratory investigations. Small samples were used in an accelerated ageing test to elucidate the correlation between water tree growth and dielectric response. Furthermore, field aged cables were investigated in the laboratory. It has been shown that the dielectric response of water tree deteriorated XLPE cables can be recognised and classified into different types of responses related to the ageing status and breakdown strength.

The influence of termination and artefacts such as surface currents was investigated. The measurement method enables us to separate the response of the cable from the influence of accessories. Finally, two different field studies of the implementation of the diagnostic method are presented. The field studies show that the fault rate decreased significantly when replacement strategy was based on the diagnostic criteria formulated.

1. INTRODUCTION

Extruded polyethylene cables were first introduced on the Swedish market in the late 1960’s. After some years, electric breakdowns due to “water trees” appeared. The first generations of medium voltage polyethylene cables were particularly vulnerable to this type of ageing mechanism [1]. A water tree [2] is a tree or bush like structure that can develop in polymeric insulation under the influence of moisture and electric field. Ageing due to water treeing significantly reduces the electric breakdown strength of the insulation.

It was found [3, 4] that the design of the cables had an important impact on their tendency to develop water trees. Gradual development of design and production technique, such as the use of extruded conductor and insulation screens, have considerably improved the characteristics. This is also confirmed by the fault statistics [3]. Even if the water tree problems of modern cables appear to be limited, large quantities of the earlier generations of polymeric cables are still in service. In Sweden circa 50% of the cross-linked polyethylene (XLPE) insulated cables installed during the early 1970’s are still in service. These cables remain a valuable asset for the utilities. The state of ageing and failure rate of these old cables varies. Some cables are still “as good as new” so to replace them all would be an unnecessary costly option. The replacement cost of one single cable length (ca. 1 km) can exceed 100 000 US$ **,** in urban areas. This cost should be balanced against the cost of power failure. In a society that is more and more dependent on continuous power, a method is needed to help the utilities, presently operating on a deregulated market, for managing their assets in the most economic way so that they can offer their customers inexpensive and reliable power.

There is hence a need for a non-destructive diagnostic technique to assess the quality of the cables and to provide realistic replacement criteria. This was the driving force behind the research project reported in this paper.

In 1992 a project was started at Kungliga Tekniska Högskolan, Stockholm (KTH) with three Ph.D. students with the aim of developing a non-destructive method which could be used to estimate the condition of water treed XLPE cables in the field. In this paper a summary of the results from this project is presented. Parts of the work have been presented as conference contributions [5, 6, 7, 8, 9, 10, 11] and as parts of student's theses [12, 13] but the full picture has never been presented.

It was observed at an early stage [14] that water tree deteriorated XLPE increased dielectric losses. Measurements both in frequency domain [15, 16] and time domain [17] indicated that measurements of dielectric response and, more specifically, the non-linearity in the dielectric response could become the basis for a tool for diagnosis of water tree degradation in cables. In Section 2 we describe the measurement technique used in our work. The system measures in the frequency domain from 0.0001 to 100 Hz at voltages 0-20 kV peak. The problems of guarding and screening when measuring samples with extremely small losses are stressed.

Accelerated ageing experiments that confirmed the link between water treeing and dielectric response are described in Section 3. In Section 4, the relation between electrical breakdown strength and dielectric response is investigated. More than 100 test objects derived from field aged cables were investigated. Both lightning impulse and AC step breakdown tests were performed. The water tree content was checked by conventional optical water tree analysis. As a result of this, quantitative relations between water trees, dielectric response and electric breakdown strength could be formulated.

Section 5 deals with the application of the diagnostic method in the field. The influences of different terminations are given special attention.

In Section 6, experience from field measurements is combined with the results from Section 4 to establish criteria for ranking cables. Based on these criteria cables could be grouped into different categories; good condition, significantly aged and severely aged. This ranking is intended as a guide for the utility when selecting cables for replacement.

Finally in Section 7, two case studies are presented where the diagnostic method was put into real practice. These studies have shown a significant reduction in failure rate after adopting replacement strategy based on criteria, which was established in this paper.

2. MEASUREMENT TECHNIQUE

2.1 CHOICE OF MEASUREMENT TECHNIQUE

The requirements of our measurement technique were

- Non-destructive
- High resolution
- Insensitive to interference
- Adapted for field work

A *non-destructive* technique in this respect means that the cable should not be exposed to risk of failure or accelerated ageing during the measurement. Our main philosophy is that the electric stress during the diagnostic measurement should not exceed the service stress. It is important at this point to make a clear distinction between high voltage (withstand) testing and diagnostic measurements.

The main target was to investigate medium voltage cables of design voltage 12 kV and 24 kV. The capacitance of such cables can run into the μF range and measurements at power frequencies imply access to significant (reactive) power. It is advantageous to use low frequencies for fieldwork, which enables the use of compact and light equipment

High resolution means the detection of slightly to moderately aged cables that can still operate safely but could be considered for replacement within a five-year period. In practice this means that our instrument must resolve e.g. loss tangents smaller than 10^{-4}. Stability and high resolution is more important in this application than absolute accuracy.

Both frequency and time domain measuring techniques were considered and resulted in the development of a high voltage frequency domain measuring system. In fieldwork it is very important to be relatively *insensitive to electrical interference*. This was one of the main reasons for choosing frequency domain techniques.

One of the goals of the project was to develop a measurement technique *adapted for fieldwork*. During the project a transportable and rugged measurement system was developed and a fast and well-defined measurement procedure established.

2.2 THE MEASUREMENT SYSTEM

No commercial system fulfilled all our requirements so a new system for measurements of dielectric response at high voltage and variable frequency was built. The design which was based on previous experience [18, 19] was further developed for high sensitivity and its suitability for fieldwork.

Figure 2.1 presents an overview of the measuring systems capable of measuring non-grounded as well as grounded objects. The frequency response analyser (FRA) outputs a sinusoidal voltage. This signal is low pass filtered and applied across the sample (cable) via the high voltage amplifier, TREK 20/20 [20]. The applied voltage is measured via a high voltage divider.

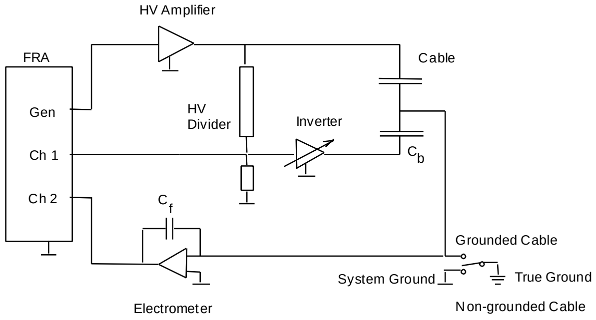

Fig. 2.1 Schematic drawing of the measurement system.

The current into the electrometer is the sum of the sample current and the current through the balancing arm. The balancing arm includes an inverter and a capacitor. The balancing reduces the electrometer input current and relaxes the requirements of accuracy and bandwidth of the electrometer. These requirements were transferred to the components of the balancing arm instead

To achieve sufficiently high accuracy, it is essential to take the non-ideal behaviour of all the components into account. Corrections are implemented in the software and calibrated against measurements on gas insulated capacitors.

The most significant corrections are due to the phase shifts in divider and inverter. Also the lead resistance, especially in the balancing arm, are taken into account. The dispersion in the balancing and feedback capacitors (C_f and C_b) was modelled as "universal capacitors" [21] with a frequency dependence w^n where n is a small number corresponding to the flat loss frequency dependence observed in low loss polymers [22]. Liquid nitrogen cooled polypropylene capacitors in the balancing arm was used for the most demanding measurements.

The high voltage amplifier is a TREK 20/20 with a maximum output of 20 mA and 20 kV peak. The built-in voltage divider introduced too high phase shifts and several different dividers were tested. Both resistive and capacitive dividers were built and modelled in the software.

In the first set-up, a Solartron 1250 [23] was used as FRA. This equipment was mainly used for the laboratory measurements (Section 3 and 4). The performance of this equipment was quite satisfactory but later versions, particularly designed for fieldwork, were built [6]. These versions use digital signal processing cards [24, 25] directly connected to a personal computer. The signal inputs are equipped with 16 bit A/D converters and anti-aliasing filters. The output has a combined low-pass filter and buffer allowing measurements on capacitive loads up to mF.

For large test objects (capacitances) the maximum output current of the TREK 20/20 high voltage amplifier limits the achievable voltage frequency product.

$$U_{MAX} \cdot C_{MAX} \cdot f_{MAX} \leq 2 \cdot 10^{-3} A \qquad \text{Equation 1}$$

Clearly, it is advantageous to measure at low frequencies. The performance of the measurement equipment is summarised in Table 2.1 below. The measurement technique has developed further hereafter and is commercially available today [26].

Table 2.1 Summary of basic properties of the measurement instruments used in this paper

Voltage output	0-20 kV peak
Frequency range	10^{-4} - 10^{2} Hz
Resolution	Loss tangent < $5x10^{-5}$ Relative change in Capacitance < $1x10^{-4}$

2.3 MEASUREMENT PROCEDURE

The measurement starts with a balancing procedure performed under software control. Balancing takes place at the highest frequency used in the particular measurement. The inverter gain is adjusted to minimise the capacitive part of the electrometer input current.

