Designation: D 3382 – 95

An American National Standard

Standard Test Methods for Measurement of Energy and Integrated Charge Transfer Due to Partial Discharges (Corona) Using Bridge Techniques[1]

This standard is issued under the fixed designation D 3382; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover two bridge techniques for measuring the energy and integrated charge of pulse and pulseless partial discharges:

1.2 Test Method A makes use of capacitance and loss characteristics such as measured by the transformer ratio-arm bridge or the high-voltage Schering bridge (Test Methods D 150). Test Method A can be used to obtain the integrated charge transfer and energy loss due to partial discharges in a dielectric from the measured increase in capacitance and tan δ with voltage.

1.3 Test Method B makes use of a somewhat different bridge circuit, identified as a charge-voltage-trace (parallelogram) technique, which indicates directly on an oscilloscope the integrated charge transfer and the magnitude of the energy loss due to partial discharges.

1.4 Both test methods are intended to supplement the measurement and detection of pulse-type partial discharges as covered by Test Method D 1868, by measuring the sum of both pulse and pulseless discharges per cycle in terms of their charge and energy.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precaution statements are given in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*

D 150 Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials[2]

D 1711 Terminology Relating to Electrical Insulation[2]

D 1868 Test Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *pseudoglow discharge, n*—a type of partial discharge characterized by pulses of relatively small amplitude, and, generally, a long rise time.

3.1.1.1 *Discussion*—As a result of the upper frequency limitation in their Fourier frequency spectrum, pseudoglow discharges are not readily detected by conventional partial-discharge-pulse detectors. Pseudoglow discharges are also characterized by a diffused glow, that cannot be visually distinguished from that due to a true-glow discharge.

3.1.2 *pulse discharge, n*—a type of partial-discharge phenomenon characterized by a spark-type breakdown.

3.1.2.1 *Discussion*—The resultant detected pulse discharge has a short rise time and its Fourier frequency spectrum may extend as far as 100 MHz. Such a pulse discharge may be readily detected by conventional pulse detectors, that are generally designed for partial-discharge measurements within the frequency band from 30 kHz to several megahertz.

3.1.3 *pulseless-glow discharge, n*—a type of partial-discharge phenomenon characterized by a diffused glow.

3.1.3.1 *Discussion*—The overall voltage waveform across a gap-space undergoing a pulseless-glow discharge does not indicate the presence of any abrupt voltage falls, except for the two at the beginning of each half cycle (for example, thyratron behavior) **(1) (2)**.[3] Although discharge energy is expended over the pulseless region, a conventional partial-discharge-pulse detector will give no indication of this as it will only respond to the two initiating breakdowns.

3.1.4 See **(3)** and **(4)** for more information on the previous definitions.

3.1.5 For definitions of other terms pertaining to this standard refer to Terminology D 1711.

3.2 *Symbols:Symbols:*

3.2.1 Refer to Annex A1 for symbols for mathematical terms used in this standard.

4. Summary of Test Methods

4.1 The dielectric characteristics of a specimen of solid insulating material may be represented by a parallel combination of capacitance and conductance. The values of capacitance

[1] These test methods are under the jurisdiction of ASTM Committee D-9 on Electrical and Electronic Insulating Materials and are the direct responsibility of Subcommittee D09.12 on Electrical Tests.

Current edition approved Sept. 10, 1995. Published January 1996. Originally published as D 3382 – 75. Last previous edition D 3382 – 86 (1990) ε1.

[2] *Annual Book of ASTM Standards*, Vol 10.01.

[3] The boldface numbers in parentheses refer to the list of references at the end of these test methods.

and conductance remain practically constant over the useful range of alternating voltage stress at a fixed frequency. If, however, the specimen contains gaseous inclusions (cavities), incremental increases in capacitance and conductance occur as the voltage stress is raised above the value necessary to initiate partial discharges in the cavities. The energy loss in the incremental conductance is considered to be that dissipated by the partial discharges.

