



IEEE Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings

IEEE Power and Energy Society

Developed by the
Electric Machinery Committee

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IEEE SA Standards Board

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Abstract: The procedure for quality control testing of external discharges on stator coils, bars, and windings of large air-cooled ac electric machines is described in this recommended practice.

Keywords: ac, acoustic emission, corona-imaging instrument, discharge inception voltage, electrical insulation, external discharges, IEEE 1799™, stator winding, ultraviolet radiation

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Introduction

This introduction is not part of IEEE Std 1799-2022, IEEE Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings.

External discharges in the end-windings are caused by inadequate workmanship for global vacuum-pressure impregnated (VPI) stators or problems on stators assembled on site. Poorly finished lashes with an insufficient gap between bars produces coil-to-coil or bar-to-bar discharges. Misalignment between adjacent coils or bars may also reduce the gap distance and generate a high electric stress larger than the air breakdown strength. Sometimes misplaced resistance temperature detector (RTD) or air gap monitor, flux and other sensors leads have been seen to cause partial discharges (PDs) with high-voltage bars or coils. External discharges for the individual coil/bar could be also a result of improper design, improper material, or improper workmanship. After many years, the deterioration induces surface degradation that may lead in the long run to a phase-to-ground fault and reduce the overall reliability of the system. (More detail on the theory of external discharges and their effects is given in [Annex A](#).) Some utilities have seen deterioration of the junction between the stress control coating and semiconducting slot coating of stator windings after only a few years of operation. Other secondary effects such as the production of a large quantity of ozone, which may be deleterious to the equipment and dangerous to personnel, is also of concern. In addition, over the years, the ground-wall insulation thickness of stator coils and bars has been reduced to improve heat transfer through the ground-wall insulation. This optimization does, however, increase the dielectric stress on the insulation and on the end-winding stress grading system making them more susceptible to developing electrical discharges.

This recommended practice presents an approach to evaluate the quality of materials and design, factory workmanship, and on-site workmanship. Two methods are proposed in this recommended practice. The first one, the blackout test, has been used for many years. The second one, the corona-imaging inspection, presents several advantages but each method has its advantages and disadvantages.

IEEE Std 1434, IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery [\[B10\]](#), mentions these two inspection methods but with very little detail.⁶ The current recommended practice includes a more elaborate description of sample preparation, bench tests, test conditions, and acceptance criteria in the factory and on site.

⁶ Numbers in brackets refer to the bibliography in [Annex F](#).

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1. Overview

~~The~~ This quality control ~~tests described in this recommended practice are~~ test is used to confirm that the insulation system of the stator winding of generator and motor operating in air, including the semiconducting slot and stress control coatings, are free of external discharges. Quality control of the semiconducting slot coating, stress control coating, and manufacturing process is best done in the factory. For stators assembled on site, such as those for large hydro-generators, additional tests can be performed on the fully assembled generator in order to control the quality of the assembly and workmanship. This control includes the following:

- a) Evaluation of the spacing between end-arms and with the phase circuit rings or connections to the main phase terminals
- b) Confirming proper alignment of the ground plane made by the semiconducting slot coating on the straight portion of the bar/coil with regard to the core pressure finger
- c) The positioning of all cables (RTD, air gap monitor, etc.) with respect to high voltage ~~and~~

- d) Inspection of imperfections that may have been introduced during assembly (presence of foreign objects, misplaced slot center filler, chips and scratches to bars or coils coating etc.)

In the case of machines assembled in the factory, such as global VPI machines, the complete quality control test can be done in the factory. However, special care should be taken so that no change in the machine ~~machine's~~ conditions occur during transportation (contamination by water and dust⁷ or damage to end-arms during movement). The use of this recommended practice may eliminate the need for users to specify minimum clearances between bars/coils in the end-winding to avoid surface discharge activity.