After balancing, the instrument proceeds to measure at the pre-selected frequencies and voltages. A number of frequencies are measured at several voltage levels. The real and imaginary parts of the capacitance are determined and stored in the computer. The real part of the permittivity is normally presented as the difference ($\Delta e'(w)$) between the value at the balancing frequency and at the measurement frequency.

One important parameter is the applied voltage, usually expressed as a fraction of the service phase voltage, U_0, defined as the system phase to ground r.m.s. voltage where U_0 is 6 kV and 12 kV respectively, for the system voltages of 10.5 kV and 21 kV.

A voltage dependence, non-linearity, of the response generates harmonics. The Fourier components of the voltage as well as the integrated current signal can also be stored.

The parameters defined in Table 2.2 are used for diagnostic purposes, and are normally measured as a function of frequency, $f = \omega/2\pi$.

Table 2.2 Parameters used for diagnostic purposes

$e'(w)$	The real part of the relative permittivity
$\Delta e'(w)$	The change in the real part of the relative permittivity
$e''(w)$	The dielectric loss, the imaginary part of the relative permittivity
$\tan d(w)$	Loss tangent = $e''(w)/e'(w)$

$\Delta e'(w)_{nonlin}$	Increase of $e'(w)$ typ. from $0.5U_0$ to U_0
$\Delta e''(w)_{nonlin}$	Increase of $e''(w)$ typ. from $0.5U_0$ to U_0
q(k),u(k) *k=1, 2, 3, ...*	Fourier coefficients of integrated current and voltage

2.4 GUARDING AND SHIELDING OF THE MEASURED OBJECTS

Measuring low loss insulation requires careful guarding and shielding of the measured object. This is of particular importance when measuring small samples or short cables. On short cables this is accomplished by separating the terminations from the measuring electrode, thereby avoiding the influence of the terminations and the creep current at the ends. The arrangement of guarding and shielding is schematically shown in Fig. 2.2.

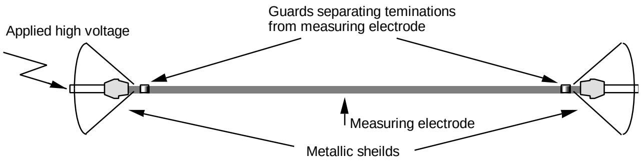

Fig. 2.2 Cable being measured, equipped with guards separating terminations from the insulation screen (measuring electrode) and metallic shields for minimising the coupling from the termination ends to the measuring electrode.

To avoid high field strength in the guard path, which could lead to creep currents, the guard distance must be kept short. If, in conjunction, a conducting layer is used to press down the field lines in the guard path as shown in Fig. 2.3, the length of the guard path is not so critical [16].

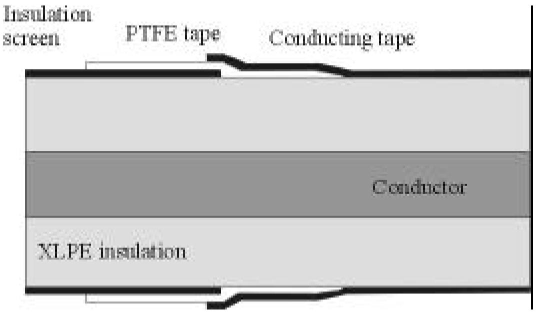

Fig. 2.3 Schematic drawing of the guard which is separating the insulation screen from the termination.

When measuring very low loss well guarded short cables, the coupling from the insulation surface at the termination to the measuring electrode may cause measurement problems [6]. In order to make proper measurements and avoid this effect, the termination ends should be shielded from the measuring electrode (Fig. 2.2).

3. ACCELERATED AGEING OF SMALL XLPE SAMPLES

3.1 MOTIVATION FOR ACCELERATED AGEING STUDY

When performing accelerated ageing there is always a risk that the ageing mechanism is not the same, or not even relevant, in the real case. There are, however, good reasons for performing also such studies. One advantage is that the samples and ageing conditions can be well defined and it is possible to monitor the progress of the water tree growth in time. This also helps in developing measurement equipment and strategy. Finally, we wanted to test the hypothesis that water tree amount and length correlate to the measured dielectric response [8, 12].

3.2 EXPERIMENTAL

3.2.1 Samples and sample preparation

To facilitate comparison with results obtained by other researchers, we adopted the same procedure for sample preparation as that used by Bulinski et al. [27]. It was also fortunate to have the same person preparing the XLPE plates [28].

Commercially available material was used such as NCPE4201 from Borealis [29]. Polyethylene granulates were melted and extruded into a tape. After moulding and cross-linking, the samples were degassed in a vacuum oven at 70 ºC for 24 h. The samples were sandblasted prior to the ageing.

3.2.2 Sample holder

The sample holder and the sample are sketched in Fig. 3.1. The design is similar to the sample holder used by Bulinski et al. [27] but with the important addition of a guarded measuring electrode that allows for dielectric measurements *in situ*. The measuring electrode consists of a thin layer of evaporated aluminium. The sample was placed on a block of stainless steel that provided quite satisfactory guarding of stray fields and leakage currents. The sample thickness was 1.0 mm and the capacitance of each sample was ca 10 pF.

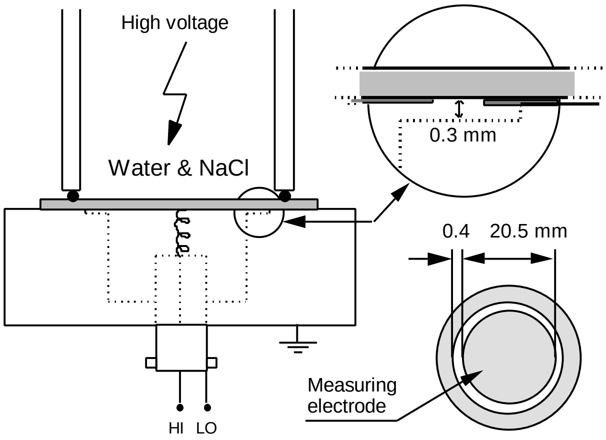

Fig. 3.1 Sample holder for small sample ageing and measurements.

3.2.3 *Ageing conditions*

A number of factors that affect the water tree growth [2] had to be considered when preparing the samples such as: material composition, sample preparation, water salinity, voltage level, frequency, temperature and mechanical stress. The influence of sandblasting, salinity and frequency was initially studied to define the experimental conditions. Finally, we chose the following conditions:

- Room temperature (22 ºC)
- Applied field 4 kV/mm @ 50 Hz.
- Ordinary tap water with 0.1 M NaCl

The high-voltage was connected to the water via a platinum wire. Eight samples were aged in parallel and a sample was taken out for optical water tree analysis every second day. The chosen conditions led to a tree length of ca 150 µm or 15% of the total insulation thickness after sixteen days.

3.2.4 *Measurement procedure on small samples*

Other people's measurements [14] in addition to those we made showed that the dielectric response of the aged samples depended on the duration and level of applied voltage and sequence of voltage application. For this reason it is important to use a well defined measurement procedure. The chosen procedure consisted of three sets of frequency sweeps in sequence: an initial set of short sweeps, a set of long sweeps and lastly a repetition of the short sweeps.

The initial short sweeps were performed directly after switching off the ageing voltage. The sets of short and long sweeps were defined as follows:

Short sweeps: Four frequencies from 10 to 1 Hz at each voltage level. Voltage levels 2, 1.5 and 1 kV. Total duration of all measurements included in the set of short sweeps is ten minutes.

Long sweeps: Sixteen frequencies from 100 to 0.001 Hz at each voltage level. Prior to each sweep the sample was short-circuited for one hour. Voltage levels were 2, 1.5 and 1 kV.

The average insulation stress for medium voltage XLPE cables in service is approximately 2 kV/mm (e.g. 12kV/5.5mm=2.2kV/mm and 6kV/3.4mm=1.8kV/mm). Therefore, the highest voltage level during diagnostic measurement was chosen to be 2 kV.

3.2.5 *Optical water tree analysis*

The aged samples were cut into 0.25-mm thick slices and optically analysed. The water tree length parameter was determined by drawing a straight line in line with the treetops. The tree length was then estimated by measuring the distance between the line and the insulation surface. The water tree amount was determined by enclosing the trees with ellipsoids and summing up the total tree volume and dividing it with the total volume. Both the length and the amount of the water trees were found to increase with ageing time (Fig. 3.2).

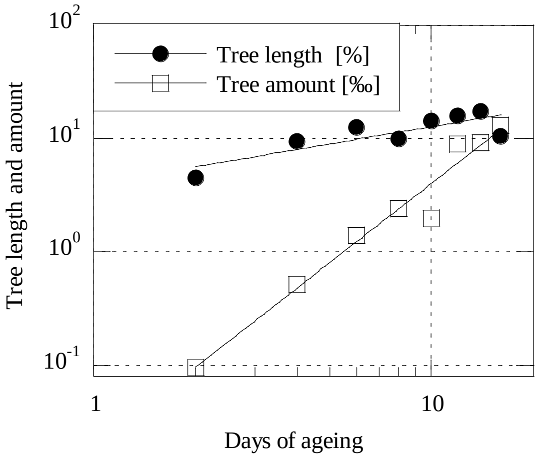

Fig. 3.2 Relative length and relative amount of water trees as a function of ageing time.