4.2 In Test Method A an initial measurement is made of the capacitance and loss characteristic of the specimen at an applied voltage below the discharge inception level. The voltage is then raised to the specified test value and a second measurement made. The energy loss due to partial discharges is calculated from the results of the two measurements.

4.3 In Test Method B a special bridge circuit is balanced at a voltage below the discharge inception level. The voltage is then raised to the specified test value, but the bridge is not rebalanced. Any unbalanced voltage at the detector terminals is displayed in conjunction with the test voltage on an oscilloscope. The oscilloscope pattern approximates a parallelogram, the area of which is a measure of the energy loss due to partial discharges.

5. Significance and Use

5.1 These test methods are useful in research and quality control for evaluating insulating materials and systems since they provide for the measurement of charge transfer and energy loss due to partial discharges **(5)** **(6)** **(7)**.

5.2 Pulse measurements of partial discharges indicate the magnitude of individual discharges. However, if there are numerous discharges per cycle it may be important to know their charge sum, since this sum can be related to the total volume of internal gas spaces that are discharging, if it is assumed that the gas cavities are simple capacitances in series with the capacitances of the solid dielectrics **(8)**.

5.3 Internal (cavity-type) discharges may be of a glow, pulseless, or pseudoglow nature, which are not indicated by conventional pulse-discharge detectors **(1)** **(2)** **(5)**. Pseudoglow discharges are detected primarily in terms of their effects upon tan δ and capacitance, since their rise times are much too long to excite pulse detectors as covered in Test Method D 1868.

5.4 Pseudoglow discharges have been observed to occur in air, particularly when a partially conducting surface is involved. Such partially conducting surfaces may develop with polymers that are exposed to partial discharges for sufficiently long periods to accumulate acidic degradation products. Also in some applications, like turbogenerators, where a low molecular weight such as hydrogen or helium is used as a coolant, pseudoglow discharges may develop.

6. Sources of Errors

6.1 *Surface Discharges*—All discharges in the test specimen are measured, whether on the surface or in internal cavities. If it is desired to measure only internal cavities, the other discharges must be avoided. In the case of an insulated conductor with an outer electrode on the surface (such as a cable or generator coil), the surface discharges at the end of this outer electrode can be removed from the measurement with a closely-spaced guard ring connected to ground. See Section 4 of Test Methods D 150.

6.2 Since tests will be made at ionizing voltage, all connections making up the complete high-voltage circuit should be free of corona to avoid measurement interference. See Section 5 of Test Method D 1868.

6.3 Other phenomena in addition to partial discharges may produce anomalous changes in insulation losses with changes in voltage stress. Such losses are a source of error in these methods, since they are indistinguishable from discharge losses. However, these losses are often negligible in comparison with partial discharge losses.

6.4 Any temperature change in the specimen between the times at which the low-voltage and high-voltage measurements are taken may cause a change in the normal losses and appear as changes in discharge energy, thus causing an error in test results. This situation can be recognized in Method B and corrective action taken (see 11.3).

6.5 Paint used to grade potential on the surface of some insulation specimens (for example, generator stator coil) should not be included in the measurement, since the conductance of such paints may change with voltage and affect the accuracy of the method as a measure of discharge energy. It is sometimes possible to exclude the painted surfaces from the measuring circuit by the use of guarding or shielding techniques.

7. Hazards

7.1 **Warning—** *Lethal voltages may be present during this test. It is essential that the test apparatus, and all associated equipment that may be electrically connected to it, be properly designed and installed for safe operation. Solidly ground all electrically conductive parts that any person might come in contact with during the test. Provide means for use at the completion of any test to ground any parts which: were at high voltage during the test; may have acquired an induced charge during the test; may retain a charge even after disconnection of the voltage source. Thoroughly instruct all operators in the proper way to conduct tests safely. When making high voltage tests, particularly in compressed gas or in oil, the energy released at breakdown may be sufficient to result in fire, explosion, or rupture of the test chamber. Design test equipment, test chambers, and test specimens so as to minimize the possibility of such occurrences and to eliminate the possibility of personal injury.*

