Design of Solid/Gas Composite Insulation System with Embedded Electrode

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ABSTRACT

Solid insulated switchgear (SIS) has been developed as a substitution for sulfur hexafluoride gas insulated switchgears in the medium voltage class. Its main circuit including a vacuum interrupter is coated with epoxy resin. An embedded electrode was employed in order to enhance the surface insulation performance for further miniaturization and higher stress design. In the previous studies, the surface insulation performance was examined by using a model electrode system which modified the electrode system of the moving part of SIS and the estimation method of the surface breakdown voltage was proposed. In addition, the simulation of the surface breakdown characteristics of a model electrode system was conducted and a design method was proposed. In the present study, the insulation performance of the solid part was taken into account and the insulation design was conducted using the proposed design method. The "equivalent insulation distance" was introduced and the partial discharge inception field strength was also taken into account. The insulation design was done for 22, 33 and 77 kV systems and the values of the design parameters were provided. In addition, it was found that two different types of the design concepts were available.

Index Terms — **composite insulation, insulation design, switchgear**

1 INTRODUCTION

IN the medium voltage class, most of the switchgear is the cubicle-type low pressure sulfur hexafluoride (SF_6) gas insulated switchgear (C-GIS). SF_6 gas has the excellent insulation performance. However, it is designated as one of the targets of emission control due to its high global warming coefficient. For that reason, attention has been paid to the substitution for the SF_6 gas insulated switchgear. A lot of research has been done and several types of the SF_6 free switchgear have been proposed [1-3].

A solid insulated switchgear (SIS), in which main circuit including a vacuum interrupter are coated with epoxy resin, has been developed as one of the substitution for SF_6 gas insulated switchgears in the medium voltage class [2]. Several research has been done on the solid insulation material and higher insulation material has been developed [4,5]. However, improvement of the insulation performance of the solid/gas composite insulation system is required for the development of higher stress and compact design.

Under the situation mentioned above, the authors investigated the insulation performance of the solid/gas composite insulation system. In the previous study [6], an embedded electrode was employed and the effect of the embedded electrode on the insulation performance was investigated. The authors also investigated the estimation of the surface breakdown voltage and an estimation method was proposed. Furthermore, the authors performed the simulation of the surface insulation characteristics based on the estimation reported previously [7], and proposed a method to design the surface insulation [8].

In the present study, the insulation of the solid part was examined and the total insulation design was conducted using the developed design method for the surface insulation. The insulation design was done for a model of insulation system with embedded electrode, and for three voltage classes of 22, 33 and 77 kV. In addition, the partial discharge inception field strength was also taken into account.

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2 TEST VOLTAGE AND REQUIREMENTS FOR INSULATION DESIGN

Table 1 shows the requirement for each insulation part.

Table 1. Requirements for insulation design.

Insulation part	Item	Requirement
Solid phase	Breakdown	Withstand test voltage (ac and impulse)
	Life against treeing	More than 30 years
Gas phase (including surface)	Breakdown	Withstand test voltage (ac and impulse)
	Partial discharge (PD)	No PD under operation voltage

The insulation system is required to withstand the test voltage. Therefore, both parts of the solid insulation (epoxy resin) and the gas insulation (air including the surface) should withstand the test voltages of AC and impulse.

The solid insulation part is also required to withstand against treeing for more than 30 years. The criterion is decided from the V-t characteristics obtained by acceleration tests, and from other field experiences.

In the gas phase, the condition of no partial discharge (PD) under the operation voltage is also required. The partial discharge on the surface deteriorates the organic insulation material. The deterioration is the long term phenomenon and the most likely cause is the partial discharge under operation voltage. The partial discharge may also cause the charge accumulation, which could lead to the unexpected faults. Therefore, the maximum field strength in the gas phase including the surface should be lower than the PD inception field strength under the operation voltage.

