21, rue d'Artois, F-75008 PARIS
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METHODOLOGY FOR HVDC CORONA TESTS

J.K. Chan EPRI USA

J. Kuffel Consultant Canada

G.C. Sibilant EPRI USA

J. Bell EPRI USA

SUMMARY

When specifying hardware for new HVDC lines or replacement hardware for existing HVDC lines, utilities generally require that the hardware meet specific corona performance requirements. While standards and test methods exist for testing hardware used on HVAC systems, no such material is available for HVDC systems

Current industry practices using dc voltages are not fully developed. Test methods have been developed and are described in the literature. However, they require precise definition and experimental confirmation. Tests for HVDC line hardware are, in some cases, conducted using ac voltage and the results obtained are then related to dc. This practice does not consider the physical differences between ac and dc corona, and does not take into account phenomena such as space charge and ion cloud formation that are unique to dc.

In 2013, the Electric Power Research Institute commenced investigations into the development of a standard methodology for testing the corona performance of HVDC line hardware. The development of the hardware corona testing guidelines began with identification and analysis of issues specific to HVDC.

In this work, HVDC corona was first studied by conducting small scale tests in a corona cage using a single conductor and a corona calibrating sphere. The limited small scale work performed in this project indicates that the practice of utilizing ac test voltage to qualify hardware performance on HVDC systems needs further review.

Following this, large scale corona cage tests utilizing full size bundle conductors and line hardware were performed under dc and ac voltages in an outdoor corona cage. It was found that approximating dc using ac peak produced reasonable results for corona sources from a sphere embedded in the conductor and from a spacer-damper with a sphere attached, a difference of 2% or less is seen. Contradictory results were found with the use of a conical corona source. Those results show differences of up to 40%. During the large scale tests, it was observed that a corona source energized with dc had erratic behavior in the presence of

jchan@epri.com

strong winds. A corona source may extinguish only to re-ignite when the winds passed, or conversely would suddenly develop a corona plume which would vanish with the breeze. Additional testing is required to explore how effective the use of ac testing can be for application to dc systems.

KEYWORDS

HVDC corona, Small scale test, Large scale test, Hardware test requirements, HVDC hardware test methodology.

BACKGROUND

Corona discharges present on line and substation hardware cause radio interference, damage to insulating composite material and unnecessary power losses. When specifying new or replacement hardware for use on high voltage transmission systems, utilities generally specify that the hardware provide adequate corona performance over their service life. While standarderdized methods exist for testing hardware used on HVAC systems, no such material is available for HVDC systems.

With an increase in the construction of HVDC transmission lines, there is a need to develop specific guidelines for HVDC hardware corona testing. Utilities and hardware manufacturers require guidance through the establishment of best practices for HVDC hardware testing so as to ensure that they obtain accurate performance data from their tests. To meet this end, a test procedure for HVDC systems needs to be developed. Logically, this procedure should, to as high a degree as possible, mirror the currently available standard test procedure for HVAC systems.

Current industry practices using dc voltages are described in the literature but they are not widely enough applied to form the basis of testing standards. Ideally, to develop industry accepted standards, the proposed procedure should be 1) carried out as part of a controlled round-robin test in different high-voltage laboratories and 2) assessed through experimental comparisons with operating HVDC lines. However, prior to this, studies aimed at developing a better understanding of the role and importance of space charge effects should be performed. Such studies, both experimental and computational,will serve to refine test procedures through the development of a better understanding of the characteristics and localized effects of space charge on the corona phenomenon on HVDC lines.

Due to the lack of industry standard HVDC corona test protocols, tests for HVDC line hardware are, in some cases, conducted under ac voltage. Typically the the peak ac voltage applied for such tests varies between 1.4 to 1.1 times the dc system voltage, depending upon the degree of conservatism desired in the results. The degree of conservatism attained is however difficult to quantify as this practice does not consider the physical differences between ac and dc corona, and does not take into account phenomena such as space charge and ion cloud formation that are unique to dc.

In order to gain an improved understanding of the importance of space charge effects as required for the development of standardized HVDC corona tests, a research project was undertaken at the Electric Power Research Institute. The initial phases of the project, comprising an investigation of the importance of space charge effects in HVDC corona testing and the potential for performing tests for HVDC hardware using ac voltages are described in this paper.