7.2 **Warning—** *Ozone is a physiologically hazardous gas at elevated concentrations. The exposure limits are set by governmental agencies and are usually based upon recommendations made by the American Conference of Governmental Industrial Hygienists.*[4] *Ozone is likely to be present whenever voltages exist which are sufficient to cause partial, or complete, discharges in air or other atmospheres that contain oxygen. Ozone has a distinctive odor which is initially discernible at low concentrations but sustained inhalation of ozone can cause temporary loss of sensitivity to the scent of ozone. Because of this it is important to measure the concentration of ozone in the atmosphere, using commercially available monitoring devices,*

[4] Building D-7, 8500 Glenway Drive, Cincinnati, OH 45211.

whenever the odor of ozone is persistently present or when ozone generating conditions continue. Use appropriate means, such as exhaust vents, to reduce ozone concentrations to acceptable levels in working areas.

TEST METHOD A

8. Procedure

8.1 Conventional circuits for the measurement of alternating-voltage capacitance and loss characteristics of insulation may be used for this method. The transformer-ratioarm bridge shown in Fig. 1, or the Schering bridge shown in Fig. X4.2 of Test Methods D 150 are well suited to this application.

8.2 Energize the test specimen at a low voltage, V_1, below the discharge-inception voltage, and measure capacitance C_{x1} and dissipation factor tan δ_1. Raise the voltage to a specified test level, V_2, and repeat the measurements for C_{x2} and tan δ_2. Calculate the power loss, ΔP, in watts due to discharges at voltage V_2 as follows:

$$\Delta P = \omega V_2^2 [C_{x2} \tan \delta_2 - C_{x1} \tan \delta_1] \quad (1)$$

$$= P_2 - (P_1 V_2^2 / V_1^2) \quad (2)$$

8.3 The increment of dissipation factor tan δ_2 − tan δ_1, called delta tan delta, and written Δ tan δ, is often used as an index of discharge intensity.

9. Precision and Bias

9.1 This test method has been in use for many years, but no statement for precision has been made and no activity is planned to develop such a statement.

9.2 A statement of bias is not possible due to the lack of a standard reference material.

10. Interferences

10.1 *Harmonics*—The test voltage must be reasonably free of harmonics in order to produce the required horizontal line below the inception voltage. Harmonics will produce a wavy rather than a flat line. If the waviness is too severe, the voltage source may have to be filtered to remove the harmonics. The removal of harmonics is more important when the quantities to be measured are small.

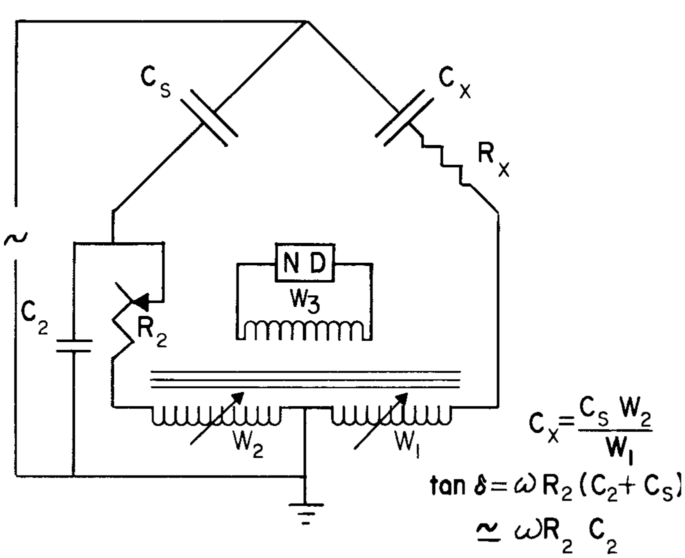


FIG. 1 Typical Transformer-Ratio-Arm Bridge (Method A)

