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RELIEF OF AN ELECTRIC FIELD VIA A CONE STRUCTURE

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Abstract

A terminated power cable is typically applied not only for terminated ends but also to connect two or more cables. The electric field inside the insulation layer becomes disturbed when a coaxial cable structure is broken and the electric stress increases near the ground edge. A structure of cone type is a major method to alter the lines of equi- potential and to relieve the electric stress around the ground. The dimensions of the cone depend on the cable structure. In this paper we introduce a way to calculate the displacement of equi-potential lines when a cone is brought into a coaxial cable, RG220, and then determine a suitable angle and length of the cone, which are important factors to withstand tens of kV and even greater. The corresponding high-voltage tests are also presented here.

INTRODUCTION

Current pulses are transmitted for the purpose of injection and extraction kickers to kick the beam from the BR to the BTS and from the BR to the SR, as Fig.1 shows. The repetition rate is 3 Hz; this width of the current pulse is about 1600 ns with the rising and falling times smaller than 400 ns [1]. The booster kickers are designed as a type in vacuum; the end of the high-voltage coaxial cable is plugged into a high-voltage feedthrough, Fig. 2 [2]. This coaxial cable has characteristic impedance 50 Ω; for the extraction kicker, the maximum current inside is 573 A that induces about 28.65 kV spontaneously. For considerations of safety and future upgrade, a cable of coaxial type RG220 is used; parameters corresponding to this RG220 are depicted in Fig. 3 [3].

When the coaxial structure becomes destroyed, the electric field inside the dielectric layer fails to maintain a uniform distribution; the electric field easily concentrates at a site at which the ground ends, presented in Fig. 4. As the electric stress would deteriorate the quality of the power cable and result in a machine shutdown, it is important to treat the distribution of electric field and to avoid stress concentrating around the ground edge. A stress-relief cone is introduced here to alleviate the stress becoming centralized. The next section explains the theory of the electric field and why a cone structure could affect the distribution of electric field to achieve a decreased localized stress.

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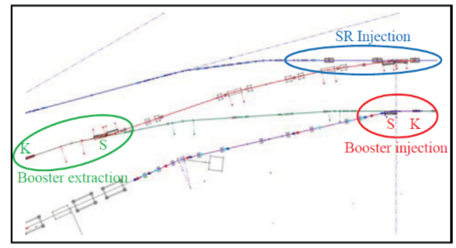

Figure 1: TPS injection and extraction skim.

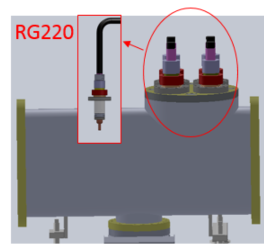

Figure 2: RG220 and high-voltage feedthrough mounted on a kicker chamber.

Figure 3: Structure of the RG220 coaxial cable.

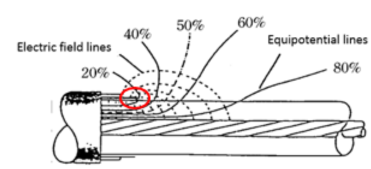

Figure 4: Electric stress takes place around the ground cutting plane.

BASIC CONCEPT OF A HV CABLE

To begin to calculate the voltage distribution inside a high-voltage cable, this coaxial cable can be viewed as the same dielectric material in a series of varied thickness; each segment sustains a different voltage but carries the same amount of charge and current of equal magnitude. As the applied voltage, V_{apply}, is known, one can deduce the corresponding voltages when the position parameter, r, is known. Those related equations are listed below. Large voltage drops occur near a conductor pin. With RG220 for example, 90 % of the applied voltage occurs at r_1=3.74 mm and 10 % at r_2=10.23 mm. If the coaxial structure is not disturbed, the electric field is greater near the conductor pin than in the ground area, but when the coaxial structure no longer holds, the electric field tends to accumulate near the ground end. Figure 5 and Table 1 present the simulation results.

