Electrode Conditioning Mechanism Based on Pre-breakdown Current under Non-uniform Electric Field in Vacuum

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Abstract- **Electrode conditioning in vacuum is very important technique for improvement of the insulation performance of vacuum circuit breakers (VCBs). This paper discusses the spark conditioning mechanism through the measurement and analysis of the pre-breakdown current under non-uniform field. From F-N plots, we made sure that the pre-breakdown current was based on field emission mechanism. We quantitatively evaluated the variation of pre-breakdown current in the conditioning process. As a result, field enhancement factor β decreased as the conditioning proceeded and reached the final value. In addition, in case of non-uniform field, we found that β on rod electrode surface after conditioning was distributed according to the electric field distribution on the surface.**

I. Introduction

Vacuum circuit breakers (VCBs) attracts attention from the view point of low maintenance-cost and environment-friendly equipment. VCB required to be developed in higher voltage level [1]. Thus, it is important to discuss the conditioning characteristics under non-uniform electric field in vacuum, because the conditioning is a key technique to a high voltage insulation of VCB [2]-[4].

In general, it is well known that pre-breakdown current occurs and leads to breakdown in vacuum [5]-[7]. However, the characteristics of pre-breakdown current in conditioning process have not been clarified. In addition, we have to consider making the insulation performance of VCBs higher, that structure of vacuum interrupter is made more complicated. Therefore, it becomes important to clarify the spark conditioning mechanism especially under non-uniform electric field.

In this paper, we discussed spark conditioning mechanism focused on the pre-breakdown current under non-uniform electric field in vacuum. Then, we evaluated the conditioning effect by using field enhancement factor β, and also proposed electrode conditioning model under non-uniform electric field.

II. Experimental Setup and Procedure

Figure 1 shows an electrode configuration for experiments. Negative impulse voltage (30/100μs) was applied to the upper rod electrode. We used rod-to-plane electrodes with the gap length d=2mm and the tip radius of rod electrode R=2mm. For the experiment, rod electrode and plane electrode made of OFHC Cu were used. Both of electrodes are treated by mechanical finish. Before the experiment, electrodes were treated in ethanol by an ultrasonic washing machine.

For voltage application procedure we used up-down method. We started it at V=24.6kV and we change the voltage as voltage step ΔV = 8.2kV. We investigated the conditioning effect of BD in the series of negative voltage applications. The voltage waveforms were repeatedly measured till the BD voltage (V_{BD}) saturated. The current waveforms were measured by a high frequency CT. Illumination spots on the electrode surface at BD were observed by a digital camera. Through all experiments, the vacuum pressure in the chamber was kept at the order of 10^{-6} Pa. Figure 2 shows the conditioning history by up-down method. Here, we found that breakdown voltage rises from 17.1kV to 96.9kV in the conditioning process.

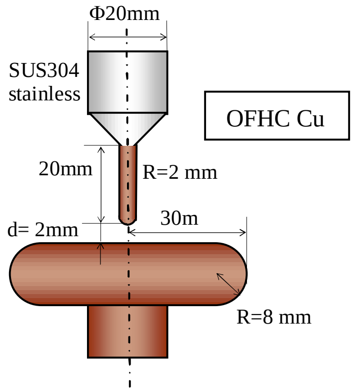

Fig. 1 Configuration of rod-to-plane electrode.

A. Conditioning history and pre-breakdown current characteristics

Figure 3 shows typical waveforms of applied voltage and current in conditioning process. We can categorize the results into three cases. Fig.3(a) shows the results for case 1, in which we could detect only displacement current I_d before BD. Fig.3(b) shows the results for case2, in which we could detect the conduction current, but BD did not occur. Fig.3(c) shows the results for case 3, we could detect the conduction current (pre-breakdown) current before BD.

During the early stage of conditioning process, case 1 often appeared rather than other cases. On the other hand, only case 2 and case 3 appeared usually in the final stage.