TEST METHOD B

11. Procedure

11.1 The test method requires the placing of the test specimen, considered essentially as a high-voltage capacitor, in series with a low-voltage capacitor, across a sinusoidal test-voltage source. See Fig. 2. Two other bridge arms provide a voltage for balancing, at an applied voltage level below inception of partial discharges, the sinusoidal voltage across the low-voltage capacitor. Any partial discharges that occur at higher applied voltages in the specimen will be integrated by the low-voltage capacitor to produce an unbalanced voltage. The unbalanced voltage controls the vertical deflection of an oscilloscope beam, while a voltage proportional to, and in phase with, the test voltage controls the horizontal deflection. A description of a suitable circuit for this test method is detailed in Annex A2.

11.2 The oscilloscope display is simply a horizontal line below the discharge inception voltage where no unbalanced voltages occur. Above the discharge inception voltage the display opens into an approximate parallelogram. The height of the parallelogram represents the sum of the partial discharges per half cycle, and the area represents the energy dissipated per cycle by the discharges. See Fig. 3.

11.3 If the parallelogram has been tilted or distorted by the increase in voltage, a small adjustment in the capacitance and resistance balance can be made to make the top and bottom of the parallelogram horizontal. This will compensate for some changes in capacitance and tan δ due to effects other than partial discharges.

12. Calibration of Oscilloscope Coefficients

12.1 In order to evaluate the parallelogram, it is necessary to determine the deflection sensitivities of the oscilloscope. See Fig. 3. The horizontal-deflection sensitivity, S_x, in volts per centimetre, is found from observing the horizontal deflection, D_{xi} or D_{xa}, in centimetres, to a test voltage having a peak-to-peak value of V_c or V_a as measured by accurate independent means.

$$S_x = V_c/D_{xi} = V_a/D_{xa} \quad (3)$$

12.2 The vertical-deflection sensitivity, S_y, in coulombs per centimetre, may be found from observing the vertical deflection, D_y, in centimetres, to a known charge, Q_c, in coulombs, by a square-wave generator having a peak-to-peak voltage, E_c, coupled to the low-voltage capacitor through a calibrating capacitor, C_c, of a much smaller value. The square-wave frequency should be of the same order as the test frequency.

$$S_y = Q_c/D_y = E_c C_c/D_y \quad (4)$$

12.3 Alternatively, Q_t, in coulombs, may be determined from the turns ratio, n, of the detector transformer, T, and the voltage, V_p, required at the vertical input of the oscilloscope to produce a vertical deflection of the same magnitude as that produced by the discharges. V_p may be directly measured by connecting a peak-to-peak voltmeter across the vertical input of the oscilloscope as shown in Fig. 2, and read when the parallelogram is obtained. Then:

