VISIBLE CORONA TESTING OF INSULATOR ASSEMBLIES AND LINE HARDWARE FOR HVDC APPLICATION

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Abstract: Corona performance is a critical design parameter for HV lines. Presence of corona discharges on the line can cause long term damage leading to failure of non-ceramic insulators, and is also responsible for power losses and generation of radio noise. There is a marked difference between the characteristics of corona produced on HVAC and HVDC lines. Test methods for ac applications are well documented in IEC standards, and an IEEE guide for the performance of visible corona tests on equipment used for ac lines is under development. There are however no test procedures for the performance of visual corona testing for HVDC applications documented in any standards published by IEC, IEEE, ANSI, CSA, or any other standards body known to the authors of this paper. In spite of this, utilities installing HVDC lines are requesting that corona tests be performed on the insulator assemblies and line hardware. The authors of the paper were requested to perform such tests for insulator assemblies and line hardware designed for use on a ± 600 kV HVDC line. The methodology used in performing the tests, its basis, the pass/fail criteria used, and the results generated in the test program are presented in the paper.

1 INTRODUCTION

Visual corona and radio influence voltage (RIV) tests were performed on transmission line assemblies designed and manufactured for use on ±600 kV transmission lines. The tests were performed between August 30 and September 3, 2010 at Kinectrics' High Voltage Laboratory in Toronto, Canada.

The visual corona and RIV tests were performed on six transmission assemblies: Line Splice, Spacer Damper (standard mounting type), Spacer Damper (wrapped mounting type), Single "I" Suspension String, Double "I" Suspension String, and Dead End String. Single "I" Suspension String.

The physical dimensions of the transmission line design were as follows:

- Conductor height, at tower 40 m
- Conductor height, minimum 24 m (15 m would be equivalent to 765 kV AC lines)
- Ground wire height, at tower 49.20 m
- Ground wire separation 12.6 m
- Pole spacing 15.14 m
- Quadruple conductor bundle:
    - = Sub-conductor spacing 600 mm
    - = Sub-conductor diameter 44.3 mm

There is no visual corona test procedure documented in any standards published by IEC, IEEE, ANSI, CSA, or any other standards body known to the participants in this test program. In the absence of a standard test procedure, one had to be developed and agreed upon through discussion between the test engineers and the clients. The procedure used and the rationale behind its development is discussed within the body of this paper.

As described in the Appendix, positive onset streamers are the main source of RIV for bipolar DC transmission lines. The onset voltage of the very regular "Trichel pulse" under applied negative voltage is close to the onset voltage of the steamers under positive voltage for the same electrode arrangement. The "Trichel pulse", however, generates significantly lower RIV than that generated by positive onset streamers. Therefore, the corona and RIV performance of transmission line assemblies for bipolar DC application needs to be evaluated under applied positive voltage only.

The pass/fail criteria set by the end-user were that there shall be no visible corona at a phase to-ground voltage of 660 kV (and 682 kV), that the radio interference voltage shall not be more than 500 μV for the spacer dampers and the line splice, and that the radio interference voltage shall not be more than 1500 μV for the hardware assemblies Selected setups, test procedure and test results are detailed in the following sections of this work.

2 SETUP REQUIREMENTS

For bipolar DC transmission lines, the positive and negative pole conductors are usually positioned symmetrically at transmission towers. With this arrangement and neglecting the effect of the overhead ground wires, all points on the virtual-plane that is perpendicular to ground, parallel to the pole conductors, and located at the mid-point between the positive and negative poles will be at ground potential. This virtual ground plane separates the positive and negative poles. Therefore, the positive or negative poles can be tested separately if a vertical ground plane is placed at the location of the above described virtual ground plane.

2.1 Setup Requirements for Testing Transmission Line Hardware to Be Used at Mid-span Using the Voltage Method

For testing hardware to be installed at mid-span, the worst case would be that the hardware is installed at the lowest point of the line (closest to ground). Therefore, the height from the conductor setup to simulate the transmission pole conductor to the laboratory floor should not be higher than the minimum height of the transmission pole conductor and the distance of the conductor from a vertical-grounded-plate or laboratory wall should not be greater than half of the pole spacing.

2.2 Setup Requirements for Testing Transmission Line Hardware to Be Used on Towers Using the Voltage Method

The height of the transmission pole conductors at the towers is usually substantially greater than half of the pole spacing or the distance from the conductor to tower body/crossarm. Therefore, the ground has less effect on the electrical field distribution near the conductor at the towers.

