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Visual corona testing of 765-kV line insulator assemblies

Streszczenie. (Badania widzialnego ulotu elektrycznego na zestawach izolatorów dla linii 765 kV). *Artykuł opisuje serie badań laboratoryjnych zestawów łańcuchów izolatorów polimerowych i porcelanowych przeznaczonych do zastosowania na projektowanej linii przesyłowej 765 kV. Badania dotyczyły ich własności pod kątem powstawania ulotu elektrycznego. Przedstawiono protokoły, procedury i wyniki wykonanych badań.*

Abstract*. A series of laboratory tests were undertaken to prove the corona performance of insulator string assemblies, both polymer and porcelain, to be utilized on a 765-kV transmission line design. The test protocol, procedures and results are presented in the paper*

Słowa kluczowe: wysokie napięcie, ulot, izolatory, linia przesyłowa.
Keywords: high voltage, corona, insulators, transmission line.

Introduction

Traditionally corona testing has been performed in laboratories by mounting a single phase mock-up of the conductor/hardware/insulator assembly at a given height above the ground and applying 110% of the rated line-to-ground operating voltage. If the test setup is shown to be free of corona by this test, then it is considered that the assembly will be free of corona under operating conditions. This method does not appear in any standards, but is used as a generally accepted test method. In spite of its general acceptance, this test method can give erroneous results. This is due to the fact that the inception of corona occurs at a given electric field gradient rather than a given absolute voltage. Under actual operating conditions, the electric field gradient at the conductor/hardware/insulator assembly is a function of phase spacing, the local geometry, and the applied 3-phase voltage. In order to correctly perform such a test in a laboratory, it is essential that the maximum gradients occurring on the conductors in the field be reproduced in the laboratory test

To reflect the true operating environment, corona testing of equipment should be carried out at a specified gradient related to the actual system-operating gradient. To establish this gradient in the test setup, three alternatives are possible. These are:

1. Build an accurate mock up of the three-phase system utilizing representative energized conductors, ground planes, spacings, etc.
2. Test the hardware on a conductor of the same size upon which it will be used in service and set the test gradient to that representative of the maximum 3-phase gradient present at the location where the test object will be installed. The test gradient can be obtained by calibrating the test setup through the use of corona calibrating spheres.
3. Test the hardware as above in 2, but calculate the applied voltage necessary to achieve the required gradient for the test setup used.

The first of these alternatives requires the use of a 3 phase supply, and an extremely large laboratory in which real setups can be constructed. In most HV labs this is not possible. Therefore, the latter two alternatives are of most interest. The second method is based on the use of gradient calibrating spheres. A calibrating sphere is a small sphere, which is mounted on a circlip and can be attached to a conductor [1]. Figure 1 shows the design details of the calibrating sphere, and how it is attached to the conductor under test. The spheres are themselves calibrated on various sizes of conductor to establish the relation between the electric field gradient at which the particular sphere will go into positive corona and the conductor diameter.