RESEARCH APPROACH

In 2013, in order to establish guidelines for the industry, the Electric Power Research Institute commenced investigations into the development of a standard methodology for testing the corona performance of HVDC hardware.

The development of the hardware corona testing guidelines began with the identification and analysis of issues specific to HVDC. Based on available literature and published test results, a test methodology with proposed guidelines was investigated for small scale tests.

Small scale tests comparing and contrasting corona under ac and dc voltage were carried out in a corona cage using a single conductor and a corona calibrating sphere. The intent was to check the validity of the proposed guidelines, and to identify and address outstanding issues of concern.

The small scale tests were followed with large scale corona cage tests utilizing full size bundle conductors and line hardware Those tests were also performed under dc and ac voltages. The objective of the large scale tests was to confirm the validity of the proposed procedure and to investigate the need for further refinements.

DEVELOPMENT OF TEST METHODOLOGY

Background

HVAC corona test techniques are reasonably well understood and standardized upon. It was decided at the onset of the work that ideally, the test procedure for HVDC systems should where possible, build upon the existing ac test techniques. The difference between HVDC and the standard HVAC tests would, however, need to reflect the physical differences between ac and dc corona, along with any significant effects of space charge. The pioneering research on HVDC visual corona and RIV testing on insulators and conductor samples was published in 1971. Different conductor configurations and insulator strings were studied under applied dc voltage. The results of the work showed that, in contrast to ac, the repetition rate of the corona pulses observed under continuous dc voltage was low. The authors of the study recommended using of a 5-minute time interval at each voltage step to minimize the uncertainty in the determination of the visual corona or RIV inception voltage.

Important conclusions drawn from the research were that:

- the positive corona inception voltage was lower than the negative corona inception voltage
- the RIV measured at positive corona inception was significantly higher than that measured at negative corona inception.

Similar conclusions were drawn from data obtained while testing insulator strings.

These conclusions were supported later by an EPRI study on the corona measured on an experimental ±600 kV bipolar dc line between July 1973 and December 1974. The bipolar line studied used a quad conductor bundle with 30.5 mm conductor diameter. With a pole spacing of 11.2 m, and an average bundle height above the ground of 15.2 m, EPRI found that the maximum RIV measured 0.5 m above the ground was directly under the positive-polarity bundle conductor. This conclusion was corroborated through more recent measurements by Chinese researchers studying a ±800 kV bipolar line using a six conductor bundle with 33.6 mm dia subconductors, a pole spacing of 22.0 m, and a minimum bundle height of 18.0 m above ground. That work showed that the maximum RIV measured at a height of 1.5 m above ground occurred directly under the positive-polarity pole, and that the main source of RIV is positive corona.

Most common dc overhead systems use bipolar dc lines with the positive and negative pole conductors positioned symmetrically about the transmission towers. With this geometry, if one neglects the effect of the overhead ground wires, then at locations away from the towers, there is a two dimensional virtual ground plane oriented perpendicular to the ground, parallel to the pole conductors, and located halfway between the pole conductors. All points on the virtual ground plane are at ground potential. Space charges created at each conductor are neutralized at the virtual ground plane. Figure 1 illustrates the concept of this virtual ground plane. Since the virtual ground plane separates the positive and negative poles, each pole can be tested separately in a laboratory by positioning it parallel to a physical vertical ground plane located half the pole-pole spacing away.