Table 2 shows the test voltage for the insulation of 22, 33 and 77 kV classes. The frequency of ac voltage is 50 or 60 Hz. The impulse voltage is a lightning impulse voltage with the standard lightning impulse waveform of 1.2/50 μs.

Table 2. Test voltage.

Voltage class (rated voltage)	Test voltage	
	AC	Impulse
22 kV	50 kVrms (70.71 kVp)	125 kV
33 kV	70 kVrms (98.99 kVp)	170 kV
77 kV	150 kVrms (212.13 kVp)	400 kV

3 INSULATION DESIGN OF SOLID PART AND SURFACE INSULATION DESIGN

3.1 DESIGN MODEL

Figure 1 shows the cross section of a design model of the solid/gas composite insulation system used in the present study. The design model is the modification of the moving part of SIS. The configuration is similar to the simulation model in the previous study [8]. However, the radius of the curvature of the edge of the embedded electrode is different. In the present study, the radius of the curvature was varied in order to examine the insulation in the solid part for the minimization of the thickness of the solid insulation. The thickness of the embedded electrode was 2 mm and the radius of the center rod electrode was 5 mm.

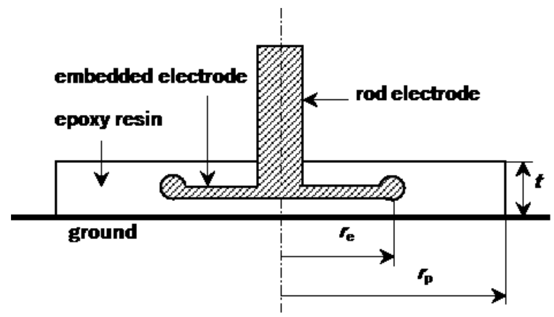

Figure 1. A design model of composite insulation system with embedded electrode. r_p is the radius of the disc-type epoxy resin plate, r_e is the radius of the embedded electrode and t is the thickness of the epoxy resin plate.

Figure 2 shows an enlarged diagram of the region around the edge of the embedded electrode. The embedded electrode has a round edge with the radius of the curvature of r. The distance between the bottom of the embedded electrode and the ground is denoted as d_1.

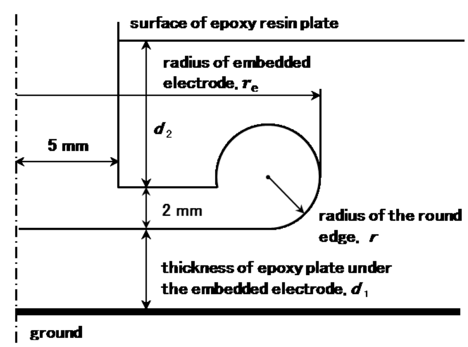

Figure 2. An enlarged diagram of the region around the edge of the embedded electrode.

3.2 INSULATION DESIGN OF SOLID PART

In the solid insulation part, two different breakdown phenomena should be taken into account. One is the dielectric breakdown. The breakdown field strength depends on the material itself. The other one is the breakdown due to the deterioration by treeing. Treeing is a long term deterioration phenomenon of organic materials. Therefore, the relation between the life and the electrical stress is important. The relation is known as V-T characteristics.

Table 3 shows the record of achievement for newly developed insulation material of epoxy resin [1-2] with filler of spherical silica.

Table 3. Record of achievement of developed epoxy resin.

Item	Record of achievement		Reference
Ac breakdown	50 % breakdown voltage	213 kVrms (301.23 kVp)	[1]
	Standard deviation	~15.5 % (33 kVrms, 46.7 kVp)	
Positive impulse breakdown	50 % breakdown voltage	357 kV	-
	Standard deviation	11.7 % (41.77 kV)	
Negative impulse breakdown	50 % breakdown voltage	386 kV	
	Standard deviation	6.4 % (24.70 kV)	
Life against treeing	10.65 kVrms/mm (15.06 kVp/mm) for 30 year (from E-t curve)		[9]

*The data were obtained with a sample of epoxy resin 3 mm in thickness.

