EVALUATION OF BREAKDOWN CHARACTERISTICS UNDER THE LIGHTNING IMPULSE VOLTAGE CONDITION FOR THE DEVELOPMENT OF AIR-INSULATED ELECTRIC POWER APPARATUS

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Abstract: For the development of compact and highly reliable air-insulated electric power apparatus, breakdown characteristics should be investigated under the various electrical insulation environments. In this study, lightning impulse breakdown characteristics of air were investigated in electrode systems which simulated the real parts of the switchgears. The lightning impulse experiments were performed for three cases: 1) bare electrodes, 2) coated electrodes, 3) electrodes with dielectric barrier. Thereafter, a breakdown voltage estimation method for each condition was established based on the analysis of the electric field distribution and discharge propagation patterns. The calculated breakdown voltages by the estimation method showed good agreements with those by experiment. Based on the newly established method, a new compact 12kV class MCSG (Metal-Clad Switchgear) was designed. Through the insulation test for the developed model, it was verified that the newly established estimation method is very useful.

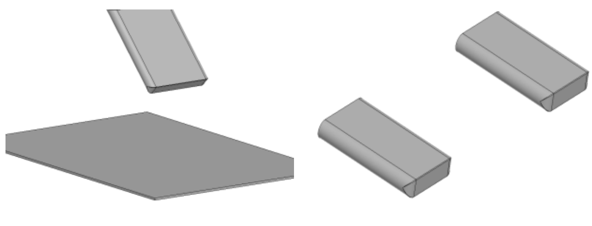
1 INTRODUCTION

Air insulation is becoming increasingly attractive owing to the environmental consideration and the advance of insulation technology. For the development of the compact and highly reliable air-insulated electric power apparatus, detailed investigation on breakdown patterns and the development of smart insulation design technologies are indispensable. In recent years, the hybrid insulation techniques have been studied extensively and verified to be effective to compensate the air insulation reliability [1, 2]. However, few studies on the estimation of breakdown voltage under the lightning impulse voltage condition in air with the electrode systems which simulated real components of the switchgear have been conducted. In this study, the lightning impulse breakdown characteristics are investigated with the three types of electrode systems in air. Based on the experimental results, a new estimation method of the breakdown voltage under the lightning impulse in air was established.

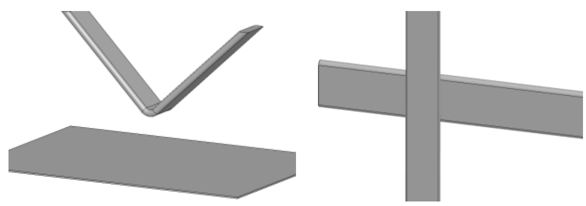
2 EXPERIMENTAL SETUP

The electrode systems were designed and made to imitate the geometrical structure of various parts of the MCSG (Metal-Clad Switchgear). Figure 1 shows the arrangements of bare electrodes in air. The electrodes, simulating busbars in the switchgear, were made of silver-coated copper and the plane electrode was made of stainless steel. In the test, the gap distance between the electrodes was varied from 50 to 200 mm. Figure 2 illustrates that hybrid insulation techniques are adopted in the same geometrical structure. Figure 2(a) and Figure 2(b) show the electrode systems with the Raychem heat-shrink tube as the dielectric coating and with BMC (Bulk Moulded Compound) plate as the dielectric barrier, respectively.

The lightning impulse voltage whose front time (T_1) is 1.2μs and time to half value (T_2) is 50μs is supplied by a Marx generator rated at 350kV, 15kJ. The breakdown voltage was determined by the 'up and down method' on a series of 10 impulses. The interval between two successive impulses is 60s. In the present study, the positive polarity where the positive high voltage is applied to the electrode whose radius is smaller than the other’s is considered exclusively.