In order to perform representative laboratory tests the DC bipolar transmission line of this specific design (i.e. pole spacing and height from ground at towers, 15.14-m pole spacing, 40-m height) must be simulated in the laboratory. One can calculate the electrical field at the transmission line conductor located at the towers with satisfactory accuracy using the multi-line-charge simulation method if the towers are removed while keeping the physical locations of the pole conductors unchanged, i.e. a bipolar transmission line without towers. Assuming now we bring a 2 x 2 m square tower body in for the conductor support, the tower body would stick out 1 m to the pole conductor from the virtual ground plane, we will find that the electrical field stress on the conductor at the tower location is increased slightly, about 1.0 to 1.5% (note that moving the virtual grounded plane 1 m closer to the conductor increases the conductor surface electrical stress approximately 4%). If we now install a crossarm on the tower, we would find that the electric field stress on the pole conductor increases significantly, by about 7.0% to 8.0%.

It is usually impractical to utilize full-size transmission line towers when performing laboratory tests. It is more reasonable to set up the conductor that is to be used to simulate the transmission pole conductor at a height from the laboratory floor which is equal to half of pole spacing, (in this case, 7.57 m). Utilizing this setup is equivalent to moving the ground from a distance equal to the tower height (in this case, 40m) to a distance of 7.57 m. Utilizing this setup, with the crossarm installed and at ground potential, would only increase the electrical field stress on the conductor by 2.0 to 3.0%.

When setting up transmission line assemblies for testing in a laboratory environment, the presence of the tower arm is necessary for suspension insulator assemblies, and is relatively easy to simulate. Therefore, evaluation of corona and RIV performance of transmission line assemblies for bipolar DC lines can be accomplished by applying a designated voltage to a conductor installed in a test setup comprising a full simulated crossarm and with the conductor installed at a distance equal to one half of the pole spacing from a vertical ground plane (or laboratory wall) and from the laboratory floor. Under these conditions, the conductor surface would be subjected to approximately the same electrical stress as that present on the operating transmission line under the same voltage since the lower stress due to the absence of the tower body is offset by the increase in stress due to the closer ground.

2.3 Testing Transmission Line Hardware Using the Voltage Gradient Method

At times, the testing laboratory may not have the proper spacing as defined in Section 2.1 or 2.2 for using the voltage method. The transmission line hardware has to then be tested using the gradient method similar to that as described in IEC 61284.

3 TESTING PROCEDURES

Visual corona was detected using a corona scope under normal laboratory lighting conditions. There is no standardized definition of the visual corona inception voltage under dc voltage. In view of the absence of such a standardized definition, the visual corona inception voltage for the assemblies and hardware under test was defined as the lowest voltage level at which at least one visible corona streamer occurs per second. The visual corona extinction voltage of the assembly or hardware under test was defined as the highest voltage level at which no corona streamers occurred over a 90-second time period.

3.1 General steps for DC visual corona and RIV tests

3.1.1 Pre-conditioning of the Assembly

A trial run was first carried out to ensure the assembly was appropriately set up after the installation. This comprised ensuring that there was no corona activity on the conductors, conductor terminations, and other parts of the set up that do not make up parts of the hardware to be tested. The pre-conditioning test on the assembly was then carried out after a successful trail run. The applied voltage was increased smoothly to the specified test voltage or the corona inception voltage as defined above. The applied voltage was then increased to about 3% above the inception voltage and maintained at that level for 5 minutes.

3.1.2 Corona Inception Voltage

The applied voltage was reduced slowly below the corona extinction level and then increased slowly to the inception voltage.

3.1.3 Corona Extinction Voltage

The applied voltage was then reduced in steps from the corona inception voltage. Each step was approximately 2% of the corona inception voltage. At each step, the voltage was maintained for 90 seconds to allow for observation to determine the corona extinction voltage of the assembly.

3.2 Radio Influence Voltage

Radio influence voltage measurements were then carried out in voltage steps around the corona extinction voltage level which had been determined step 3.1.3. The measurements were started at a voltage equal to at least three voltage steps below the corona extinction level. Each voltage step was about 3% - 5% of the corona extinction voltage.

The radio influence voltage tests were performed in accordance with NEMA Standards Publication No. 107 1987. The measuring instrument and the detecting circuit comply with the NEMA standard. The radio influence voltages were measured using a Radio Interference and Field Intensity Meter tuned to a frequency of 1.0 MHz. The resistance used in the detection circuit was 150 Ω.