3.2.6 *Dielectric response measurements*

The dielectric response was measured before the samples were taken out for optical water tree analysis. The real ($\Delta e'$) and imaginary (loss) part (e'') of the permittivity was calculated. The real part measurements present the difference between the actual measurement and that at the balancing frequency 100 Hz. Measurements were also performed on a reference sample which was placed in water but without applied electric field.

Figure 3.3 shows results after 16 days of ageing. Several observations can be made. The dielectric losses are much higher for the aged samples, depending largely on the applied voltage and change during the measurements. Both time dependence and voltage dependence were obtained.

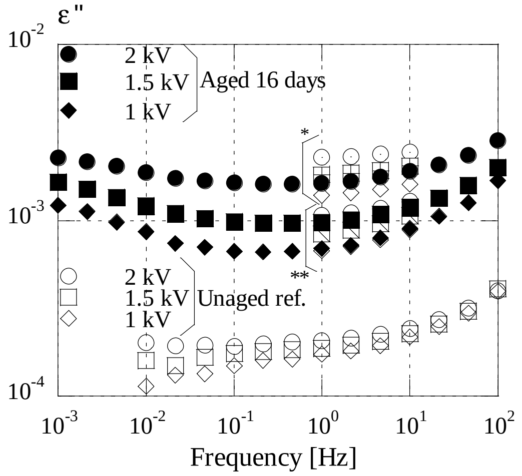

*Fig. 3.3 Dielectric loss, $e''(w)$, as a function of frequency for a sample aged for 16 days and a reference sample. * Short sweeps immediately after ageing power is disconnected. ** Short sweeps immediately after the long sweeps.*

Both the change in real part of permittivity, $\Delta e'(w)$, and loss, $e''(w)$, increases with ageing time (Fig. 3.4).

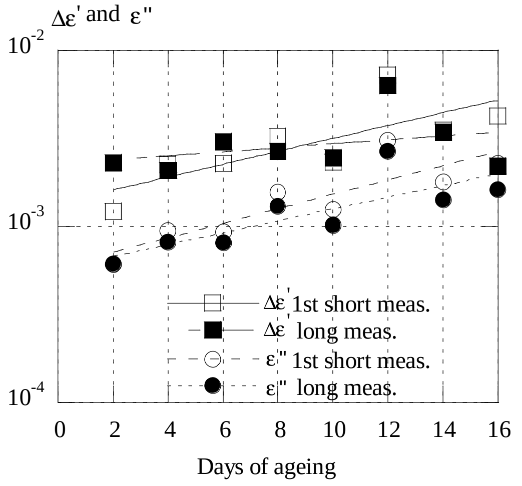

Fig. 3.4 Change in the real part of permittivity and loss as a function of ageing time, values shown for U = 2 kV and f = 1 Hz.

The non-linearity was also studied by analysing the harmonics in the measured integrated current. The ageing produced a significant increase in especially the third harmonic. This observation is consistent with what others observed [16, 30] and with what we later observed in field aged cables (Section 4).

In fact, most of the features of the small samples that were observed are also characteristic for water tree deteriorated field aged cables, as can be seen below.

3.2.7 Relation between non-linear dielectric response and water trees

The electric measurements were related to the amount and length of the water trees determined by optical examination of the samples. The non-linearity was characterised by taking the difference between measurements at 1 kV and 2 kV. The voltage levels correspond to 1/2 U_0 and U_0 for medium voltage XLPE cables, see Section 3.2.4.

It was found that the water tree amount (relative volume) correlates well with the non-linear dielectric response (Fig. 3.5).

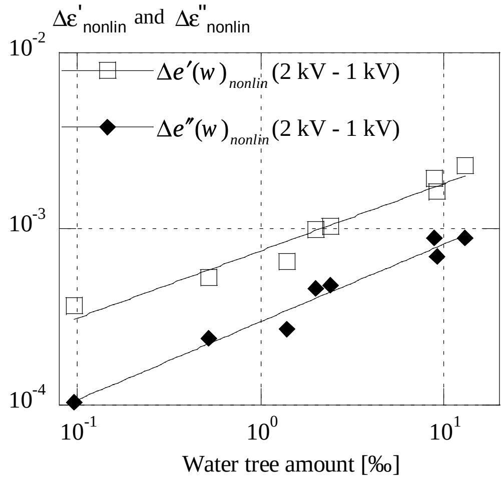

Fig. 3.5 Relation between the relative amount of water trees and the non-linear response.

3.3 CONCLUSIONS OF THE SMALL SAMPLE EXPERIMENTS

The sample experiments gave some valuable qualitative conclusions for further studies of real cable insulation. A non-deteriorated sample has linear dielectric response with low loss, while a water tree deteriorated sample has increased loss and voltage dependence in both loss and permittivity. Earlier applied voltages also influence the measured response. Therefore, it is important to follow a well-defined measurement procedure. The loss level as well as the non-linear effect in the loss and the permittivity correlates well with the water tree length and water tree amount of the sample. Water trees, which are considerably shorter than the insulation thickness can be detected.

4. WATER TREES, BREAKDOWN STRENGTH AND TYPE OF DIELECTRIC RESPONSE

4.1 INTRODUCTION

The experiments described in Section 3 verified the correlation between water tree content and dielectric response parameters for artificially aged samples. The question was whether corresponding relations could be found for real cables aged under normal service conditions and whether the responses also could be related to the remaining insulation strength of the cables? These questions are dealt with in this section.

More than one hundred field aged cable samples were investigated in the laboratory. A few cables were used for establishing a stable measuring procedure. Most of the cables were exposed to dielectric response measurements, breakdown tests and optical water tree analysis. The breakdown study comprises two investigations performed on a total of 96 samples from thirty-two different cables of different design and state of ageing. The first investigation included breakdown tests with standard lightning impulse. In the second investigation AC breakdown tests were performed. A selection of cables measured in the field is also included in this section.

The results show that dielectric response measurements can be used to determine the condition of service aged cables. In Section 4.6.2 different types of cable responses are described and how the cable responses relate to water tree deterioration and breakdown strength.

4.2 TYPES OF CABLES INVESTIGATED IN LABORATORY

XLPE insulated cables, with different designs and coming from all around Sweden, that were commissioned between 1970 to 1980 were collected and sent to the laboratory. The ambition was to collect cables with a good spread in ageing status.

In Investigation 1 (Lightning Impulse (LI) Test), five different three-phase cables were used, making a total of 15 cable samples. The cables were installed between 1970 and 1976 and came from two different manufacturers and were collected from two different utilities. The cables had an extruded conductor screen and the insulation screen constituted tape and graphite type. The conductor material was aluminium and the area varied between 95 mm^2 to 185 mm^2.

In Investigation 2 (AC Step Test), 27 three phase cables, twelve 12 kV cables and fifteen 24 kV cables, from four different manufacturers were investigated i.e. a total of 81 cable samples. They were installed between 1970 and 1980. Two cables were spare cables and have never been installed, although manufactured around 1970. This resulted in a material with a fairly good spread in ageing status. All cables had an extruded conductor screen, but the insulation screen constituted three different types: tape and graphite semiconductor, taped semiconductor, and an extruded strippable semiconductor. The conductor was made of both copper and aluminium and the area varied from 35 mm^2 to 300 mm^2.

4.3 EXPERIMENTAL PROCEDURE

In order to establish a reliable procedure, studies were made to determine the possible influence of the preconditioning of cable samples on the measured dielectric response.

4.3.1 Voltage duration

The small sample tests presented in Section 3 show that the voltage duration affects the dielectric response. Measurements were made on both a new and a water tree deteriorated cable sample in order to study the phenomena for a real cable [13]. 50 Hz voltage equal to U_0 was applied to the cable samples during 12 hours and dielectric measurements at 1 Hz were performed at regular intervals during that period. Both real part of the permittivity and dielectric loss of the aged cable increased during the first hour after the voltage application and then stabilised. The new cable was not influenced.

4.3.2 Influence of humidity

In order to investigate the humidity influence, also studied by others [17, 31, 32], two cables were selected, cable A (a new 12 kV cable) and cable B (a water tree aged 24 kV cable taken from service) [5]. The cables were measured in both a dry and a wet condition and during drying and wetting. The wetting was accomplished by placing each cable in a plastic tube filled with water. The cable was dried by means of heating in an oven at 80 ºC.

Figure 4.1 shows the dielectric responses in dry and wet conditions of the cables. When the aged cable (B) was wet, after having been stored in water for more than six months, the loss was high and very dependent on applied voltage level. The non-linearities appear over the whole frequency range. As the cable was drying the response became both smaller and more linear. In dry conditions the loss was low and the cable looked almost like the new cable (A), though with greater loss at lower frequencies. The new cable (A) looked the same whether dry or wet. Obviously the humidity in the cable environment has a great influence. If e.g. an aged cable is left to dry, the dielectric losses are reduced and approach the loss level of a new cable.

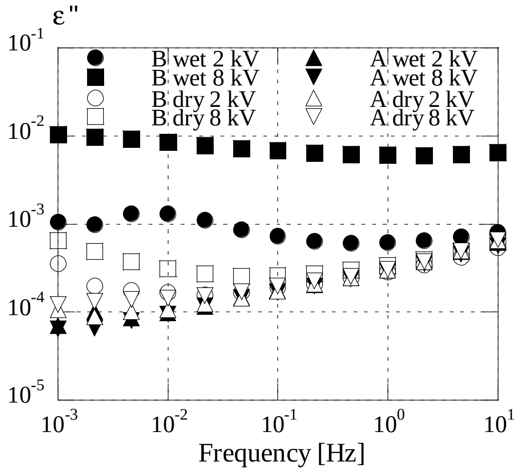

Fig. 4.1 Dielectric loss, $e''(w)$, as a function of frequency for a new (A) and an water tree aged (B) cable in wet and dry conditions.

