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IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers

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Sponsored by the Electronics Transformer Technical Committee

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IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers

Sponsor

Electronics Transformer Technical Committee of the IEEE Power Electronics Society

Approved February 11, 1991

IEEE Standards Board

Abstract: A uniform procedure for making corona (partial discharge) measurements by electrical means on electronic transformers is presented. Methods of applying voltage stress, the use of a sine-wave voltage to simulated dc and ac combinations, the types and limitations of voltage stresses encountered, and the acceptable limits of discharge pulse energy are included. Recommended test conditions and the need for negotiation of special tests are discussed. Test apparatus and calibration are described. The aim is to establish a common ground of understanding between transformer and systems design engineers and transformer manufacturers in the development of service and performance requirements.

Keywords: corona, partial discharge, insulation breakdown, transformer insulation

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Foreword

(This Foreword is not a part of IEEE Std 436-1991, IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers.)

This guide was written to provide electronics transformer engineers with a standard method for detecting and measuring corona (partial discharge) in electronics transformers. Since there is no simple definition or unit for corona, it is felt that a guide of this nature will be useful in establishing a common ground of understanding between transformer and systems design engineers and transformer manufacturers in the development of service and performance requirements.

This publication was prepared by the Insulation Systems Subcommittee of the Electronics Transformers Technical Committee of the IEEE Power Electronics Society. The Subcommittee membership was as follows:

R. A. Frantz, *Chair*

J. S. Andresen
C. J. Elliott
H. Fickenscher
P. K. Goethe
R. R. Grant
H. E. Lee
D. N. Ratliff
R. L. Sell
B. D. Thackwray
R. M. Wozniak

When the Electronics Transformer Technical Committee approved this guide, the membership was as follows:

H. Fickenscher, *Chair*

E. D. Belanger
C. J. Elliott
R. A. Frantz
P. K. Goethe
J. Silgailis
J. Tardy
B. D. Thackwray
R. M. Wozniak
H. E. Lee
W. E. Lucarz
D. N. Ratliff
R. L. Sell

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O. Kiltie
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R. Lee
H. W. Lord
W. Lucarz
D. Ratliff
R. L. Sell
J. Silgailis
J. Tardy
B. D. Thackwray
H. I. Tillinger
R. G. Wolpert
R. M. Wozniak

The final conditions for approval of this guide were met on February 11, 1991. This guide was conditionally approved by the IEEE Standards Board on September 28, 1990 with the following membership:

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IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers

1. Scope

This guide covers the detection of corona (partial discharge) and the measurement of its magnitude in electronics transformers. Test conditions, test apparatus, calibration, and test requirements are included.

2. Purpose

Corona (partial discharge) is an ionization phenomenon that can cause deterioration in certain insulation systems. Its presence in electronic equipment can be harmful through its manifestation as circuit noise, spurious voltage or current pulses, or other undesirable effects that lead to circuit malfunctions. Transformers and inductors used in electronic circuits at high voltages can be locations where this harmful phenomenon originates. Even in instances where discharges are not of concern in circuit performance, they may be of concern because of their adverse effect on component life. It is, therefore, essential that the insulation system be free of corona discharges at operating voltage stresses. The magnitude or intensity of these discharges is usually of such a low level that very sensitive electronic measuring apparatus and techniques are required to detect them.

This guide presents a uniform procedure for making corona (partial discharge) measurements by electrical means on electronics transformers. Methods of applying voltage stress, the use of a sine-wave voltage to simulate dc and ac combinations, the types and limitations of voltage stresses encountered, and the acceptable limits of discharge pulse energy are included. Recommended test conditions and the need for negotiation of special tests are discussed.

3. References

This guide shall be used in conjunction with the following publications.

[1] ASTM D1868-1981 (R1990), Standard Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems.[1]

[2] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms—4th ed. (ANSI).[2]

[3] MIL-T-27E, Military Specification Transformers and Inductors (Audio, Power, and High-Power Pulse), General Specification for (4 April 1985).[3]

4. Definitions

Electrical terms used in this publication are in accordance with those given in IEEE Std 100-1988 [2].[4]

[1]ASTM publications are available from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, (215) 299-5400.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, 1-800-678-4333.