1.1 Scope

This recommended practice provides procedures ~~a procedure~~ to detect external discharges in form-wound bars and coils and complete stator windings of rotating machines operating in air with a rated line-to-line voltage greater than 2300 ~~4200~~ V at power frequency. The recommended practice is applicable to bars, coils, and complete stator windings. The recommended practice covers two inspection methods~~—~~the visual blackout test⁷ and the use of corona imaging instruments.

1.2 Purpose

The purpose of this recommended practice is to suggest specimen preparation, test parameters, and procedures for detecting external discharges associated with bars, coils, and complete stator windings using the above-mentioned methods. It also recommends acceptance criteria and a procedure for retest in the event of a test failure.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7, 8}

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60204-1, Safety of machinery—Electrical equipment of machines—Part 1: General requirements.⁹

IEC 61508, Functional safety of electrical/electronic/programmable electronic safety-related systems.

⁹ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<http://www.ansi.org/>).

IEEE Std 4TM, IEEE Standard Techniques for High-Voltage Testing.^{10, 11 1, 2}

IEEE Std 4aTM, Amendment to IEEE Standard Techniques for High-Voltage Testing.

IEEE Std 510TM~~1983~~ (Withdrawn), [IEEE](#) Recommended Practice for Safety in High-Voltage and High-Power Testing.^{12 3}

ISO 14121-1, Safety of Machinery—Risk Assessment—Part 1: Principles.¹³

ISO/TR 14121-2, Safety of Machinery—Risk Assessment—Part 2: Practical Guidance and Examples of Methods 2.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

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blackout test: A test performed after eliminating all ambient light, specifically on energized electrical equipment, to detect external or surface discharges visible with the human eye (“naked eye”) after at least 15 min of acclimatization.

conducting materials: Composition materials ~~that~~ ~~which~~ usually have a dielectric binder and conductive filler. For example: ~~(e.g.,~~ electrical insulation coating or compound filled with copper, silver powder, etc.)~~.~~

conductive materials: Solid materials ~~that~~ ~~which~~ have a large number of free electrons that can easily be put into motion to create an electric current. For example: ~~(e.g.,~~ metal (as steel, copper) sheet; copper foil; copper, silver powder, etc.)~~.~~

corona (air): A luminous discharge due to ionization of the air surrounding a conductor or insulated conductor caused by a voltage gradient exceeding a certain critical value.

corona imaging instrument: An instrument used for ~~the visual~~ detection of corona or external surface discharges on energized test objects in ambient light and offers a visual representation of the discharge superimposed on a visible light image of the test object. Corona imaging instruments, frequently ~~use~~ ~~using~~ ultraviolet radiation emitted by the discharge source, but other signals such as acoustic emissions can also be used. It should be pointed out that acoustic emissions can come from internal and external discharges and depending on the detection frequency range it will be more sensitive to one or the other.

NOTE—In the current document, only external discharges are of interest.

discharge extinction voltage (rotating machinery) (DEV): (ionization or corona-extinction voltage):
The voltage at which discharge pulses that have been observed in an insulation system, using a discharge detector of specified sensitivity, cease to be detectable as the voltage applied to the system is decreased.

discharge inception voltage (rotating machinery) (DIV): (ionization or corona inception voltage):
The voltage at which discharge pulses in an insulation system become observable with a discharge detector of specified sensitivity, as the voltage applied to the system is raised.

external discharge: An external discharge is a partial discharge that occurs on the exterior of the bar/coils or other energized parts of the winding. In rotating machines, external discharges may occur on the surface of bars/coils or in any air gap present between the bar/coil surface and the stator core, or in the end-winding of the stator (between bars/coils of different phases or between bars/coils and ground, such as pressure fingers or leads from sensors or other coils near ground).⁵

groundwall insulation: The main high-voltage electrical insulation that separates the copper conductors from the grounded stator core in motor and generator stator windings.

high-potential test (power operations): A test that consists of the application of a voltage higher than the rated voltage for a specified time for the purpose of determining the adequacy against breakdown of high voltage insulation system and spacing under normal conditions. *Syn:* high pot ~~or~~ hipot.

