Georgia Tech NEETRAC
National Electric Energy Testing, Research and Applications Center

CHAPTER 12

Other Diagnostic Techniques

Jean Carlos Hernandez-Mejia & Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the links below for the version with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

Users are strongly encouraged to consult the link below for the most recent release of Chapter 4:

Chapter 4: How to Start

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

This document was prepared by Board of Regents of the University System of Georgia by and on behalf of the Georgia Institute of Technology NEETRAC (NEETRAC) as an account of work supported by the US Department of Energy and Industrial Sponsors through agreements with the Georgia Tech Research Institute (GTRC).

Neither NEETRAC, GTRC, any member of NEETRAC or any cosponsor nor any person acting on behalf of any of them:

a) Makes any warranty or representation whatsoever, express or implied,
   i. With respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
   ii. That such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or
   iii. That this document is suitable to any particular user's circumstance; or
b) Assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if NEETRAC or any NEETRAC representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process or similar item disclosed in this document.

DOE Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

Copyright of this report and title to the evaluation data contained herein shall reside with GTRC.

Reference herein to any specific commercial product, process or service by its trade name, trademark, manufacturer or otherwise does not constitute or imply its endorsement, recommendation or favoring by NEETRAC.

The information contained herein represents a reasonable research effort and is, to our knowledge, accurate and reliable at the date of publication.

It is the user's responsibility to conduct the necessary assessments in order to satisfy themselves as to the suitability of the products or recommendations for the user's particular purpose.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

12.0 OTHER DIAGNOSTIC TECHNIQUES

This chapter describes other diagnostic techniques infrequently used in the U.S. and Canada but might potentially be used for condition assessment of MV or HV power cable systems. The diagnostic techniques are as follows:

- Dielectric Spectroscopy.
- DC leakage current.
- Recovery voltage.
- Polarization/depolarization current or isothermal relaxation current (IRC).

These techniques have all been described in the past (prior 2005); however, during the last decade, they have mainly been used on laboratory and/or pilot studies not for making decisions regarding the condition assessment of real power cable systems. Thus, their application is still limited. Detailed descriptions of each technique follow.

12.1 Dielectric Spectroscopy

12.1.1 Test Scope

Dielectric Spectroscopy is a similar technique to Tan δ; however, the Tan δ is established by measuring the real and imaginary components of a cable system current at a range of applied voltage frequencies, typically 0.001 to 100 Hz [1-9]. The benefit of this process is that it supplies additional information about the cable system insulation. In general, the Tan δ varies inversely with frequency (since the capacitive current is directly proportional to the applied ac frequency) and will therefore be larger and more easily measured at lower frequencies (Figure 1 [9] and Figure 2 [5]). The loss current, on the other hand, remains constant with frequency unless there is degradation present in the cable system.

The data that result from dielectric spectroscopy measurements are essentially frequency spectra that contain considerable information, and consequently require more careful interpretation than Tan δ measurements made at one frequency. It is instructive to note the strong frequency and voltage stress dependencies in Figure 1 and the strong frequency and age dependencies (Cable 1 – 20 yrs., Cable 2 – 50 yrs.) [5] in Figure 2.

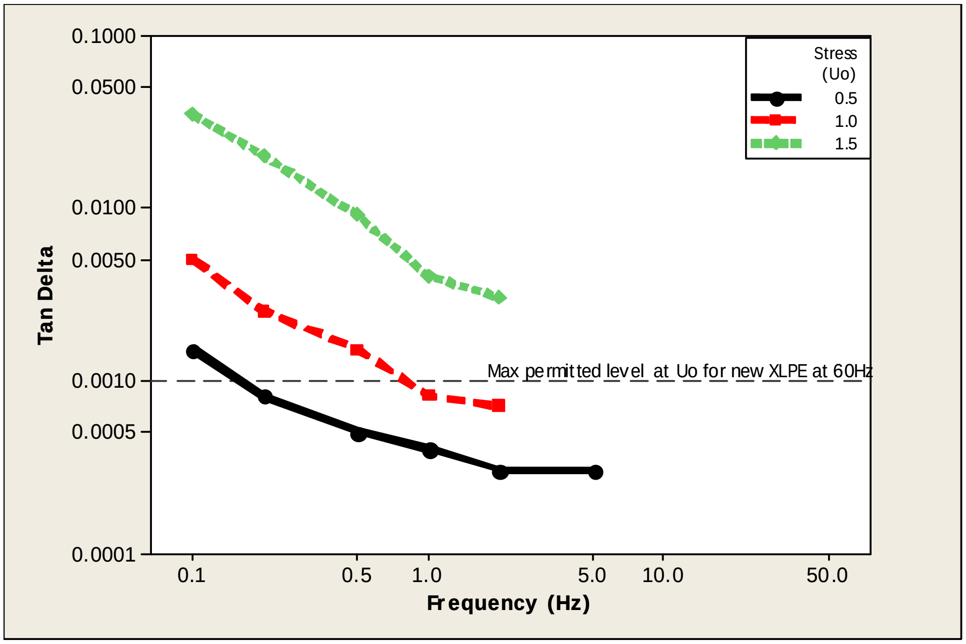

Figure 1: Dielectric Spectroscopy of Aged XLPE Cables [9]

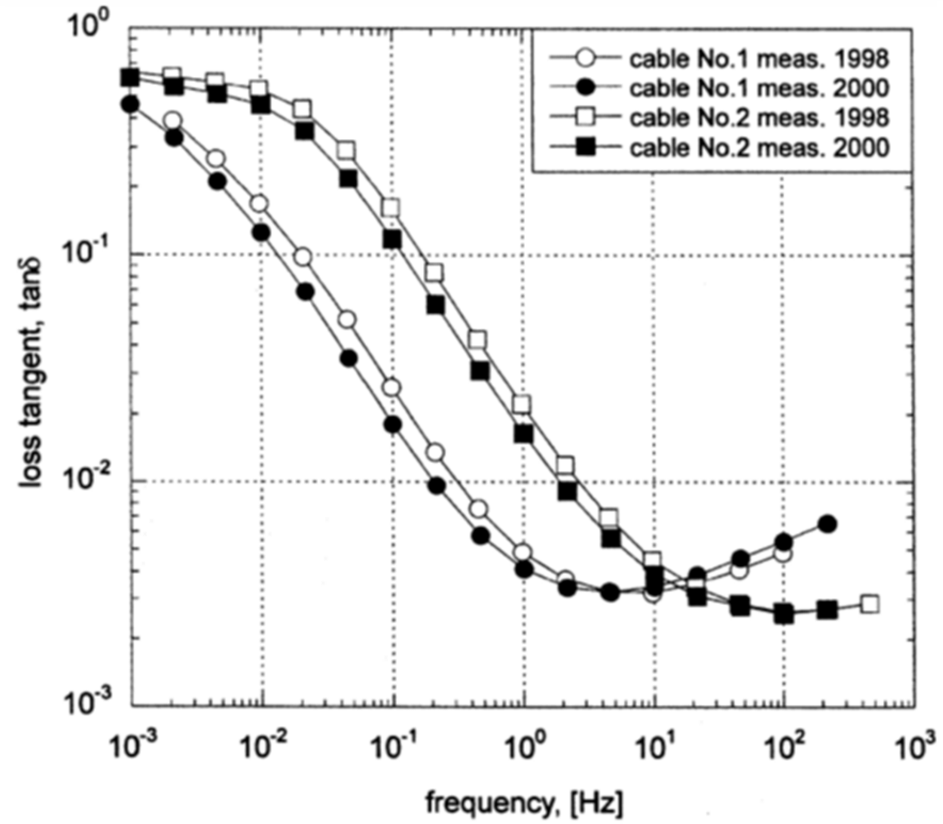

Figure 2: Dielectric Spectroscopy of Aged Paper Cables [5]

12.1.2 How It Works

There are two ways to obtain the dielectric loss spectra:

- Frequency Domain Spectroscopy (FDS) – Employ a variable frequency source and perform conventional current measurement and phase angle calculation
- Time-Domain Spectroscopy (TDS) – Measure a number of DC currents as a function of time and then transform to the frequency domain using the Hamon approximation [4]

The variable frequency/conventional data (FDS approach) are obtained by applying voltages at discrete frequencies and then calculating the real and imaginary parts of the current at that frequency. The Tan δ is then the ratio of these two parts. The frequency is then stepped to cover the complete frequency range. The data may be interpreted as frequency spectra [9] or via equivalent circuit models [2, 9]. The equivalent circuit model translates the measured "complex" current into a "complex" permittivity where the real part of the permittivity represents the direct capacitance and the imaginary part represents the resistive or loss component. The Tan δ then becomes the ratio of the imaginary permittivity to the real permittivity. The effects of age, moisture, and temperature can then be analyzed using either of these approaches. Figure 3 shows examples of frequency domain permittivity measurements on paper cables with different moisture contents.

