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Novel HVDC Spacers in GIS/GIL by Adaptively Controlling Surface Charges - Insulation Compounding Scheme

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***Abstract*—The spacer is a challenging part of high voltage direct current (HVDC) gas-insulated switchgear (GIS) and gasinsulated transmission lines (GILs). Based on the charge adaptively controlling strategy verified by our previously published papers, this paper serves as an important step towards further industrialization of charge adaptively controlling spacers. The insulation compounding scheme based on previous researches is focused in this paper. Spacers composed of insulating regions and charge adaptive control regions with different mass fractions of nonlinear materials were prepared. The mechanical properties, as well as the DC and AC surface flashover performance of these spacers were investigated. The results show that the DC surface flashover voltage is greatly reduced using spacers with a pure insulating region and with a doped charge adaptive region. As the doping ratio of the nonlinear material in the insulating region increases, the surface flashover voltage increases remarkably. However, the mechanical stress decreases dramatically when the mass ratio of nonlinear material is beyond 35%. The different doping ratios of nonlinear materials does not make a difference in AC surface flashover voltage. However, these surface flashover values obtained by bowl shaped spacers are much more stable and higher than that of the values measured from traditional cone type spacers at AC. The results in this paper can be a key step and are helpful in further determining the preferred option of the industrial spacer that can be potentially used in HVDC GIS/GILs. Meanwhile, based on the advanced performance, the idea of the novel bowl shape has potentially possibility in the application field of AC GIS/GILs.**

Keywords*—*HVDC GIL, insulators, epoxy resins, surface charge accumulation, surface flashover, nonlinear material

I. Introduction

Spacers operating with DC application must face the problem of surface charge accumulation, which is of vital importance since surface charges accumulating on the spacer surface distort local electric field and may be a potential trigger of surface flashover [1]. There has been many studies in recent decades regarding the surface charge origin and suitable solutions to decay these charges [2, 3]. In a recently published paper, a field dependence theory is introduced that determines the origin of surface charges according to the electric field range [4]. It is illustrated that most of the surface charges are from the component of the volume conduction current in moderate electric field, while charges of hetero polarity may occur if there were local defects on the surface of the enclosure [4]. Meanwhile, a lot of efforts have been paid by researchers to find the most suitable solution for the decay of surface charges [5-7]. However, although we can speculate the origin of these charges, still it is quite difficult to stop them or even modify them without affecting the other insulating properties, i.e. leakage current due to a surface modification to create a more conductive surface layer [7, 8].

In our previously published series papers [9-11], a novel designed HVDC model spacer (charge adaptive control spacer, CACS) used in GIS/GILs was introduced that is based on the concept of adaptively controlling surface charges. In case of a CACS, charges from volume or from gas are controlled by the electric field lines and accumulate on the surface of the charge adaptive region (CAR). The doping of nonlinear material in CAR ensures the limitation of surface charge amount on the surface of CAR. As a consequence, we do not care where the charge comes from or how much amount the charge is. As long as the existing charge amount exceeds a certain value, the CAR adaptively dissipates charges. Meanwhile, this spacer can be prepared by one-shot molding without subsequent surface treatment procedures. In addition, the leakage current can be well controlled under a suitable electric field [9].

In this paper, we mainly focus on the insulation compounding scheme based on previous ideas. The mechanical property as well as AC and DC surface flashover of spacers with different doping ratio are tested. The results in this paper can be a key step and are helpful in further determining the preferred option of the industrial spacer that can be potentially used in HVDC GIS/GILs.

II. EXPERIMENTAL DESCRIPTION

TABLE I. The mass ratio of the fillers in the insulation region and in the charge adaptive control region.

Sample	Mass ratio (Al_2O_3:SiC)	
	Insulation region	**Charge decay region**
B1 _0% _0%	Al_2O_3:SiC =330:0	Al_2O_3:SiC =330:0
B2 _0% _30%	Al_2O_3:SiC =330:0	Al_2O_3:SiC =231:99
B3_10%_25%	Al_2O_3:SiC =297:33	Al_2O_3:SiC =247:83
B4_15%_35%	Al_2O_3:SiC =280:50	Al_2O_3:SiC =214:116
B5_20%_30%	Al_2O_3:SiC =264:66	Al_2O_3:SiC =231:99
B6_25%_35%	Al_2O_3:SiC =247:83	Al_2O_3:SiC =214:116