NOTE—The test is used as a proof test of new apparatus, a maintenance test on older equipment, or as one method of evaluating developmental insulation systems.⁵

ionization: (A) A breakdown that occurs in parts of a dielectric when the electric stress in those parts exceeds a critical value without initiating a complete breakdown of the insulation system. Note: Ionization can occur on both internal and external parts of a device. It is a source of radio noise and can damage insulation. **(B)** The process by which an atom or molecule receives enough energy (by collision with electrons, photons, etc.) to split into one or more free electrons and a positive ion. Ionization is a special case of charging.

noise: Unwanted disturbances superimposed on a useful signal that tend to obscure the signal's information content.

off-line testing (test, measurement, and diagnostic equipment): Testing of the unit under test removed from its operational environment or its operational equipment. Shop testing.

⁵~~Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.~~

partial discharge (PD): An electric discharge that ~~which~~ only partially bridges the insulation between conductors, and which may or may not occur adjacent to a conductor.

NOTE 1—Partial discharges occur when the local electric-field intensity exceeds the dielectric strength of the dielectric involved, resulting in local ionization and breakdown.

NOTE 2—Depending on intensity, partial discharges are often accompanied by emission of light, heat, sound, radio influence voltage (with a wide frequency range) and oxidation if PD occurs in the presence of oxygen. ~~“Corona” has also been used to describe partial discharges. This is a non-preferred term since it has other unrelated meanings.~~

NOTE 3—“Corona” has also been used to describe partial discharges. This is a non-preferred term since it has other unrelated meanings.

surface resistivity: The resistance of a thin film material measured between two opposite sides of a square and is independent of the size of the square or its dimensional units. ~~ohms per square: A unit of surface resistivity used to characterize the resistance of a thin film material measured between two opposite sides of a square and is independent of the size of the square or its dimensional units.~~ Surface resistivity can also be measured in a concentric ring fixture. The units of surface resistivity are ohms per square.

semiconducting materials: Composition materials, which usually have dielectric binder and semiconductive filler. For example: ~~(e.g.,~~ electrical insulation coating or compound filled with graphite, carbon black powder; SiC grains, etc.~~).~~

semiconducting slot coating (rotating machinery): A coating, applied on the insulation surface of the slot parts of winding. The semiconducting coating, compound, or tape ~~has a in which the~~ powder filler or portion of powder filler ~~that~~ is a semiconductive material. ~~and~~ The ~~electrical~~ surface resistivity of this coating ~~must be large enough to prevent thermal aging and vibration sparking and low enough to prevent slot discharges in such that, when converted into a semiconducting solid layer, is in the range of 1×10^2 — 5×10^5 Ohms per square.~~ This semiconducting slot coating must have uniform tight contacts with the grounded walls of the stator slot. This coating ~~reduces the provides minimum~~ voltage between the surface of the coil or bar and the grounded stator core. ~~(adapted from Younsi, K., Ménard, P., and Pellerin, J. [B29])~~⁶

NOTE—See Liese and Brown [B15], Malamud and Cheremsciov [B17],[B18],[B19], Stone, et al. [B24].

~~NOTE—semiconductive slot coating:~~ This alternative terminology, as well as “slot corona protection” and “conductive armor,” of the ~~previous~~ ~~above~~ definition is also used in the industry but will not be used in this document.

semiconductive materials: Solid materials ~~that~~ ~~which~~ have limited free electrons and main conduction is carried by “electron - hole” conductivity, (n - p transition). ~~For example: (e.g.,~~ graphite, carbon black powder, SiC grains, etc.).

stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond ~~Coating used for external discharge suppression in the end turn parts of a winding. The semiconducting coatings, compounds, or tapes are often filled with semiconductive material such as silicon carbide grains. The resistivity of this composite is a non-linear function of electric field, which modifies the surface resistance and consequently controls the surface potential gradient to a level that is lower than the breakdown strength of the surrounding media, or of the air, in air-cooled machines. An overlap between the stress control coating and the semiconducting slot coating~~ in high-voltage stator bars and coils. The stress control coating often contains silicon carbide particles that tend to linearize the electric field distribution along the coil or bar end turn. The stress control coating overlaps the semiconducting coating ~~is made~~ to provide electrical contact between ~~them the two coatings.~~

⁶ ~~The numbers in brackets correspond to those of the bibliography in Annex F.~~

[NOTE—See Bui, et al. \[B4\], El-Kishky, et al., \[B5\], Kimura, et al. \[B11\], Okamoto, et al. \[B20\], Sharifi, et al. \[B21\], Train, et al. \[B27\], and Tremblay, et al. \[B29\], \[B28\].](#)

[ultrasonic emission: Acoustic emissions that accompany surface PD or corona that occur in the 20–100 kHz band, which is above the frequency the human ear can detect.](#)

~~NOTE—Other terms for this coating are “end grading system” and “stress grading protection” but are not used in this document.~~

ultraviolet radiation: In general, any radiant energy within the wavelength 10 nm to 380 nm (nanometers) is considered ultraviolet radiation. For power engineering purposes, the band of interest is the one of the emission spectrum of electrical discharges in air. The emission bands of nitrogen dominate the optical spectrum of discharges in air. Ninety percent of the total energy of the emitted optical spectrum of PD is in the ultraviolet region (280–~~nm~~–405 nm). The main part of the emission is invisible to the human eye. A relatively weak emission around 400 nm can be observed under conditions of absolute darkness.

[3.2 Acronyms and abbreviations](#) [DEV discharge extinction voltage](#) [DIV discharge inception voltage](#) [PD partial discharge](#)

[RTD resistance temperature detector](#)

UN line-to-line voltage

U_o line-to-ground voltage

[VPI vacuum-pressure impregnated](#)

4. Test preparation and safety

WARNING

The test voltages employed for the tests herein can cause personal injury, loss of life, or property damage. Accordingly, appropriate safety precautions are necessary to reduce the risk of such losses.

The testing described in this document shall be carried out according to the safety procedures described by any relevant regulatory agencies and the safety procedures of the organization having control over activities at the test site.

Preparation for the test should include⁷ but not be limited to⁷ the installation of warning signs and safety barriers around the test equipment and the machine to be tested. Grounds shall be installed as required by any relevant regulatory agencies and the local controlling authority. Other safety measures can be found in IEEE Std 510-1983, ISO 14121-1, ISO/TR 14121-2, IEC 60204-1, and IEC 61508.⁷

All personnel involved in the test shall be thoroughly familiar with the test, the test equipment, the machine to be tested⁷ and the hazards involved. When equipment is energized, no personnel shall infringe upon the minimum limits of approach described by any relevant regulatory agency or the local controlling authority.

5. Test equipment and connections

Care must be taken in the selection of the ac power supply. The duration of the test, the test voltage, and the capacitance of the winding under test are the major factors to consider in the selection. Requirements for factory tests on bars or coils will be different with respect to the test object load and test time (duty cycle of the supply). The test should be done at 50 Hz or 60 Hz.

It is hard to predict in advance the duration of quality control testing of external discharges on a stator winding. The duration of a particular test, if the three phases of the winding are tested separately, will typically take several minutes to an hour but could be longer when the number of discharge sites is large. It is then important to stay within the current limits and duty cycle of the power supply, especially when the load represented by the winding under test is close to the load rating of the power supply. In this condition, the power supply risks overheating rapidly and being seriously damaged if not ventilated properly.

⁷~~Information on references can be found in Clause 2.~~

It is recommended that the test voltage be in the upper range of the output voltage range of the power supply.

When using a resonant test set, a measurement of the capacitance of the test object should be made at the test frequency before starting the test in order to adjust the test set properly. Do not depend on the hipot set metering; but rather use a calibrated voltage divider to accurately measure voltage during the test.