For the insulation of the solid part, AC breakdown voltage, impulse breakdown voltage, and the life against the treeing were taken into account. However, the performances are different. It is impossible to compare directly with each other. Then, the authors introduced a specific parameter of "equivalent insulation distance." The equivalent insulation distance may be also expressed as a severity factor of the item, such as ac flashover, to consider in the insulation design. The value of the parameter was obtained from the test voltages and the records.

In the case of breakdown, the voltage of V_{50}-3σ was considered, where V_{50} is the 50 % breakdown voltage and σ is the standard deviation. Therefore, the probability of breakdown is less than 0.15 %. Then, the value of V_{50}-3σ was divided by the gap length (thickness of the solid material: 3 mm). As a result, V_{50}-3σ was transformed into the field strength, E_{50}-3σ. The value of the equivalent insulation distance (EID) for the solid part, $\mathrm{EID_s}$ [mm] was obtained by the following equation.

$$\mathrm{EID_s} = \frac{\text{Test voltage [kV]}}{E_{50} - 3\sigma} \quad (1)$$

In the case of the life against treeing, $\mathrm{EID_s}$ is obtained from E-T characteristics, where E is the applied field strength in the acceleration test. Honda *et al* [9] measured E-T characteristics of the epoxy resin and gave the relation between E [kV/mm] and the life T [min.] expressed with the following equation.

$$T = \left(\frac{E}{30}\right)^{-16} \quad (2)$$

The value of E for 30 years was estimated 15.06 kVp/mm from equation (2). Therefore, EID against treeing becomes to be expressed by the following equation.

$$\mathrm{EID_{s-tree}} = \frac{\text{operation voltage [kVp]}}{15.06} \quad (3)$$

where, the operation voltage is the value against the ground.

Table 4 shows the list of calculated $\mathrm{EID_s}$ for each test item and the voltage class.

Table 4. Test item and EID for solid part, $\mathrm{EID_s}$.

Voltage class	Test item		$\mathrm{EID_s}$ [mm]
22 kV	AC breakdown		1.36
	Impulse breakdown	positive	1.62
		negative	1.20
	Life against treeing		1.19
33 kV	AC breakdown		1.91
	Impulse breakdown	positive	2.20
		negative	1.64
	Life against treeing		1.79
77 kV	AC breakdown		4.09
	Impulse breakdown	positive	5.18
		negative	3.85
	Life against treeing		4.17

The value of $\mathrm{EID_s}$ is considered to indicate the degree of the influence on the insulation design. In any voltage class, $\mathrm{EID_s}$ for positive impulse was the largest. Therefore, the design of the insulation of the solid part can be performed only using the field strength for the positive impulse.

Incidentally, if the breakdown of the solid part depends on the field strength at the flat uniform region around the center of the embedded electrode, the required thickness becomes a few mm. However, the characteristics of the breakdown voltage of the newly developed epoxy resin [1,2] in non-uniform field has not been clarified. Therefore, the breakdown of the epoxy resin was assumed to depend on the maximum field strength in the present study.

In order to find the suitable radius of the embedded electrode and the distance between the embedded electrode and the ground, field calculation was done using a simple model of sphere-plane electrode in dielectric (epoxy resin, dielectric constant: 2.3) and using a field calculation software, Ansoft Maxwell (Ansoft Japan). The calculation results are shown in Figure 3.