4.3.3 Temperature dependence

Temperature studies were made on a significantly water tree deteriorated cable. A 2-m long cable, which was stored in water for two years, was placed in a plastic pipe with water. The arrangement was inserted into a temperature-controlled tube. The temperature was varied between 25 and 10°C and dielectric response measurements were performed at various temperatures. The cable was allowed to rest at each temperature sufficiently long so as to obtain moisture equilibrium [10].

The results showed slight temperature dependence in the dielectric response. The loss and the non-linearities increased with increasing temperature. However, the temperature dependence was so small that it did not change the judgement of the cable.

4.3.4 Procedures

All the test objects were prepared with guards, and those cable samples included in Investigation 2 were additionaly shielded, see section 2.4. The effective cable lengths (between the guard paths) were approximately 10 m in Investigation 1 and 5 m in Investigation 2.

In Investigation 1 (LI Test) the cables were taken out of service approximately one week before the measurements and stored outdoors.

In Investigation 2 (AC Step Test) special care was taken to obtain well-defined environmental conditions before and during the measurements. The cables were stored in tap water during at least 6 months. The cables were then energised at U_0 a period of 15 hours prior to the measurements.

In Table 4.1 the main procedure for Investigation 2, is shown. The measurement procedure consists of a number of frequency sweeps at increasing voltage levels up to U_0 followed by one or two sweeps at lower voltage. Two measurements at each frequency were done. The harmonic contents of the voltage and dielectric response were also recorded.

The 12 kV cables included in Investigation 2 were also measured using a procedure up to a highest voltage level of $2U_0$.

Table 4.1 The main procedure of dielectric response measurement used in Investigation 2 consisted of 6 frequency sweeps at different voltage levels performed in consecutive order as indicated in the table

Sweep no.	Voltage [kV]	Frequency range [Hz]
1	$0.25 \bullet U_0$	1 - 0.2
2	$0.5 \bullet U_0$	1 - 0.1
3	$0.75 \bullet U_0$	1 - 0.2
4	U_0	1 - 0.1
5	$0.5 \bullet U_0$	1 - 0.2
6	$0.25 \bullet U_0$	1 - 0.1

4.4 BREAKDOWN TESTS

The breakdown tests in Investigation 1 were done with standard lightning impulse according to IEC 60. Before the lightning impulse tests, the cable was split into its three phases to avoid possible damage to the adjacent phases at breakdown. The tests started at 24 kV and the level was then increased in 10 kV steps until breakdown occurred. Three negative impulses were applied at each level.

In Investigation 2 an AC step test was used with a starting voltage equal to U_0. The voltage was increased every 5 minutes by 20% until 2.5 U_0 was reached. Thereafter, 0.5 U_0 steps were used until breakdown occurred. The AC step test was made with all phases in the jacket since the limited current at breakdown did not affect the adjacent phases.

In the following the term normalised breakdown strength, U_{bd}/U_0, will be used and is defined as the ratio between breakdown voltage and system phase voltage. After the breakdown tests a short piece of the cable was cut off in the vicinity of the breakdown point and water tree analysis was made.

4.5 OPTICAL WATER TREE ANALYSIS

The water tree analysis was made on a 5-mm sample taken in the vicinity of the breakdown point. The sample was cut into 10 slices, each 0.5-mm thick, and the density and maximum length of the vented trees from the insulation screen was recorded. Three of the slices were selected for determination of the distribution of the length and width around the circumference. The volume of the water trees was then calculated by approximating the water trees by an ellipsoid. Image analysis equipment [33] was used in the analysis.

4.6 RESULTS

4.6.1 Water tree analysis

The analysed cables showed water trees with different shapes and densities, and in Fig. 4.2 some typical examples are shown. The water trees in cables with tape and graphite insulation screens were normally thin and long with a high density. The water trees in cables with tape-only insulation screens had less density and various shapes. The cables with strippable insulation screens showed few water trees but they were in some cases large in both length and width.

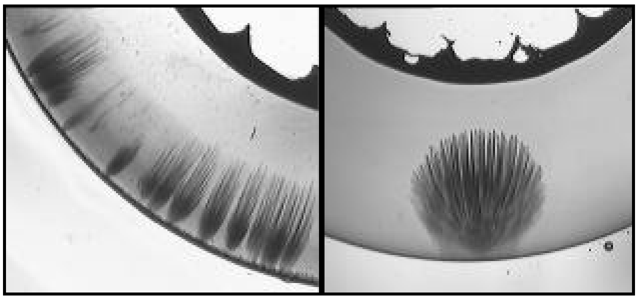

Fig. 4.2 Typical water trees found in field-aged cables. To the left, trees from a cable with tape and graphite insulation screen. To the right trees from a cable with extruded insulation screen.

A clear relation between water tree length and electrical breakdown strength was derived from the results of Investigation 2, (Fig. 4.3) which verified earlier studies [2, 34].

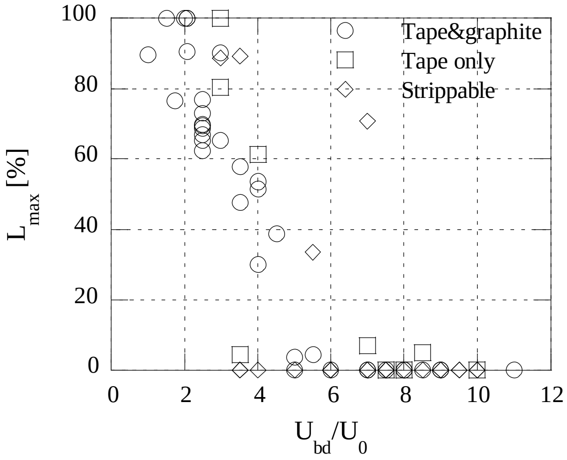

Fig. 4.3 Relation between normalised breakdown strength, U_{bd}/U_0 , and longest observed water tree in investigated cables. The results are from Investigation 2.

It is important to note that the analysis was only made on five-mm pieces of each cable. The analysis may therefore not give the correct picture of the whole cable length; in particular of the cables with strippable insulation screens that had relatively few but large water trees.

Thereafter, a few cable samples with relatively low breakdown strength and with no water trees found were further investigated. Half a meter of the insulation screen was removed and the insulation surface was visually inspected. As expected, water trees were found in those cable samples as well.

4.6.2 Types of dielectric responses

In this section we introduce a classification of different types of responses from cables. The response types were first identified during field measurements. The same types were found in the laboratory investigations and could be related to breakdown strength and water tree ageing.

Low Loss Linear Permittivity (Type LLLP):

The LLLP response is characterised by an almost frequency independent $e'(w)$ of approximately 2.3. The loss, $e''(w)$, is low, in the range of 10^{-4}, and has also a very weak frequency dependence. Both $e'(w)$ and $e''(w)$ are independent of applied voltage, i.e. the insulation material is linear. LLLP response is typical for new or non-water tree deteriorated cables.

The dielectric response of a water tree deteriorated XLPE cable is divided into three types, which are characterised by their frequency and voltage dependence.

Voltage Dependent Permittivity (Type VDP):

The VDP response is characterised in that both $e'(w)$ and $e''(w)$ increases with increasing voltage. The increase is almost independent of frequency (Fig. 4.4). As mentioned in Section 3.2 and 4.3, the response of water tree deteriorated XLPE cables is both voltage and time dependent. A repeated measurement usually yields a slightly higher permittivity and loss.

The measurement procedure consists of a number of frequency sweeps at increasing voltage levels followed by one or two sweeps at a lower voltage. The last sweeps at lower voltages are used for revealing this voltage and time dependence. In Fig. 4.4 this phenomena is shown where the last sweep at 3 kV (4: 3 kV) is affected by the previous measurements at higher voltages. Both $\Delta e'(w)$ and $e''(w)$ are increased by previous measurements at higher voltages compared with the initial 3 kV sweep (1: 3 kV).

This hysteresis effect is more significant if the cable has been disconnected a long time before the measurement. This effect has to be taken into account when interpreting field measurements.

VDP response is typical for cables with significant water tree deterioration but the trees have not penetrated the whole of the insulation yet.

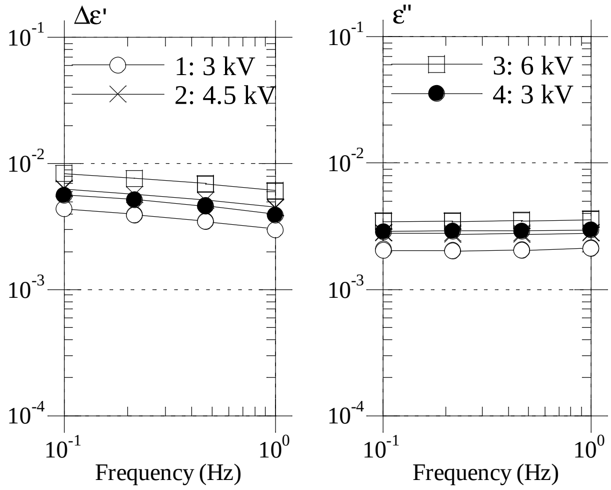

Fig. 4.4 VDP (Voltage Dependent Permittivity) response on a typical water tree aged XLPE cable. The different frequency sweeps are labelled with a sequence number and the voltage level.