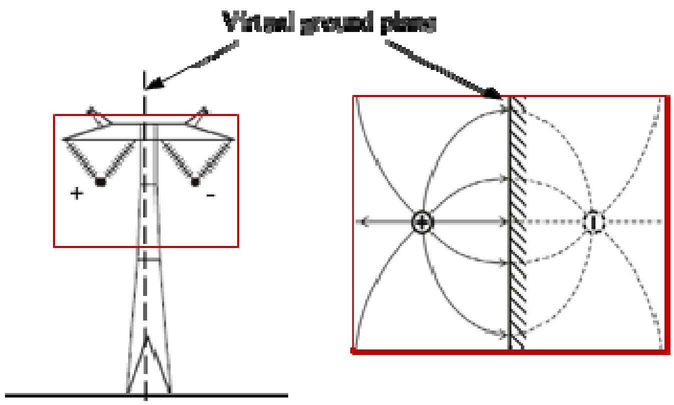

Figure 1 : Virtual Ground Plane Representation of Bipolar DC Line

Hardware such as spacers, dampers, and splices installed at mid-span locations are not influenced by the tower structures. In these applications, the electric field distribution on the hardware is governed by the distance to the virtual ground plane and the height of the hardware above ground. Since the distance between the pole conductors and the virtual ground plane is generally much smaller than the height of the pole conductors above ground, the former dimension becomes the key parameter affecting the electric field on the surface of hardware. Proposed testing procedures utilize this fact as a basis for constructing test setups. The situation becomes more complex when testing hardware such as insulator assemblies, corona rings, and acing horns which are installed near towers locations where, the electric field on the hardware surface is governed by the proximity to the tower rather than by the virtual ground plane. In these cases, the test setups include installation of simulated tower bodies and arms.

Small Scale Tests

Key factors in the development of an HVDC corona test procedure include characterization of differences between dc and ac corona inception and extinction levels, and an understanding of whether the presence of dc corona can result in significant differences between laboratory tests and in-service field conditions. These key factors were first studied by conducting small scale tests.

The goals of the testing were to:

- investigate if dc corona inception and extinction levels are significantly influenced by the presence of space charge and ions present in HVDC systems
- assess whether air movement, typical of what would be present in an indoor test environment (heater or air-conditioning circulation fans) would affect corona inception and extinction voltages
- compare positive and negative corona inception and extinction voltages under dc and ac conditions
- provide visual images of positive and negative corona under ac and dc voltage using typical tools available for the detection and observation of corona under laboratory and the field conditions.

The research comprises an initial series of tests carried out in a corona cage using a single conductor and a corona calibrating sphere. The tests were performed under conditions of no forced air movement and a low degree of forced air movement.

<u>Test Setup:</u>

The cage was 80” long with a 19” radius. To grade the field and to eliminate possible end effects, the ends of the cage were covered with field grading rings with a 2” radius. The corona cage was suspended horizontally from the ceiling of the test chamber by high voltage insulating rope. The cage was positioned equidistant from each wall, and the walls and ceiling of the test chamber were covered with a fine steel mesh screen that was connected to earth-ground. The corona cage was also connected to earth-ground via a metallic grounding strap.

A 1.25” diameter conductor was placed in the center of the cage. The ends of the conductor were terminated with 2 ½” radius spheres so as to eliminate corona at the conductor ends. The conductor was suspended using monofilament line attached to composite insulators which were hung from the ceiling. This allowed for accurate centering of the conductor within the cage. The connection to the high voltage source was made at one of the terminating spheres and sheilded using an 8” grading ring. The conductor was energized using both ac and dc voltage which was increased and decreased to allow varying degrees of positive and negative dc and ac corona

A spherical corona calibrator was used as a field perturbation source. The copper coated steel sphere had a diameter of 0.170 inches. The sphere was soldered directly to the conductor in the center of the cage oriented upwards as shown in figure 2.

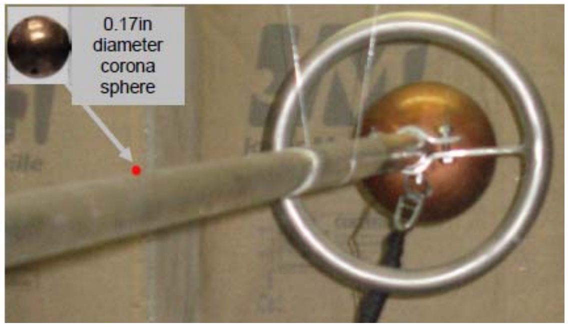

Figure 2: Corona Calibrating Sphere in Corona Cage

The general setup of the test bay is shown in the figure 3.

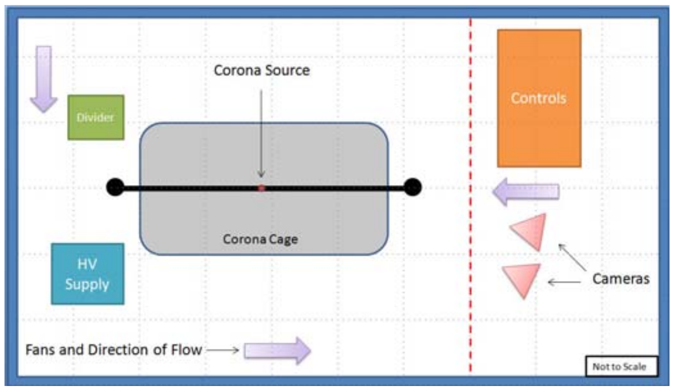

Figure 3 : Diagram of Test Setup

The blue "wall" represents the faraday cage screening and the red dashed line represents a protective gate circuit that isolates the operators from the energized components. Behind the controller is an overhead door that can be opened to quickly vent ozone if concentrations become high enough to pose a health hazard. The high voltage connection was made using 1.5" diameter aluminum flexible conduit.