The inverse number of the maximum field strength for the unit voltage has the same meaning of $\mathrm{EID_s}$. Therefore, $\mathrm{EID_s}$ obtained from the calculated value is shown in Figure 3. The horizontal axis of the Figure 3 is the distance between the top of the embedded electrode and the ground. The radius of the curvature of the edge of the embedded electrode is expressed

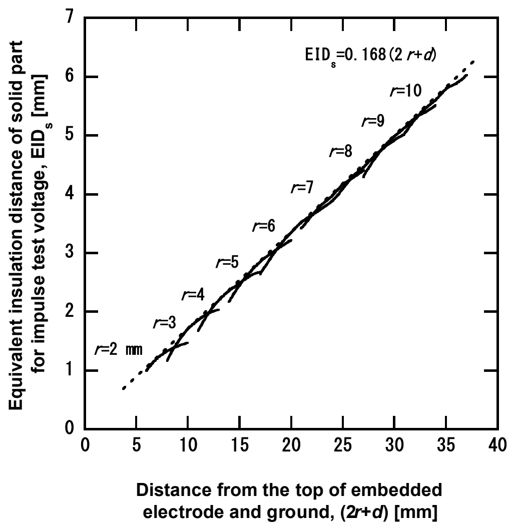

Figure 3. Relation between equivalent insulation distance of solid part for impulse test voltage and the distance from the top of the embedded electrode and the ground.

with r, and the distance between the bottom of the embedded electrode and the ground is expressed with d_1. Then, the value of the horizontal axis in Figure 3 gives d_1+2r [mm].

The edge effect was not considered in the reference [1]. It was taken into account in the present study. That is, the maximum field strength on the surface of the embedded electrode was taken into account.

Calculation curve was shown for each radius of the curvature of the edge of the embedded electrode. The envelope of these calculation curves gives a straight line. That means the minimum value of the distance between the top of the embedded electrode and the ground will be found when EID for the impulse test voltage, $EID_{s\text{-imp}}$ is given. The relation between $EID_{s\text{-imp}}$ and the minimum value of the distance between the top of the embedded electrode and the ground is expressed as a following equation:

$$(d_1 + 2r)_{\min.} = \frac{EID_{s-imp}}{0.168} \quad (4)$$

From equation (4) and Table 4, the suitable radius of the curvature of the edge of the embedded electrode and the distance between the bottom of the embedded electrode and the ground was obtained for each voltage class. They are listed in Table 5.

Table 5. Design of solid part.

Voltage class	Radius of the curvature of embedded electrode [mm]	Distance between embedded electrode and ground [mm]
22 kV	3	4
33 kV	4	5
77 kV	10	12

3.3 SURFACE INSULATION DESIGN

The gas insulation part including the surface is required to withstand the test voltages and is also required to be the condition of no PD on the surface under operation voltage.

(1) Surface PD prevention under operation voltage

The maximum field strength along the surface was calculated by varying the radius of the embedded electrode r_e. The calculation was done using a field calculation software, Ansoft Maxwell (Ansoft Japan) and was done under the conditions listed in Table 5. An example of the calculation results when r_p=200 mm and t=25 mm is shown in Figure 4. Except for the small r_e region, the maximum field strength was almost constant. In the flat electric field region, the maximum field strength on the surface appears at the position just above the top of embedded electrode. On the other hand, the maximum field strength appears on the surface of center rod electrode in the small r_e region.

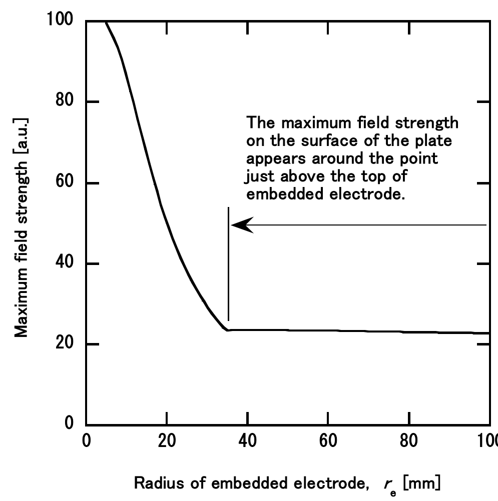

Figure 4. Relation between maximum field strength along the surface and the radius of embedded electrode r_e.