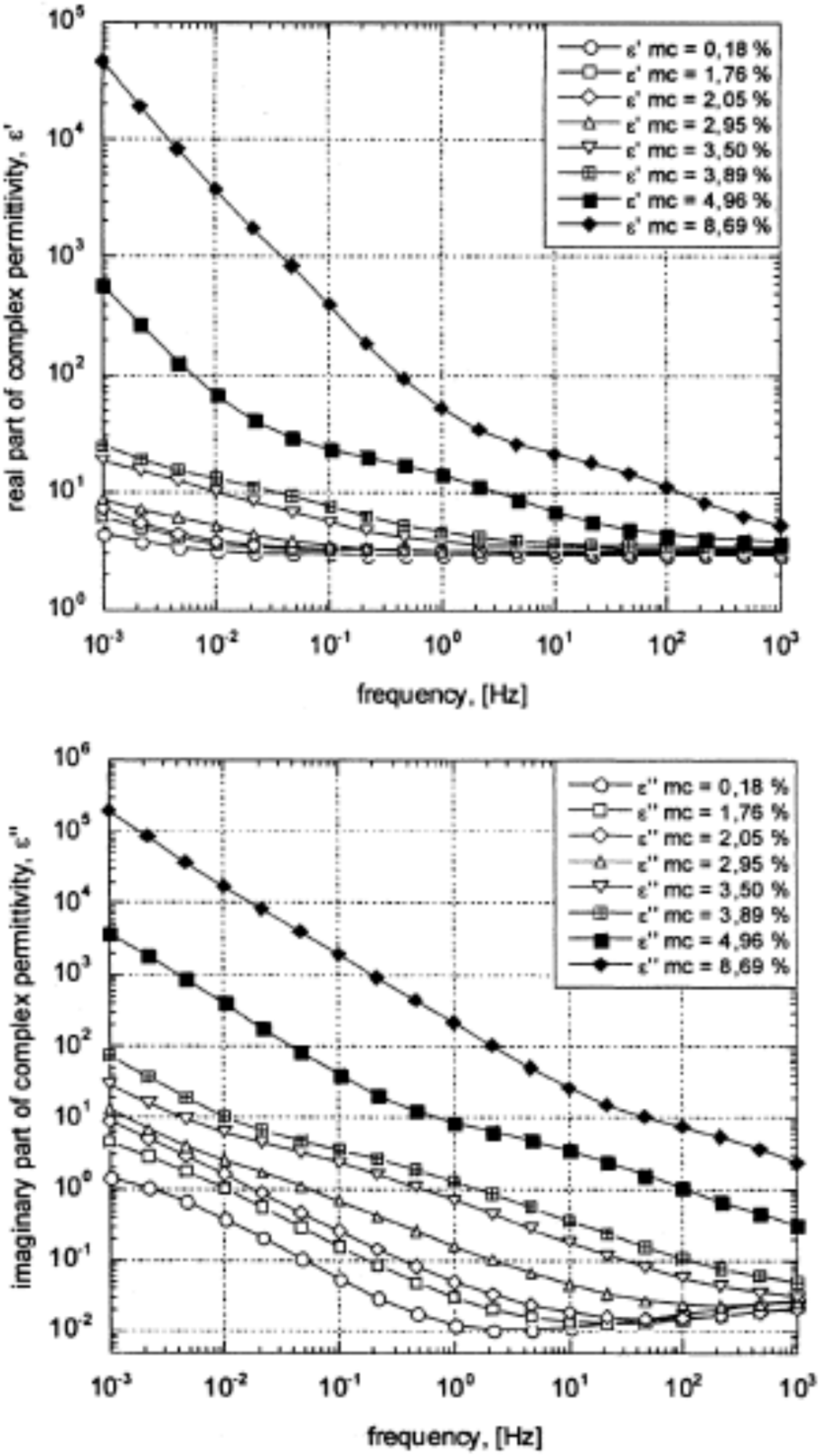

Figure 3: Real (top) and Imaginary (bottom) Parts of Complex Relative Permittivity for Paper Cables with Different Moisture Contents

The TDS approach, as compared to the FDS approach, uses a DC voltage applied for sufficient time to obtain measurements of the cable system loss current as a function of time. These measurements are subsequently transformed to the frequency domain using the Hamon approximation. The basic approach to TDS with the contributing currents is set out in Figure 4. As this figure shows, measurements are made both with voltage (polarization mode) and without voltage (depolarization mode) applied. Three current components make up the currents measured with voltage (i_{pol}) and without voltage (i_{depol}):

- i_{cap} – capacitive current (charging current)
- i_{abs} – absorption current (loss current)
- i_{qc} – space charge/quasi-conduction current

Equation 1 shows i_{pol} and i_{depol} as functions of the above current components.

$$\begin{aligned} i_{pol} &= i_{cap}\left(t\right) + i_{abs}\left(t\right) + i_{qc}\left(t\right) \\ i_{depol} &= -i_{cap}\left(t\right) - i_{abs}\left(t\right) \end{aligned} \qquad \textbf{Equation 1}$$

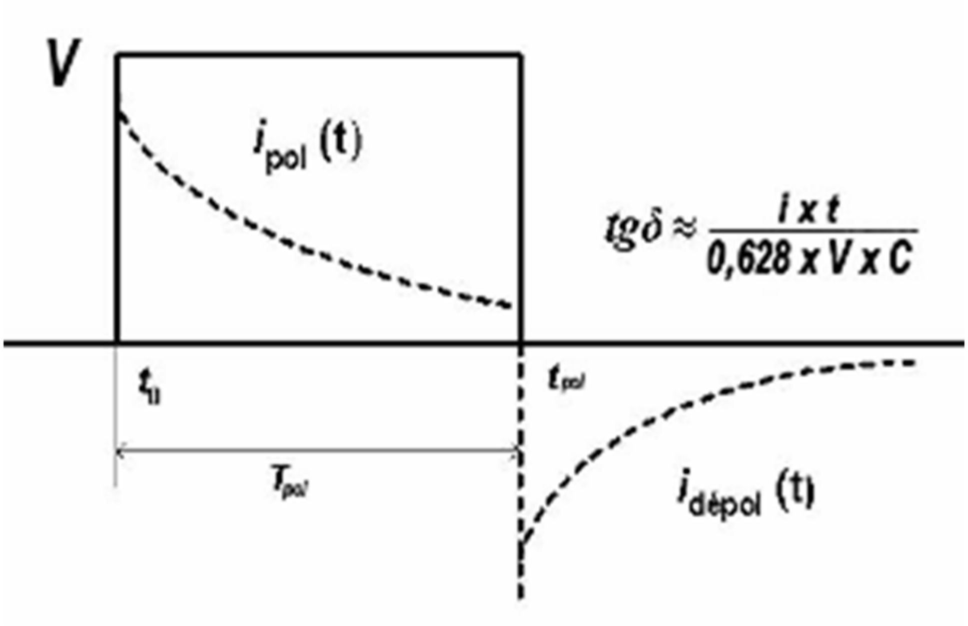

Figure 4 Currents and Voltages for Tan δ Estimation using TDS

An estimate of the Tan δ is given by the Hamon approximation once the capacitance (C) and the absorption (i_{abs}) current are measured. Figure 4 shows that two currents can be derived from the application of DC (polarization and depolarization) thus giving two ways to estimate Tan δ via the two formulas shown in Figure 4. In theory, the polarization and depolarization absorption currents should be equal for the case where the charging time is infinitely long. Such long test times are not practical and so the charging and discharging times are selected to allow for reasonably complete charging and discharging of the dielectric, the actual charging and discharging currents end up appearing similar in shape but different.

12.1.3 How It Is Applied

Figure 5 shows a TDS unit with the typical voltage application protocol used in the field. Note that the voltage protocol uses a polarization and depolarization period for each voltage step. Furthermore, the time duration of the depolarization phase is significantly longer than that of the polarization phase.