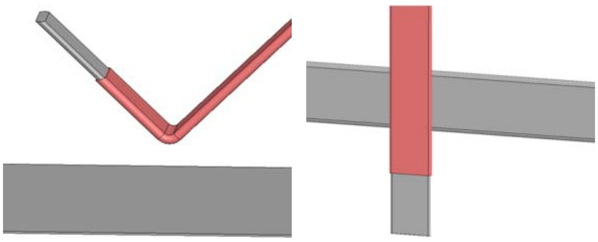


(a) Busbar edge-to-plane (b) Busbar edge-to-edge

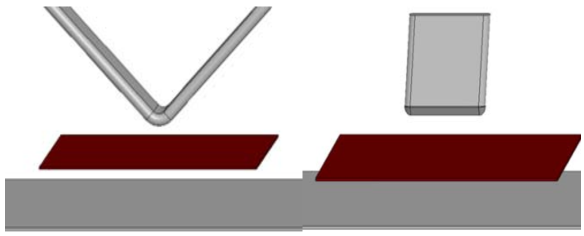


(c) Busbar bend-to-plane (d) Crossed busbars

Figure 1: Bare electrode systems for air insulation experiments



(a) Electrode systems with dielectric coating



(b) Electrode systems with dielectric barrier

Figure 2: Electrodes systems with dielectric materials for hybrid insulation experiments

3 RESULTS AND DISCUSSIONS

3.1 Air insulation experiment results

Generally the dielectric breakdown electric field intensity (E_{bd}) of air gap in uniform field is expressed as:

$$E_{bd} = 2.405\delta(1.0 + \frac{0.328}{\sqrt{\delta d}})\ [kV/mm] \qquad (1)$$

where δ is relative air density when the air density at 760Torr and 20^{o}C is 1.0, d is the gap distance between two electrodes [3]. However, there is a time lag in a dielectric breakdown under lightning impulse voltage condition. Though the shape of the impulse (virtual T_1 and T_2) is identical, the time lag and the breakdown voltage can be changed if the peak value is changed. As a result, the breakdown electric field intensity under the lightning impulse is a difficult subject yet [4, 5].

In case of air only insulation systems, the lightning impulse breakdown voltage test was repeated ten times for each condition (arrangement of bare electrodes, the gap distance). The eight values except the maximum and the minimum were selected and analyzed with statistical method. The results are shown in Figure 3. The 50% probability breakdown voltages according to the gap distance and the arrangement of electrodes are plotted. The breakdown voltage is normalized to the breakdown voltage for busbar bend-to-plane gap distance of 80mm. It is observed that the breakdown voltage increases logarithmically as the gap distance increases. The increment per gap distance becomes smaller as the gap distance increases and this tendency is also observed regardless of the electrode shapes.

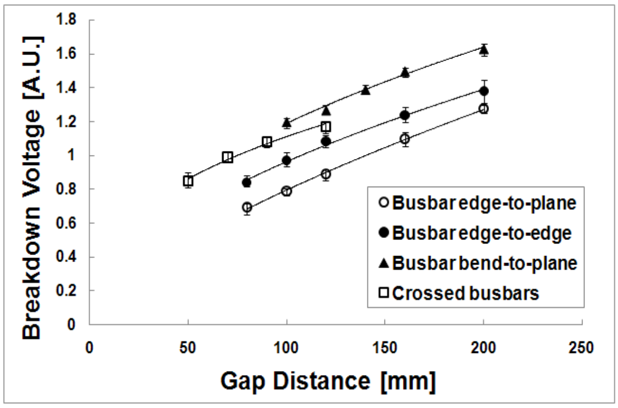
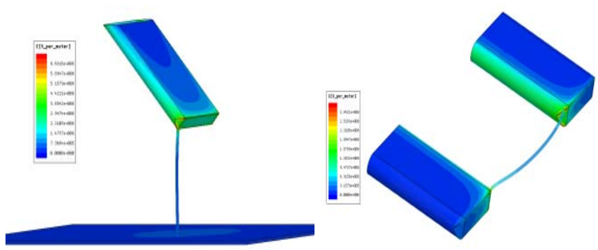


Figure 3: Breakdown voltages with respect to the different gap distance (*A.U.: Arbitrary Unit)