Using the calculated values of the maximum field strength [kV/mm] in the flat region, equivalent insulation distance for the surface insulation EID_p [mm] was obtained from the following equation.

$$EID_p = \frac{\text{Applied voltage [kV]}}{\text{Calculated field strength [kV/mm]}} \quad (5)$$

Figure 5 shows the relation between calculated EID_p and the thickness of the plate. The conditions of the calculation were listed in the figure. The value of EID_p increases with the thickness of the plate.

The partial discharge inception field was measured and it was reported 2.5 kV/mm in the previous paper [6]. The partial discharge inception field strength was also normalized as the equivalent insulation distance for AC and impulse test voltages using the following equation.

$$EID_{pd} = \frac{\text{Test voltage [kV]}}{\text{PD inception field (2.5 kV/mm)}} \quad (6)$$

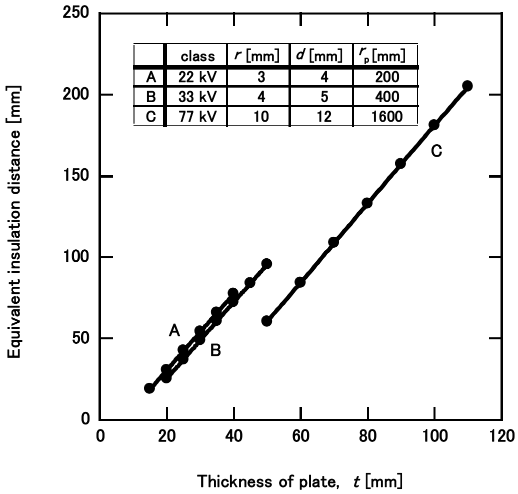

Figure 5. Relation between equivalent insulation distance along the surface and the thickness of the epoxy resin plate t.

In the case of the partial discharge under operation voltage, ac test voltage is concerned. The values of the equivalent insulation distance for AC test voltage ($EID_{pd\text{-}ac}$) are listed in Table 6. From the comparison between the equivalent insulation distance for ac test voltage ($EID_{pd\text{-}ac}$) and the equivalent insulation distance (EID_p) in Figure 5, the required thickness of the plate was obtained. The value corresponds to the minimum thickness and is listed for each voltage class in Table 6.

Table 6. EID for AC test voltage and required thickness of the plate.

Voltage class	EID for AC test voltage, $EID_{pd\text{-}ac}$ [mm]	Thickness of the plate, t [mm]
22 kV	28.3	19
33 kV	39.6	26
77 kV	84.9	60

Moreover, the characteristics of the equivalent insulation distance (EID_p) in Figure 5 indicates that the partial discharge prevention design under impulse test voltage is possible if the large value of the thickness is acceptable. That is, there are two ways of surface insulation design. One is PD prevention design and the other one is the surface flashover prevention design. If PD prevention is achieved, surface discharge which leads to the surface flashover does not take place.

(2) Surface PD prevention design

From the equivalent insulation distance for impulse test voltage ($EID_{pd\text{-}imp}$) calculated from equation (6) and the relation shown in Figure 5, the required thickness of the plate for the prevention of surface PD under impulse test voltage was obtained. The minimum thickness is listed in Table 7 for each voltage class. When the thickness is larger than the values listed in Table 7, surface PD is not supposed to take place under impulse voltage up to the test voltage level.

Table 7. EID for impulse test voltage and required thickness of the plate.

Voltage class	EID for impulse test voltage, $EID_{pd\text{-}imp}$ [mm]	Thickness of the plate, t [mm]	Radius of the plate, r_p [mm]
22 kV	50	29	71
33 kV	68	39	103
77 kV	160	92	308

In order to decide the radius of the plate the relation between the maximum field strength and the radius of the embedded electrode was examined by varying the radius of the plate r_p. As shown in Figure 4, the maximum field strength on the surface of the plate appears around the position just above the top of the embedded electrode except for the case of small r_e. Also it is almost constant regardless of the radius of the embedded electrode except for the case of small r_e. Figure 6 shows the relation between the maximum field strength on the surface and the radius of the plate when the position of the maximum field strength appears around the position just above the top of the embedded electrode. The maximum field strength is found to be lower than 2.5 kV/mm (measured PD inception field strength) when the radius of the plate is relatively large. However, when the radius of the plate becomes smaller than a critical value, the position of the maximum field strength moves to the edge of the plate and the maximum field strength becomes large with the radius of the plate decreasing. The critical radius is shown in Figure 6 and it becomes the minimum value of the radius of the plate. The values are listed in Table 7.