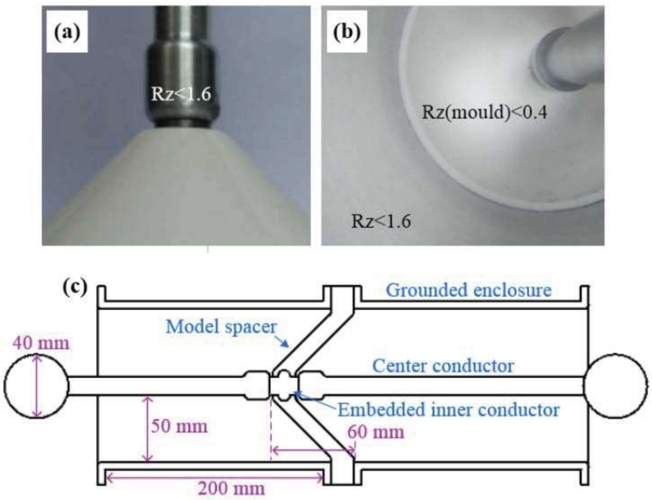

Fig. 1. Photographs showing a magnified view of the experimental sample model (panels (a) and (b)). Panel (c) shows a diagram of the installed spacer in the system.

The manufacturing methods and the curing process of experimental samples were the same as for real-sized industrial spacers, and the manufacturing process details can be referred to our previous published articles [9-11]. For experimental bowl shaped spacers, the fillers used in the insulation region and the charge decay region were prepared separately, and the mass ratio of the fillers in the two regions can be found in Table 1.

TABLE II. Experimental methods.

Test item	Details
Mechanical test	Water pressure test [11].
DC surface flashover	Step voltage application: To apply a DC voltage to -240 kV by - 3 kV per second for 30 min and then increase the DC voltage by about - 1 kV per second to - 250 kV. Repeat this process until the surface flashover occurs [10].
AC surface flashover	To increase the AC voltage by about -1 kV per second to measure the surface flashover voltage [10].

During the experiment, the spacer to be tested was fixed into a model enclosure (shown in Figure 1) and this model was placed inside a 220kV GIL [10]. The details of experimental tests can be found in Table 2. For the pure spacers, we changed a new one after a DC breakdown test, while the doped spacers were multiply used: after DC test, we modified the surface to remove the traces and surface charges from surface flashover and reused this sample. In the AC test, the tested samples were dropped after each flashover test since the samples would be seriously damaged due to a high power of the AC energy source.

III. RESULTS

A. Mechanical test

In this test, only the pressure from the concave side is tested since it has already been verified that the pressure from the convex side is much higher compared with that of the cone type spacer tested in the same condition in our previous paper [11]. Figure 2 shows (a) the experimental setup of water pressure test as well as (b) the pictures of spacers after this destructive test. It can be found that the breakdown region locates at the edge of the spacer near the flange, which is similar compared with that of the cone type spacer [11]. It is interesting to note that the connection section between the insulation region and the charge adaptive control region was previously supposed to be the weakest point since this section was formed between two curing stages with a time interval of 4 hours in between. However, this section shows good property in CACS.

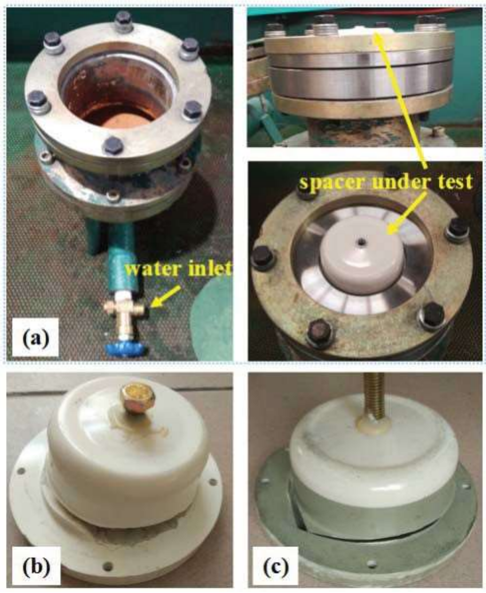

Fig. 2. (a) The experimental setup of water pressure test as well as (b) the pictures of spacers after the destructive test.

For samples with lower doping ratio of nonlinear materials, the mechanical breakdown strength shows almost the same values. The breakdown strength was slightly reduced only in samples with high doping ratios, i.e. B5_25%_35%. This result can be understood since the high doping ratio results in a viscous mixed solution during the manufacturing process. This would result in a dispersion that is not evenly distributed. Meanwhile, the local strength could occur inside the volume, which may lead to a decrease in mechanical test.