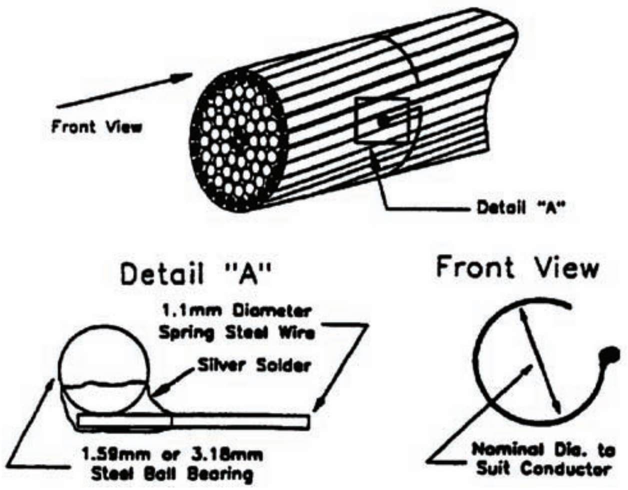


Fig. 1. Conductor surface gradient calibration sphere

When performing the laboratory corona test, the previously calibrated sphere is mounted at the centre of a length of conductor and is used as a calibration device to relate applied voltage to conductor gradient. After the applied voltage – conductor surface gradient calibration factor is established, the sphere is removed and the hardware under test installed. The applied voltage is then raised to the level required to produce the maximum conductor surface gradient as specified under operating conditions. In the third approach, the required test voltage is calculated through the application of electric field modeling techniques. These modeling techniques are then used to establish the single phase test voltage, which when applied to a test assembly in the laboratory, will produce gradients on the equipment which are equal to those the equipment sees when installed on the transmission line.

This paper describes a series of tests utilizing the second of these methods. This test method is described in detail in Canadian standard CAN/CSA-C411.4-98 [1] and in IEC Publication 61284, 1987 [2]. The tests were performed on a variety of suspension and dead-end assemblies utilizing polymer and porcelain suspension insulators intended for use in American Electric Power’s (AEP’s) new 765-kV line design. This new design was adopted by AEP for a new 90 mile (145 km) line currently under construction.

It incorporates the use of a 6-conductor bundle which supersedes their earlier 4-conductor bundle design. The goal of implementing the 6-conductor bundle design is to provide a reduction in audible and electrical noise generated by corona discharges. Gaining assurance that the line will operate corona-free is particularly important in this case since polymer insulators are used on portions of this line. The tests were intended to demonstrate that the new design would be corona free under normal operation thereby eliminating the possibility of in-service corona discharges and potential life reduction of the polymer insulators. Kinectrics, in Toronto, Canada worked with AEP in the design and performance of the corona and RIV test program.

Test program

The first step in the test program development was the calculation of the values of the maximum midspan operating gradients characterizing the line design. Based on these, the voltage gradient at which the testing was to be performed was established. Following this, full scale suspension and dead-end assemblies were erected in the high voltage laboratory and subjected to visual corona testing.

Calculation of the mid-span conductor surface gradients

The mid-span conductor surface gradients were calculated for the line deign provided by AEP. The maximum operating voltage of the AEP 765-kV system is 805 kV. Based on this value, the maximum mid span sub-conductor surface voltage gradient on the operating line was calculated as being 18.27 kV/cm. In order to account for the reduced air density in the highest area of the AEP service territory in which this design could be utilized, and for the surface ageing that occurs on line hardware exposed to nature, the value of the subconductor surface voltage gradient set for acceptance was set at 1.3 times the maximum operating gradient. Therefore, the assemblies were tested at a subconductor surface gradient of 23.7 kV/cm.

Calibration of the single phase test setup

The first step in the calibration of the full single phase test setup comprised the calibration of the corona calibrating sphere which would be utilized in establishing the relationship between the voltage applied to the full single phase test setup and the electric field at the outside surface of the individual subconductors [3].

The diameter of the calibrating sphere chosen for use was 3mm. Calibration of the calibrating sphere on a conductor of the same diameter as that of the bundle subconductors was performed so that the sphere could be used to set the test voltage to the value which would produce the required electric field at the bundle subconductor surface.

The calibration procedure is based on the use of a geometry characterized by a known and easily calculable electric field distribution. Typically the geometries used are either a single conductor positioned above a ground plane or a coaxial geometry with the conductor placed in the central axis of a metal cylinder. Both of these geometries allow for accurate and simple calculation of the electric field at the conductor surface. The calibrating sphere is mounted on a conductor at its midpoint. The length of the conductor used is sufficient to ensure that the electric field at the centre of the conductor is not subject to end effects. In this case the calibration of the corona calibrating sphere was done utilizing a single conductor positioned a given distance above the laboratory ground plane.