Since the load of the winding under test is predominantly capacitive, it can be calculated using Equation (1):

$$P_r = 2\pi fCV^2 \quad (1)$$

where:

P_r = reactive power in VA

f = test frequency in hertz

C = total test load capacitance in farads

V = test voltage in volts

It is recommended to use a power supply providing reactive compensation to cancel out most of the capacitive load presented by the winding under test. A resonant or primary-compensated power supply should be used.

It is recommended to connect both ends of the phase, line, and neutral ends to avoid surge voltages in the event of a sudden voltage interruption.

5.1 Sensitivity of the corona imaging instruments

The use of a corona imaging instrument to enhance detection of UV radiation, [ultrasonic emissions](#), [or other signals that accompany surface](#) ~~by external~~ discharges may simplify and accelerate the test. Portability and the option to take a picture or video are features of interest. However, the main feature is the sensitivity, and not all corona-imaging instruments are equal with respect to [discharge](#) ~~UV~~ detection. Moreover, specification sheets, which use different units [for UV detectors](#) (~~e.g.,~~ lux, watt/cm², [dB](#), picocoulomb, [etc.](#)) ~~are~~ not always related to the phenomenon of interest here. ~~It makes,~~ ~~make~~ it difficult to compare different instruments. In order to select a corona-imaging instrument, a simple test can be done to determine whether it answers the need for a quality control test. Instead of running a complex [test such as the](#) UV [or acoustic detection](#) spectrum [and comparing it](#) ~~test that needs to be compared~~ with the emission spectrum of the discharge activity, [which](#) ~~and~~ requires a specialized spectrometer, ~~which is~~ not available to most people in the electrotechnical industry, a comparison of the response of the corona-imaging instrument with the naked eye can be used. For many years, the naked eye was the reference for external-discharge detection during a blackout test. The sensitivity of the eye after several minutes in complete darkness is good and can make out the faint light of discharges extending to the lower visible wavelengths. [Typically, it takes](#) (~~typically~~ more than 20 min [for the human eye](#) to reach a good sensitivity. In the rest of the document 15 min is used for convenience, but [a](#) longer time will lead to improved eye sensitivity. Here, since the goal is to qualify corona imaging equipment, a slightly longer time is used. Thus, any corona-imaging instrument performing equally well as, or better than, the eye in these conditions will be considered acceptable. This test, described [next](#) ~~below~~, can be used to qualify corona-imaging instruments before they are used in the field or in the factory.

Standardization of the test configuration provides reproducibility; however, a corona-imaging instrument qualification test should also be easy without necessarily requiring an elaborate test facility such as a [climate chamber](#) ~~climatic room~~ for atmospheric pressure, temperature, and humidity control. A simple way to check the sensitivity of the corona-imaging instrument is to create a non-uniform field with a needle plane configuration as shown in Figure 1 and to detect the discharge inception voltage (DIV) at the tip of the needle first with the naked eye in the dark (after 20 min). Then, test again with the instrument under evaluation. Since observation with the eye has been used with satisfaction in the blackout test for years, it can be used as a reference for the DIV of the setup. Thus, if the setup or ambient condition varies slightly from one user to the next, the minimum sensitivity requirement will always be determined with reference to the eye under the same conditions.

Since there is inherent variability while performing such DIV tests for different consecutive trials, a margin of 1.0 kV can be tolerated. The final acceptance criterion is that the DIV detected with the corona-imaging instrument should be within 1 kV of the one observed with the naked eye after being in complete darkness for at least 20 min. The test with the corona-imaging instrument can be performed under normal room lighting, but reduced lighting can somewhat improve the sensitivity ~~to of PD~~ [of UV imaging instruments vs. light](#) ~~versus~~ ambient light ratio. The use of incandescent light instead of UV emitting fluorescent light would also help. [The ambient light level has no effect on acoustic imaging. Instead, it is acoustic noise, especially at the lower frequencies that may affect sensitivity.](#) If the corona-imaging instrument does not respect this criterion, it is considered not sensitive enough in the spectrum of interest to be used for external-discharge detection.