[3]This Military Specification is available from the Commanding General, US Army Communications—Electronics Command, Ft. Monmouth, NJ 07703.

[4]The numbers in brackets refer to those of the references in Section 3.

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5. Test Conditions

5.1 Application of This Guide. The test conditions applicable to electronics transformers include all the configuration and circuit arrangements used in power transformers and, in addition, include a large number of inductive devices with special circuit characteristics and with electrical stress on insulation covering the entire range of frequencies from dc through microwave and all combinations of these frequencies. At the present time, this guide will be limited to detection and measurements with sine-wave applied voltage ranging in frequency from zero to approximately 2000 Hz. The detection and measurement of corona discharges with applied voltages at higher frequencies or with nonsinusoidal wave shapes requires special techniques, since the discharge pulse itself also has a wide frequency spectrum, a portion of which may fall within the operating frequency range.

5.2 Conditions for Acceptable Corona Tests. The duplication of the exact voltage stresses that occur in service, including frequencies and transients, is acknowledged to result in the most accurate corona discharge measurements; however, insistence on exact conditions may be impractical. The fundamental conditions for acceptable corona tests are based on the assumptions and limitations that follow.

5.2.1 Frequencies at Which Corona Measurements May Be Performed. Corona discharges are a function of the peak-to-peak voltage, provided the voltage contains no intermediate peaks and is applied long enough for ionization to take place. Corona measurements may be performed at any frequency under 2000 Hz; they need not be made at the operating frequency. However, discharges are affected by the test frequency; as the frequency is increased, variations occur in the response times of ions within the insulation to the rapidly varying externally applied electric field. The resulting nonuniform internal electrical stress leads to a decrease in the corona inception voltage. Care must therefore be taken in interpreting the results of tests performed at other than the operating frequency.

5.2.2 Effects of Voids in Solid Insulation. Corona discharges across voids in solid insulation transfer some of the voltage stress to the solid insulation, thus reducing the stress on the void. This removes the condition necessary for additional discharges until some of the charge dissipates or until the applied voltage changes enough to reestablish the stress required for corona discharge.

5.2.2.1 Testing With DC Voltage. When the applied voltage is dc, continuous corona (recurring discharges) usually requires a higher voltage than when the stress is ac. The overvoltage necessary to establish continuous corona with dc applied will depend largely on the resistance of the insulation through which the charge must dissipate to reestablish the stress. This means that in apparatus where dc stress alone is characteristic, the corona discharges should be measured with dc voltage applied. Caution should be used when the applied voltage exceeds the peak working voltage of the transformer, since the ratio of the corona inception voltage to the insulation breakdown voltage may be very close to unity. However, this ratio may be as low as 0.5 when the applied voltage is ac.

5.2.2.2 Testing With Combined DC and AC Voltage. When the voltage stress is combined dc and ac, continuous corona discharges will be due to the peak-to-peak voltage (calculated by summing the dc and peak ac voltages) and therefore will occur as if due to an ac voltage of the same peak-to-peak value. This means that in transformers characterized by combined ac and dc stress, measurements should be made using ac test voltage whose magnitude is determined with a peak-to-peak voltmeter (see 6.7).

5.2.3 Corona Discharge Pulse Rise Time. The corona discharge pulse voltage is assumed to have a sufficiently high rate of increase that its initial distribution throughout the circuit is controlled by the circuit capacitances.

5.2.4 Circuit Response. The response of the circuit, which includes the insulation system, to frequencies and their harmonics may complicate corona discharge tests. Square waves, unidirectional pulses, rapid switching, or high frequencies will produce stress patterns. The application of test voltages below rated design frequencies is generally valid, but caution must be observed when these voltages

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are applied by induction so as not to saturate the core.

