Research on Corona Onset Field Strength of Large-size Cylinders and Rings on DC Transmission Line

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Abstract

Corona discharge phenomenon ought to be considered as a key technical problem during the design, construction and operation of UHVDC transmission line. As indispensable and important attachments, research on fitting's corona is a significant issue to electromagnetic environment (EME) of DC transmission project. The size design of fittings, especially large-sized cylinders and rings, is based on Peek's formula. However, it is proposed by experimental results of small-radius wires. Peek's result should be further discussed about the applicability to large-sized electrode and in three-dimensional electric field distribution situation. This paper presents corona test set-up plan of large-sized cylinders and rings on HVDC transmission line. Experimental results confirm the corona onset voltage of these specific fittings. Ansoft FEM calculation software presents the maximum surface field strength of fittings. The theory of secondary electron collapse suggests the form of formula about corona onset field strength. Based on it, formulas about large-sized cylinders' and rings' corona inception E-field are proposed.

1. Introduction

As to power transmission for long distance and large quantity, DC transmission system plays a significant role in grid development plan [1-3]. As a key technical problem, Corona discharge phenomenon ought to be considered during the design, construction and operation of UHVDC transmission line. This issue is more prominent especially in UHVDC along with the voltage increasing [4].As metal attachments to transmission line, the distribution of surface electric gradient of fittings is within the scope of non-uniform field. Size of fittings determine if the fitting produce corona while it is based primarily on Peek's formula [5]. However, Peek's result should be further discussed about the applicability to large-size electrode and in three-dimensional electric field distribution situation: it is proposed by results of small-radius wires and concerning only two-dimension situation, while the field distribution such as rings is three-dimension and it is not suitable to describe the curvature only by radius of pipe or ring. Corona experiment and test method on fittings mainly focus on AC transmission line [6-10] and on DC transmission line are rarely mentioned. In order to research the relationship corona inception voltage and electrodes' size and shape, this paper presents a simple but typical experiment protocol which was conducted in National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, China) and confirms corona onset voltage of different samples. E-field is calculated according to the voltage in Ansoft FEM platform. The theory of secondary electron collapse suggests the form of formula about corona onset field strength. Based on it, formulas about large-sized cylinders' and rings' corona inception E-field are proposed, which would make a certain significance of further size design and calculation.

2. Experiment of Corona Test

2.1 Experiment Condition

Experiment has been conducted in the National Engineering Laboratory for Ultra High Voltage Engineering Technology (Kunming, China). The lab is located near Kunming, Yunnan Province, whose altitude is 2100m. The outdoor test site cover an area of 197m×103m. There is a door-frame in the field region with clearance distance of 70m ×70m, as Fig. 1 shows. Hanging height is adjustable between 0~60m. Capacity of DC generator is 1600kV/50mA with ripple factor ≤3%. It include capacity divider for voltage measurement with uncertainty ≤3%. The generator could fast switch polarity with conversion time ≤1 min.Silicon stack would cause radio interference while DC generator works. According to the standard for radio interference voltage (RIV) in IEC 61284:1997 [11], preparing the follow-up RIV test and eliminating the adverse effects for measurement, a trap and a coupling capacitor are installed between the DC generator and test samples to isolate the interference.

2.2 Experiment Method

From engineering view, negative problem need more attention because corona inception voltage in negative situation is lower than that in positive. Therefore the experiment only focuses on negative situation. Refer to IEC 61284 requirements for test for fittings of overhead lines, corona onset voltage was confirmed. Corona inception voltage usually refers to the voltage in which corona can be seen on the fittings. But light intensity of testing environment, human factors and other reasons lead to error existing during direct observation. UV released by corona provides methods and ideas for observe corona on transmission line and substation equipment. Taking advantage of UV imager accuracy in observation, test use Israeli Super B equipment with gain of 250 and auto-focus mode to measure onset voltage.Test voltage gradually rises until corona on the samples is observed and shall be held for a minimum of 5 min, recording this voltage as corona onset voltage of this sample.Corona onset characteristic is extremely sensitive to humidity. In order to guarantee accuracy, test should be conducted while outside weather conditions remain basically unchanged.