The dimensions in Figure 1 are given as guidelines, but other similar dimensions could be used, bearing in mind that this test is a comparative evaluation of the corona-imaging instrument against the sensitivity of the eye.

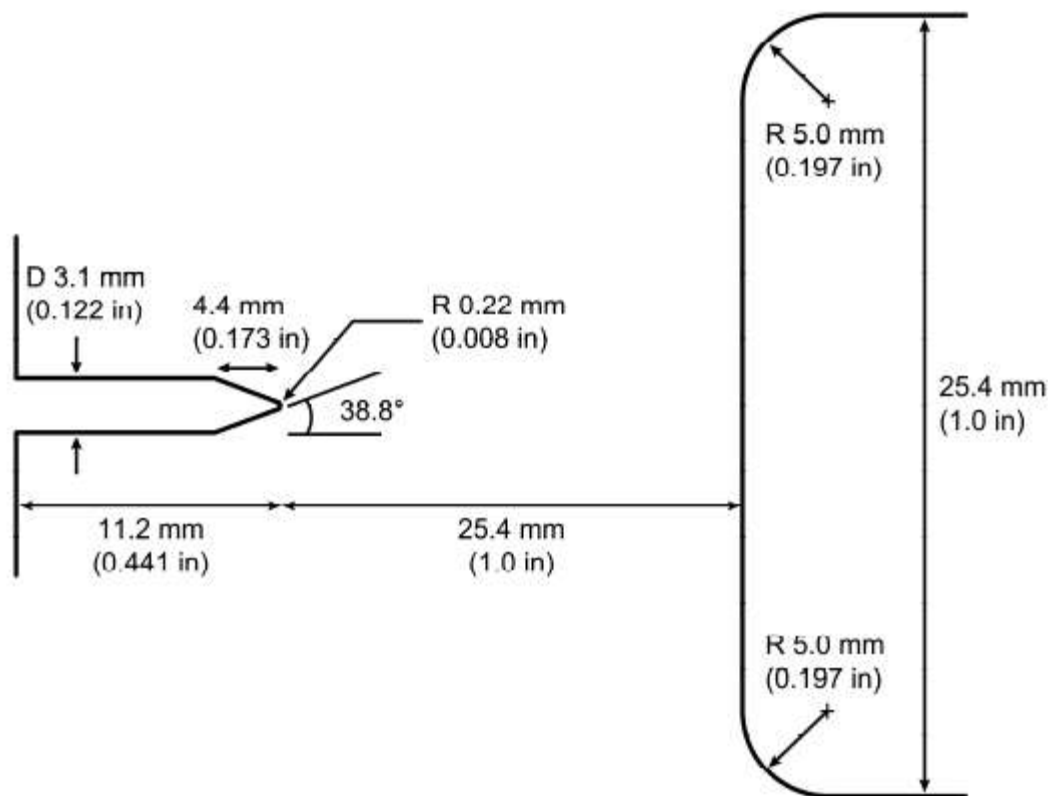


Figure 1 – Needle plane electrode configuration to create discharge activity in air

It should be noted that a non-uniform electrical field is used in order to have a significant difference between the DIV and the breakdown voltage of the test gap. With the dimensions in Figure 1, at an atmospheric pressure of 101.3 kPa (1 atm), a temperature of 22 °C (71.6 °F) and relative humidity of 60%, the DIV is ~~approximately about~~ 6.3 kV, and the discharge extinction voltage (DEV) is 5.8 kV. The typical intrinsic variability of the DIV and DEV from one trial to the next is presented in Table B.1. Under the same conditions, the breakdown voltage of this gap ~~was is~~ 14.5 kV. Thus, if the voltage is raised slowly to the DIV, the risk of dielectric breakdown of the air gap while performing observation of the discharge activity at or close to the DIV is reduced.