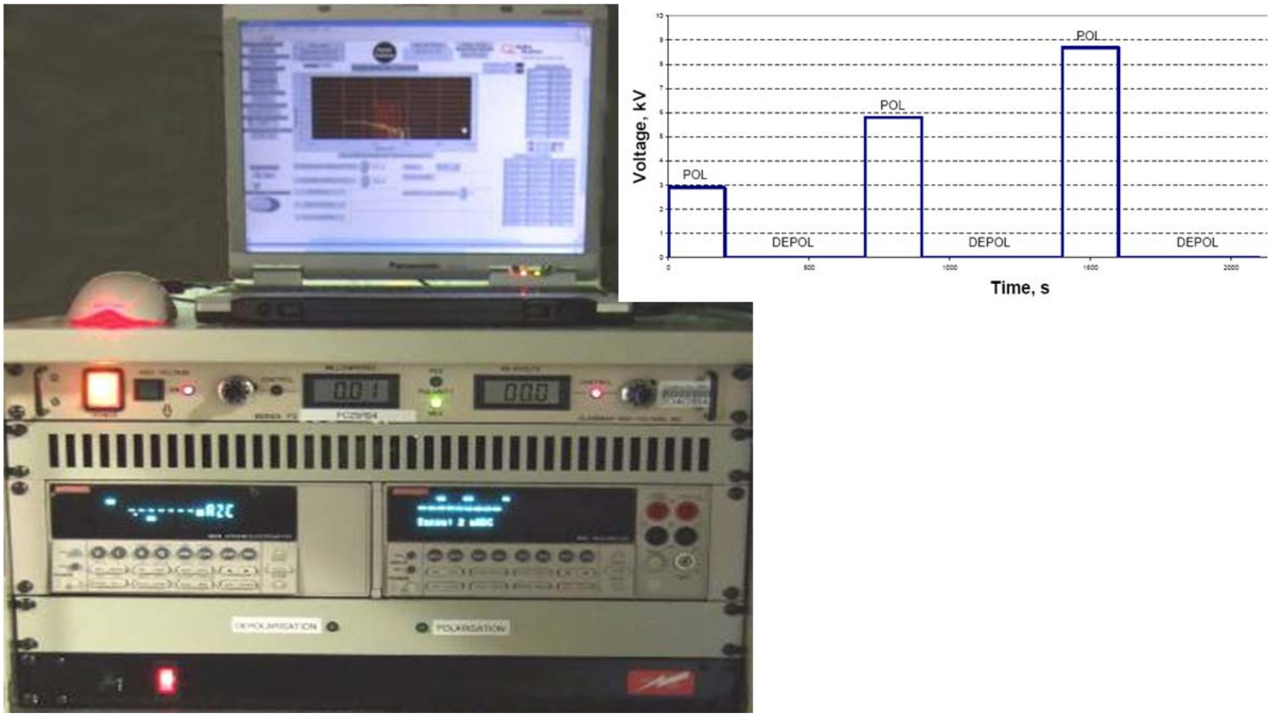

Figure 5: TDS Unit and Voltages Used for the step tests

Figure 5 shows the setup of power supply (top) and digital meters (bottom) for the measurements; not shown is a capacitance meter. The data obtained using the TDS approach are presented as current versus time and Tan δ versus frequency graphs as shown in Figure 6 and Figure 7. These figures show the measurements made during both polarization and depolarization modes.

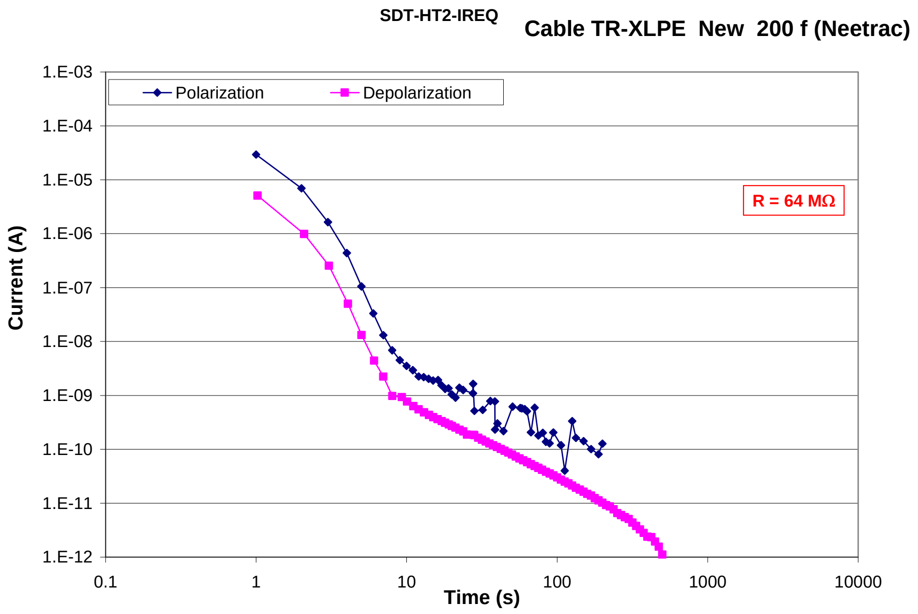

Figure 6: Time-Domain Current Measurements Using TDS Approach

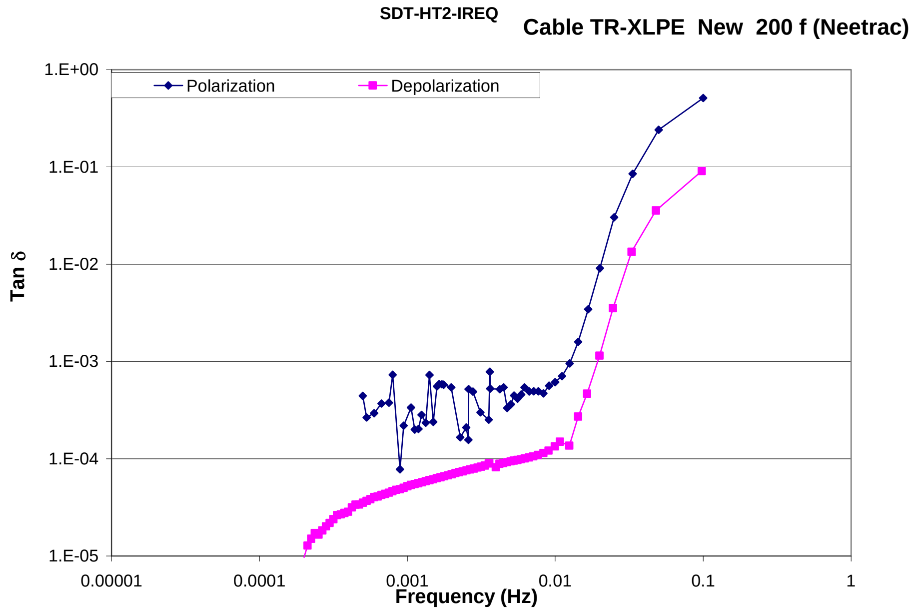

Figure 7: Transformed Tan δ Spectra from Figure 6

As the above figures show, the transformation from the time-domain to the frequency-domain is a one-to-one mapping of the data points. The currents and their components appear in Figure 6. Currents measured at short times (< 10 sec in Figure 6) are dominated by the capacitive current (i_{cap}) while currents measured at long times (>10 sec) are dominated by the absorption current (i_{abs}). The absorption current is the current that is of interest for determining the Tan δ. When these currents are transformed to the frequency domain using the Hamon approximation ($f = 0.1/t$), shorter times correspond to higher frequencies and longer times to low frequencies so the absorption current becomes dominant at frequencies generally below 0.01 Hz. The practical consequence is that currents at higher frequencies have considerable capacitive components that mask the absorption current. This means that Tan δ measurements using the Hamon approximation at higher frequencies (>0.01 Hz) and shorter times may not be accurate estimations of the Tan δ since the capacitive current is likely still masking the absorption current. Cable system length (capacitance) determines the precise cut off frequency for the capacitive current.

The advantages and disadvantages of Dielectric Spectroscopy appear in Table 1 and Table 2.