Transition to Leakage Current (Type TLC):

Initially, at low voltage levels, this response is similar to the VDP response. At higher voltages the response changes and a leakage current behaviour is added to the response. The transition shows up as an increased loss as a function of the time of applied voltage, i.e. the second measurement at a specific voltage level and frequency has a higher loss than the initial measurement (Fig. 4.5). The following measurements, at a lower voltage, usually show a leakage current response; the losses increase with decreasing frequency. A pure DC conductance is characterised by a frequency dependence of the loss as w^{-1}. The real part of permittivity still shows the VDP flat, non-linear response.

In cables with TLC response one usually finds water trees penetrating the whole insulation and significantly reduced breakdown strength.

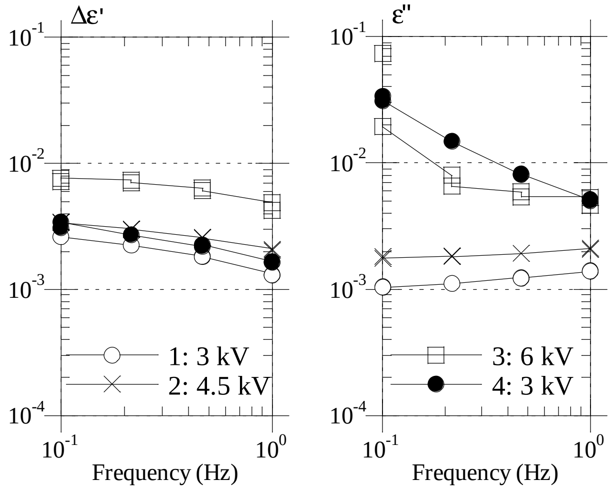

Fig. 4.5 TLC (Transition to Leakage Current) response on a water tree aged XLPE cable.

Leakage Current (Type LC):

LC response shows a leakage current behaviour in the loss part already at low voltages. Increasing loss with decreasing frequency, with a slope near -1 in a log-log diagram (w^{-1}), while the real part of permittivity still shows the VDP response (Fig. 4.6).

As in the case with TLC, response one usually finds water trees penetrating the whole insulation in these cables. These cables have low breakdown strength.

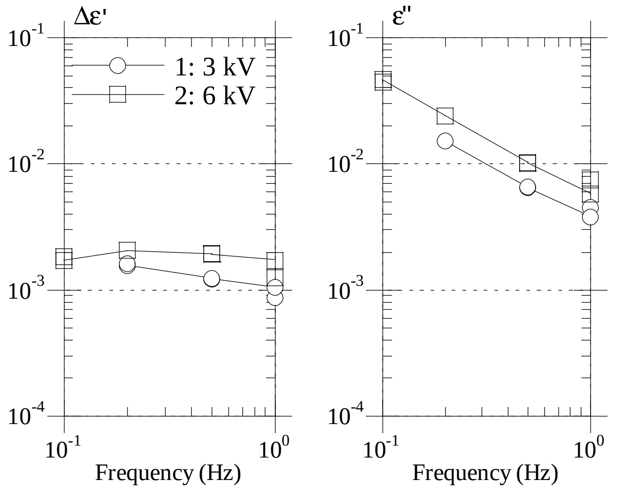

Fig. 4.6 LC (Leakage Current) response on a water tree aged XLPE cable.

There are important advantages of measuring both $\Delta e'(w)$ and $e''(w)$ at several frequencies compared with measuring only tanδ at a single frequency.

The frequency and voltage dependence of the response reveals the type of response and gives an estimate of the degree of water tree deterioration. Secondly, if the response in the case of field measurements, does not fit any of the above shown response types then it is most probably due to the influence of some artefact such as creep current at terminations. These types of effects usually increase the loss but do not change the capacitance. Therefore, it is important to study both $\Delta e'(w)$ and $e''(w)$.

4.6.3 Origin of the non-linear response

Several models have been proposed for explanation of the dispersion and loss in water treed cables.

Patsch et al. [14] proposed a simple equivalent circuit in order to describe the water-treed insulation. The untreed insulation is represented by a loss free capacitor. The treed part is modelled by a capacitor with a parallel resistor representing increased conductivity within the water tree region. It is possible to explain the increase in both capacitance and loss by means of this model.

Hvidsten et al. [36] proposed a water tree model in order to explain the non-linearity effect in water treed XLPE insulation. The water-treed region, according to their model, consists of water droplets forming “strings of pearls” interconnected by narrow channels of crazed insulation. This model explains the characteristics of TLC and LC response by the establishment of electric contact between the water droplets bridging the whole insulation thickness.

Although these models explain many of the features observed there are still some significant shortcomings. In particular, none of the models can explain the correct combination frequency dependence and loss level.

4.6.4 Correlation between dielectric response and breakdown strength

In Investigation 1 (LI Test), three cable samples showed LC response while the other samples showed VDP response. The LC cable samples all had low breakdown strength. The normalised breakdown strength, $U_{bd}/U_{0,}$ of the samples was 2, 2.3 and 5.7. The U_{bd}/U_0 for the VDP samples was in the range 7 - 34.

In Fig. 4.7, the correlation between losses at 0.1 Hz and U_{bd}/U_0 is shown for measurements on cable samples with VDP type response. Because the VDP response is flat; the correlation for another frequency in the measured range is similar.

The results show that test objects with LC type response have lower breakdown strength than objects having VDP type response. The correlation between the loss level and U_{bd}/U_0 is evident for cables with VDP response (Fig. 4.7).

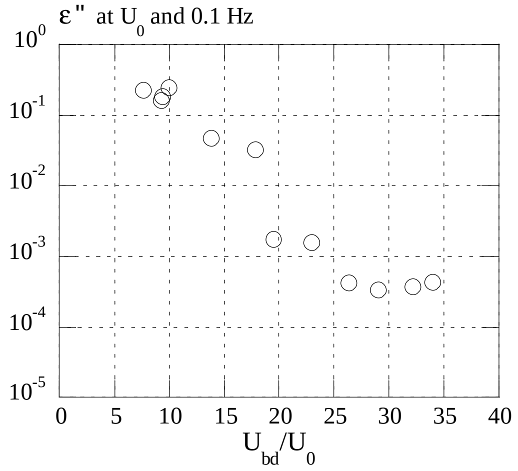

Fig. 4.7 e'' as a function of U_{bd}/U_0 for cables having a VDP type response. Only cable samples showing VDP response are included. The results are from Investigation 1.

In Investigation 2 (AC step), five cable samples showed LC response, four samples TLC response and the remaining 66 samples showed VDP response. Six of the test objects suffered breakdown already in the preconditioning and were never measured. Cable samples having LC response have in general very low breakdown strength. The normalised breakdown strength, U_{bd}/U_0, was in the range 1 - 2.1. The cable samples with TLC response also had low U_{bd}/U_0, although slightly higher than the LC samples. The U_{bd}/U_0 for the TLC samples was in the range 1.7 - 4.

The results of the VDP cable samples are shown in Fig. 4.8 and Fig. 4.9. The loss level as a function of U_{bd}/U_0 is shown in Fig. 4.8. A clear relation between the loss level and the breakdown strength can be observed, the loss level tending to increase when the breakdown strength is below 4. The same relation is encountered for the non-linearity parameters in Fig. 4.9 where the non-linearity in loss level, $\Delta e''(w)_{nonlin}$ is shown as a function of U_{bd}/U_0.

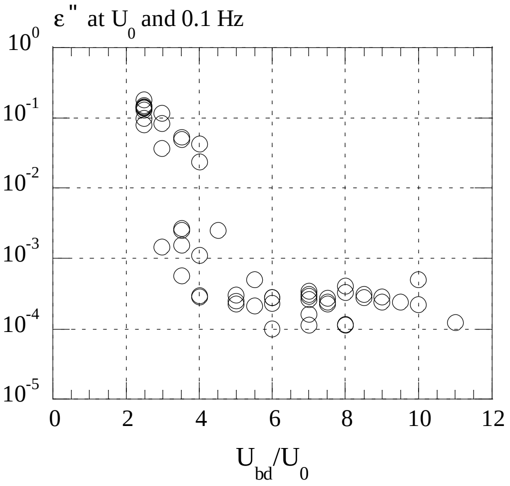

Fig. 4.8 e'' as a function of normalised breakdown strength, U_{bd}/U_0, (AC step). Only cable samples showing VDP type response are included. The results are from Investigation 2.

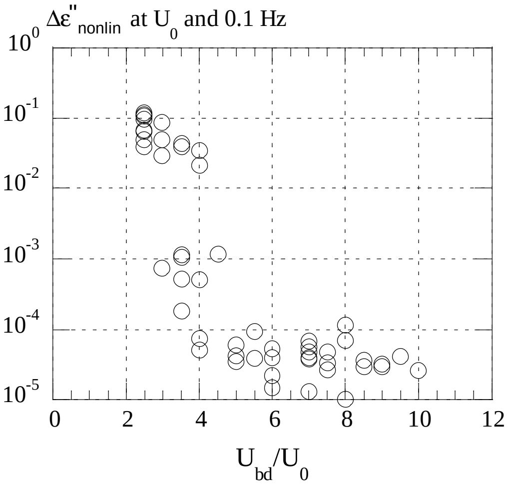

Fig. 4.9 The non-linear loss parameter, $\Delta e''_{nonlin}$, as a function of normalised breakdown strength, U_{bd}/U_0, (AC step). Only cable samples showing VDP type response are included. The results are from Investigation 2.