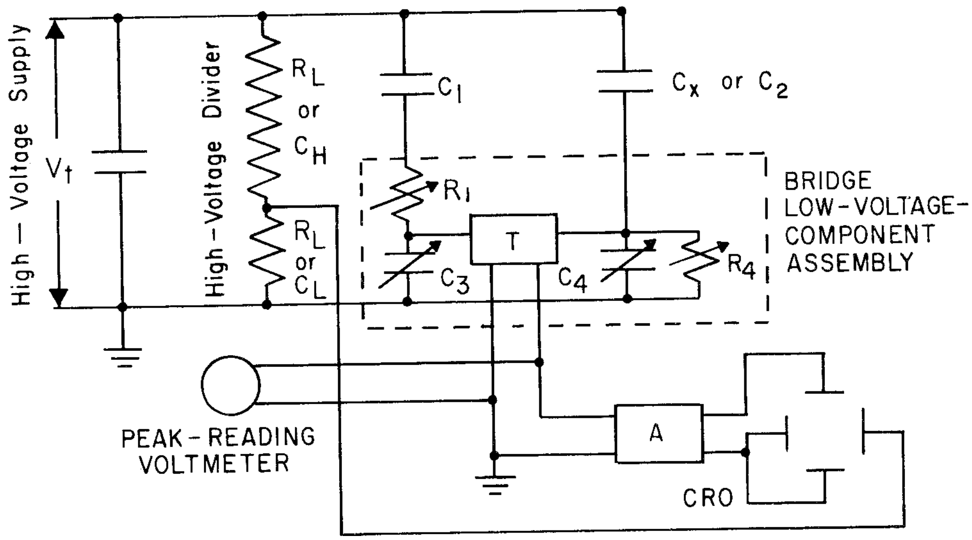
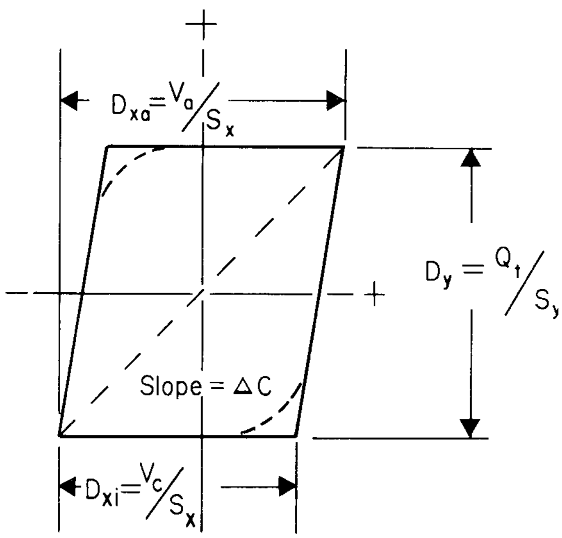


FIG. 2 Typical Charge-Voltage-Trace Bridge (Method B)



V_c = discharge inception voltage peak to peak
V_a = applied voltage peak to peak
D_yS_y = Q_t coulombs per half cycle
S_yS_xA = W joules per cycle
A = area = $D_{xi}D_y$
ΔC = slope = $C_x' - C_x = D_yS_y/D_{xa}S_x$

FIG. 3 Idealized Loop Trace (Method B)

$$Q_t = nV_pC_4 \tag{5}$$

where Q_t is the total charge per half cycle, or

$$S_y = nV_pC_4/D_y \tag{6}$$

where D_y is the height of the parallelogram in centimetres.

13. Calculation

13.1 *Integrated Charge*—The integrated-charge transfer per half cycle, Q_t, is the product of the vertical deflection, D_y, of the oscilloscope (the height of the parallelogram) multiplied by the vertical-deflection sensitivity S_y:

$$Q_t = D_yS_y \tag{7}$$

13.2 *Energy*—The energy, W, in joules per cycle, is the area, A, of the parallelogram measured in the same units as the deflection sensitivities:

$$W = AS_xS_y \tag{8}$$

Where the parallelogram is well defined, the area is the product of the parallelogram heights, D_y, and the width, D_{xi}, conveniently measured along the center axis of the oscilloscope raster. Thus

$$W = D_{xi}D_yS_xS_y \tag{9}$$

13.3 *Capacitance Increase*—The increase, ΔC, of the specimen capacitance with voltage, from the voltage below the discharge inception, where the bridge is initially balanced, up to the test voltage is:

$$\Delta C = Q_t/V_a \tag{10}$$

where V_a is the applied peak-to-peak voltage at which the test is being made. This voltage corresponds to the total horizontal projected width of the parallelogram.

13.4 For further analysis of measurements see Annex A3.

14. Report

14.1 Report the following information:

14.1.1 *Identification*—Include information that describes the specimen, so as to permit comparison between similar systems or different production lots of the same system, and to permit other types of comparison between different materials,

14.1.2 *Test Method*—Include a description of the test procedure, test apparatus, test specimen, the test voltages and length of time applied, preconditioning and history, and ambient conditions and any other factors that may influence the performance of the test and the result obtained, and that will permit exact duplication of the tests at a later time,

14.1.3 Date of test,

14.1.4 Where tests were performed and by whom,

14.1.5 *Test Results*—Include experimental values obtained, number of specimens tested, along with results from appropriate calculations such as average (mean), standard deviation, etc., and

14.1.6 *Observations*—Include information of importance to the understanding or interpretation of the test method and results that have not been included in the foregoing sections.