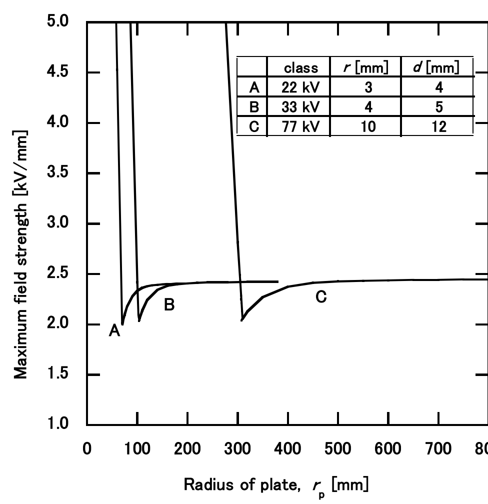

Figure 6. Relation between the maximum field strength along the surface and the radius of the epoxy resin plate t.

(3) Surface flashover prevention design

Surface flashover prevention design is an insulation design in which the partial discharge is allowed but the surface flashover is not allowed under impulse test voltage. Therefore, the design is performed based on the surface discharge propagation characteristics. In this study, design for prevention of the surface flashover was done using the method proposed in the previous paper [8]. However, the radius of the curvature of the edge of the embedded electrode is different. Therefore, the simulation was done using the radius of the curvature listed in Table 5. The thickness of the embedded electrode was remained at 2 mm and the radius of the plate was set large enough, 200 mm for 22 kV class, 400 mm for 33kV class, and 1600 mm for 77 kV class. At first, the divided voltage ratio was calculated.

The divided voltage ratio was almost constant except for the small region of the radius of the embedded electrode. It was similar to the calculation result reported in the previous paper [8] (Figure 4 in [8]). Then, the average of the divided voltage ratio, D_a is calculated in the same way proposed in the previous paper [8]. Figure 7 shows the relation between the average value D_a and the thickness of the epoxy resin plate. The value of D_a decreased with the thickness of the plate. Since the values of r and d are different in each case, the distance between the top of the embedded electrode and the surface of the epoxy plate is different even if t is the same. The value of D_a strongly depends on the distance between the top of the embedded electrode and the surface of the epoxy resin plate. Therefore, the characteristic of D_a was influenced by the configuration of the electrode system as shown in Figure 7.

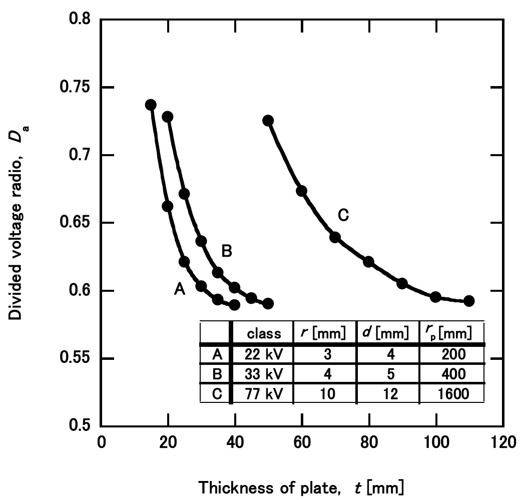

Figure 7. Relation between D_a and the thickness of the epoxy resin plate t.