Test Results and Analysis:

A summary of the corona inception and extinction values obtained under ac and dc voltages is shown in table 1.

Table 1 : AC and DC Corona Results

Polarity		Fans Setting	Average Onset Voltage (kV)	Average Extinction Voltage (kV)
DC -		Off	-79.8	-77.3
DC +		Off	91.3	90.1
DC -		On	-76.8	-75.6
DC +		On	91.4	90.1
AC -	**rms**	Off	-58.9	-56.6
	peak	Off	-82.9	-80.0
AC+	**rms**	Off	88.5	83.9
	peak	Off	125.2	118.7

Note: The AC voltages were measured using an rms reading meter. The ac peak values were calculated as the rms multiplied by √2.

The limited small scale work performed indicates that the practice of using ac test voltage to qualify hardware performance on HVDC systems needs to be further reviewed. Table 2 shows the experimentally determined relation between corona inception under ac and dc voltage. The percent difference between two numbers is the absolute value of the difference between the two numbers (voltages), divided by the average of those two numbers. The results indicate that there is a definite difference between the ac peak corona inception levels and the dc corona inception levels. This difference is more pronounced for the positive polarity. The results of these initial tests indicate a need for further work aimed at developing a better understanding of the impacts of the differences between dc and ac corona on the use of ac voltages for testing dc hardware.

Table 2 : Test Results Analysis

Polarity	Fans	Onset Voltage (Avg)	Abs Difference from AC Peak	% Difference from AC Peak	Extinction Voltage (Avg)	Abs Difference from AC Peak	% Difference from AC Peak
DC -	Off	-79.8	3.50	4.29	-77.3	2.70	3.43
DC +	Off	91.3	33.9	31.3	90.1	28.6	27.4
DC -	On	-76.8	6.50	8.12	-75.6	4.40	5.66
DC +	On	91.4	33.8	31.2	90.1	28.6	27.4
AC – (peak)	Off	-83.3	-	-	-80.0	-	-
AC+ (peak)	Off	125.2	-	-	118.7	-	-

Note: The AC voltages were measured using an rms reading meter. The ac peak values were calculated as the rms multiplied by square root of 2.

The small scale tests performed lead to the following conclusions:

- The small scale test data strongly suggest that the results of corona tests performed with ac voltage are not simply transferable to HVDC applications.
- Limited investigation of the effects of slow air circulation versus still air conditions on dc corona showed a small, but measureable decrease in negative polarity inception and extinction levels when air motion was introduced. No measureable effect was observed on the onset and extinction of positive dc corona between tests with and without air slowly circulating about the room.

Specialized commercially available instruments such as the Corocam and the Daycor aid considerably in the performance of both dc and ac corona tests. Images produced using these devices are effective in differentiating between positive and negative corona in ac testing. Based on the findings of this initial work, the following recommendations ware made for further study:

- The effects of space charge and ions produced during sustained periods of corona such as those forming a part of standard test procedures should be further investigated. The variables considered should be duration and intensity of sustained corona, size of the test chamber, and air motion.

- Tests on full scale transmission assemblies should be performed with both ac and dc voltages to determine whether the difference between ac and dc results identified in the small scale tests carries over to full scale tests.
- While several corona viewing devices proved effecive at identifying corona onset and extinction, different instruments produce differing visualizations of corona inception and extinction. As such, it would be useful to provide guidance on the interpretation of the results obtained using the various corona viewing aids.

Large Scale Tests

The large scale testing was performed in an outdoor corona cage (See Figure 3 below). The principle advantage of the outdoor corona cage is its size. HVDC lines generate charges in space. These charges will drift towards other conductors or towards the ground. The time of flight for a discrete portion of charge will be directly proportional to the voltage and indirectly proportional to the distance. Within the smaller indoor cage the charges are able to quickly travel to ground, as there is a ground plane nearby and covering all 360 degrees of freedom, and therefore they cannot collect around the conductor. With the outdoor cage the distance to ground is increased and the ability for charge to accumulate is greater. The downside to this approach is the large cage requires working outdoors, where factors such as wind cannot be controlled. Even a gentle breeze may blow ions and charged aerosols well out of the corona cage. During testing any changes that occurred as wind speeds increased or decreased were noted.