The calibration was performed by raising the voltage applied to the conductor and determining the applied voltage at which the corona calibration sphere went into positive corona. This was repeated 5 times for two heights of conductor above ground. The positive corona inception voltage was established as the average of the 5 measurements taken at each of the 2 heights above ground. This value was then used to determine the electric field required at the conductor surface to give positive corona inception on the calibrating sphere. For the single conductor above ground geometry utilized, the relation between the applied voltage and the electric field at the conductor surface is given by

$$E = \frac{V}{r \ln \frac{2h}{r}} \tag{1}$$

where: V is the applied voltage, r is the radius of the conductor, h is the height of the conductor above ground.

This value of electric field was then assigned to the particular corona calibration sphere as the electric field at which the calibrating sphere goes into positive corona when mounted on this particular sized conductor.

Figures 2 and 3 show the setup used for calibration of the corona calibrating sphere and the details of how the calibrating sphere is attached to the conductor. The results of the calibration are □urf □u Table 1.

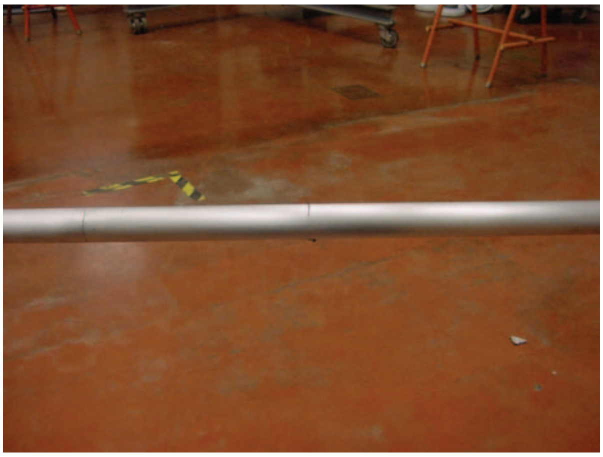


Fig. 2. Setup for calibration of the corona calibrating spheres

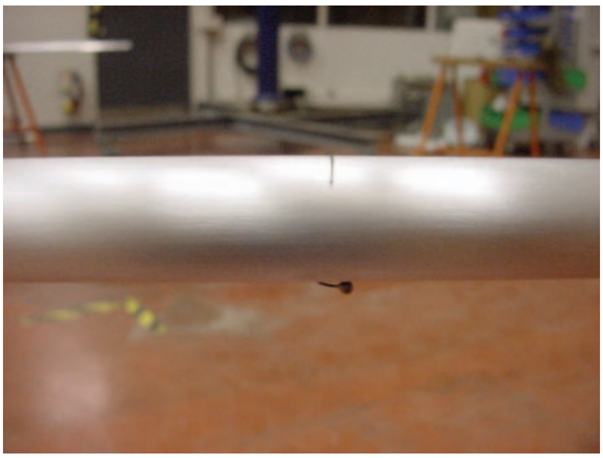


Fig. 3. Details showing installation of the corona calibrating spheres

Upon completion of the calibration process for the corona calibrating sphere, the sphere was used to obtain a calibration between the applied voltage and the electric field present at the surface of the single phase test setup's bundle conductors. The single phase test setup consisted of a 15.24 m length of 6-conductor bundle utilizing smooth metal tubes as subconductors and was erected in the centre of the high voltage laboratory at a height of 4.8 m above the ground. One end of the conductor bundle was shielded using corona rings and the other was shielded by inserting the bundle into the corona ring of the voltage divider. The use of smooth metal tubing in place of stranded conductor represents a practical simplification to assist in the test setup. The conductor used was a rigid aluminium tube having a diameter equal to the specified conductor. The error introduced through this substitution of smooth aluminium tubes for stranded conductors is accepted as being negligible and allowed in the standards [1,2].