The minimum radius of the embedded electrode was newly obtained from the calculation of the surface potential distribution, using the same procedure explained in the previous paper [8]. The results are shown in Figure 8.

The relation between the breakdown voltage (BDV) and the thickness of the plate was calculated as a function of the radius of the plate. In the calculation, the radius of the embedded electrode was set at the optimum value obtained using the same procedure explained in the previous paper [8]. Figure 9 shows an example of the calculation for 33 kV class. The value of

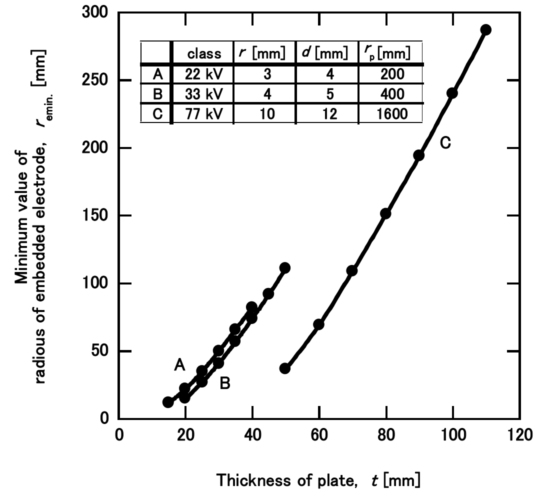

Figure 8. Relation between the minimum value of the radius of the embedded electrode and the thickness of the epoxy resin plate t.

BDV increased with the thickness of the plate. As reported in the previous paper [8], the radius of the embedded electrode is limited by the minimum value. Therefore, the BDV is also limited as shown in Figure 9.

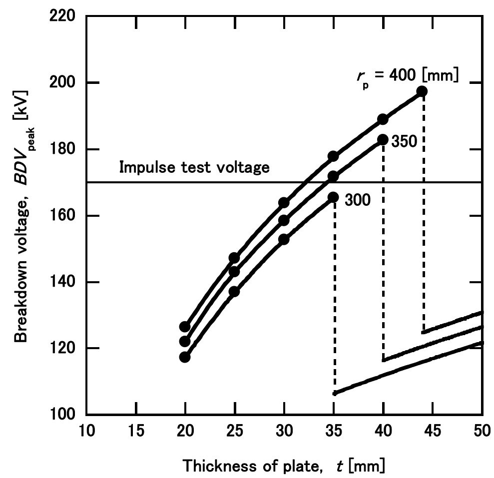

Figure 9. An example of the relation between the peak value of the impulse breakdown voltage and the thickness of the plate t, as a function of the radius of the plate r_p :33 kV class.

From Figure 9, the maximum BDV and corresponding t for each r_p are found. On the other hand, from the comparison between BDV and the test voltage, the minimum value of t at which the surface breakdown does not occur under the test voltage is found for each r_p. From these data, the relation between the radius and the thickness of the plate is obtained. The relation between the radius and the thickness of the plate is shown in Figure 10. This is an example of the design curve for 33 kV class. Curve 1 in Figure 10 is obtained from the crossing point of BDV_{peak}-t characteristics and the impulse test voltage in Figure 9. The crossing points are obtained for r_p. Curve 2 in Figure 10 is obtained from the conditions where the values of BDV_{peak} have the maximum as shown in Figure 9.

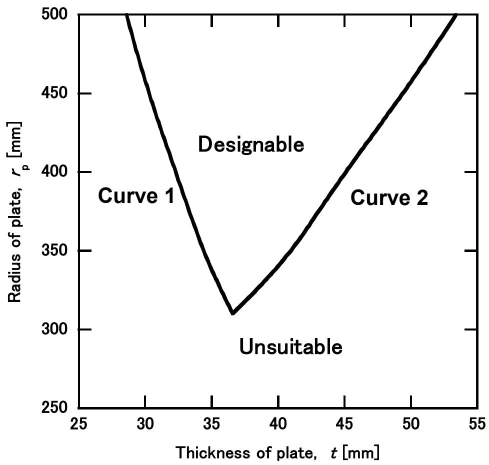

Figure 10. Critical conditions of the radius and the thickness of the plate for 33 kV class: the relation between the radius and the thickness of the plate.