Figure 3: Large Scale Corona Cage

<u>Test Results:</u>
Three corona sources were used in the study. They are shown in Figures 4 and 5.

Figure 4: Medium sphere attached to the bottom of subcoductor

 

Figure 5: Spacer damper in outdoor cage with a conic source (left) and with a spherical source (right)

It was noted that the occurrences of the highest onset and extinction levels for the sphere test occurred when the winds were the highest. Sources that were emitting corona would extinguish when the wind speeds picked up. This strongly suggests a possible correlation between wind and corona values. These data are not RAD (relative air density) corrected. Test results are shown in Table 3, 4 and 5. The average values shown in the tables represent the average obtained over 5 tests.

Analysis of Results:
For the medium sphere embedded in the conductor, the positive corona onset and extinction under AC peak and DC showed good agreement. The difference was within 1kV, which is much less than 1% difference. For the case of the spacer-damper with a corona sphere attached, a difference of 2% is seen. These results indicate that using AC peak is a very good approximation of DC corona performance.

Table 3: Average Values of Positive DC with Medium Sphere

	Positive DC - Medium Sphere				Positive DC – Damper w/sphere		
	Onset	Continuous	Flicker	Extinction	Onset	Continuous	Extinction
AVG	276	278	274	269	318	-	310
STD Dev	4.317	2.926	5.083	3.124	2.236	-	1.118

Table 4 : Average Values of Positive AC with Medium Sphere

	Positive AC - Medium Sphere		Positive AC – Damper w/ Sphere	
	Onset	Extinction	Onset	Extinction
AVG	195	191	220	217
STD Dev	1.082	0.6248	0.765	1.066

Note: Values in table are rms voltage.

Table 5: Average Values of Positive AC with Conic Source

	Positive AC Damper with conic source		Positive DC – Damper with conic source		
	Onset	Extinction	Onset	Continuous	Extinction
AVG	300	291	298	298	274
STD Dev	1.166	1.166	6.708	6.708	7.151

Note: Values in table are rms voltage.

Contradictory results were found with the use of a conic corona source. Those results show a difference of approximately 40%. Anecdotal tests were performed which showed that a simulated broken conductor strand gives results with a similar percentage difference as those obtained with the conic source. This is believed to be due to the shape of the corona source. A pointed source will more readily go into negative corona. Therefore for the AC testing the negative corona burst will generate a local ion cloud. These ions will shield the onset of positive corona during the positive half-cycle as a result of the polarity of the cloud. This would appear to indicate that full scale testing is needed on a variety of components to determine where the transition between a spherical and conic source geometry occurs. It was also observed during the full scale tests that a corona source energized with DC had erratic behavior in the presence of strong winds. A corona source may extinguish only to re-ignite when the winds passed, or conversely would suddenly develop a corona plume which would vanish with the breeze.

CONCLUSIONS AND CONTINUING WORK

The reduced scale tests showed that under positive polarity for certain corona sources there was a large deviation between the corona onset and extinction voltage under ac and dc voltage. The highest deviation was seen with the intermediate sized corona source, therefore it is inferred that the ratio of conductor diameter to corona source was a factor. These small scale results were contradicted for a smooth corona source on an actual conductor placed within a larger corona cage and for a smooth corona source placed on a piece of hardware, a spacer-damper. The results were confirmed for “pointy” corona sources, such as a sharp edge or a broken strand.

It is therefore shown by both tests that for some conditions the conversion from ac to dc corona performance may be adequate. However, this is not true for all cases. Therefore the corona performance of additional conductor configurations, corona sources, and hardware is required to establish the bounds of cases for which ac performance may be carried over to dc. This would require full scale testing on a variety of components to determine where the transition between a spherical and conic source geometry occurs, and if this transition point is relevant to the practical geometries encountered in line hardware design.

Several corona viewing devices proved effecive at identifying corona onset and extinction. Different instruments produce differing visualizations of corona inception and extinction. As such, it would be useful to provide guidance on the interpretation of the results obtained using the various corona viewing aids.

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