The length of the bundle was 50 feet. The centre of the bundle was 15 feet 10 inches above the laboratory floor. The bundle was located 22 feet and 8 inches from the south wall of the laboratory and 24 feet from the north wall of the laboratory. A structural beam with its full length covered with an 8-ft wide screen (to be used as the cross arm for the assemblies) was hung 20 feet and 5 inches over the midpoint of the bundle. The beam was oriented perpendicular to the bundle. The diameter of the sub-conductors making up the bundle was 27 mm and the bundle diameter was 762 mm (30 inches). A photograph of the setup used for calibration of the applied voltage vs. bundle subconductor surface gradient is shown as Figure 4.

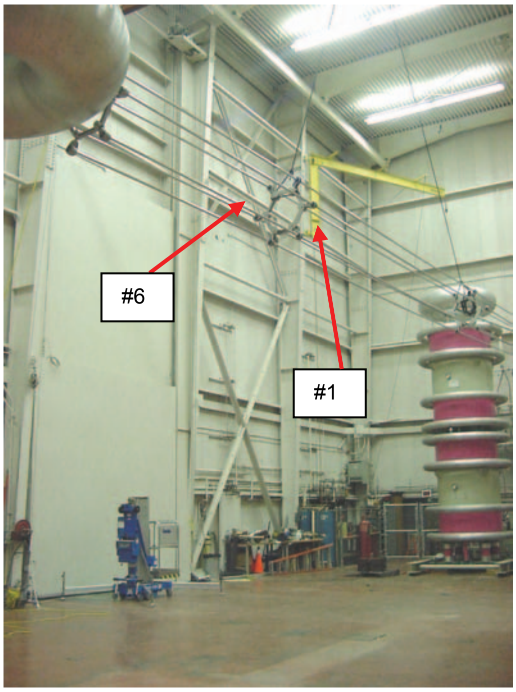


Fig. 4. The six-conductor bundle set up for calibration

Table 1: Corona Sphere Calibration

High above □urfac (ft)	Corona Inception Voltage (kV)						□urfach Gradient (kV/cm)
	1	2	3	4	5	Average	
2.0	92.7	91.6	91.6	91.2	91.7	91.6	15.49
3.0	101.5	100.5	100.0	100.0	100.0	100.5	15.48

The calibration of the setup was performed by attaching the 3 mm diameter calibrating sphere to the bundle sub-conductors at a position mid-way along the bundle length. Calibration of the sphere had shown that, when mounted on a 27mm diameter conductor, it would have a positive corona inception gradient of 15.49 kV/cm. Utilizing this calibration data for the sphere, the relation between applied voltage and subconductor surface gradient was established by mounting the calibrating sphere on each of the sub-conductors in turn and following the procedure outlined below.

Voltage was applied to the conductor bundle, and the test voltage at which positive corona inception occurred on the calibrating sphere was established. This was done by first raising the voltage to above the corona inception level to condition the calibrating sphere and to allow the observer to locate the sphere. The voltage was then lowered to below the corona extinction level, and then respectively raised and lowered to the positive corona inception voltage and 30% below the positive corona extinction voltage of the calibrating sphere. The voltage was raised and lowered five times. During the voltage excursions, the voltage at which positive corona inception occurred on the calibrating sphere was recorded. Following this, the positive corona inception voltage was calculated as the average of the inception readings obtained during the 5 voltage excursions. This procedure was repeated for each of the bundle subconductors.

Based on the determined positive corona inception voltage, the required test voltage for the assembly, was calculated using the relation (2).

$$V_r = \frac{E_s}{E_c} V_c \qquad (2)$$

where: V_r = The required applied test voltage; E_s = The voltage gradient at which the test assembly must be free of positive corona; E_c = The positive corona inception voltage gradient for the sub-conductor mounted calibrating sphere (in this case 15.49 kV/cm); V_c = The applied voltage corresponding determined as the positive corona inception voltage obtained during the bundle calibration.

Table 2 shows the results. Based on these data, it was agreed that 530 kV was to be used as the pass/fail voltage criterion of the transmission assemblies.