Table 1: Advantages and Disadvantages of Dielectric Spectroscopy for Different Voltage Sources

Source Type	Advantages	Disadvantages
DC (Time Domain)	• Testing equipment is small and easy to handle. • Multiple voltage levels up to and above U_0 can be applied. • Tip Up can be easily computed. • Comparing polarization and depolarization Tan δ provides an additional diagnostic feature not available in other Tan δ diagnostics.	• Long Test Times (> 10 minutes per voltage step) are required to charge and discharge the cable circuit. • Requires very low current measurements on the order of nano and pico amps. • May inject space charge at the higher voltages (>20 kV/mm and times longer than 100 sec). • The polarization and depolarization estimates of Tan δ complicate interpretation since there are two estimates of Tan δ for every frequency.
Variable Frequency AC Sinewave (Frequency Domain)	• Testing equipment is small and easy to handle. • Waveform is the same shape as the operating voltage waveform.	• Test voltages may be limited to a fraction of U_0 due to the difficulty of synthesizing frequencies >0.1 Hz. • Long test times are associated with frequencies below 0.01 Hz (i.e. times >100 sec per cycle) • May inject space charge at low frequencies (<0.01 Hz) and higher voltages

The application of voltages above U_0 for a long period (defined by either cycles or time) may cause further degradation of an aged cable system. The impact of this effect warrants consideration for all the methods of Dielectric Spectroscopy described in this section. The precise degree of degradation will depend upon the voltage level, frequency, and time of application. Thus, when undertaking spectroscopic measurements, a utility should consider that a circuit can fail during the test and may want to have a repair crew on standby.

Table 2: Overall Advantages and Disadvantages of Tan δ Dielectric Spectroscopy Techniques

Advantages	• Adds Tan δ frequency dependence as a diagnostic feature. • Measurements on a given phase are comparable to adjacent phases, so long as the phases have the same configuration (Also applies to T-branched or other complex circuit configurations). • Periodic testing provides numerical data that can be compared with future measurements to establish trends. • Indicator for the overall degree of water treeing in XLPE cable. • Data obtained at lower voltages ($<U_0$) are generally as useful as data at higher voltages. • Test results are simple numerical values that can easily and quickly be compared to other measurements or reference values. • Simple numeric results enable a quick risk assessment to be made prior to proceeding to higher test voltage levels.
Open Issues	• The relationship between the measured loss on the entire system and the loss at a specific location (such as an accessory or cable defect) needs to be established. • Development of the equivalent circuit from the data. • Identification of defects from the loss measurements. • The importance of differentiating between the loss characteristics of different EPR insulation materials needs to be established. • Methods to interpret results for hybrid circuits need to be established. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • May be possible to determine the equivalent electrical circuit. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC has not been established. • Effect of single or isolated long water trees on the Tan δ. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable must be taken out of service for testing. • Not an effective test for commissioning newly installed cable systems. • Few data sets are available to determine the usefulness of this approach. • Accurate Pass / Not Pass levels not yet established. • Test at different voltage levels require longer test times.

To enhance the effectiveness of Tan δ measurements at variable frequencies, the measurements should be made periodically, preferably over several years. In general, an increase or shift in the spectra in comparison to previously measured values indicates that additional degradation has occurred.

It is important to bear in mind that some accessories employ stress relief materials with non-linear loss characteristics (dielectric loss changes nonlinearly as a function of voltage). Some have suggested that these materials might have an influence on the measured loss values. However, the evidence available indicates that the type of stress relief may have a smaller effect on the overall loss measurement for the circuit than losses associated with severely degraded or improperly installed accessories. Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Tan δ over time.

12.1.4 Success Criteria

There is insufficient data to provide definitive success criteria. However, the success criteria provided earlier for measurements made at 0.1 Hz are applicable for data developed at the same frequency. However, there are no guidelines on how to interpret frequency dependent Tan δ data.

12.1.5 Estimated Accuracy

The *CDFI* lacks sufficient dielectric spectroscopy data to estimate the accuracy of this measurement technique.

12.1.6 *CDFI* Perspective

12.1.6.1 Comparison with other Techniques

Collaborative research work between NEETRAC and IREQ [7] has shown that, within comparable frequency ranges, 0.1 Hz VLF-sinusoidal Tan δ and DC dielectric spectroscopy (TDS) give very comparable data. Figure 8 shows results from the TDS and standard variable frequency VLF Tan δ measurement techniques on a heat shrink joint. The upper group of curves comes from the TDS polarization current measurement whereas the lower group comes from the depolarization current measurement. This finding held true for EPR, WTRXLPE, and XLPE cables and for joints as well. The data developed in the *CDFI* show that the Tan δ values estimated using the TDS polarization technique agree with measurements made on the same cable using the standard VLF Tan δ measurement technique. It is also possible to derive Tip Up (or differential dielectric loss data) by applying different polarization voltage levels. Note that dielectric loss estimates from depolarization (discharge measurements) do not directly follow the polarization results. In fact, this difference is useful as a diagnostic feature because the depolarization loss is a “voltage off” estimate. In a lightly degraded and, hence, linear cable system the two measurements should be in close agreement. If these measurements differ from each other, then this indicates a non-linear cable system that must have some form of degradation present to generate this behavior.

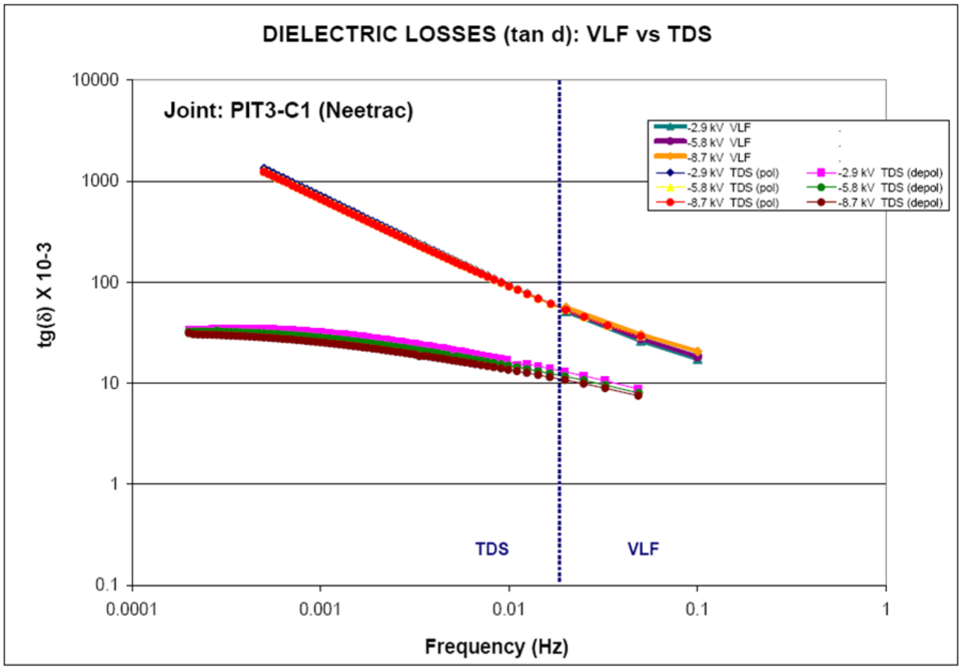

Figure 8: Frequency Spectroscopy on a Heat Shrink Joint using Variable Frequency VLF and TDS Dielectric Loss Measurement Equipment

12.1.6.2 Diagnosis for Paper Cable

Work undertaken in Sweden [5] using variable frequency Dielectric Spectroscopy provides data for paper insulated cables as shown in Figure 9. The authors of this work have suggested that the loss results are correlated to the moisture content of the cables to the extent that the loss measurements may be used to determine the moisture content directly. In this case, the magnitude of the minimum loss, measured over a wide frequency band (0.001 Hz to 1 kHz), is determined, and related to the moisture content via Equation 2.