In addition, the mechanical strength of bowl shaped spacer without doping of nonlinear materials and with lower doping ratio is similar, with the breaking strength ranging from 7 MPa to 8 MPa. To note that the shape of these spacers is modified compared from that of the cone type spacer and the data obtained in this paper can only be used for contrast between bowl shaped samples with different doping ratios. Due to the size effect and the change of local thickness, the conclusions of this paper are difficult to be referenced when large-sized spacers are manufactured for destructive tests.

B. Surface flashover test

Figure 3 shows the DC surface flashover test results of experimental samples. It can be found that the doping of nonlinear material can affect the surface flashover voltage. While it is not always the case that the doping of nonlinear material can increase the surface flashover voltage. For sample B2, i.e. samples without doping of nonlinear material in the dielectric region, the surface flashover voltage shows the worst values which are less than 180 kV. This value is lower compared with pure samples B1, whose surface flashover voltage values ranges from 270 to 280. When the insulation region and the charge adaptive control region are both doped with nonlinear material, the surface flashover can be increased. However, only when the doping ratio of the insulation region increases more than 15% can the surface flashover voltage be higher than 300 kV. The DC surface flashover voltage of tested spacers can be stabilized at 310±5 kV (more than about 10% compared with that of the traditional cone type spacer [10]), when the mass fraction of nonlinear materials doped in the insulating region and the charge adaptive region are 20% and 30%, respectively. It is experimentally verified that samples with the optimum doping ratio are B5_20_30.

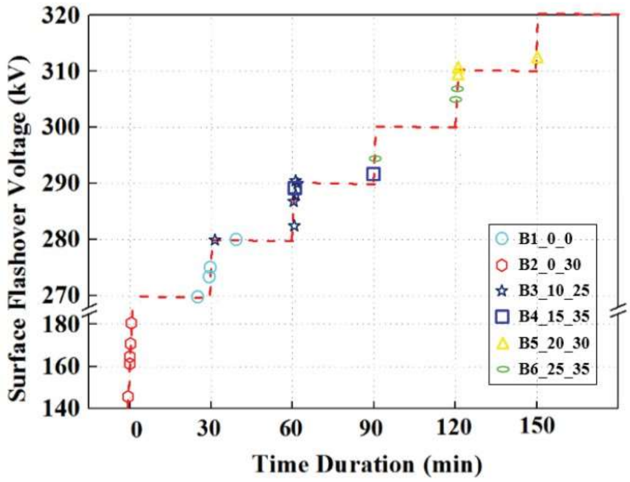

Fig. 3. DC surface flashover test results of experimental samples.

For the AC surface flashover test, the results of the samples being tested are similar, with the values ranging from 200 kV to 230 kV which can also be found in our previous researches [10]. Figure 4 shows photos of samples after AC surface flashover test. It can be found that most of the surface flashover arcs occur at the concave surface side. This phenomenon is different compared with that of samples after DC surface flashover test [9]. However, it is interesting to note that for samples that are doped with nonlinear materials, although there is not much differences in the flashover voltage data compared with that of the pure samples, the breakdown traces show quite different marks. The breakdown traces always develop from the conductor and through the volume of the charge adaptive region or the interface between the dielectric region and the charge adaptive region, shown in Figure 4 (c) and (d). This founding prompted us to think about the feasibility of the modification using an insulating barrier inside the volume of the spacer to further increase the AC breakdown voltage. Relative researches are being performed in our lab.

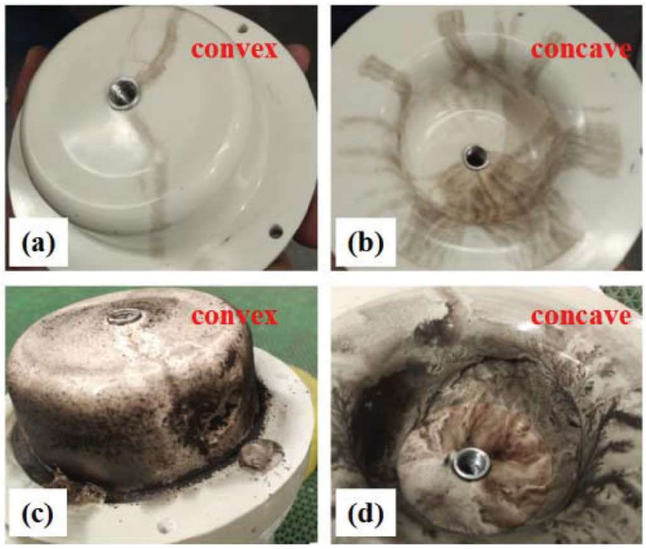

Fig. 4. Photos of samples after AC flashover test. (a), (b) are pure spacers after AC surface flashover test and (c), (d) are samples doped with nonlinear materials after AC flashover test.