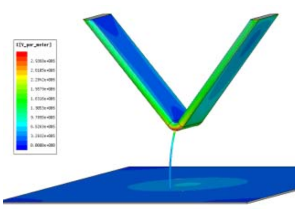
In order to analyze the breakdown characteristics of test electrode systems with the various geometric factors, the field utilization factor is taken into account. It is the ratio of the mean electric field to the maximum electric field and it can be a good measure of the field uniformity which is governed by the gap distance, the electrode size, and etc. [6]. So as to calculate the field utilization factor for each experiment case, the electric field is analyzed by FEM (Finite Element Method). Figure 4 shows the results of the analysis with the gap distance of 100mm. An arbitrary voltage, V_{in} *[kV]* is applied to the electrode with positive polarity and the counter electrode is grounded. From the results, the maximum electric field and the utilization factor are calculated for all the conditions.

The breakdown electric field intensity is derived from 50% probability breakdown voltage and it is plotted with respect to the utilization factor to find a correlation between them in Figure 5. It was observed that the breakdown electric field can be fitted by a decaying exponential function. From this result, the breakdown electric field can be estimated with the calculated utilization factor without the further insulation test if the electric field data with the different utilization factors exists.

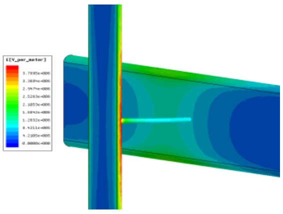


(a) Busbar edge-to-plane (b) Busbar edge-to-edge

Figure 4: Electric field analysis results of bare electrode systems



(c) Busbar bend-to-plane



(d) Crossed busbars

Figure 4: Electric field analysis results of bare electrode systems (cont'd)

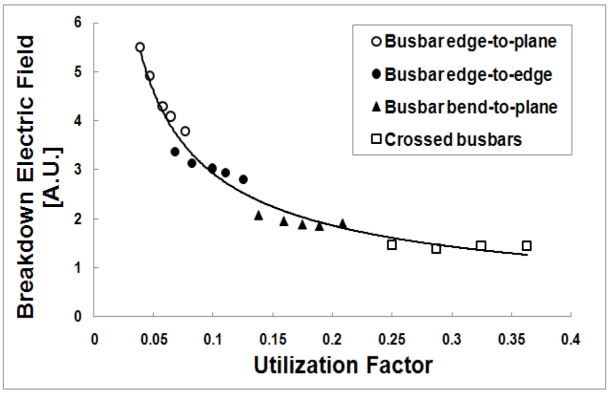


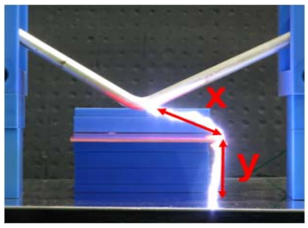
Figure 5: 50% breakdown electric field intensity with respect to utilization factors

3.2 Hybrid insulation experiment results

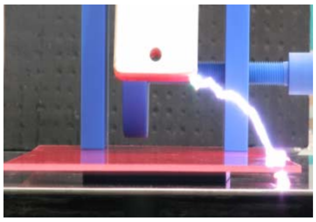
The dielectric strength in the electrode system with the hybrid insulation technique is improved mainly due to the dielectric materials acting as a geometrical obstacle to direct discharge. When the dielectric barriers inserted between the electrodes, the barrier alters the space charge distribution. The ions constituting this space charge are stopped by the dielectric barrier and spread on its surface, creating a surface charge. As a result, the electric field between the dielectric barrier and the electrode becomes uniform and the breakdown voltage increases [7].

The barrier effect for the busbar-to-plane electrode systems was investigated considering the influence on the barrier position and discharge pattern. Figure 6 shows the photographs of the discharge propagation between the busbar and the plane electrodes with the gap distance, *d*, of 100mm. The discharge propagated from the busbar electrode via the barrier edge to the plane electrode regardless of the position of dielectric barrier. The discharge propagation distance, *d'* is practically equal to the sum of two distances: *x* from busbar to barrier edge and *y* from barrier edge to plane as seen in Figure 6. It is known that the breakdown voltage corresponding to the discharge propagation distance in the electrode system with dielectric barrier is equivalent to that corresponding to the gap distance equal to the sum of *x* and *y* in the electrode system without barrier [7]. A comparison between the breakdown voltages measured in the electrode systems with and without dielectric barrier is given on Figures 7. The discharge propagation distance and the breakdown voltage increase simultaneously as the dielectric barrier is moved to the busbar electrode. Although the breakdown voltage at the near busbar is lower than that at the equivalent gap distance without dielectric barrier, the equivalence between both systems is verified to be generally valid for barrier positions.