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$$\frac{C_i}{l} = \frac{2\pi\varepsilon}{ln(\frac{D_i}{d_i})} \qquad (eq.1)$$

$$(C_{apply}V_{apply} = C_iV_i \qquad (eq.2)$$

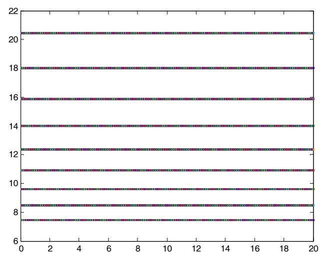

Figure 5: 10 % (top) to 90 % (bottom) voltage drop diagram for RG220.

Table 1: Fraction of Applied Voltage and Its Corresponding Positions

ID=6.6mm/ OD=23.2 mm	
90%	7.48 mm
80%	8.49 mm
70%	9.62 mm
60%	10.91 mm
50%	12.37 mm
40%	14.03 mm
30%	15.91 mm
20%	18.04 mm
10%	20.46 mm

CONE STRUCTURE

Adding a cone to a coaxial cable can affect the overall voltage distribution and hence alter the distribution of electric field so as to avoid a localized electric stress. The principal idea of a cone is to increase the dielectric thickness; as the outer diameter becomes larger than the original one, the separation of lines of equipotential also increases. A cone bends the equipotential lines such that one can control the slope of a cone to relieve a suitable electric stress, described in Fig. 6. Figure 7 compares two conditions, with and without a cone of tilt 45°. The gap between the two potentials becomes enlarged as the cone length increases; the steepness depends on the geometry of the cone. The slope of each potential line is variable; a line of small potential far from the conductor pin increases more severely than others near the conductor pin. This method slows the concentration of electric stress by a geometric effect; another method involves pasting a material of large κ that mitigates the variation of potential inside that material [4]. The angle and length of a cone are determined on considering the operating voltage and safety margin. A voltage drop occurs not only inside the insulation layer but also along the insulation surface. In the termination of the cable, a greater creepage distance is better to hinder flash over. Figure 8 shows that increasing the creepage distance would improve the extent of voltage drop along the insulation surface [5]. The separation between two potentials is suggested to be less than 700 V/mm on the air side. For this case, angle 45° and a bevel face of length 9 mm are proposed; see Fig. 9. The cone is made of silicone with 60° hardness. The cone must surround the insulation layer tightly; its diameter is set to be 0.02-0.05 mm smaller than the matching part.

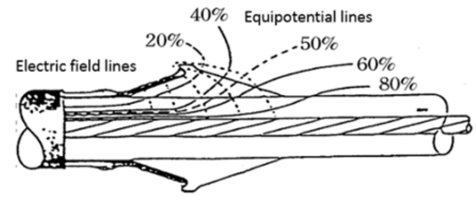

Figure 6: Cone function for stress relief.

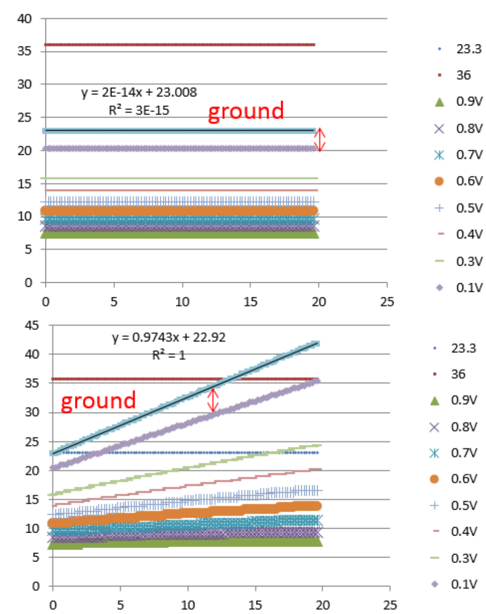

Figure 7: Lines of equipotential of two cases; upper: normal case; lower: 45° stress relief cone.