$$Moisture = \alpha + \beta \ln(Tan\delta_{Min})$$ **Equation 2**

where,

α, β – Constants to be determined empirically

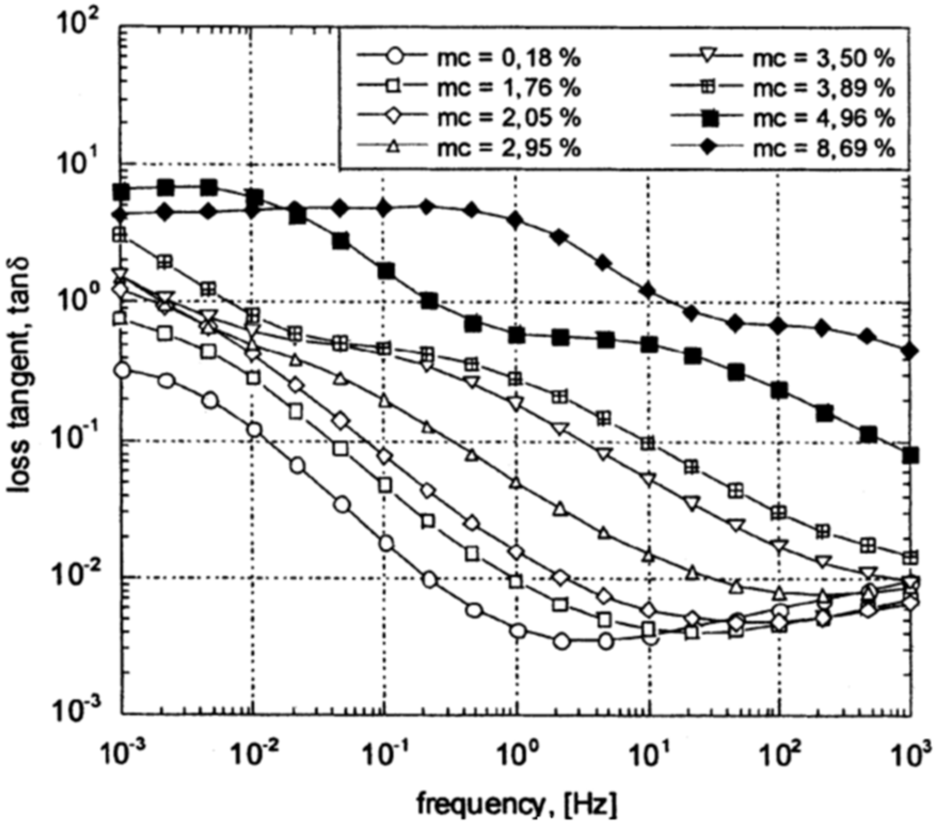

Figure 9: Relationship between Loss and Frequency for Selected Moisture Contents

This proposed correlation [5] may be practical at low moisture contents as the minima are expected to be within the low frequency range. This is not the case for higher moisture contents. Thus, it was decided to investigate the relationship of the absolute loss measured at 0.1 Hz since this frequency is commonly employed in field measurements of Tan δ. It was found that the Tan δ versus moisture data could be modeled so that Tan δ could be used to ascertain the average moisture content of the cable system. Using the data shown in Figure 9, the corresponding Tan δ/moisture content model appears in Figure 10. The data in Figure 2 were then used to test the usefulness of this model since these measurements originated from different cable systems. The reference lines on Figure 10 show the Tan δ and moisture contents measured for Cable 1 and Cable 2 from Figure 2. The model appears to be valid since these data points fall on the curve.

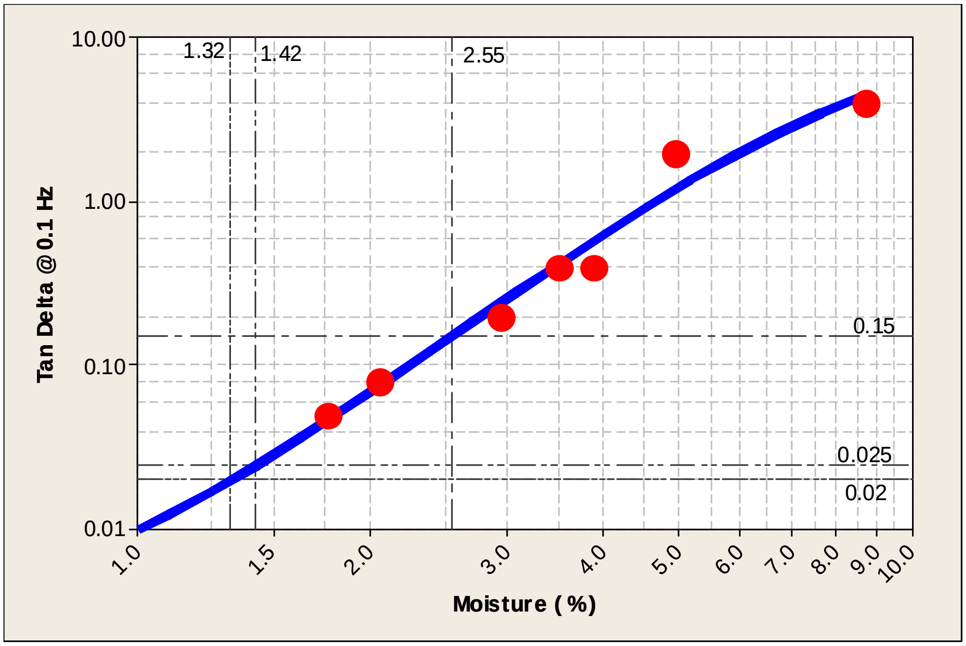

Figure 10: Relationship between Tan δ at 0.1 Hz (from Figure 9) with Moisture Content

12.1.7 Outstanding Issues

Outside of laboratory research, this technique is not used in the U.S. or Canada and so additional data is needed to fully evaluate its validity.

Section 6.6.14 of Chapter 6 discusses the use of Dielectric Spectroscopy for subsea and HV cable systems.

12.2 DC Leakage Current Measurement Technique

12.2.1 Test Scope

DC leakage current tests consist of the application of dc voltage (lower than that used in dc withstand tests described in Chapter 9) with the simultaneous measurement of leakage current. It can be applied to all cable circuits. However, research has shown that the application of dc voltage to aged XLPE insulated cables can cause premature failure by injecting space charge into degraded regions of the insulation [10 - 14]. This trapped charge, if not discharged from the cable system leads to enhanced stress within the insulation once the circuit is re-energized with 60 Hz ac.

12.2.2 How It Works

A dc voltage is applied to the circuit. Once at steady state, the dc current required to maintain a given cable circuit at a specified voltage is measured.

12.2.3 How It Is Applied

This technique is performed offline. Its intent is to measure the global condition of the cable system insulation, but it can also be used for measuring tracking currents at insulation interfaces or on the external surface of terminations. A dc test voltage is applied between the conductor and the insulation shield and the resulting current is measured. The test voltage is increased stepwise. Each step usually takes 30 seconds. The total test duration is approximately 10 minutes. The maximum voltage is typically twice the peak value of the rated line-to-ground voltage of the cable. For new circuits, as an acceptance test, the voltage may be as high as 6 U_0.

The advantages and disadvantages of the dc leakage current measurement technique appear in Table 3.

The application of high voltages for a long period (defined by either cycles or time) may cause further degradation of an aged cable system. The impact of this effect warrants consideration for all the methods of dc leakage current described in this section. The precise degree of degradation will depend upon the voltage level and time of application. However, there are numerous studies that show that the rate of degradation is heightened when dc voltages are used – see discussion in Chapter 2. Thus, when applying elevated voltage to a cable system, a utility should have a repair crew on standby to address possible failures.

It is important to note that some accessories employ stress relief materials with non-linear loss characteristics. There have been suggestions that these materials might influence the measured values. *CDFI* has not explored dc leakage testing or data analysis to any significant degree, so the impact of these materials on dc leakage measurements is unknown.

Table 3: Overall Advantages and Disadvantages of Leakage Current Technique

Advantages	• Provides a general (though simplistic) condition assessment of a cable system. • The technique can be automated. • Test equipment is small, inexpensive, and easy to deploy. • Periodic testing provides historical data that enhances future testing by establishing trends.
Open Issues	• DC leakage tests may not be able to detect dirty terminations.
Disadvantages	• DC voltages (>U_0) create space charge accumulation that can cause aged XLPE insulated cables to fail prematurely after returning to service. • Before and after each test, cable must be completely discharged – these times can be long; > 4 times the length of the test. • The duration of voltage application is not well established. Typical times range from 15-60 minutes. • The cable system must be taken out of service for testing. • DC only detects severe cable system defects.

DC leakage testing has been deployed for many years and it is still used today, though mostly for industrial cable applications. In many cases, this appears to be a legacy issue from the previous common practice of dc hipot testing, rather than the proven efficacy of the technique.

12.2.4 Success Criteria

Leakage current results are reported in terms of the basic data.

Table 4: Pass and Not Pass Indications for Leakage Current Measurements

Cable System	Pass Indication	Not Pass Indication
HMWPE WTRXLPE XLPE	No uniform criteria established	No uniform criteria established
EPR		
PILC		

There are no unified success criteria for leakage current measurements (Table 4). Establishing such criteria is complicated in that the values depend not only on the cable system quality, but also on the cable/accessory technologies employed, the applied voltage, the circuit length, and the humidity (which may impact the measurement equipment and terminations) at the time of the test.

Although no unified criteria are available, a number of references indicate some useful features that form a basis for diagnostic conclusions (Table 5).