15. Precision and Bias

15.1 This test method has been in use for many years, but no statement for precision has been made and no activity is planned to develop such a statement.

15.2 A statement of bias is not possible due to the lack of a standard reference material.

16. Keywords

16.1 bridge circuits; bridge techniques; capacitance increase; charge-voltage-trace bridge; corona; discharge energy; discharge inception level; energy; harmonics; integrated charge transfer; internal discharges; ionizing voltage; loop trace; partial discharges; pseudoglow discharge; pulse discharge; pulseless-glow discharge; pulse measurements; solid insulating materials; surface discharge; transformer-ratio-arm bridge

ANNEXES

(Mandatory Information)

A1. LIST OF SYMBOLS

A	area of parallelogram, also amplifier
A_m	measured area of parallelogram
C_1, C_2, C_3, C_4	capacitances, see Fig. 2
C_2	capacitance, see Fig. 1
C_x	specimen capacitance
C_{x1}	specimen capacitance, low voltage, Test Method A
C_{x2}	specimen capacitance, high voltage, Test Method A
C_x'	specimen capacitance, high voltage, Test Method B
ΔC	specimen-capacitance increment, Test Method B, see Fig. 3
C_H, C_L	capacitances, see Fig. 2
C_c	calibrating capacitor
C_s	standard capacitor, see Fig. 1 and Test Methods D 150, Fig. X4.2
D_{xi}	CRO deflection, *x*-axis at discharge inception voltage, see Fig. 3
D_{xa}	CRO deflection, *x*-axis at applied voltage above inception, see Fig. 3
D_y	CRO deflection, *y*-axis, see Fig. 3
E_c	square-wave-generator voltage, peak-to-peak, see Eq 4
f	frequency
ND	null detector, see Fig. 1
n	turn ratio of transformer *T*, see Fig. 2
P	power, Test Method B
P_1	low-voltage power, Test Method A
P_2	high-voltage power, Test Method A
ΔP	power increment, Test Method A
Q_t	total charge per half cycle, see Fig. 3
R_2, R_4, R_H, R_L	resistances, see Fig. 2
R_2	resistance, see Fig. 1
R_x	specimen resistance, see Fig. 1
S_x	CRO *x*-axis sensitivity, see Fig. 3
S_y	CRO *y*-axis sensitivity, see Fig. 3
T	transformer, see Fig. 2
V_t	supply voltage, see Fig. 2
V_1	low voltage, Test Method A
V_2	high voltage, Test Method A
V_a	applied voltage above discharge inception, Test Method B
V_c	applied voltage at discharge inception, Test Method B
V_p	calibrating voltage, Test Method B, see 11.3
W	work, energy, Test Method B
W_1, W_2, W_3	transformer turns, see Fig. 1
ω	$2\pi f$
δ	dielectric loss angle

A2. CIRCUIT COMPONENTS AND MEASUREMENT PROCEDURE FOR TEST METHOD B (SEE Fig. 2)

A2.1 Apparatus

A2.1.1 *Bridge*—The bridge shown in Fig. 2 consists of four essentially capacitive arms. There are two high-voltage arms, as in a high-voltage, Schering-type bridge. One of these, C_x(or C_2), is the specimen to be measured. The second, C_1, is a high-voltage discharge-free capacitor, usually a 100-pF standard capacitor, with tan $\delta < 0.001$. The two low-voltage arms, C_3 and C_4, are capacitance arms, used for balancing the bridge at a voltage just below the discharge-inception voltage. The unbalance voltage above the discharge-inception voltage is proportional to the sum of the discharges in the specimen per half cycle, provided that certain precautions are taken. The unbalance voltage of the bridge is displayed on the vertical axis of an oscilloscope, and the horizontal axis is driven by a voltage proportional to, and in phase with, the high voltage applied to the bridge. The oscilloscope display properly consists of a horizontal line at balance below the discharge-inception voltage. Above the discharge-inception voltage, the display breaks into an approximate parallelogram, with small steps on each sloping side, but with a flat, smooth trace on the top and bottom. The sloping sides of the parallelogram are the discharging portion of the voltage cycle, and the top and bottom are the nondischarging portions of the cycle.