5.3 Signal-to-Noise Ratio. A minimum signal-to-noise ratio of 2 to 1 should be established by reducing all electromagnetic interference, regardless of its origin, to less than one half of the amplitude of the minimum corona discharge level to be detected.

5.4 Discrimination Device Sensitivity. It should be demonstrated that equipment incorporating discrimination devices (circuitry intended to isolate and identify corona discharges) does in fact discriminate between the minimum level specified for discharges in the unit under test and the interference otherwise present in the test system.

6. Apparatus

The equipment required for quantitative corona (partial discharge) measurements typically includes the following: a test voltage supply, a coupling capacitor, a corona detector (frequently a single instrument combining an amplifier and an oscilloscope), a coupling impedance, a calibration pulse generator, calibration coupling circuitry that often includes a calibration capacitor, and the transformer under test. Figures 1 and 2 show two of the several corona discharge measurement circuits that can be assembled using this equipment. The choice of test circuit involves such factors as the size of the test transformer, whether it should be isolated from or connected to ground, minimizing stray capacitance in the lead wires, and the resultant detection sensitivity.

6.1 Test-Voltage Supply. The test-voltage supply is normally variable and should be capable of supplying a higher voltage stress than that required for corona inception. When ac voltage is used, there should be less than 5% overall harmonic distortion when supplying the test load. The voltage waveform need not be purely sinusoidal, but it should contain no intermediate peaks. It should be measured with a peak-to-peak voltmeter. The series inductor shown in the test-voltage supply connections of Figs 1 and 2 should have a self-resonant frequency of approximately 10 MHz. Electromagnetic filtering may also be required in order to eliminate voltage supply noise.

6.1.1 Self-Excitation. As an alternative to the use of an external high-voltage source to supply the test voltage, the high-voltage stress across a winding may be induced through self-excitation. In this method, a lower-voltage winding in the transformer is excited by the use of a low-voltage power source (including a filtered ac line) whose waveshape characteristics remain as stated in 6.1. The transformer ratio is used to create a high-voltage stress across the winding under test. The stress distribution in this winding, and the resulting discharge distribution, will differ from that of an externally applied voltage, where the entire winding is at a common potential. However, the revised distribution may better represent actual operating conditions. Figure 3 shows the modified connections to the transformer under test required for the circuit of Fig 2; the circuit of Fig 1 is not suited for self-excitation tests. The remainder of the circuit in Fig 2 and the apparatus and test procedure described below continue to apply.

6.2 Coupling Capacitor. The coupling capacitor isolates the detector from the test voltage. Other isolation, such as a transformer or a parallel-T RC filter network (as shown in Fig 4) may be used, subject to the requirement that the initial division of both the calibration and the corona pulse voltages through the circuit is determined by the circuit capacitances. The capacitance value is selected in relation to other circuit components to realize the desired circuit sensitivity. In general, increasing the capacitance improves circuit sensitivity. A value not exceeding 100–200 pF is often satisfactory at 60 Hz; lower capacitance values are necessary at higher frequencies.

6.3 Coupling Impedance. The coupling impedance presents the discharge pulse to the input of the pulse amplifier. It may be resistive or inductive. Its selection will depend on the test frequency and the configuration of the other parts of the detection system. It is connected to the corona detector so that it appears across the input terminals to the detector.

6.4 Corona Detector. The corona detector usually combines an amplifier and a signal readout instrument such as an oscilloscope.