The minimum radius of the plate is found from Figure 10. The relations among the surface BDV, and the critical conditions of the radius and the thickness of the epoxy resin plate were similar to those reported in the previous study [8]. In the same procedure mentioned above, the minimum radius and the maximum thickness of the plate for 22 kV class and 77 kV class were also obtained.

4 COMAPRISON OF DESIGN PARAMETERS

The minimum values of the design parameters of two different design concepts were compared. Table 8 shows the design parameters for 22 kV class. The thickness of the plate in the surface flashover prevention design was 25 mm when the radius of the plate was the minimum value of 180 mm. The thickness t can be reduced; however, radius of the plate r_p becomes much larger. The values of t and r_p are decided in the designable region similar to that in Figure 10. The radius of the embedded electrode r_e in the surface flashover prevention design was obtained by the equation of optimum radius of the embedded electrode, presented in the previous paper [8].

Table 8. Comparison of design parameters for 22 kV class.

Design parameters	Partial discharge prevention design	Surface breakdown prevention design
r [mm]	3	
d [mm]	4	
t [mm]	29	25*1
r_e [mm]	49	36.1*2
r_p [mm]	71	180

*1: The value is in the case r_p=180 mm.
*2: The value is the optimum radius calculated for t and r_p.

Two different design concepts can be utilized in this voltage class. In PD prevention design, the radius of the plate can be set considerably smaller than that of the surface flashover prevention design. However, the thickness of the plate for the minimum radius of the PD prevention design is slightly larger than that of the surface flashover prevention design.

Table 9 shows the design parameters for 33 kV class. Two different design concepts can be utilized and the geometry of the insulation system is also similar to the case of 22 kV class.

Table 9. Comparison of design parameters for 33 kV class.

Design parameters	Partial discharge prevention design	Surface breakdown prevention design
r [mm]	4	
d [mm]	5	
t [mm]	39	37*1
r_e [mm]	74	63.4*2
r_p [mm]	103	310

*1: The value is in the case r_p=310 mm.
*2: The value is the optimum radius calculated for t and r_p.

Table 10 shows the design parameters for 77 kV class. In this class, only PD prevention design can be utilized. The conditions for PD prevention design cover the conditions for the surface flashover prevention design. Therefore, it is not necessary to take the surface discharge propagation into consideration for the surface insulation design of 77 kV class.

Table 10. Comparison of design parameters for 77 kV class.

Design parameters	Partial discharge prevention design	Surface breakdown prevention design
r [mm]	10	
d [mm]	12	
t [mm]	92	118*1
r_e [mm]	237	343.4*2
r_p [mm]	308	1490

*1: The value is in the case r_p=1490 mm.
*2: The value is the optimum radius calculated for t and r_p.

5 CONCLUSION

Related to the solid insulated switchgear (SIS) developed as one of the substitution for medium voltage SF_6 gas insulated switchgear, the authors performed the insulation design using a model electrode system and a design method proposed previously. In the present study, the partial discharge inception condition was also taken into account. The design was performed for 22, 33 and 77 kV systems and the following results were obtained.

(1) The required performance for the insulation design was converted into the "equivalent insulation distance". The introduced value made the performances of different test items comparable.

(2) It was found that two different design concepts can be utilized. One was partial discharge (PD) prevention design and the other one was the surface flashover prevention design. However, the condition of PD prevention design covered that of the surface flashover prevention design for 77 kV class.

(3) In PD prevention design, the thickness of the epoxy resin plate becomes slightly large. However, the radius of the plate can be decreased significantly compared with the surface flashover prevention design. In the actual design, one of these design concepts can be chosen according to the requirement for the geometry of the equipment.

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