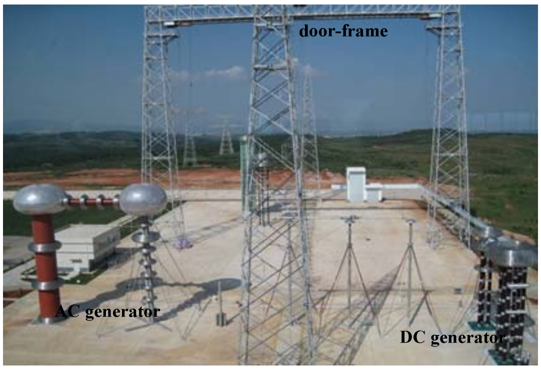

Fig. 1 Outdoor Test Site

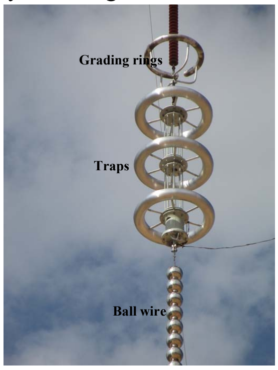

Fig. 2 Traps and Its Accessories

2.3 Experiment Arrangement

Symmetrically arrangement is more suitable and it is much more convenient for calculating and checking the results. So aluminum cylinder and rings are the master study objects. Field distribution of cylinders is approximate to wires. The diameters of these cylinders are as follows to supplement large-size electrode in two-dimension: 30mm, 60mm, 90mm and 120mm. The sizes of rings are: R550/Φ100, R286/Φ32, R275/Φ50, R270/Φ60, R270/Φ80, R410/Φ80, R400/Φ100, R400/Φ120, R360/Φ120, R510/Φ120 and R760/Φ120 in which R means the radius of the whole ring and □ means the radius of pipe in millimeter. Aluminum cylinder is horizontal hanged and the suspension height is 6m to the ground as shown in Fig.3. Corrugated hoses trap the drain line to avoid corona on power drain wire grading rings are arranged at both ends of cylinder whose radius is larger than cylinders to shield corona produced. Layout of aluminum ring arrangement should guarantee the uniformity of E-field distribution along the ring. A cylinder is arranged to the center of ring and hangs it, the same 6m height to the ground as shown in Fig.4. Analogously, the drain wire is shielded by the corrugated hoses.

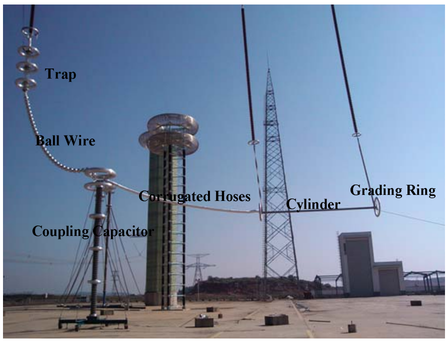

Fig. 3 Arrangement of Cylinder

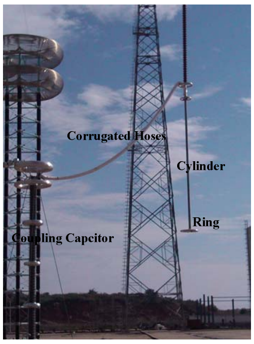

Fig. 4 Arrangement of Ring

3. Experiment Result

Corona onset voltage can be determined by the UV imager. When continuous discharge points appear in the photon counting box and the rate suddenly reached 10^3 or more from observation, the voltage applied to the fittings is the onset voltage. Single discharge point appeared on the cylinder and distributed randomly at low voltage levels while multiple points at high level. The same situation fits rings. Figures Fig. 5 to Fig. 8 are corona photos of cylinder and ring and Table. I is the onset voltage of them.