4.6.5 Harmonics

As shown, water tree deteriorated XLPE cables have a voltage dependent dielectric response. This non-linear response also manifests itself in the harmonics. Three parameters were calculated to describe the harmonic content of a response. These parameters are the total, odd and even harmonic distortion of the integrated current. The parameters are defined by the following equation:

$$HD = \frac{\sum_{k\in\Omega}^{n} q(k)}{q(1)} \qquad \text{Equation 2}$$

Where q(k) is the Fourier coefficient corresponding to the frequency $k \cdot w_0$ of the integrated current w_0 being the fundamental frequency measured. The total harmonic content is achieved by the sum of all harmonics (Ω={2, 3 ... n}). The odd and even harmonic contents are obtained by only summing up the odd (Ω={3, 5 ... ≤n}) or even (Ω={2, 4, ... ≤n}) harmonics respectively.

The different types of responses could also be recognised in the harmonic content. Cables with LLLP response have low levels of both odd and even harmonic distortion. Cables with VDP response have an increased harmonic distortion but the increase is larger in the odd distortion compared with the even distortion. In cables with TLC or LC response, the harmonic distortion increases even more and the odd and even distortion are within the same range.

Results from Investigation 2 show that the harmonic content in the integrated current relates to the breakdown strength in the same manner as e'' and $\Delta e''_{nonlin}$, as shown in Fig. 4.10. Here the total harmonic distortion, HD_{tot}, measured at U_0 and 0.1 Hz, is shown as a function of U_{bd}/U_0.

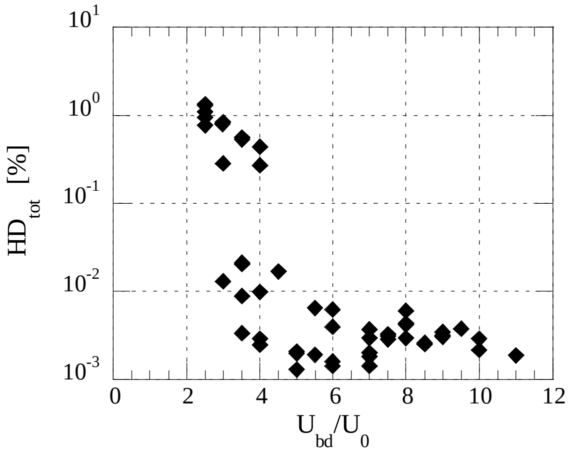

Fig. 4.10 Total harmonic distortion, HD_{tot} at U_0 and 0.1 Hz, as a function of normalised breakdown strength, U_{bd}/U_0, (AC step). Only cable samples showing VDP type response are included. The results are from Investigation 2.

4.6.6 Relations between non-linear parameters

As has already been noted both $\Delta e'(w)$ and $e''(w)$ are voltage dependent in water treed cables. The two non-linearity parameters, $\Delta e'(w)_{nonlin}$ and $\Delta e''_{nonlin}$ (see Table 2.2), are related as shown in Fig. 4.11; results from

Investigation 2. In the figure the parameters at both 1 and 0.1 Hz are plotted. Test objects with TLC and LC responses are omitted since they are easily recognised by their frequency dependence and the non-linear parameters are not always possible to determine.

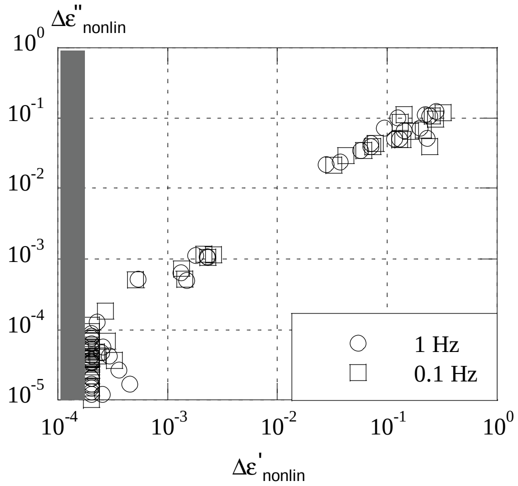

Fig. 4.11 Relation between non-linearity parameters at 1 and 0.1 Hz. Only cable samples showing VDP type response are included. The results are from Investigation 2. The smallest $\Delta e'(w)_{nonlin}$ *is limited to* $2x10^{-4}$.

The same relation for the two non-linearity parameters was found for field measurements as well. In Fig. 4.12 the correlation between $\Delta e'(w)_{nonlin}$ and $\Delta e''_{nonlin}$ at 1 Hz for some selected field measurements is shown. In the figure, cable phases repaired after early failure are illustrated as filled squares.

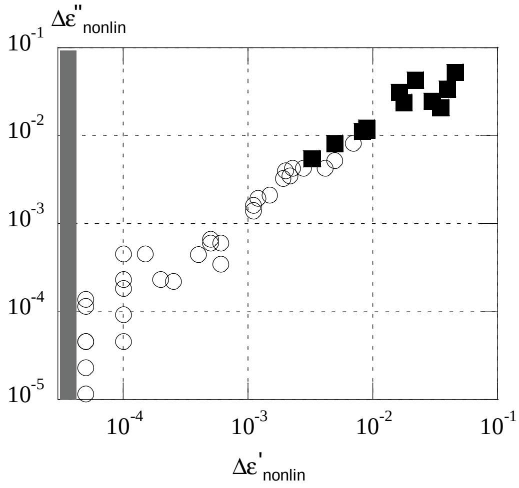

Fig. 4.12 Relation between non-linearity parameters at 1 Hz. Results from selected cable phases with VDP response measured in the field. Cables that failed earlier in service have filled symbols. The smallest $\Delta e'(w)_{nonlin}$ *is limited to* $5x10^{-5}$.

The harmonic content relates also to the non-linearity parameters. In Fig. 4.13 the total harmonic distortion, HD_{tot}, is shown as a function of $\Delta e''_{nonlin}$; results from Investigation 2.

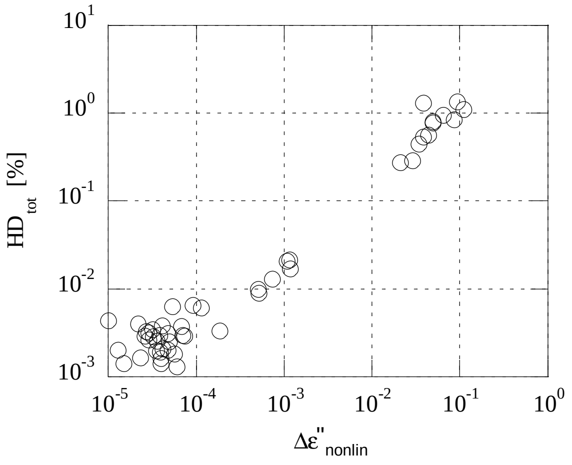

Fig. 4.13 Total harmonic distortion at U_0 *and 0.1 Hz as a function of non-linearity in loss level,* $\Delta e''(w)_{nonlin}$. *Only cable samples showing VDP type response are included. The results are from Investigation 2.*

4.6.7 Measurements at higher voltages

Measurements up to U_0 showed that cable samples with breakdown strength above $4U_0$ (AC step) had low and nearly linear response. Cables with breakdown strength in the interval $3\text{-}4U_0$ had in general an increased loss and a significant voltage dependence in both $\Delta e'(w)$ and $e''(w)$. However, some cables in this interval had low loss and nearly linear response. There is always the possibility of increasing the voltage in order to achieve higher resolution if one is prepared to take the higher risk of breakdown during the measurement. To see the effect of higher voltages, all 12 kV cable samples in Investigation 2 were subjected to measurements of up to $2U_0$ [9, 13].

The results show that cable samples with an AC breakdown strength in the range $3\text{-}4U_0$ obtained a loss increase or as in some cases, transition to leakage current at $1.5U_0$. Cables having AC breakdown strength above $4U_0$ only showed a slight increase in $\Delta e'(w)$ and $e''(w)$.

As expected, more information about water tree deterioration is obtained by measurements at higher voltages. However, measurements of up to $2U_0$ should not be a general procedure. Deteriorated cables might breakdown during measurements at $2U_0$ [35] but could still function in service for a long time with an option for later replacement at a suitable time.

5. FIELD APPLICATION OF DIAGNOSTIC METHOD

5.1 INTRODUCTION

More than two hundred 12 and 24 kV three-phase XLPE cables have been measured in the field. Most of the cables were measured in Sweden but the method has also been applied in Norway, Denmark, the Netherlands, Canada and USA. Experience from all these measurements has been taken into account.

A database for diagnostic measurements has been structured. The database includes relevant information for the diagnosis of the cable condition, diagnostic measurements, cable design, service conditions, failures, and judgements of cable condition etc.

Furthermore, others have also evaluated the method [35].

5.2 MEASUREMENT PROCEDURE

Since this is an off-line method, the cable has to be disconnected from the network before the measurements begin.