Table 5: Useful Judgment Criteria for the DC Leakage Current Technique [13]

Observed Characteristic	Judgment		
	No signs of deterioration	**Middle signs of deterioration**	**Marked signs of deterioration**
Leakage current changes with time during test	Current tends to decrease	Current tends to decrease	Current tends to increase
Rate of change of current changes during test	Rate of change decreases	Constant Rate	Rate of change increases
Leakage current (relative to reference cable)	Same as reference	2 to 10 times reference	>10 times reference

12.2.5 Estimated Accuracy

The *CDFI* does not have sufficient dc leakage current data to estimate the accuracy of this measurement technique.

12.2.6 *CDFI* Perspective

The *CDFI* does not have sufficient dc leakage current data to establish a *CDFI* perspective.

12.2.7 Outstanding Issues

This technique was historically utilized as part of a withstand program (see Chapter 10 – Monitored Withstand). To date, only one utility is known to have used it in North America. Data has not been collated in a coherent manner thus no research was possible within *CDFI*.

12.3 Recovery Voltage Technique

12.3.1 Test Scope

This diagnostic technique can be applied to any single cable insulation type (not hybrid circuits) with conventional or non-linear stress relief accessories. However, the availability of success criteria has effectively limited its use to paper insulated cables.

12.3.2 How It Works

This technique is sensitive to the level of water tree degradation in the insulation [14 - 18], or moisture ingress in PILC cables. It measures the increase in voltage caused by the release of trapped charges within the insulation. Absorbed moisture within the insulation likely causes charges to be trapped. The voltage measured across the cable system dielectric after the applied test voltage is removed is called the recovery voltage.

12.3.3 How It Is applied

This technique is conducted offline and measures the global condition of the insulation. Very little Recovery Voltage testing was performed in the *CDFI* so the following discussion is based on information from the literature.

The procedure follows the scheme shown in Figure 11. The cable circuit is charged using dc voltage for a given time. Typical values range from 1 to 2 kV. Charging time is usually 15 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a ground resistor. The open circuit voltage is then measured. This voltage is known as the recovery voltage.

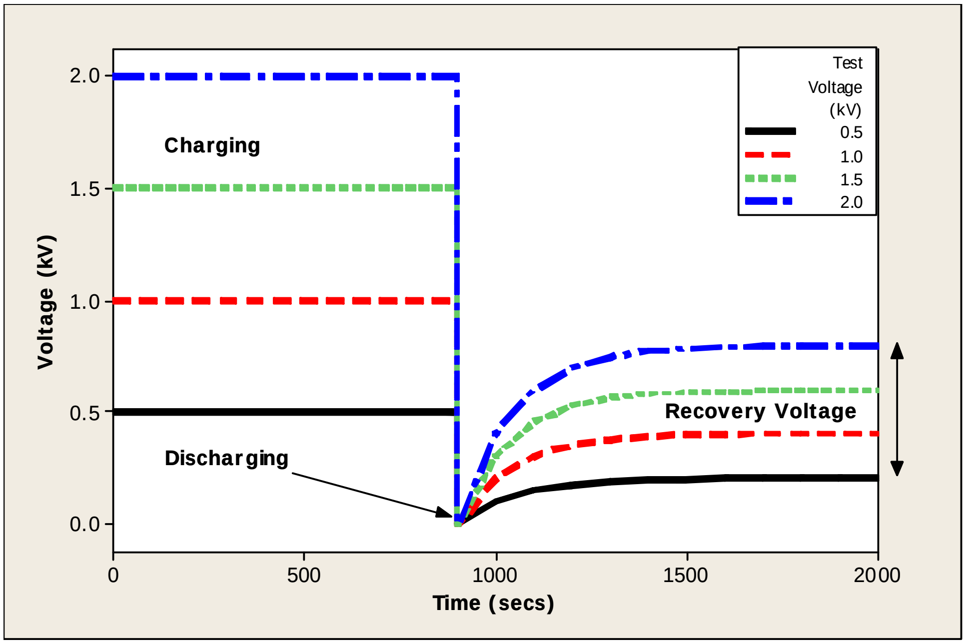

Figure 11: Schematic Representation of the Recovery Voltage Measurement Technique

Data from Kuschel et al. [13] (Figure 12) display the magnitudes expected from tests on new (unaged) cables. Figure 11 shows the different discharging characteristics and that the Recovery Voltages are in the range of 0.1% to 0.2% of the dc charging voltage. These data used the following test protocol:

- charging voltage: 3 kV dc
- charging time: 15 min (900 sec)
- discharge time: 5 sec

The data appear in Figure 12 for the maximum measured voltage and the result after a decay time of 10,000 sec.

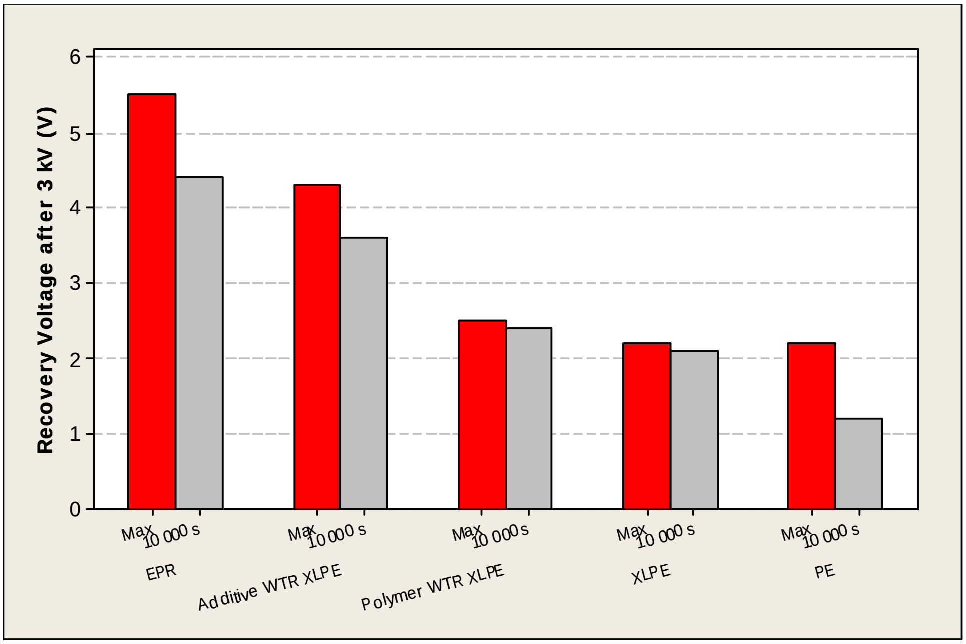

Figure 12: Recovery Voltage Data [13]

In the recovery voltage technique, the diagnostic factor D describes the level of damage to the cable. The diagnostic factor D is the ratio between the maximum recovery voltage with U_0 as the charging voltage and the maximum recovery voltage with 2 U_0 as the charging voltage. This ratio appears in Equation 3.

$$D = \frac{\text{Recovery Voltage}_{\text{Max}}(2U_0)}{\text{Recovery Voltage}_{\text{Max}}(U_0)}$$ **Equation 3**

Where:

D - Diagnostic factor
Recovery Voltage$_{Max}$ *($2U_0$)* - Maximum recovery voltage recorded for 2 U_0
Recovery Voltage$_{Max}$ *(U_0)* - Maximum recovery voltage recorded for U_0

The standard diagnostic criterion is the "non-linearity" of the return voltage at its maximum value. For unaged (undamaged) cables, D should equal two. That is, if the charging voltage doubles then the recovery voltage should also double as there is a one-to-one correspondence between the recovery and charging voltages. A heavily aged cable system will not behave linearly and so the diagnostic factor (D) for such a system would be different from the ratio of the two charging voltages [15 - 17].

Although the nonlinearity of the dielectric response seems to be a good diagnostic parameter for water tree detection, a false diagnosis is possible if the degree of non-linearity is exclusively described by a single numerical value, i.e. the value of D established using measurements at U_0 and $2U_0$. Thus, better discrimination may be attained if D is computed for a range of voltages and thus shown to be linear or near-linear.

Advantages and disadvantages for the Recovery Voltage technique appear in Table 6.

Table 6: Overall Advantages and Disadvantages of Recovery Voltage Technique

Advantages	• Provides a general condition assessment of cable system insulation. • Test equipment is small.
Open Issues	• Historically applied to all cable types but currently recommended only for paper cables. No data on paper cables are available. • Accessory behavior must be considered to properly assess cable system insulation condition. • Cable must be completely discharged after each test.
Disadvantages	• No application guidelines are available. • Cannot detect localized defects. • Cannot be applied to hybrid circuits due to the responses of different insulation materials. • Cable must be removed from service for testing.