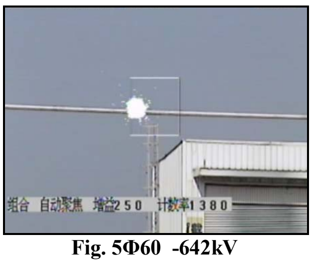

Fig. 5Φ60 -642kV

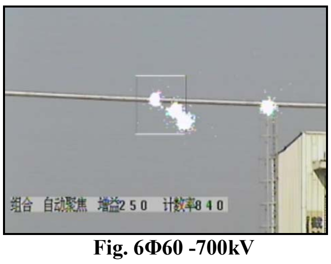

Fig. 6Φ60 -700kV

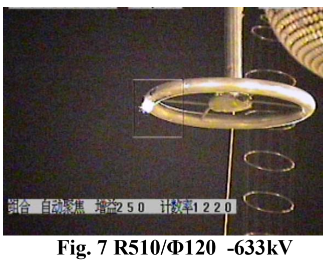

Fig. 7 R510/Φ120 -633kV

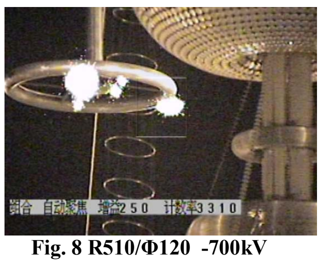

Fig. 8 R510/Φ120 -700kV

Table I Corona Onset Voltage

Size of Ring	Corona Onset Voltage	Size of Ring	Corona Onset Voltage	Corona Onset Voltage	Corona Onset Voltage
R286/Φ32	307	R400/Φ100	525	Φ150	710
R275/Φ50	335	R400/Φ120	540	Φ120	682
R270/Φ60	342	R510/Φ120	633	Φ90	595
R270/Φ80	360	R550/Φ100	690	Φ60	461
R340/Φ80	400	R760/Φ120	723		
R410/Φ80	471				

4. Analysis on Relationship of Corona Onset E-field and Electrodes' Size and Shape

Three-dimension models are constructed in Ansoft FEM platform to calculate the surface E-field at the moment corona produces, which do not concern space charge distort the field. As a comparison, onset field strength is calculated by Peek's formula. Curvature of cylinder is decided by its radius and that of rings is radius of pipe. Roughness coefficient m is set 0.8. Air density is 0.774 with average atmospheric pressure 0.791×10^5 MPa and average temperature 23 °C. Onset E-field of experiment and Peek's formula is shown in Fig. 9. Obviously, Peek's expression gives higher values than experimentally observed, which has been developed in the Schumann's measurement in 1923[12]. Actually Peek's result has some deviation when the radius is higher than 1 cm.

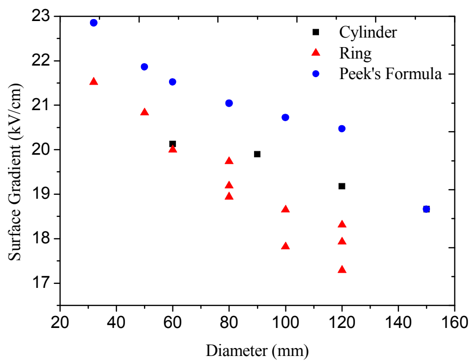

Fig. 9 Onset Gradient of Experiment and Peek's Formula

Onset surface field has a close relationship with curvature because a condensed air film at the surface of the conductor stores energy. The surface field must be raised above the actual breakdown gradient in order to store sufficient energy to cause breakdown at a distance which is determined by the value of radius *r*. Lowke's [13] research give the relationship between the gradient and radius based on secondary electron collapse, which verify the correctness of form of Peek's formula shown in (1).

$$E_c = E_0\delta\left[1+\frac{(\ln Q)^{1/2}}{(E_0/N_0)(\delta BN_0 r)^{1/2}}\right] \tag{1}$$

Following the above ideas the form of gradient and curvature is considered. The definition of curvature is key point mathematically. Curvature in two-dimension is radius of close circle, such that it is always *1/r* of a circle with radius *r*. But it cannot be defined like this in three-dimension space because the trends in different curved surface. Fig. 9 shows the distinct gradient of cylinder and ring with same radius of pipe. So cylinder and ring present separate situation in calculation and Peek's formula is not applicable to these two kinds of electrodes.