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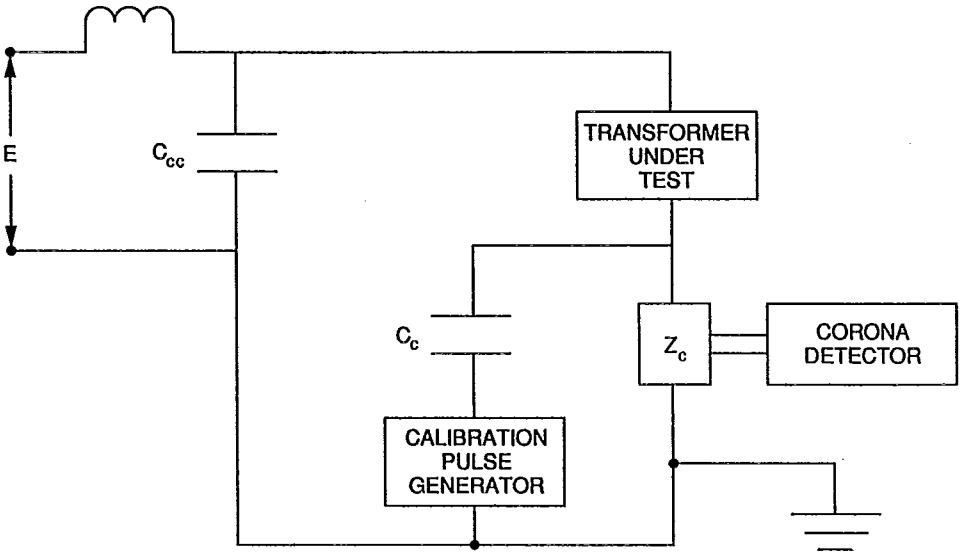


Fig 1
Typical Circuit for Corona Measurement, Circuit 1

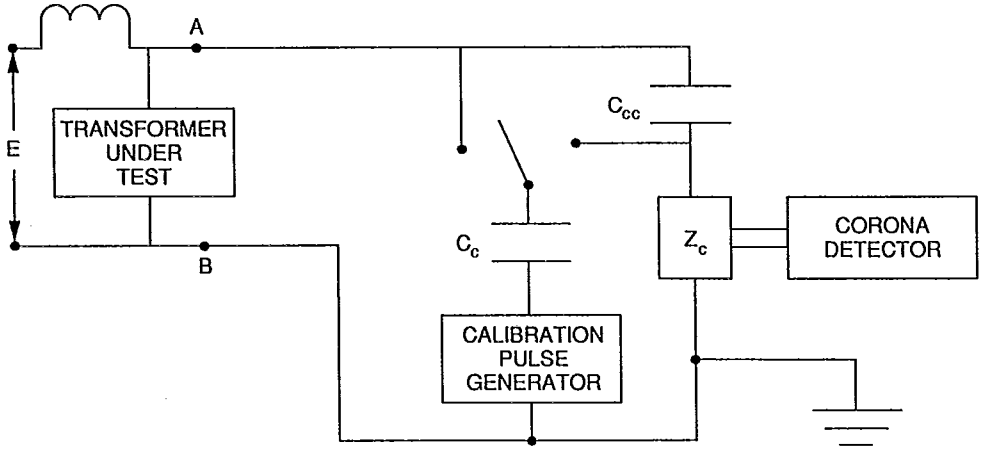


Fig 2
Typical Circuit for Corona Measurement, Circuit 2

LEGEND (FIGS 1 AND 2)
C_{cc} = coupling capacitor
C_c = calibration coupling capacitor
Z_c = coupling impedance
E = high-impedance test-voltage supply