IV. Discussion

The doping of nonlinear material dramatically affects the DC electrical property of the bowl shaped spacer. It can be found in figure 5 that the electric field of the Sample_0_30 and the Sample_10_25 show similar curves with a mutation at the interface of the spacer and with a higher value near the HV conductor. This is because the nonlinear property of epoxy doped with 10% mess ratio of SiC is not obvious. Meanwhile, the Sample_0_30 shows the worst performance in the DC surface flashover test. This is due to the high electric field strength in the triple junction near the high voltage electrode. However, for sample with a doping ratio of more than 15% in the insulation region, the doping of nonlinear particles can introduce nonlinear property at high electric field near the high voltage conductor. As consequence, the DC surface flashover values of the Sample_20_30 and Sample_25_35 are higher than that of the Sample_15_30.

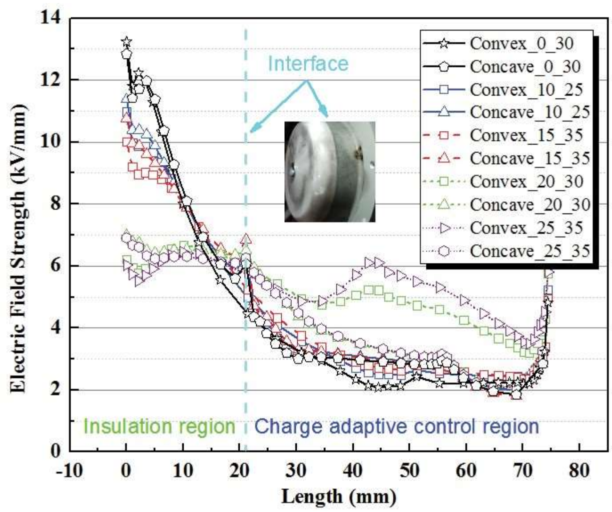

Fig. 5. The electric field strength of the bowl shaped spacer under application of 250 kV.

The DC surface flashover voltage of the pure sample is higher compared with that of Sample_0_30. This is due to the reason that most of the voltage potential drops at the charge adaptive control region for Sample_0_30, resulting in a high electric field near the triple junction at the high voltage conductor, as shown in figure 5. Meanwhile, the electric field mutation in the interface could also excite a discharge activity which introduces more charges to be accumulated on the spacer surface. When the doping ratio of the nonlinear material increases up to 20 % for the insulation region and for the charge adaptive control region, the electric field near the high voltage conductor and the interface region are controlled automatically due to changing of the conductivity. Meanwhile, the conductivity of the charge adaptive control region is increased when charges accumulate on the surface of the charge adaptive control region. This increase can accelerate the decay rate of surface charges and decrease the surface charge amount in this region. As a result, Sample_20_30 and Sample_25_35 show higher DC surface flashover performance. However, due to a large increasing of leakage current, Sample_25_35 may not be a suitable option to be a model in the manufacturing enlarged spacers.

V. CONCLUSION

Bowl type spacers with different doping ratio of nonlinear material were prepared and AC and DC performance is tested as well as mechanical withstand experiment is performed. The effect of surface charges on surface flashover phenomenon was discussed. The conclusions can be found as follows:

(1) There is not much differences between the mechanical strength property of experimental samples except for B6_25%_35%. The decrease of mechanical property of B6_25%_35% is due to the internal stress concentration.

(2) The DC surface flashover voltage of tested spacers can be stabilized at 310±5 kV (more than about 10% compared with that of the traditional cone type spacer), when the mass fraction of nonlinear materials doped in the insulating region and the charge adaptive region are 20% and 30%, respectively. It is experimentally verified that samples with the optimum doping ratio are B5_20_30.

(3) Based on the AC surface flashover test results and the breakdown trace found in the spacer, the doping of nonlinear material in the bowl type spacer could has potentially possibility to increase the insulation level in the application field of AC GIS/GILs.

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