Figure 8 shows the breakdown voltage with respect to the barrier position ratio of the distance between the busbar and barrier to the gap distance. It is noticed that the breakdown voltage reaches a maximum value when the barrier position ratio is about 0.2 and the optimal increase value is 63.6% for the busbar edge. When the barrier position ratio is below 0.1, the sliding discharges on the barrier surface are observed. The superficial sliding discharges facilitate the breakdown and cause the breakdown voltage to decrease at the low barrier position ratio.



(a) Busbar bend-to-plane with dielectric barrier



(b) Busbar edge-to-plane with dielectric barrier

Figure 6: Photos of discharge light emission in electrode systems with dielectric barrier

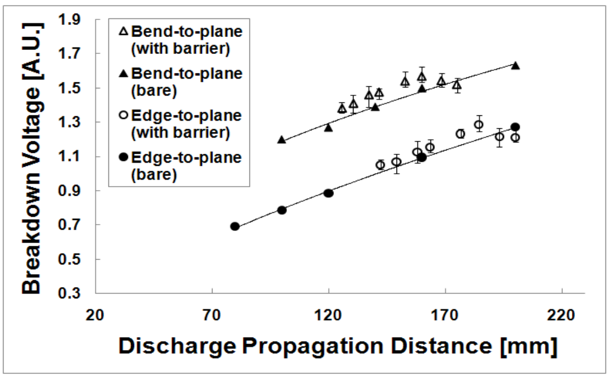


Figure 7: Breakdown voltage comparison between electrode systems with and without dielectric barrier

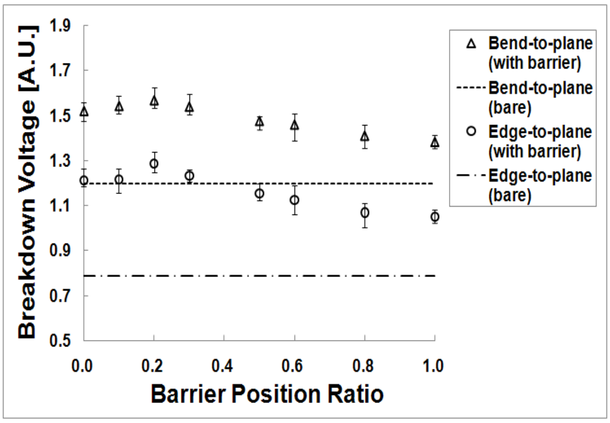
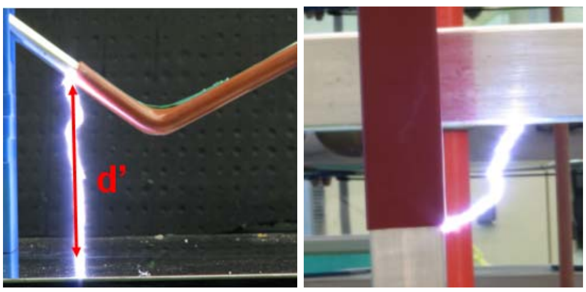


Figure 8: Breakdown voltage traces with respect to the barrier positions

To investigate the effect of the coated electrode, the discharge patterns are analyzed in the busbar electrode systems with heat-shrink tubes. Figure 9 shows the photographs of the discharge propagation when the gap distance of the busbar-to-plane electrodes and the crossed busbar electrodes are 100mm and 70mm respectively. The discharge propagates from the uncoated part of busbar electrode to the plane electrode. Similar to the barrier, the coating materials play a role of the electrical obstacle by the space charge deposited on its surface. It alters the electric field distribution and facilitates the discharge through the bare parts devoid of the space charge. Therefore, the discharge propagation distance increases because the breakdown does not occur through the minimum gap between the electrodes but through the discharge channel between the bare parts and it leads the breakdown voltage to increase. Figure 10 shows that the breakdown voltage increases as the discharge propagation distance is enlarged. It means that the estimation method by the equivalence of discharge propagation distance is also valid to the coated electrode systems.



