Shape Optimization of the Spacer of 220 kV DC GIL

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ABSTRACT

Both experimental and numerical studies demonstrate that electric field formation mechanisms and insulation behavior at SF6/epoxy interface are substantially different for ac and dc voltage excitations. In this paper, based on fixed dc GIL dimensions and spacer-electrode joints, three types of alumina filled epoxy resin spacers with different shapes were designed with FEA software in order to find a way to provide a reliable spacer performance in HVDC gas insulated systems. The generalized design criteria for dc spacers were put forward. Results show that shape design of spacer in dc GIL is distinct from that in ac GIL. Moreover, distinctions between dc spacer and ac one in shape design are proposed, which could be beneficial for practical use of dc GIL.

INTRODUCTION

Although gas insulated transmission lines (GIL) have been widely used in many special environments, it's always operated under ac voltage [1-4]. The applications of dc GIL have been scarce so far due to surface charge accumulation and metal particle contaminations that rarely happen in ac GIL [5-7].

Many researches have been carried out to solve the problem of HVDC SF6 apparatus design. Studies reported in [8] reveal that in order to reduce accumulated surface charges in dc GIS, \( \eta \) which is the adjustment coefficient accounting for the reduction in spacer surface strength during the transition period should be increased remarkably. \( \eta \) satisfies the inequality of \( E_{s\text{max}} \leq \lambda \cdot \eta \cdot E_{g\text{max}} \). \( E_{s\text{max}} \) is the maximum field strength along surface of the solid insulator. \( E_{g\text{max}} \) is the maximum field strength in SF6 gas. \( \lambda \) is a margin to correct for statistical spread of discharge voltages on the spacer surface. Jiangbo Jia from Xi'an Jiaotong University studied the influence of metal conducting particles on the spacer under dc voltage in SF6 gas. Results show that the electrostatic force acting on the particle is reduced when the included angle between spacer side surface and the grounded electrode is obtuse. So the probability of particle levitating or clinging onto spacer surface is decreased and the insulation reliability of GIS is improved [9].

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On the basis of the previous studies on HVDC SF6 apparatus design, this paper addresses the shape optimization of alumina filled epoxy resin spacers in 220 kV dc GIL. Moreover, distinctions between dc spacer and ac one in shape design are proposed.

**ASSEMBLY DRAWING AND SIMPLIFIED MODEL OF 220 KV DC GIL**

The assembly drawing of 220 kV dc GIL is as shown in Fig. 1. The spacer shown in Fig. 1 is widely used in 220 kV ac GIL. Because electric field distribution along spacer surface under dc voltage is different from that under ac voltage, the shape of spacer that behaves well under ac voltage needs to be optimized in dc GIL.

As compared to ac SF6 apparatus, specific insulation behavior in HVDC GIL requires significant enlargement in the coordinating margin between spacer surface and SF6 gap insulation levels. However, we still should attempt to find a reasonable alternative in order to avoid an undesirable reduction in dc operating voltage or GIL dimensions enlarging. Thus, the shape optimization of spacers is based on the fixed inner diameter of enclosure, outer diameter of HV electrode and spacer-electrode joints. The enclosure is 320 mm in inner diameter and HV electrode is 92 mm in outer diameter. The axial distance of the spacer is 193 mm.

The dc electric field distribution of the spacer is dominated by conductivity. According to studies, alumina filled epoxy resin spacer is one of the best insulating materials in HVDC GIL. The recommended physical parameters of alumina filled epoxy resin in HVDC apparatus are as follows. The values of volume conductivity and surface conductivity are $4.42 \times 10^{-16}$ S/cm and $7.41 \times 10^{-14}$ S respectively, while relative dielectric strength is no more than 5. Therefore, the calculation is on the basis of alumina filled epoxy resin with these parameters.

![Figure 1. Assembly drawing of 220 kV dc GIL.](image1)

The simplified model of 220 kV dc GIL is shown in Fig. 2. It's necessary to simplify the assembly drawing for calculation with finite element analysis (FEA) software. Due to axial symmetry of dc GIL two-dimensional model is used for calculation.