A2.1.2 Normal losses in the specimen are balanced by a variable resistor, R_1, in series with C_1. A convenient range for R_1 is from 0 to 1 MΩ. Further balance is provided by variable resistor R_4 in parallel with C_4. Resistor R_4 also functions to control the average voltage level across C_4, which might rise to unacceptable values if the discharges of one polarity recurrently exceed those of the other polarity. Resistor R_4 should have a sufficiently high value to avoid any significant drain on the charge accumulated on C_4 during one half cycle of the test voltage. Thus $R_4C_4 > 100/f$ where f is the frequency of the test voltage.

A2.1.3 The loss tangents of variable capacitors C_3 and C_4 should preferably be less than 0.0001. If greater than 0.0001, and unequal in value, their loss tangents will have to be compensated for by adjustment of R_4 and R_1. In this latter case, it would not be possible to calculate the loss tangent of C_x from the values of R_1 and C_2 or R_4 and C_4.

A2.1.4 Transformer T should have a ratio near unity (3/1 has been used), with the primary having the most turns. The primary should have a 60-Hz impedance greater than 0.2 MΩ.

A2.2 High-Voltage Divider

A2.2.1 A high-voltage divider consisting of either resistors or series capacitors, giving a negligible phase shift, is required. Since it is desirable to have a maximum voltage of 100 V across the low-voltage series element at the highest test voltage, V_t, the following condition should be met: $(R_L/R_H)\ V_t < 100$ or $(C_H/C_L)\ V_t < 100$, where $V_t = V_\alpha/2\sqrt{2.R_H}$ or C_H should be selected to withstand the highest test voltage and frequency without excessive heating or corona. The phase angle of R_L and R_H, or C_H and C_L, should be the same within 1 %.

A2.3 Oscilloscope

A2.3.1 An oscilloscope with vertical, y, and horizontal, x, inputs which are adjustable, is used. The sensitivity of the vertical input should preferably be I mV/cm or better, with calibrated sensitivity. (It may be desirable and convenient to connect a peak-reading meter in parallel with the vertical input to the oscilloscope to read the vertical deflection more conveniently.)

A2.4 High-Voltage Transformer

A2.4.1 The high-voltage transformer should supply a test voltage with low harmonic content. It may be necessary to filter the test voltage to reduce the harmonic content, especially when low-energy discharges are to be measured. A capacitor (C_2) in Fig. 2, having a capacitance large in comparison with that of the test specimen, should be connected across the high-voltage winding of the transformer to permit the transfer of discharges from the test specimen C_x to the integrating capacitor C_4.

A2.5 Measurement Procedure

A2.5.1 Connect the specimen, C_x, in the bridge, as indicated in Fig. 2. Raise the applied voltage to 500 to 1000 V (rms), which is usually below the discharge-inception voltage. With thick specimens, higher voltages may be used. With very thin specimens, it may be necessary to stay below 300 V to obtain an initial balance. In balancing the bridge, element C_4 is usually set first so as to achieve maximum sensitivity without exceeding 100 V on the element $C_4 > (V_t/100)\ C_x$. This requires a knowledge of the approximate capacitance of the specimen. If this is not known, a safe high value of C_4 may be chosen for a preliminary balance. Calculate the value of C_x as follows:

$$C_x = (C_1C_4/C_3), \tag{A2.1}$$

and reset C_4 for a second balance. Balance the capacitance by adjusting C_3 after C_4 is set. Balance the tan δ of the specimen by adjusting R_4 or R_1.