It is important to bear in mind that some accessories specifically employ stress relief materials with non-linear loss characteristics, that is, their dielectric loss does not vary linearly with the applied test voltage. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available to date for dielectric loss measurements (Chapter 6), which are related to Recovery Voltage, shows that the type of stress relief is likely to show a smaller effect than either:

a) the aging of the accessory or

b) incorrect installation depending on the tested segment length

Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Recovery Voltage values.

12.3.4 Success Criteria

Recovery Voltage results are reported in terms of basic recovery voltage measurements as a function of charging voltage.

There are some success criteria for recovery measurements (Table 7) that provide a hierarchy of levels. General criteria for all cable types are used but it is expected that the criteria depend on not only the quality of the cable system, but also on the cable and accessory technologies employed and the stress associated with the application (charging) voltage.

Table 7: Pass and Not Pass Indications for Recovery Voltage Measurements

Cable System	Pass Indication	Not Pass Indication
HMWPE WTRXLPE XLPE	No unified criteria	No unified criteria
EPR		
PILC		

Although no unified criteria are available, a number of references indicate some useful features to form a basis for diagnostic conclusions (Table 8).

Table 8: Interpretation Rule of Diagnostic Factor D Obtained From Maximum Recovery Voltages at U_0 and $2U_0$ [15]

Diagnostic Factor D	Evaluation	Action
2.0 – 2.5	Insulation in good condition	No action
2.5 – 3.0	Insulation in fair condition	Other tests are recommended to identify isolated weak areas
> 3.0	Severely damaged	Replace cable

Figure 13 graphically illustrates the criteria shown in Table 8.

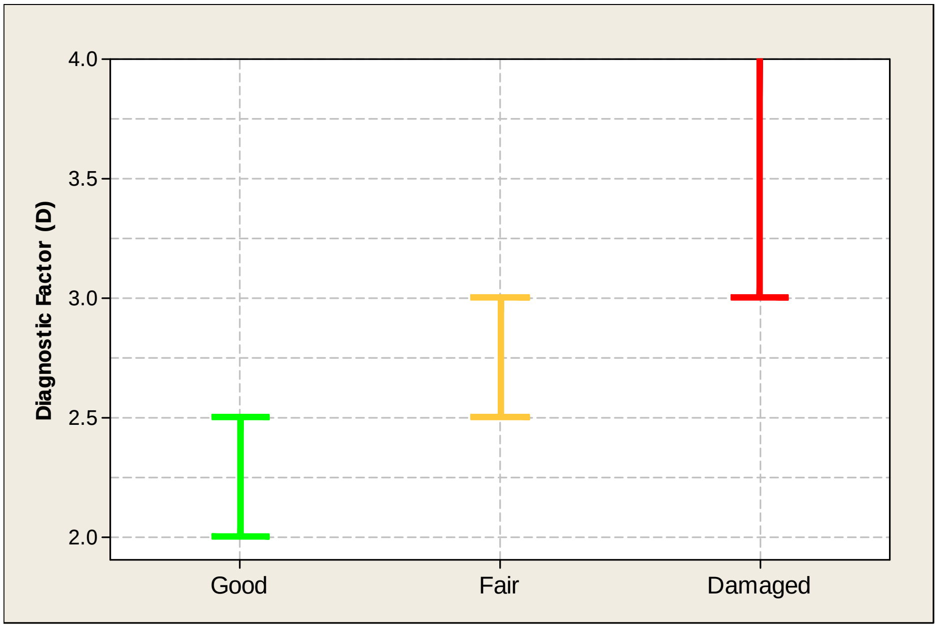

Figure 13: Interpretation of the Diagnostic Factor D

12.3.5 Estimated Accuracy

No information is available to *CDFI* to make this assessment.

12.3.6 *CDFI* Perspective

This technique is not used in the U.S. or Canada so no significant data have been provided to the *CDFI*. Thus no perspective on this technology was developed.

12.3.7 Outstanding Issues

This technique is not used in the US or Canada and so additional data is needed to fully evaluate its validity.

12.4 Polarization/Depolarization Current Or Isothermal Relaxation Current (IRC) Technique

12.4.1 Test Scope

This test involves the short-term application of low dc voltages to extruded cable circuits having only one type of insulation material. Very little IRC testing was performed in the *CDFI* so the following discussion is based on information from the literature.

12.4.2 How It Works

It measures the time constant of trapped charges within the insulation as they relax by measuring the discharge current over time after the application of a prescribed dc voltage [18 - 19].

12.4.3 How It Is applied

This technique is performed offline. The measured results relate to the global condition of the insulation and the presence of water trees. The procedure is as follows: The cable circuit is charged using dc voltage (1 kV) for a given time. The charging time is usually 5 to 30 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a resistor to ground. The discharge current is then measured for 15 to 30 minutes. This current is known as the depolarization or Isothermal Relaxation Current (IRC). The voltage application is similar to that described for Recovery Voltage in Figure 11, but the measured parameter is a current, not a voltage. The measured current appears schematically in Figure 14.

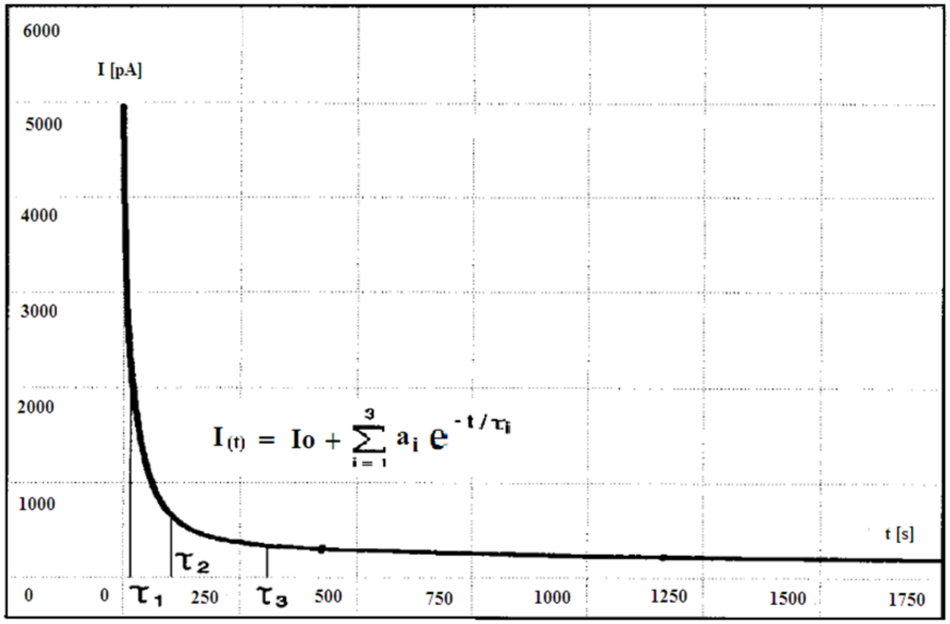

Figure 14: Schematic Representation of Measured Current from the IRC Technique [18]

It is assumed that the measured discharge current is comprised of three current components (similar to the discussion on Dielectric Spectroscopy in earlier in the chapter), which must be separated and compared. The separation applies an assumed model that considers three exponential currents, each with a different time constant. These three currents are computed and identified as -

a) current related with the cable insulation
b) current related with the semi conductive layer and
c) current related with insulation defects

Each current has a corresponding duration and, thus, represents a certain amount of charge: Q1, Q2, and Q3. The current of most concern is that which generates Q3. In fact, the larger the peak of Q3 as compared to Q2 or Q1, the worse the condition of the cable insulation [17]. Figure 15 shows these principles graphically. See [18] for definitions of the terms used in this figure.