The following standard procedure was used for the radio influence voltage measurements. The applied voltage was raised smoothly to the first voltage step and the initial RIV measurement was taken. The voltage was then increased in steps to above the corona inception voltage and reduced using the same voltage steps to the voltage at which the initial RIV measurement was taken. At each of the voltage steps a radio interference measurement was carried out. The voltage was maintained at each step for 90 seconds and RIV level was the maximum value recorded during the 90-second time period.

4 GENERAL SETUP USED FOR TESTING

Due to the space limitations within the laboratory, the quadruple bundle conductor was set up 6 m from the laboratory floor and 6 m from the south wall of the laboratory as shown in Figure 1. The length of the conductor bundle was 12 m, and the ends of the conductor bundle were properly terminated to ensure that no corona occurred on the ends of the conductor bundle. Due to page limitation for this paper, only the tests performed on the Line Splice and Single “I” string are presented below.

Figure 1: Setup of the positive pole of the bipolar dc transmission line

5 TESTS ON A LINE SPLICE

Figure 1 shows also the line splice setup. With this set up the conductor bundle was stressed close to its corona inception level at the required test voltage of 660 kV. Positive corona streamers were initiated from the conductor bundle at irregular intervals and locations. Therefore, the RIV reading for the line splice had to be taken while there was no corona discharge observed on the conductor bundle with the aid of the corona scope. It was found that the corona extinction voltage for the line splice was 610 kV with a RIV reading of 420 µV.

Although the 610 kV corona extinction voltage was below the required 660 kV test voltage, the fact that the limited space in the laboratory influenced the test result must be taken into consideration. Due to the limited space, the 610-kV voltage applied to the laboratory test setup resulted in higher stress at the line splice than would normally exist when it is installed on the pole conductor under a maximum operating voltage of 660 kV because the clearance between the conductor bundle and the laboratory floor was significantly less than the minimum height of the pole conductor and the clearance between the conductor bundle and the vertical ground plane (in this case the laboratory wall) was also lower than desired half of the specified pole-to-pole. The effect of this lower than desired spacing is explained below.

It can be shown through calculation using the physical line dimensions given previously that the surface stresses on the pole conductor when the line is energized to 660 kV are:

- when minimum height from ground is assumed to be 24 m (21.89 kV/cm)
- when minimum height from ground is assumed to be 15 m (22.98 kV/cm)

We also found, through calibration, that a 3.18-mm calibration sphere, as detailed in IEC 61284, mounted on a 44.3 mm diameter conductor (the same size conductor for used to made up the conductor bundle) exhibited corona inception at a surface gradient of 19.22 kV/cm. When performing the voltage calibration during testing, (using the same calibrator) mounted on the sub-conductors of the conductor bundle) the observed average corona inception voltage of the calibration sphere was found to be 470 kV. This means that the conductor surface gradient of the conductor bundle was 19.22 kV/cm when the setup was energized to 470 kV.

Using the aforementioned data, it can be found that the 610 kV corona extinction voltage is indeed equivalent to 716 kV as follows:

$$610 \times \frac{19.22}{470} \times \frac{660}{22.98} = 716\ kV \quad for\ height = 15\ m$$

6 TESTS ON A SINGLE “I” SUSPENSION STRING ASSEMBLY

Figure 2 shows the single “I” suspension assembly setup. Table 1 shows the corona inception and corona extinction voltages for the single “I” string. Figure 3 shows the images taken at the single “I” string’s corona inception and extinction levels.

Figure 2a: Full view of the single “I” string suspension assembly

Figure 2b: Close–up View of the single “I” suspension string assembly

Table 1: Corona inception and extinction voltages of the single “I” string

Corona Inception Voltage (kV)	Corona Extinction	
	Voltage (kV)	RIV (µV)
750	730	810

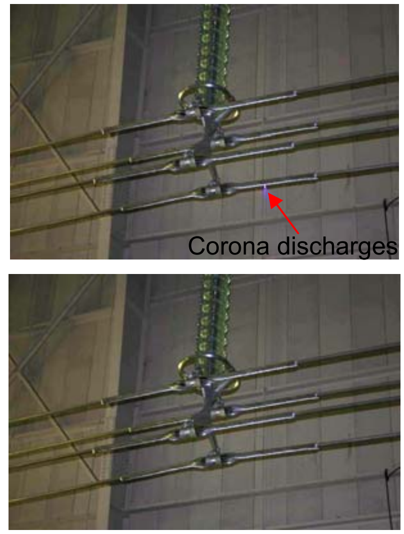


Figure 3: The single “I” string at its corona inception and extinction voltages

As previously described (in section 5) the RIV reading for the single “I” suspension string at its corona extinction voltage had to be taken while there was no corona discharge observed on the conductor bundle with the aid of the corona scope. Table 2 shows the RIV measurement at the last run as the voltage was decreased from the corona inception level.