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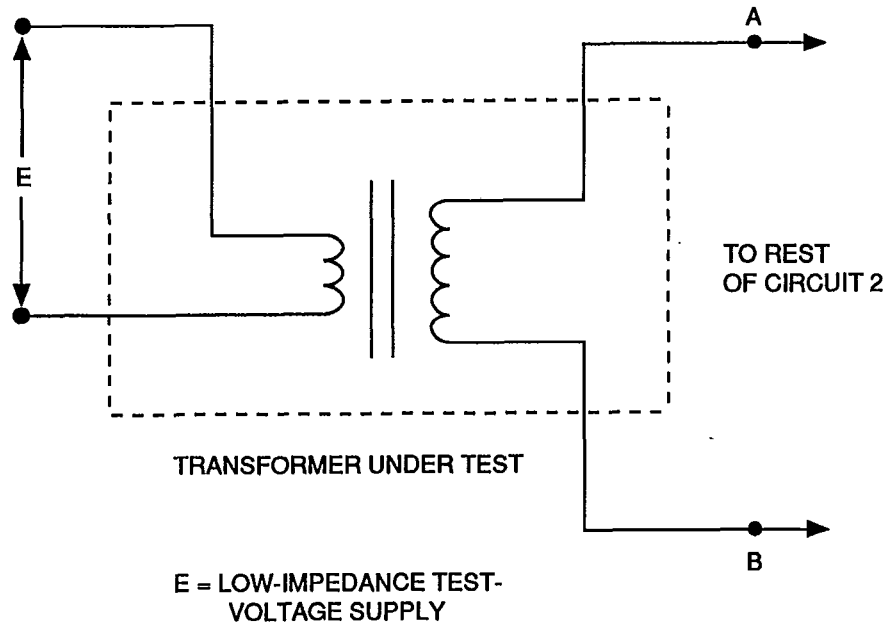
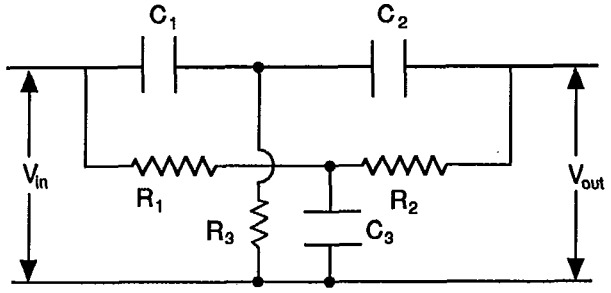


Fig 3
Circuit Modifications for Self-Excitation



TRANSMISSION IS ZERO IF
$X_1X_2 = (R_1 + R_2)R_3$
AND $R_1R_2 = (X_1 + X_2)X_3$
WHERE $X_n = (\omega C_n)^{-1}$

Reference: L. Stanton, "Theory and Application of Parallel-T Resistance-Capacitance Frequency-Selective Networks," *Proceedings of the IRE,* July 1946, p. 447.

Fig 4
Parallel-T RC Filter Network

6.4.1 Amplifier. The amplifier presents the discharge pulse to the readout equipment at an appropriate level. The band-pass characteristics should be selected to provide maximum attenuation of the test-voltage frequency and its harmonics as well as any other unwanted signals. A parallel-T RC filter network may be used to eliminate the test-voltage frequency from the amplifier input while still transmitting the corona discharge pulses accurately.

6.4.2 Signal Readout Instrument(s). An oscilloscope may be used to display the signals from the amplifier. It is well suited for detecting individual discharge pulses and their phase occurrence with respect to the test voltage. Frequently an oscilloscope is the primary readout instrument with one or more other devices operated in conjunction with it when more data is required. Such other devices include peak-to-peak reading voltmeters,

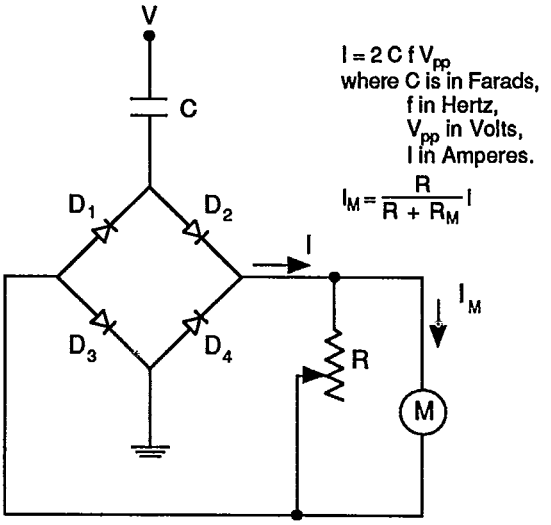
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graphic recorders, and pulse counters; the latter are particularly useful when pulse height analysis can be used to define the discharge pulse spectrum in terms of pulse amplitude and repetition rate.