Table 2: Calibration Results

Sub-conductor	Average Test Voltage for 15.49 kV/cm (kV)	Voltage for 23.7 kV/cm (kV)
1	348.0	532
2	337.0	516
3	347.5	531
4	353.2	540
5	340.0	520
6	333.0	510

Testing of the assemblies and results

Full scale replicas of the following 7 single phase test assemblies were erected in the laboratory:

1. 3 designs of single "V" suspension assemblies
2. 2 designs of double "V" suspension assemblies
3. 1 design of a quadruple tension assembly.
4. 1 design of jumper loop support assembly

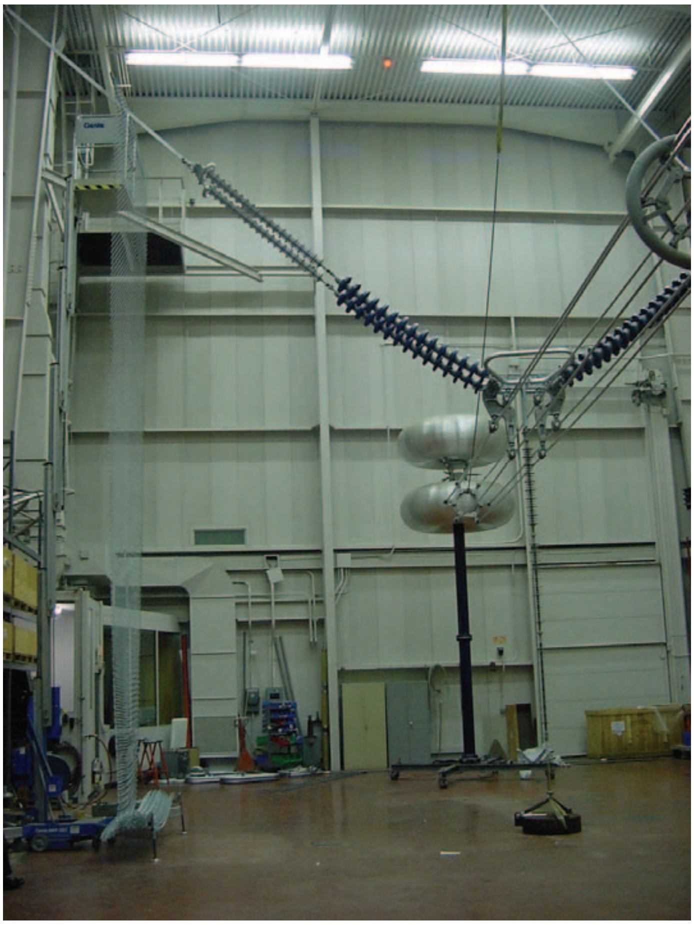
The assemblies under test were installed in the same location as the bundle conductor assembly used for calibration had been mounted. As required by the standard test procedure [1,2], the effects of the grounded structures in the vicinity of the suspension and tension assemblies were simulated through the use of large grounded metallic screens. The location of these screens was adjusted to approximate the location of the tower present in the in-service installation.

The visual corona testing of the various assemblies was performed in a darkened laboratory with the aid of an image intensifier, as well as in a fully lit laboratory with the aid of a Coronascope and a Daycore corona camera.

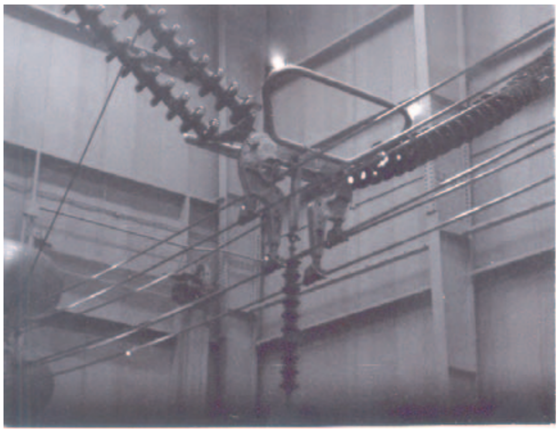
The test procedure comprised raising the applied voltage to above the level at which positive corona appeared on the assemblies under test, and then lowering the voltage until corona extinction was observed. In each case, the corona extinction and inception voltages were based on the average values as determined from a series of 5 voltage excursions. If the voltage at corona extinction was above the required 530-kV test voltage, then the assembly was considered to have passed the test. If corona extinction did not occur until the test voltage was reduced to below 530-kV, then the assembly was considered to have failed the test.