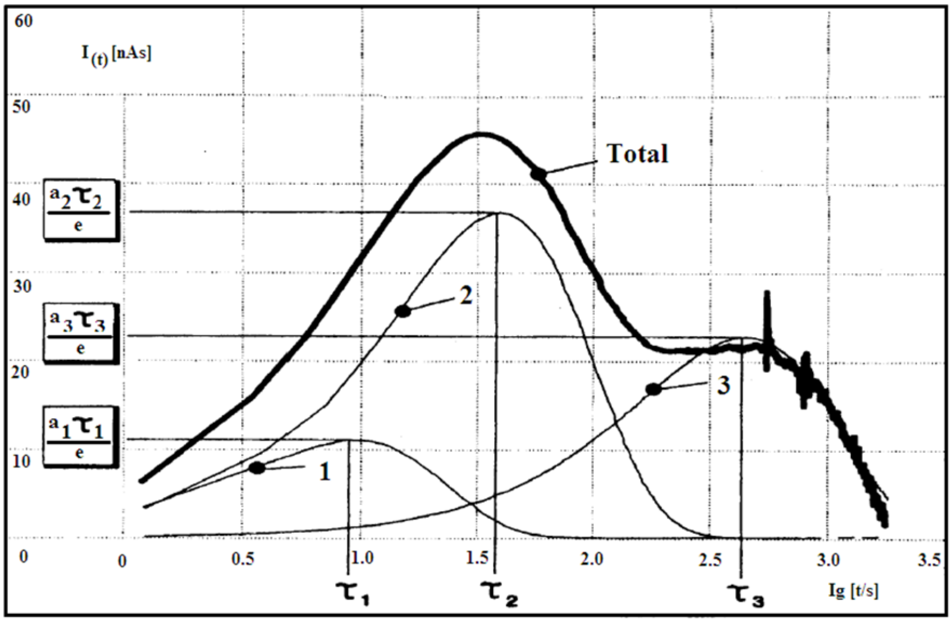

Figure 15: Principles of IRC Current Separation and Charge Calculation [18]

Advantages and disadvantages for the IRC approach to diagnostic testing appear in Table 9.

Note that some accessories specifically employ stress relief materials with non-linear loss characteristics. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available for dielectric loss, which is related to the IRC measurement, shows that the type of stress relief is likely to show a smaller effect than either -

a) the aging of the accessory or
b) incorrect installation depending on the tested segment length

Therefore, the best practice is to perform periodic tests at the same voltage level(s) while observing the general trend in IRC values.

Table 9: Overall Advantages and Disadvantages of Polarization/Depolarization Current Technique

Advantages	• There are well-established criteria for evaluating German XLPE cable systems against accelerated laboratory endurance tests. • Test equipment is small.
Open Issues	• No assessment criteria for U.S. cables. • Criteria not established for WTRXLPE or EPR cable systems. • Accessory behavior may need to be included to properly assess cable system condition. • Assumes a three time constant model. This model may not be appropriate. • Reproducibility of measurement for very small currents on the order of nano amps. • Stability of the mathematical separation techniques for the current. • Cables need to be energized prior to testing to ensure adequate polarization. • The technique is apparently sensitive to the presence of water trees.
Disadvantages	• Difficult to measure new extruded cables due to presence of crosslinking byproducts. • The small currents measured are very sensitive to the test environment. • Cannot detect localized defects. • Cable must be completely discharged after each test. • Cable must be taken out of service for testing. • Cable neutral must be ungrounded. • Computationally difficult to extract model parameters. • Long length required to get sufficiently large signal.

In the IRC technique, the aging factor (IRCA) describes the level of damage to the cable. The aging factor is the ratio between the trapped charge in the insulation defects and the trapped charge in the semiconductor layers of the cable [18]. This ratio appears in Equation 4.

$$IRCA = \frac{Q_3}{Q_2}$$ **Equation 4**

Where:

$IRCA$ - Aging factor

Q_3 - Trapped charge in the insulation

Q_2 - Trapped charge in the semiconductor layers

12.4.4 Success Criteria

General criteria depend on the cable system quality, the cable and accessory technologies employed, and the stress associated with the application voltage. Table 10 and Table 11 show the interpretation of IRCA.

Table 10: Pass and Not Pass Indications for Recovery Voltage Measurements

Cable System	Pass Indication	Not Pass Indication
XLPE	See Table 11	See Table 11
HMWPE WTRXLPE	No unified criteria	No unified criteria
EPR		
PILC		

Table 11: Correlation Between Aging Class and Aging Factor for XLPE Cables [18]

IRCA	Aging Class
Less than 1.75	Good
Between 1.75 and 1.90	Middle
Between 1.90 and 2.10	Aged
More than 2.10	Critical

12.4.5 Estimated Accuracy

This technique is not used in the USA or Canada and thus no extensive data are available for analysis.

12.4.6 *CDFI* Perspective

No *CDFI* perspective exists due to the limited information available on this technology.

12.4.7 Outstanding Issues

This technique is not used in the USA or Canada and so additional data is needed to fully evaluate its validity.

12.5 References

1. P. Mohaupt, M. Baur, and T. Schlick, "VLF Testing and Diagnosis on Medium Voltage Power Cables," IEEE 10th Inter. Conf. on Transmission and Distribution Construction, Operation, and Live Line Maintenance, pp.202-209, Apr. 2003 IEEE ESMO.
2. A. Jonscher, *Dielectric Relaxation in Solids*, Chelsea Dielectrics Press, 1983.
3. C. Potvin et al, "Diagnostic Testing Of MV Accessories By Time Domain Spectroscopy (TDS)," *International Conference on Insulated Power Cables, JICABLE07*, Versailles France, June 2007.
4. J. F. Drapeau et al, "Time Domain Spectroscopy (TDS) As A Diagnostic Tool For MV XLPE Underground Lines," *International Conference on Insulated Power Cables, JICABLE07*, Versailles, France, June 2007.
5. R. Neimanis and R. Eriksson, "Diagnosis of moisture in oil/paper distribution cables - Part I: Estimation of moisture content using frequency-domain spectroscopy," IEEE Transactions on Power Delivery, Volume 19, Issue 1, Jan. 2004, pp. 9 – 14.
6. Hampton, R. N. and Patterson, R., "Tan Delta Testing: Effect of Terminations," Minutes of IEEE ICC Spring 2008 Meeting, St Petersburg, FL, 2008.
7. J. F. Drapeau and J. C. Hernandez, "Measurement of Cable System Losses using Time Domain and VLF Techniques," IEEE Insulated Conductors Committee, Subcommittee F Fall 2008.
8. R. N. Hampton, G. A. Saunders, and A. M. Stoneham, "The frequency dependent response of the electrical impedance of UO_2," *J Nucl Mater* 139 (1986) 185190.
9. P. Werelius, P. Tharning, R. Eriksson, B. Holmgren, and U. Gafvert, "Dielectric Spectroscopy for Diagnosis of Water Tree Deterioration in XLPE Cables," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 8, no. 1, pp 27-42, Mar 2001.
10. G. S. Eager, C. Katz, B. Fryszczyn, J. Densley, and B. S. Bernstein, "High Voltage VLF Testing of Power Cables," IEEE Transactions on Power Delivery, vol. 12 no. 2, pp. 565–670, 1997.
11. N. H. Srinivas and B. S. Bernstein, "Effect of D.C. Testing on Aged XLPE Insulated Cables with Splices," *International Conference on Insulated Power Cables, JICABLE91*, Paris, France, Paper B.3.1, June 1991.
12. N. H. Srinivas, B. S. Bernstein, and R. Decker, "Effects of DC Testing on AC Breakdown Strength of XLPE Insulated Cables Subjected to Laboratory Accelerated Aging," IEEE Trans. on Power Delivery. Vol. 5. No. 4. Oct. 1990, pp. 1643-1657.
13. M. Kuschel, R. Plath, I. Stepputat, and W. Kalkner, "Diagnostic techniques for service aged XLPE insulated medium voltage cables," *International Conference on Insulated Power Cables, JICABLE95*, pp. 504 – 508.
14. Draft: IEEE Guide for Field-Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5kV and above with High Direct Current Voltage, IEEE Std. 400.1™, Draft 5 D5, Oct. 2004.
15. E. Ildstad and S. Gubanski, "Dielectric properties of water-treed XLPE insulation," Proc. of the IEEE Conf. on Electrical Insulation 1994 (CEIDP'94), 1994, pp. 497-505.
16. B. Oyegoke, P. Hyvonen, M. Aro, and N. Gao, "Application of Dielectric Response Measurements on Power Cable Systems," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 10, No. 5, October 2003, pp. 862-873.
17. J. Jung, R. Pastsh, and D. Kamenka, "Return voltage- a reliable diagnosis for water treed

cable" Proc. of the IEEE Conf. Electrical Insulation and Dielectric Phenomena," (CEIDP'99), 1999, pp. 626-629.

18. G. Hoff and H. Kranz, "Condition based maintenance of PE/XLPE-insulated medium voltage cable networks - verification of the IRC-Analysis to determine the cable age," Proc. of the IEEE International Symposium on Electrical Insulation 2002, 2002, pp. 53-56.
19. P. Birkner, "Field experience with a condition-based maintenance program of 20 kV XLPE distribution systems using IRC-analysis," IEEE Trans. on Power Delivery, vol.19, no. 1, pp. 3-8, Jan. 2004.