6.5 Calibration Pulse Generator. The calibration pulse generator is the source of a pulse that, when properly coupled to the terminals of the apparatus under test, produces a response in the detection equipment that approximates a discharge pulse response in magnitude. The pulse should have a rise time of no greater than 0.1 μs and a decay to half peak of no greater than 1 ms. The output impedance of the generator is in series with the calibration coupling capacitance; it must be small, so that the amplitude of the output pulse can be determined to an accuracy of at least ± 3%, and it must be known, so that the combined impedance in parallel with the coupling impedance can be calculated. A typical square-wave generator with an output impedance of 50 Ω satisfies these various requirements.

6.6 Calibration Coupling Capacitor. The calibration coupling capacitor couples the calibration pulse generator to the insulation system under test (normally to the terminals of the transformer). The value of the calibration coupling capacitance should be small with respect to the internal capacitance of the apparatus under test. Usually 200 pF maximum is suitable at 60 Hz, while lower values are appropriate at higher frequencies. The actual capacitance value of the calibration capacitor should be known to an accuracy equal to the accuracy of the measurement of the calibration signal generator pulse. When discharge signal magnitude measurements are to be made during testing, the calibration coupling capacitor should have a voltage rating suitable for isolation of the calibration equipment.

6.7 Control Metering. Control metering should have an accuracy of ± 3%. Metering for an ac test voltage source should be a peak-to-peak voltmeter (as shown, for example, in Fig 5). This measurement circuit should be calibrated with sine-wave rms so that the test voltage may be specified in rms units. When the test voltage is induced through self-excitation, the peak-to-peak test voltage should be measured directly.



(Voltage Drops in Diodes and Meter << Peak-to-Peak Voltage.)

Fig 5
Peak-to-Peak Voltmeter Circuit

7. Calibration

7.1 Deflection Sensitivity. The test circuit is calibrated to determine the deflection sensitivity of the corona detector in terms of discharge pulse voltage amplitude or terminal corona charge. The deflection sensitivity is influenced by the specimen capacitance, stray capacitance, and the amplifier gain. Since these factors may vary from specimen to specimen, the entire circuit should be calibrated as part of the test procedure and also whenever any of the influencing factors are significantly changed. The amplifier gain should not be changed between calibration and test.

7.2 When Calibration Is Performed. Normally, the calibration is performed with the specimen de-energized either before or after applying test voltage. When it is desired to make signal magnitude measurements during testing, the calibration equipment may be switched in. These calibration measurements should be verified at zero test voltage.

7.3 Calibration Technique. To calibrate, introduce a pulse of known amplitude from the calibration pulse generator into the circuit at the terminals of the specimen, that is, the point

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at which the discharge pulse is to be detected. Observe the signal magnitude on the readout device with the amplifier gain set at the level required for observation of the actual corona discharges. Measure the maximum deflection caused by the calibrating pulse. From this measurement and from the constants of the circuit, calculate the deflection sensitivity of the readout device to the discharge pulses. (See 9.2.)

7.4 Calculating Detection Sensitivity. To simplify the calculation of detection sensitivity, the terminal corona pulse voltage (that is, at the terminals of the transformer under test) and the calibration pulse voltage are both considered to be step functions. The initial division of voltage throughout the circuit is considered to be determined by the circuit capacitances. ASTM D1868-1981 [1] derives sensitivity equations for several acceptable calibration circuits.

8. Test Method

The test voltage should stress the insulation as it will be stressed in normal operation including interwinding, intrawinding, bias, and termination stresses. Because it is often not practical to test transformers in the actual circuit in which they are designed to operate, test facilities should simulate operating conditions as nearly as possible. To accomplish this, electronics transformers and inductors may be classified in three groups. Complete evaluation will sometimes require more than one type of voltage application.