Table 2: Radio influence voltages of the Single “I” string

Applied Voltage (kV)	Radio Influence Voltage (µV)
760	27,000
730	540
700	540
670	540
640	378
610	324

When carrying out the RIV measurements at voltages below the “I” string’s corona extinction voltage, sporadic spikes in RIV were recorded at several voltage levels. These sporadic spikes were ignored as they were shown to result from sporadic corona activity on the conductor bundle and not the assembly under test.

7 CONCLUSION

There has been little research done on corona and RIV phenomena on transmission line assemblies under DC voltage. However, it is reasonable to suggest that corona and RIV tests on transmission line assemblies be performed under positive applied voltage only based on rod-plane discharge studies and the corona and RIV studies on conductors.

APPENDIX

BACKGROUND OF DC CORONA PHENOMENA

A classical electrode configuration for the study of the physical mechanism of corona and breakdown in air gaps is the hemispherically capped rod-plane as shown below [1]. Point-plane electrode arrangement is also used for studies that require highly localized electrical field stress.

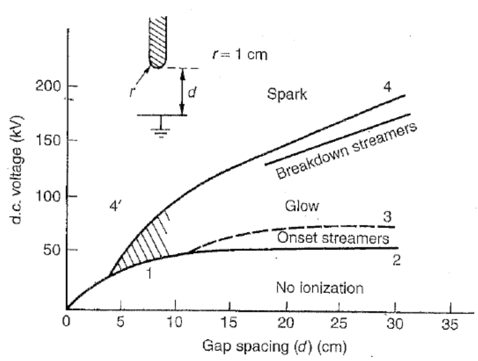
For a hemispherically capped rod-plane gap, the electrical field non-uniformity factor *f*, the ratio of the maximum electrical field stress and the average electrical field stress, can be evaluated by the following equations [2]:

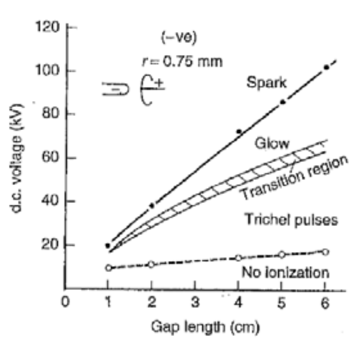
$$f = 0.45\,\frac{d}{r}\cdot\frac{\ln(6\cdot d/r)}{\ln(d/r)} \quad 3 < d/r < 50$$

$$f = 0.85(1 + d/r) \quad d/r < 3$$

d/r	f (computed)
1	1.739
2	2.539
5	4.826
10	8.381
20	15.06
50	33.74
100	63.23
200	120.0
500	285.3

It can be seen that the advantage of this electrode configuration is that the different degrees of field non-uniformity can be readily achieved by varying the radius of the rod electrode tip.





POSITIVE CORONA AND BREAKDOWN OF AIR GAPS

For a hemispherically capped rod-plane subjected to a positive dc voltage, if the gap length is small and the voltage is gradually raised, no appreciable ionization is detected up to breakdown, a typical breakdown mechanism often observed in quasi-uniform fields.

As the gap is increased, the non-uniformity of the field increases. On increasing the voltage an avalanche starts to develop towards the rod electrode in the continuously increasing electric field. The highest field-intensified ionization activity occurs off the tip of the rod electrode, with a spherical volume close to the rod electrode and a conical volume directed away from the rod electrode.

The electron avalanche is initiated by free electrons created by natural processes, not at the electrode surface. As the voltage is further increased a transient slightly branched filamentary discharges appear. These discharges are called **streamers**. Under steady state the streamers develop with varying frequency, giving rise to currents that are proportional to their physical length. These streamers are sometimes called **burst pulses** or **onset streamers**.