In most situations, the cable conductors are unbolted from the stations and the terminations are cleaned with alcohol. This is done in order to minimise the effects of substations and creep currents. However, in the few cases where this procedure is not possible, measurements can be made with the cable still connected to the substation

The high voltage output is connected to the cable conductor. In general the cable shield is kept grounded and therefore the electrometer input (Fig. 2.1) is connected to the ground. The two phases, which are not currently measured, are grounded.

The high voltage is enabled and the measurement begins. The normal procedure consists of a sequence of five frequency sweeps 10-0.1 Hz at 25%, 50%, 75%, 100% and 50% times U_0. The maximum current of the high voltage amplifier (see equation 1) limits the upper frequency. The measuring time is approximately 7 minutes per phase. After the measurements have been completed, the cable is reconnected to service.

5.2.1 Maximum used voltage levels

The above-mentioned procedure includes five frequency sweeps at a maximum voltage U_0. A cable showing TLC response or LC response already at low voltage levels indicates severe ageing (Section 4) and the measurement is then interrupted. There is no benefit in endangering the cable by going to higher voltages.

On the other hand, we have the case of the cable not showing any sign of water tree response even at the highest voltage. If the utility in question agrees to it, a higher voltage level ($\leq 2U_0$) can be recommended in order to detect ageing in some types of cables (compare Section 4.6.7). At higher voltage levels it is possible to detect water trees that otherwise would not have been seen. This however always implies a risk of cable damage.

5.3 INFLUENCE OF ACCESSORIES

In the field in general no guarding or shielding arrangements can be made. The cable is measured with its terminations and joints. In some cases, where it is impossible to disconnect the conductors from the station, support insulators in the substation are also included. Since the loss of non-aged XLPE is very low, these accessories will in most cases influence the measurement.

The influence of accessories, e.g. terminations, can be divided into two parts; the accessory itself and the creep currents along the accessory surface.

5.3.1 Influence of surface currents

The creep currents depend mainly on the surface condition and the humidity. An example of how surface currents can influence the measurements is given in Fig. 5.1 and Fig. 5.2. The creep currents (from the termination and the connected substation) are minimised by disconnecting the cable from the station and cleaning the termination surface with alcohol.

In Fig. 5.1, the cable circuit was measured with the conductors connected to the station and the terminations not cleaned. The loss, $e''(w)$, was relatively high at 0.1 Hz and had a considerable voltage dependence. The losses increased considerably as the frequency was lowered. However, $\Delta e'(w)$ was independent of voltage. This is not the characteristic for water tree deteriorated XLPE cables (Section 4.6.2.) and can relatively easily be separated from water tree deterioration.

In Fig. 5.2, the same circuit was measured with the conductors unbolted from the station and the terminations cleaned. The loss was low and both $\Delta e'(w)$ and $e''(w)$ were independent of the applied voltage. This is typical for a good cable.

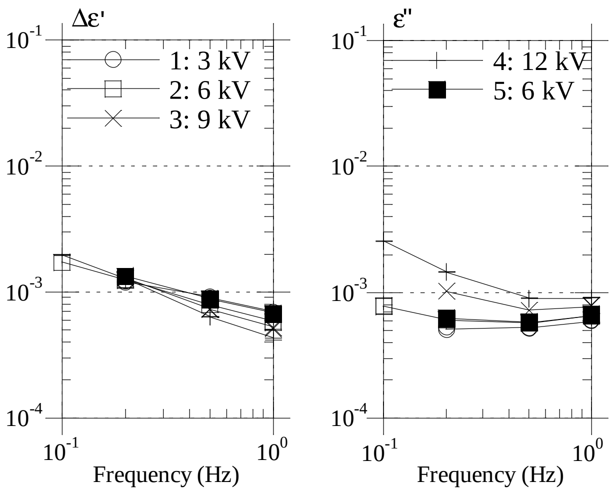

Fig. 5.1 $\Delta e'(w)$ *and* $e''(w)$ *for a XLPE cable measured with the conductors connected to the station without any cleaning of terminations.*

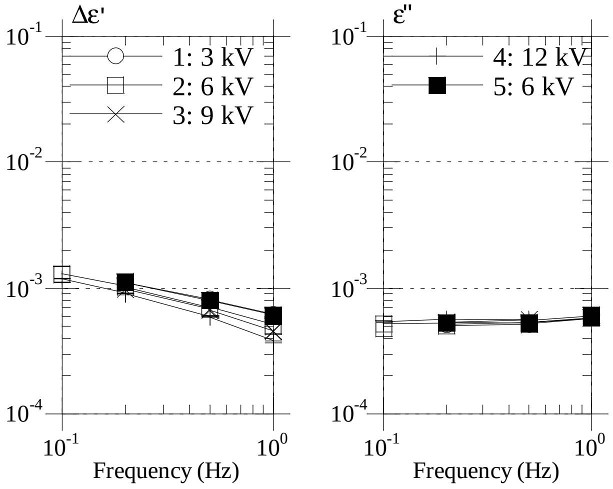

Fig. 5.2 $\Delta e'(w)$ *and* $e''(w)$ *for a XLPE cable measured with the conductors not connected and the terminations cleaned.*

In more humid situations, such as rain, fog and dew a more dominant leakage current can in some cases influence the measured loss. This increasing high loss is more difficult to separate, especially from cables showing LC response. (Section 4.6.2.). A solution in such situations could be to guard the electrode by means of conducting tape, e.g. around the termination.

5.3.2 Different terminations' influence on the dielectric response

The influence of the termination itself depends on termination design. Therefore a laboratory investigation concerning 11 different termination designs' impact on the dielectric response was conducted [11]. The measured samples consisted of a termination mounted on a short piece of a non-aged XLPE-cable with a design voltage of 12 kV.

The difference between the terminations was great. The capacitance of the samples was in the range 17-110 pF. The losses expressed as tanδ were in the range 0.001–0.14 at 6 kV. Two different general response types were found: linear, where the applied voltage had no influence and non-linear, where there was voltage dependence. In general the responses decreased with increasing frequency.

Figure 5.3 shows measurements of tanδ at 6 and 12 kV for a 6 m long cable with and without one of the non-linear terminations with high losses. The cable responses without terminations at 6 and 12 kV coincide, the response being linear. The termination changes this response dramatically. The measured response of the 6 m cable plus termination is non-linear and having a much higher loss level.

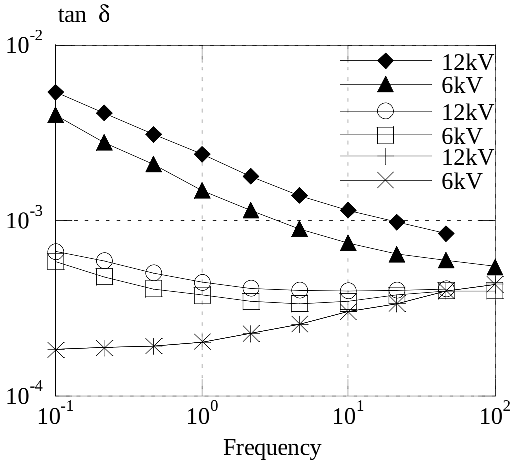

Fig. 5.3 Measured response of new cable (cross symbols), new 6m cable plus one non-linear termination with high losses (filled symbols) and calculated response of 120m new cable plus two non-linear terminations with high losses (open symbols).

Software for subtraction of the termination contribution was developed. For comparison purposes, the response of a 120-m new cable having two terminations has been calculated and is shown in Fig. 5.3. The termination has clearly a considerable influence upon the response in this case.

The influence of the terminations was also studied for field conditions, and measurements on cables having different lengths and degradation were performed. The critical cable length of new XLPE cables, above which the influence of the termination on non-linearity becomes insignificant, was found to be between 30m and 300m for the investigated terminations.

Several ways were found in order to distinguish a response influenced by terminations from a response of a cable with water trees. The frequency dependence of the terminations is different from that of water trees. In the case of non-linear terminations, the non-linearity is visible in the whole measured voltage range while water treed cables usually have a pronounced voltage dependence at some specific voltage interval.

5.4 PARTIALLY DETERIORATED CABLES

Dielectric response measurements are averaging measurements. A cable with very few water trees has of course a lower response than a cable with a lot of water trees. However, the very large increase of non-linearities due to water treeing makes it possible to detect also local defects. Experimental work [13, 36] has shown that cables having only approximately a 5% water treed portion could quite easily be detected. This can be illustrated by an example: lets assume that 5 % of the cable length has a lot of water trees which create a high loss and high voltage dependence then; $e''(w)$ = 1x10^{-2}, $\Delta e''_{nonlin}$ = 6x10^{-3} and the remaining cable has; $e''(w)$ = 6x10^{-4}, $\Delta e''_{nonlin}$ = 0. The total loss will then be $e''(w)$ = 1.1x10^{-3} and $\Delta e''_{nonlin}$ = 3x10^{-4} which is significantly higher than a non-deteriorated cable (Fig. 4.8 and Fig. 4.9).

The loss at low frequencies in water treed cables having LC or TLC response is orders of magnitude larger than that of un-aged insulation. Therefore, the characteristic frequency dependence can be recognised even if only a small part of the cable contributes to the leakage current.