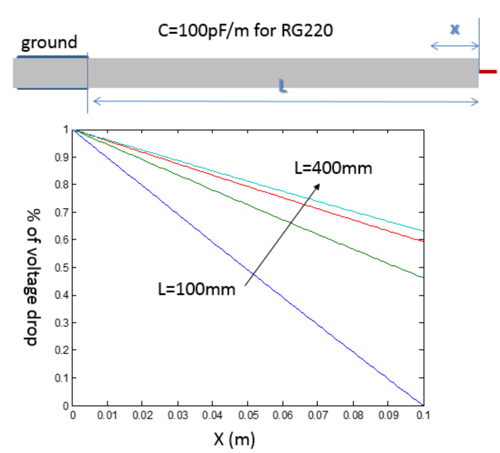

Figure 8: Voltage drop along the insulation surface (PE material).

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Figure 9: Cone of stress relief compatible with a RG220 structure.

PROCEDURES TO TERMINATE A HV CABLE

1. Remove the jacket to a marked position.
2. Trim the copper braid to the marked position.
3. Uncover the insulation to a length appropriate for a terminal.
4. Stretch off the semiconductor layer and leave a sufficient distance for creepage (depending on the applied voltage).
5. Use sand paper to polish the insulation surface (#800, #1000, #1200, #1500, #2000).
6. Assemble the silicone stress-relief cone and other kits onto the RG220.
7. Measure the relative positions of all parts.

When making the cable terminations, mind the relative position and the surface condition of the insulation layer. The ability to withstand a high voltage relies on the quality of the insulation layer and the precision of assembly. Misalignment would result in a worse situation than a case not been treated to the termination process. A power cable is typically composed of a conductor pin, an insulation layer, a shielding layer, a copper braid and a jacket. The work of termination involves substituting a new insulator layer, new shielding and a new ground to the sliced one. Make an effort to let the air gap die away between two mating surfaces because an air gap would degrade the capability of withstanding a voltage. Steps 1 to 6 are presented in Fig. 10.

Figure 10: Steps to prepare a cable termination: upper, steps 1 to 3 (right); lower, steps 4 to 6 (right).

RESULTS OF HIGH-VOLTAGE TESTS

A test of high-voltage DC insulation begins from 10 kV to 35 kV; each step is 5 kV and the testing voltage less than 20 kV is held for 30 s; the interval for other voltage testing remains 1 min. A tester to withstand a DC voltage (MUSASHI 3802) was used; Table 2 shows the test results. Another way to certify the insulation quality is to measure the current magnitude at durations 10, 60 and 600 s. If the I_{600}/I_{60} ratio is less than 1, the insulation quality is satisfactory, implying that the leakage current does not increase with testing time; it is a norm to judge the insulation quality of a power cable.

Table 2: Results of Tests Withstanding HV DC

HV DC insulation test	
10 kV for 30 s	0.10 μA
15 kV for 30 s	0.15 μA
20 kV for 1 min	0.20 μA
25 kV for 1 min	0.22 μA
30 kV for 1 min	0.29 μA
35 kV for 1 min	0.86 μA

35 kV	
10 s	0.8 μA
30 s	0.5 μA
60 s	0.6 μA
600 s	0.4 μA

CONCLUSION

In termination of a high-voltage cable, the distance of surface insulation and the thickness of the dielectric layer are two major parameters. A 15-kV power cable is designed typically to have a PE dielectric layer of thickness at least 4 mm; when terminating a cable, remember to leave a sufficient distance of insulation surface. For example, reserving an insulation distance more than 100 mm for a 15-kV power cable is required. A cone to relieve stress is generally used because silicone rubber is easily manufactured and cheap. A bevel 40-60^{o} of a cone is recommended; if a power cable is operated under poor conditions, one should consider what kinds of materials are suitable for cable termination. For a greater voltage, 60 kV, in pulsed operation, a stress-relief cone of this type must have its outer diameter widened to 40 mm with the same steepness of bevel. It is convenient for one to use cones made of silicone rubber to alleviate electric field stress. When RG220 cable ends are plugged into a high-voltage feedthrough, some insulating grease is wiped on the insulation surface of the RG220 to compensate the air gap between the RG220 and the feedthrough.

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