![Figure 2. Simplified model of 220 kV dc GIL.](image2)
SHAPE DESIGN OF ALUMINA FILLED EPOXY RESIN SPACER

The attention points of spacer's shape design are as follows. Firstly, field strength in the triple junction area should be reduced as much as possible. Secondly, electric field lines flowing into or out of spacer surface should be decreased. Thirdly, for practical spacers made of standard epoxy resins and working at normal operating SF6 pressures, it could be recommended that $EN<1 \text{ MV/m}$, $ET<3.5\text{MV/m}$, where $EN$ is the maximum normal components of initial field strength along spacer surface and $ET$ is the maximum tangential components of initial field strength along spacer surface [10]. Fourthly, the whole $E_\tau$ has much to do with creepage distance. The integral of $E_\tau$ of every point along spacer surface approximates to the value of applied voltage. Meanwhile, the whole $E_n$ has much to do with inclination angle of spacers. If the tangent line of one point along spacer surface tends to be perpendicular to equipotential line of this point, $E_n$ of this point is getting smaller. $E$ is the field strength along spacer surface, so $E_\tau$ is the tangential component of field strength along spacer surface and $E_n$ is the normal component of field strength along spacer surface.

Alumina filled epoxy resin spacers with three different shapes are shown in Fig. 3, and spacer A of that shape is widely used in 220 kV ac GIL.

![Figure 3. Alumina filled epoxy resin spacers with three different shapes.](image)

ELECTRIC FIELD DISTRIBUTION OF ALUMINA FILLED EPOXY RESIN SPACER

Equipotential line distribution of spacers with three different shapes under 220 kV dc voltage is shown in Fig. 4.

![Figure 4. Equipotential line distribution of spacers with three different shapes under 220 kV dc voltage.](image)
From Fig. 4, it can be seen that for the area enclosed by concave surface of spacer and HV electrode, equipotential lines in the vicinity of spacer A are the most concentrated among these three types of spacers. For the area enclosed by convex surface of spacer and enclosure, equipotential lines in the vicinity of spacer B are the most concentrated. Meanwhile, the distance between convex surface of spacer B and enclosure surface is quite short. Moreover, electric field strength in the middle part of convex surface of spacer B is quite high after long-term dc voltage application. Therefore, partial discharge even flashover is prone to occur due to electric field distortion between convex surface of spacer B and enclosure surface. The electric field distribution along the surface of spacer C is moderate compared to other two types of spacers.

Electric field distribution comparison among spacers with three different shapes is shown in Fig. 5.

From Fig. 5, $E_n$ along concave surface of spacer A is much higher than that of spacer B in the vicinity of HV electrode. Meanwhile, $E_n$ along concave surface of spacer A is much lower than that of spacer B in the vicinity of enclosure, so are $E_n$ along convex surface of these two spacers. Moreover, $E_t$ along surface of these two types of spacers are both low in the vicinity of enclosure. Therefore, $E_t$ along concave surface of spacer A is much lower than that of spacer B in the vicinity of enclosure, so are $E_t$ along convex surface of these two spacers. The values of $E_n$ along concave surface of spacer C are basically lower than 1 MV/m, which meets the requirements of shape design for reduction of surface charge accumulation. The distribution of normal components of electric field along convex surface of spacer C is similar to that of spacer A and obviously better than that of spacer B. The distribution of tangential components of electric field along both sides of surface of spacer C is optimum among three types of spacers.
The values of $E_t$ along both sides of surface of all types of spacers aren’t more than 3.5 MV/m. However, the values of $E_n$ along surface of spacer A and B obviously exceed 1 MV/m in many points, which can lead to serious charge accumulation along the spacer surface after long-term dc voltage application [11].

These three types of spacers are designed on the basis of the same inner diameter of enclosure, outer diameter of HV electrode and spacer-electrode joints. The shape of spacer B is originally designed to amend disadvantages of the shape of spacer A. However, design results shows that general field strength along surface of spacer B is quite high in the vicinity of enclosure, which is opposite to common tendency of gradual reduction of field strength along spacer surface from HV electrode to enclosure. This distinction does harm for control of surface charge accumulation and metal particles. The trade-off of shape design is proposed, i.e. spacer C. The electric field distribution along surface of spacer C is better than that of previous spacers regardless of concave or convex surface. In all, it’s comparatively the optimum plan to choose spacer C as the final spacer shape in 220 kV dc GIL.

Spacer C is the optimum spacer in 220 kV dc GIL and Spacer A is the optimum spacer in 220 kV ac GIL. Thus shape design of spacer in dc GIL is distinct from that in ac GIL.

CONCLUSION

If dc GIL dimensions compared to ac ones aren't enlarged and spacer-electrode joints are unchanged, then shape design of dc spacer should be adjusted compared to ac spacer. On one hand, creepage distance along surface of dc spacers should be slightly increased. On the other hand, the distance between concave surface of spacer and HV electrode surface should be obviously increased in the vicinity of HV electrode, while the distance between convex surface of spacer and enclosure surface should not be decreased a lot in the vicinity of enclosure.

REFERENCES