Burst corona occurs at the onset of positive corona and is caused by electrons that lose their energy due to ionization activities just before they are absorbed in the rod electrode. The positive ions created in the immediate vicinity of the rod tip build up cumulatively to form a positive space charge and suppress the discharge. The spread of electrons then moves to another part of the rod electrode. Each time ionization spreads around the rod surface and is suppressed subsequently by space charge, a small positive corona current pulse is produced.

Onset streamer, unlike burst corona, onset streamers (sometimes also known as "plumes,") results from the radial development of the discharge. Due to the higher electric field in this case, the positive ion space charge near the rod-tip enhances the electric field away from the rod sufficiently to cause subsequent electron avalanches and lead to the development of a streamer channel in the radial direction. The positive ion space charge created by successive avalanches away from the rod reduces the electric field near the rod surface and eventually suppresses the streamer. The discharge activity stops during an interval of time necessary to clear the space charge and resumes as soon as the original field distribution is restored. Thus, the positive onset streamer mode of corona is pulsed in nature, producing corona current pulses with larger amplitudes and low repetition rates.

When the voltage is increased further, the streamers become more frequent until the transient activity stops, the discharge becomes self-sustained and a steady glow appears close to the rod tip, the **positive glow**. This glow gives rise to continuous but fluctuating current. The luminosity of the glow increases both in area and intensity as the voltage is increased further. It is believed that, the transition from burst corona mode (streamer) to a stable glow corona mode rather than to the onset streamer mode requires special conditions and is difficult to obtain even under laboratory conditions and may occur on transmission lines but only under very special conditions.

On increasing the voltage still further, new and more vigorous streamers appear. The streamers ultimately lead to complete breakdown of the gap, the **breakdown streamer**.

NEGATIVE CORONA AND BREAKDOWN OF AIR GAPS

When the rod electrode is negative and the voltage is increased to above the onset voltage level, the current flows in very regular pulses known as "Trichel pulses". The onset voltage of a "Trichel pulse" is practically independent of the gap length and is close to the onset steamer voltage under positive polarity for the same arrangement. The pulse frequency increases with the voltage and depends on the radius of the rod electrode, the gap length and the pressure.

As the voltage is further increased, a transition from Trichel pulse to a steady glow discharge occurs. The transition from Trichel pulses to glow discharge is not sharply defined. On increasing the voltage further, the glow discharge persists until breakdown occurs at considerably higher voltage than under positive polarity.

SOME RESEARCH ON DC CORONA AND RIV MEASUREMENTS

The landmark research paper on HVDC visual corona and RIV testing on insulators and conductor samples was published in 1971 [3]. Different conductor configurations and insulator units/strings were studied under DC voltage. The researchers found that the repetition rate of the corona pulses was extremely low at the corona onset level. It required up to 5 minutes to determine whether a corona pulse existed at a given voltage level. As the result, the researchers decided to utilize a five-minute time interval at each voltage step to minimize the uncertainty in the determination of the visual corona or RIV inception voltage.

If at least one visible corona pulse was detected during the 5-minute period at a voltage level, this voltage was defined as the corona inception voltage. The RIV level was taken as the maximum value recorded during the same period of time.

There was substantial voltage difference, roughly 25% between the voltage level as defined above and the voltage level at which the corona phenomena appears practically permanent, that is, with a pulse repetition rate higher than one pulse per second.

An important conclusion drawn from the research data is that for all the conductor configurations, the positive corona inception voltage was lower than the negative corona inception voltage. The measured RIV at the positive corona inception voltage was also significantly higher than the measured RIV at the negative corona inception voltage. Similar conclusions can be drawn from the data for insulator units/strings.

This research conclusion was supported by a later study by EPRI on the corona measured on an experimental ±600 kV bipolar DC line from July 1973 to December 1974 [4]. The bipolar line was equipped with 4X30.5 mm conductor bundle. The pole spacing was 11.2 m and the average height of the bundle from the ground was 15.2 m. EPRI found the maximum RIV measured at 0.5 m from the ground was directly under the positive-polarity bundle conductor.

This research conclusion was further supported by more recent measurements on a ±800 kV bipolar line by Chinese researchers [5]. The bipolar line was equipped with 6X33.6 mm conductor bundle. The pole spacing was 22.0 m and the minimum height of the bundle from the ground was 18.0 m. The Chinese researchers also found the maximum RIV measured at 1.5 m from the ground was directly under the positive-polarity bundle conductor. They concluded that the main source of RIV is positive corona.

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