For the 2D surface embedded in Euclidean space R3, the intersection determined by this surface and another plane, which is decided by normal vector at one point and a tangent vector, is a line with a curvature. The curvature changes along with the tangent vector. As a consequence, there are maximum and minimum values, which are called principal curvature k_1 and k_2. k_1k_2 is Gaussian curvature and k_1+k_2 is Mean Curvature. Gaussian curvature of infinitely long cylinder is 0, while mean curvature is not suitable to describe the large-radius ring and Gaussian curvature is attempted to calculate the gradient. Without consideration of air density, fitting situation about radius and onset gradient in cylinder is shown in (2) and Fig.10 with fitting rate 0.99997. To rings, Gaussian curvature's 4th root is the basic variable and gradient is the dependable variable. Fitting situation is shown in (3) and Fig.11 with fitting rate 0.9956. Based on (1), (4) and (5) takes account of air density δ.

$$E = 14.42(1+\frac{0.8}{\sqrt{r}}) \tag{2}$$

$$E = 11.79\left(1+2.15\sqrt[4]{k_1k_2}\right) \tag{3}$$

$$E = 18.63\delta(1+\frac{0.8}{\sqrt{\delta r}}) \tag{4}$$

$$E = 18.63\delta(1+\frac{0.8}{\sqrt{\delta r}}) \tag{5}$$

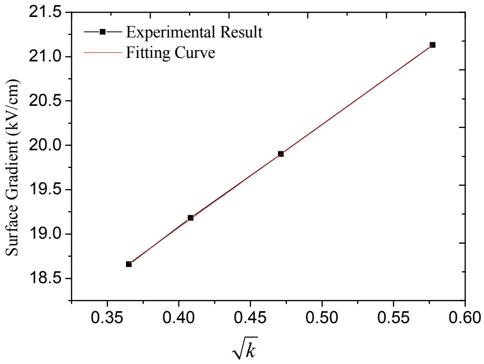

Fig. 10 Cylinders' Surface Gradient Fitting

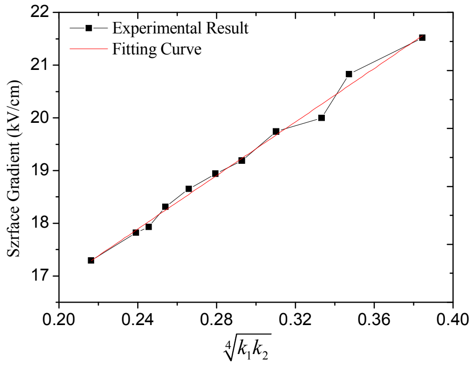

Fig. 11 Rings' Surface Gradient Fitting

5. Conclusion

Peek's formula is still in use during these past years, while which was proposed in 1911 for the first time, improved and published in 1929. It is based on the experimental result of small-radius wires and can accurately describe corona onset surface gradient in 2D field and small-sized electrodes. However, in 3D and large-sized situation, such as aluminum cylinders and grading rings on transmission line, its applicability needs further discussion. This paper presents experiment and calculation for this problem. Tests confirm the negative corona onset voltage of 4 kinds of cylinders and 11 kinds of rings. Without considering the electrode field distortion caused by space charge, calculation of onset surface gradient in Ansoft platform is conducted. The theory of secondary electron collapse suggests the form of formula about onset E-field approximate with Peek's formula. This conclusion provides fitting method about the relationship between gradient and curvature of electrodes. In 2D field, experimental results presents Peek's conclusion gives higher values for smooth aluminum cylinders with radius 30~75 mm. Fitting results possess that gradient has good positive linear correlation with radius' function $1/\sqrt{r}$. In 3D field, corona onset voltages are distinct for rings with same pipe radius but different whole-ring radius, and vice versa. They are all lower than calculation in Peek's formula in which *r* is pipe radius. Fitting uses Gaussian curvature instead of 2D plane curvature and more accurately describes onset characteristics about rings. These two empirical formulas match with experimental results better and can be applied to forecast onset surface gradient within the range of samples' size in the test.

6. References

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