6. DIAGNOSTIC CRITERIA

The diagnostic criteria presented in this section are based on laboratory investigations as well as experience from the field. The criteria use the definition of responses defined in Section 4.6.2. As a result of the criteria the measured cables are divided into three different categories:

Severely aged:

If a TLC or LC type response is observed during the measurement, the measurement is usually interrupted and the cable is judged bad. Depending on leakage current level, cable design and the voltage level of the network, the cable can be used for some additional time or has to be replaced immediately. In general, the breakdown strength of these cables is relatively low, the normalised AC breakdown strength being estimated in the range $U_0/U_{bd} \leq 2.5$. Laboratory measurements show that the harmonic distortion is high and that the odd and even harmonic distortion is of the same range.

Significantly aged:

Cables with VDP type response, which is the case for most water tree deteriorated cables, have a normalised AC breakdown strength; U_{bd}/U_0, estimated at 2.5-4. According to our experience, the breakdown strength is low and these cables can remain in service without failure for many years. The limits for clear identification of the VDP response in the laboratory are as follows:

- 8x10^{-4} ≤ $e''(w)$ at U_0
- 1x10^{-4} ≤ $\Delta e''(w)_{nonlin}$
- 2x10^{-4} ≤ $\Delta e'(w)_{nonlin}$

Laboratory measurements show that the harmonic distortion is quite high, especially for odd harmonics. The pronounced increase of odd harmonics indicates a possibility to separate the VDP response from TLC and LC response.

In the field, where the response is influenced by accessories, the limits presented above need to be slightly increased depending on the measured cable circuit. However, the limits can still be kept at a low level since measurements over a frequency range allows discrimination of accessories, see Section 5.3.

The judgement of the cable could differ depending on the response and circumstances, such as cable design, load etc. It could for instance be recommended that the cable should be put in schedule for renewal or a new diagnostic measurement within a 2-5 year period.

Good condition:

Cables with LLLP type response have usually breakdown strength above 4U_0. Since the response is linear, the harmonic distortion is low. However, a “good” cable does not necessarily mean that the cable insulation does not have any water trees. Therefore, depending on the cable design, a new diagnostic measurement is recommended within a 5-10 year period.

7. CASE STUDIES

7.1 CASE STUDY: THE 21 KV NETWORK NORTH BOTKYRKA

7.1.1 Background

“Energibolaget i Botkyrka och Salem” is a utility outside Stockholm presently owned by Vattenfall. A part in their district, North Botkyrka, was built in the early seventies and therefore most of the medium voltage cables originates from that period.

Until 1992, the fault rate in North Botkyrka was at an acceptably low level. However, in 1993 the fault rate increased rapidly. Multiple faults and cables failing again after repair led to the insight that there was a problem regarding water treeing and the added problem of how to react in such a situation.

When a cable failed, a section of 25 m in each direction from the fault position was replaced. The cable sometimes withstood reconnection to service but at other times it failed. The very low frequency, VLF, withstand test (0.1Hz 3U_0 for

60 min.) was tried as a diagnostic test. However, most of the cables failed and they failed at multiple sites.

7.1.2 Dielectric response and ranking of cables

Several dielectric response test measurements were initiated together with “Energibolaget i Botkyrka och Salem” in 1995. Both cables that had failed earlier and cables without earlier faults were measured. Furthermore, results were compared with optical water tree analysis and VLF tests in the field. In total, 68 cable circuits were selected for diagnostic measurements, which is a little more than 50% of the total amount of cables installed in the network North Botkyrka.

All 68 cables, with a design voltage of 24 kV, were measured using the procedure described in Section 5.2. If a cable phase showed leakage current (LC response) or transition to leakage current (TLC response) at a lower voltage level, the measurement was interrupted avoiding unnecessary stress of the cable insulation.

The ranking of the cables was made according to the measurement results. Cables with LC response or TLC response were judged as severely aged and it was recommended that they be replaced as soon as possible. The other cables were graded according to the level of the response and how much the second ½ U_0 measurement differed from the first ½ U_0 measurement. Of the measured cables, approximately 10% were classified as severely aged, 50% were significantly aged and approximately 40% were in good condition.

7.1.3 Cable faults in the test period, 1995-1996

During the two years of testing and measurements the cables continued to fail. However, no cable failed during the diagnostic measurement.

The cables that were measured and later failed had all shown a leakage current response (LC response) at low voltage. It was concluded that if a cable, with a design voltage of 24 kV installed in a 21 kV network, has LC response it would have to be replaced as soon as possible.

7.1.4 Replacement strategy

By autumn 1996 the majority of diagnostic measurements were completed and cables had been replaced based on failures and failures, in a few cases, combined with diagnostic results**.** However, then the replacement strategy was changed and based on the diagnostic measurement results together with the experience gained during the measurement period. Cables that were judged as severely aged were set at the highest priority for replacement. The order of replacement for the other cables that were judged significantly aged was based on the insulation status as well as other aspects. Examples of other aspects are consequence of failure, dig permissions and economical aspects.

7.1.5 Evaluation and summary

To date, February 2000, the utility has replaced all cables judged severely and significantly aged accordingly to the new replacement strategy. That is ca 35% of the cables in the network North Botkyrka. No cable fault has occurred in the network since autumn 1996 (Fig. 7.1)

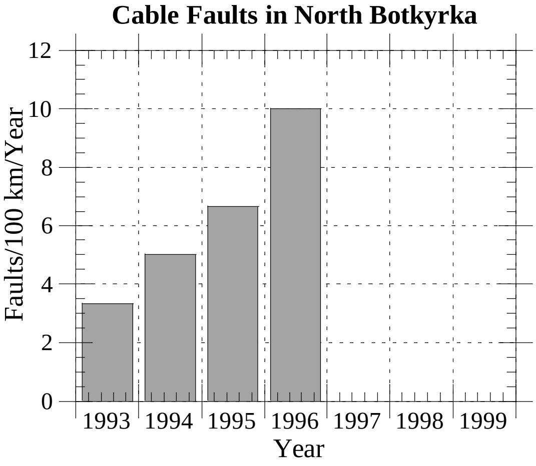

Fig. 7.1 Faults per 100 km and year in North Botkyrka. No fault has occurred since 1996.

7.2 CASE STUDY: THE 6 KV (10.5 KV) NETWORK ON VEN

7.2.1 Background

Ven is a Swedish island in Öresund between Denmark and Sweden. The system voltage in the distribution network at Ven was earlier 6 kV although the design voltage was 12 kV. All cables were installed in the seventies (1975-76) and had an insulation screen of tape and graphite.

After a few faults in their network, the utility applied VLF test technique on a single circuit, resulting in several faults. However, approximately half the cable length passed the test and was kept in service.

7.2.2 Dielectric response and ranking of cables

In July 1996 dielectric response measurements were performed on a total of nine cable circuits. The cables, with a design voltage of 12 kV, were measured using the procedure described in Section 5.2. The system voltage was as mentioned 6 kV. However, due to considerations of upgrading the network, the highest voltage level in the diagnostic measurements was set to 6 kV. 6 kV is normally the highest voltage level used in diagnostic measurements in a 10.5 kV system.

Of the nine cables, six cables did not show any significant ageing, two cables showed TLC response and one cable showed LC response. The cable having LC response, was the same cable that had been VLF tested. Since the response did not show any significant hysteresis, the interpretation was unclear. The cables having TLC response where judged severely aged and the other cables were in good condition.

Even though cable circuits were judged severely aged they were put back in service. The reason for this consideration is the relatively low insulation stress on a 12 kV cable installed in a 6 kV network.

7.2.3 The decision to upgrade the network

The utility decided to upgrade the system voltage from 6 kV to 10.5 kV later the same year (1996). In this connection the two severely aged cables were replaced. The cable with LC response was kept in service however due to the unclear interpretation in combination with the hurry to increase the voltage level.

7.2.4 Evaluation and summary

The utility managed to replace the two circuits and upgrade the system voltage. The network withstood the voltage rise and was run without failure all winter. The LC response cable failed and was replaced in spring (1997). To date, February 2000, the network is operated at 10.5 kV and no fault has occurred since the one mentioned in the spring of 1997.

8. CONCLUSIONS

The dielectric spectroscopy measurement system developed for diagnostics of medium voltage XLPE cables has been found capable of detecting water tree deterioration with very good results. The measurement system is suitable for laboratory as well as field measurements. Water treed XLPE insulation has a characteristic response that can be divided into different types related to their degree of water tree deterioration and remaining breakdown strength. The characteristic responses have been found in small samples artificially aged in the laboratory, field aged cables measured in laboratory as well as in field measurements on site.

The time, level and frequency of applied voltage affect the response of water tree deteriorated insulation. Also the humidity in the water-treed insulation have a strong influence on the response. For this reason, it is of great importance to use a well-established and stable procedure when making diagnostic measurements.

Based on dielectric response measurements, water tree analysis and breakdown tests in the laboratory, criteria for assessment of medium voltage XLPE cables, are proposed. Experience from field measurements and investigations concerning characterisation of different terminations have made the criteria applicable to field measurements.

In most cases the cable insulation can be assessed using voltage levels of up to U_0. However, in a few particular cases, especially on newer cable designs, a slightly higher voltage level could be necessary in order to detect water tree deterioration on cables assessed as being in good condition at measurements of up to U_0. The characteristic responses of XLPE cables, both non-deteriorated and water tree deteriorated, make it possible to separate the cable response from the influence of accessories. Field experience shows that water tree deteriorated cables, with relatively low breakdown strength, can remain in service for many years.

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