A2.5.2 After initial low-voltage balance is achieved, raise the voltage to selected levels above the discharge-onset voltage, which is evident from a sudden change in the oscilloscope trace from a nearly horizontal line to an open (approximate) parallelogram with step sides. Whether or not the steps are apparent depends on the detector sensitivity and the ratio of individual pulse-discharge size to the sum of these per cycle.

A2.5.3 When the voltage is raised above the discharge-onset voltage the parallelogram figure may sometimes tilt so as to have sloping top and bottom sides or develop a curved top. This is due to changing tan δ or capacitance of the solid (or liquid) insulation of the specimen with voltage, not due to discharges. If this happens, a small adjustment in C_3, R_1, or R_4 may correct the orientation and curvature so that the top and bottom are horizontal and flatter.

A2.5.4 In Annex A3 an equation (Eq A3.7) is given for Δ tan δ that involves a magnitude of C_x at some value of V_a above V_c. It is identified as C_x' in Eq A3.7. It can be determined by repeating the procedure given in A2.5.1 at V_1, that is:

$$C_x' = C_1C_4/C_3 \tag{A2.2}$$

or

$$C_x' = C_x + \Delta C \tag{A2.3}$$

where C_x was initially determined as in A2.5.1, and ΔC determined as shown in Fig. 3.

A3. ADDITIONAL MEASUREMENT ANALYSIS (TEST METHOD B)

A3.1 Referring to Fig. 3, and based on the equations given in Sections 12 and 13, the measurement can be further analyzed as follows:

$$P,\ \text{watts} = fW = (\omega/2\pi)W \tag{A3.1}$$

$$W,\ \text{joules/cycle} = D_{xi}D_yS_xS_y \tag{A3.2}$$

$$P,\ watts = (\omega/2\pi)D_{xi}D_yS_xS_y \tag{A3.3}$$

A3.2 The ideal shape of the parallelogram shown in Fig. 3 by the solid lines applies to cases where the discharge onset in all cavities occurs at the same value of applied voltage. In practical insulating systems, cavities generally have unequal breakdown or ionization voltages, with the result that at partial-discharge onset not all cavities necessarily undergo ionization. Therefore, as the applied voltage is increased, more cavities begin to discharge, and this effect causes smooth curvatures of the parallelogram corners as shown by the dashed lines in contrast to the sharp corners of the idealized trace shown in Fig. 3. As a result, when a certain degree of accuracy is required, (Eq 1) and (Eq 4) or (Eq 5) cannot be used to calculate energy by (Eq 7). Instead, the discharge-energy-loss per cycle must be determined by using a planimeter or other area measuring device of equal or greater precision to obtain the area, A_m, of the trace. This procedure will constitute a direct measure of the discharge energy and power loss, that is:

$$W = A_m S_y S_x \quad \text{(A3.4)}$$

$$P = (\omega/2\pi) A_m S_y S_x \quad \text{(A3.5)}$$

A3.3 It is sometimes desirable to determine the effect of discharges on the dissipation factor, $\Delta \tan \delta$. For the idealized case (Fig. 3):

$$\Delta \tan \delta = 8P/\omega C_x' V_a^{\,2} \quad \text{(A3.6)}$$

where $C_x' = C_x + \Delta C$ (see A2.5.4)

$$\Delta \tan \delta = 8\omega A S_y S_x / 2\pi\omega C_x' V_a^{\,2} = 4W/\pi C_x' V_a^{\,2} \quad \text{(A3.7)}$$

Where the area of the parallelogram needs to be measured, A in Eq A3.7 should be replaced with A_m.

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(**7**) *Engineering Dielectrics, Volume 1: Corona Measurement and Interpretation, ASTM STP 669*, ASTM, 1979.

(**8**) Dakin, T. W., "The Relation of Capacitance Increase with High Voltages to Internal Electrical Discharges and Discharging Void Volume," AIEE Trans. on Power Apparatus and Systems, Vol 78, 1959, pp. 790–795.