In many cases the assemblies passed the test successfully, while in others they failed. On assemblies which initially failed to pass the test, modifications were made during the testing. In some cases, the assemblies could be made to pass the test through simple modifications such as moving, adjusting, or re-orientating the corona rings. In these cases, the new positioning and orientation of the rings was included as a part of an immediate design revision. In other instances, more extensive modifications were required. Here, solutions such as changing the shape or increasing the diameter or the size of tubing used in the ring construction were identified and proven to work in mock-up form, later re-tested to ensure that the revised designs met the test. Following the identification of the potential solutions, the design was revised, new rings were manufactured, and the assemblies were requirements.

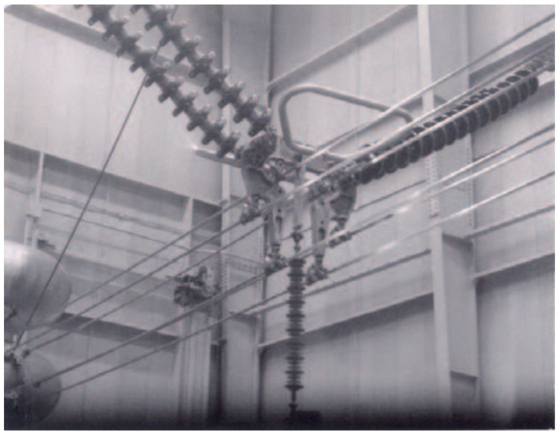
Sample photographs of the double V and the quadruple tension assemblies showing the setup, and the corona extinction and inception details are shown in Figures 5 and 6.



Test setup



Corona present

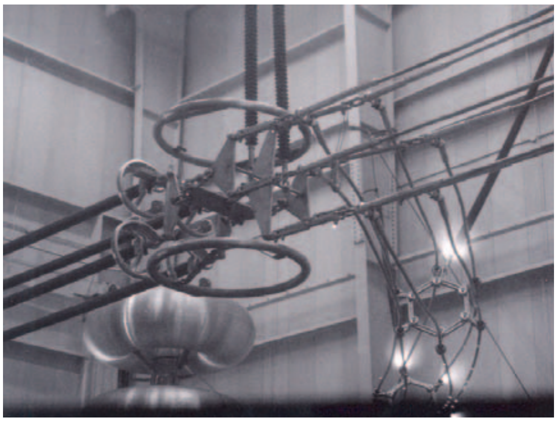


Corona extinction

Fig. 5. Photographs of the double “V” porcelain suspension assembly

Test setup

Corona present



Corona extinction

Fig 6. Photographs of the quadruple tension assembly

Conclusions

Voltage gradient based visual corona tests [1,2] were carried out on several assemblies for use in AEP's new 765-kV transmission construction.

The tests confirmed that several of the assemblies would operate free of positive corona in fair weather conditions.

In some instances, the initial designs did not meet the test requirements. For these cases, improvements to the design were formulated and their effectiveness was checked during the testing.

Assemblies requiring significant modification were re-tested after the identified modifications had been made.

REFERENCES

[1] CAN/CSA-C411.4-98, Composite Suspension Insulators for Transmission Applications

[2] IEC Publication 61284, 1997, Overhead lines - Requirements and tests for fittings

[3] O. Nigol, Development and Testing of Corona-Free High Voltage Line and Station Hardware, 3rd Int. Symposium on High Voltage Engineering, Milan, Italy, 1979

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