8.1 Group I. Group I includes transformers that are fully insulated for all applied or induced voltages normally encountered in operation and in which insulation between windings or from winding(s) to ground, or both, is to be tested for corona discharges. The test voltage is applied across the insulation that is stressed in normal operation. This test usually does not include induced voltages.

8.2 Group II. Group II includes transformers that operate with specified voltage limits, either ac or dc, across specified insulation. The limits may be external circuit bias or the result of required connections. Test voltage may be either applied directly or induced across the insulation to be investigated, depending on requirements.

8.3 Group III. Group III includes transformers with induced voltage stresses within winding(s), from portions of winding(s) to other winding(s) or circuit elements, or any combination of these. Test voltages are normally induced by transformer action within the transformer under test, by autotransformer action, or by direct application across the winding under test. Normally, a point in each winding is grounded or connected to a common reference. When the test is made on a winding which does not have restrictions as in 8.2 above, the test should be repeated with the high voltage and ground connections reversed in order to test both ends of the windings and terminations.

9. Test Requirements

Unless otherwise specified, the following requirements should apply.

9.1 Ambient Conditions. Corona (partial discharge) tests should be performed at 25 ± 5 °C, atmospheric pressure of 101 kPa ± 20%, and relative humidity of 70% maximum. Transformers should be conditioned by remaining in the ambient conditions for at least 8 h prior to testing.

9.2 Calibration Sensitivity. In Appendix B, it is shown that the meaningful quantity to be measured is the energy of discharge. W is in nanojoules when V_i is in kilovolts peak and Q is in picocoulombs as shown below:

$$W = 1/2\, Q_a\, V_i\,.$$

Test-set sensitivity is usually expressed in picocoulombs and voltage in rms units. Therefore,

$$Q_a = \sqrt{2}\, W / V_a$$

where Q_a is the calibration sensitivity in picocoulombs, W is the discharge pulse energy in nanojoules, and V_a is the applied voltage in kilovolts rms.

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9.3 Test Voltage. Any convenient frequency from 50 to 2000 Hz inclusive may be used for ac tests; however, the caution in 5.2.1 should be noted. Induced voltage tests should be conducted at a frequency that will not result in core saturation or other forms of wave distortion. The rms test voltage should be 120% of the rms working voltage.

9.3.1 DC Plus AC Test Voltage. When the test voltage is dc plus ac, the dc components should equal the rated dc bias or 50% of the peak working voltage, whichever is greater. The ac component should be such as to cause 120% of the peak working voltage stress across the insulation under test.

9.4 Rate of Application. The test voltage should be raised uniformly from zero to 50% of the maximum in not less than 5 s. From 50% to the maximum, the rate of rise should not exceed 500 V/s.

9.5 Duration of Tests. The test stress should be maintained for a minimum of 1 min or 10 000 cycles, whichever comes first, but not for less than 18 s.

10. Bibliography

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Appendixes

(These Appendixes are not part of IEEE Std 436-1991, IEEE Guide for Making Corona (Partial Discharge) Measurements on Electronics Transformers, but are included for information only.)

Appendix A
Preconditioning for Determination of CIV

In some insulation systems employing high resistivity materials, such as epoxies, the initial observation may not be representative of operating experience due to the time dependency of the onset of corona discharges. One way to determine the corona inception voltage (CIV) quickly and reliably is to raise the test voltage to some predetermined higher voltage for a short time (the transformer may be well into the partial discharge range but below dielectric flashover). The test voltage is then reduced to zero and immediately reapplied, increasing at a specified uniform rate until continuous corona discharges are detected. This will be the CIV.

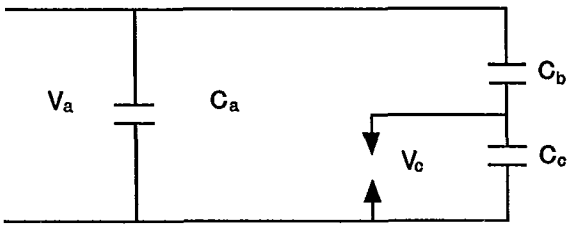
In liquids, on the other hand, a corona extinction voltage (CEV) lower than the CIV may be the result of liquid breakdown forming gas bubbles that continue to allow discharges well below the stress level at which they were formed. In this case, preconditioning cannot be used and, in fact, may be injurious to the system.