(a) Busbar-to-plane (b) Crossed busbars

Figure 9: Photos of discharge light emission in electrode systems with dielectric coating

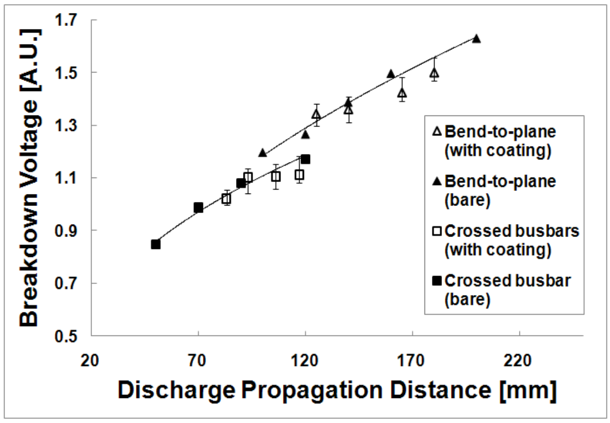


Figure 10: Breakdown voltage comparison between electrode systems with and without dielectric coating

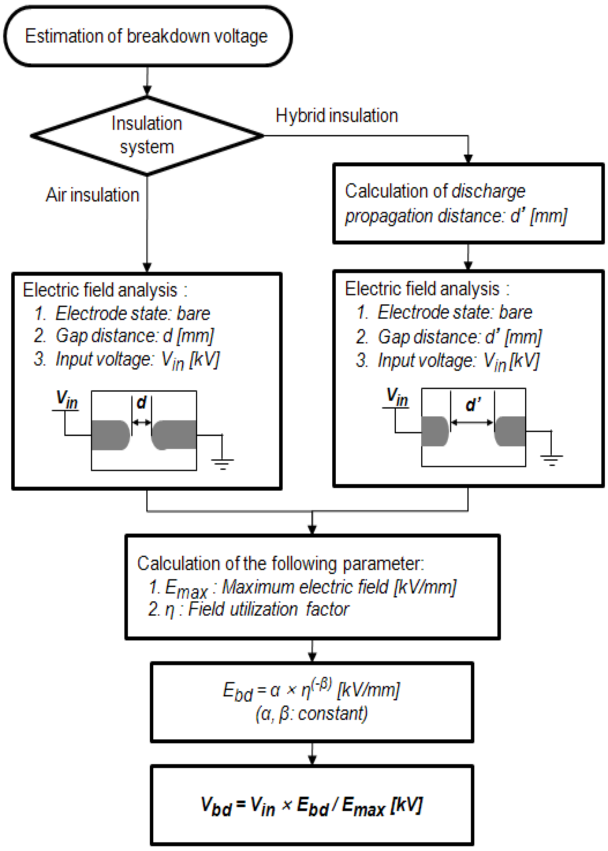


Figure 11: Flow chart to estimate the breakdown voltage for air and hybrid insulation systems

4 CONCLUSION

The breakdown characteristics under the lightning impulse were investigated with the various electrode systems for the establishment of the breakdown voltage estimation method. The lightning impulse experiment results are summarized as follows:

1. In air insulation systems, it is found that the breakdown electric field intensity exponentially increases as the field utilization factor decreases and the breakdown voltage can be estimated with the relationship of the utilization factor.

2. In hybrid insulation systems, the discharge propagation patterns are analyzed and it is found that the breakdown voltage estimation method based on the discharge propagation distance is effective to the electrode systems both with the dielectric coating and the dielectric barrier.

Based on the newly established estimation method, a new compact 12kV class MCSG was developed. Through the insulation test of the developed model, it was verified that the newly established estimation method is very useful.

5 REFERENCES

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