When preconditioning voltage is to be used, the magnitude and time of application should be specified.

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Appendix B
The Magnitude and Energy of Discharges

When there is a discharge, it occurs as if the small capacitor C_c in the model circuit was instantaneously short-circuited. A charge transfer occurs, given by



V_a = peak applied voltage
V_a = V_i = CIV
Q_a = apparent discharge magnitude detected at the terminals

$$Q_c = \left(C_c + \frac{C_a C_b}{C_c + C_b} \right) \delta V_c = \delta V_c \frac{C_a C_c + C_b C_c + C_a C_b}{C_a + C_b} \quad \text{Eq B1)}$$

Simultaneously, a voltage pulse, which is effectively a step voltage having a rise time of between 10 and 100 ns, is generated at the terminals of the insulation.

$$\delta V_a = \delta V_c \frac{C_b}{C_a + C_b} . \quad \text{(Eq B2)}$$

The apparent discharge magnitude, observed at the terminals, is

$$Q_a = \delta V_a \left(C_a + \frac{C_b C_c}{C_b + C_c} \right) = \delta V_a \frac{C_a C_b + C_a C_c + C_b C_c}{C_b + C_c} \quad \text{(Eq B3)}$$

Let

$$C_3 = C_a C_b + C_a C_c + C_b C_c . \quad \text{(Eq B4)}$$

Usually, a small area of the discharge site is almost completely discharged, so that

$$\delta V_c = V_c = V_i \frac{C_b}{C_b + C_c} \quad \text{(Eq B5)}$$

$$\frac{Q_c}{Q_a} = \frac{\delta V_c}{\delta V_a} \frac{C_3}{C_a + C_b} \frac{C_b + C_c}{C_3} \frac{\delta V_a}{\delta V_c} \frac{C_a + C_b}{C_b}$$

$$= 1 + \frac{C_c}{C_b} . \quad \text{(Eq B6)}$$

If it is assumed that most of the charge is liberated from the region where $\delta V_c \rightarrow V_c$, the energy liberated will be

$$W = 1/2\, Q_c\, V_c = 1/2\, Q_a \left(1 + \frac{C_c}{C_b} \right) V_i \frac{1}{1 + \frac{C_c}{C_b}} = 1/2\, Q_a\, V_i \quad \text{(Eq B7)}$$

where W is in nanojoules, V_i is in kilovolts peak, and Q_a is in picocoulombs.

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Appendix C
Suggested Specification Requirements

The specification of requirements other than the basic ones listed herein may require special test equipment. Requirements that include the use of dc voltages, specific frequencies, wave shapes other than sinusoidal, measurement of discharge pulse energy at specified voltage(s), or special ambient conditions should be negotiated.

C1. Normal Requirement

The normal requirement is that no continuous discharges shall occur at the specified pulse energy level and at the ac test voltage in 9.3.

C2. Pulse Energy Level Classes

The pulse energy levels shall be selected from the following classes. In selecting the class, consideration must be given to the fact that calibration sensitivity depends on test voltage level.

Class I. For insulation systems with a history of satisfactory life at the voltage stress used—70 nJ maximum.
Class II. For insulation with considerable tolerance for discharges such as inorganic insulation—700 nJ maximum.
Class III. Pulse energy level to be specified.

C3. Other Information

The specification of other information shall be considered special and should be negotiated. Examples of such information are:

(1) Corona inception voltage (CIV). Conditioning in accordance with Appendix A must be defined.
(2) Corona extinction voltage (CEV).
(3) Pulse energy of maximum discharge pulses at specified voltage(s).
(4) Number of discharge pulses of given pulse energy at specified voltage(s) per unit of time.

Pulse height analysis techniques are particularly useful in providing the last two items of information.

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