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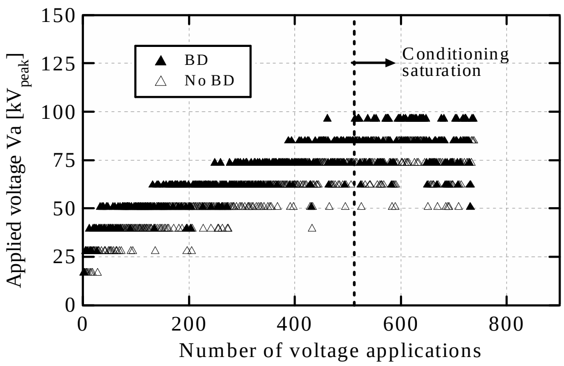


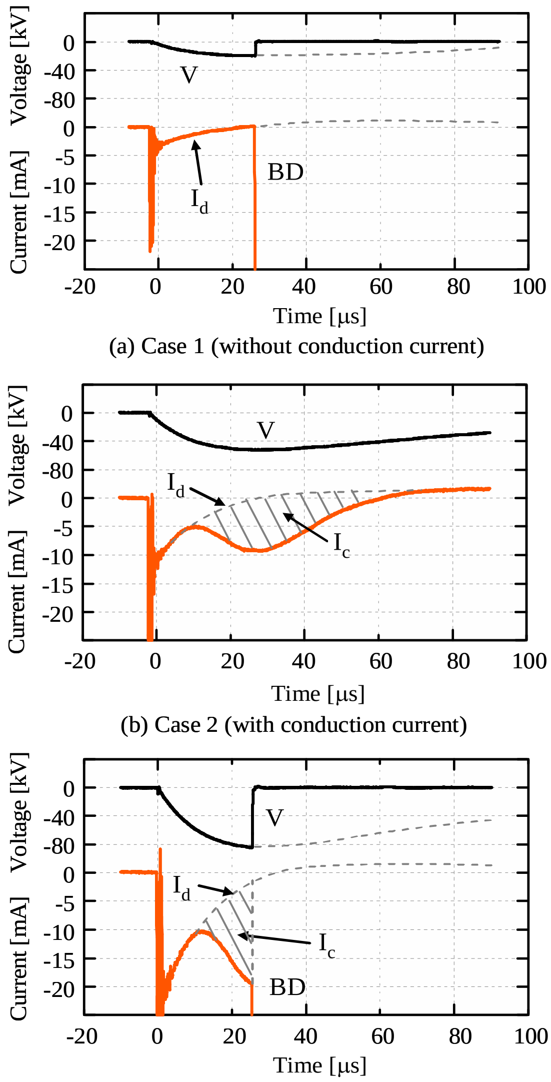
Fig.2. Conditioning history of up-down method

Figure 4 shows transition of pre-breakdown current during conditioning. We calculated maximum value of pre-breakdown current from measured waveform. We found that the pre-breakdown current decreased when the same voltage was applied repeatedly during conditioning. It shows that surface of rod electrode was gradually improved. However, after the electrode was fully conditioned, the value of pre-breakdown current did not decrease any more.

B. Transition of field enhancement factor β of rod electrode during conditioning

If the pre-breakdown current is owing to field emission mechanism, the measured current should agree with Fowler-Nordheim equation. In this case, we may obtain field enhancement factor β from F-N plots [8].

However, in non-uniform field, we need to consider the different process from uniform field. In our past study, we have clarified that the BD illumination spot on rod electrode moves upward gradually during conditioning [9]. Figure 5 shows the electric field distribution on rod electrode. E_{sta} is field strength on the rod electrode at 100kV applied. E_{max} is maximum field strength at the tip of rod electrode. Figure 6 shows illumination of breakdown spot, and Figure 7 shows transition of BD region during conditioning. We found that BD Spot region moved from the tip of rod electrode with high electric field to upward with low electric field.



(a) Case 1 (without conduction current)

(b) Case 2 (with conduction current)

(c) Case 3 (with pre-breakdown current)

Fig.3. Typical waveforms of voltage and current waveforms.
(I_d : displacement current I_c : conduction current)

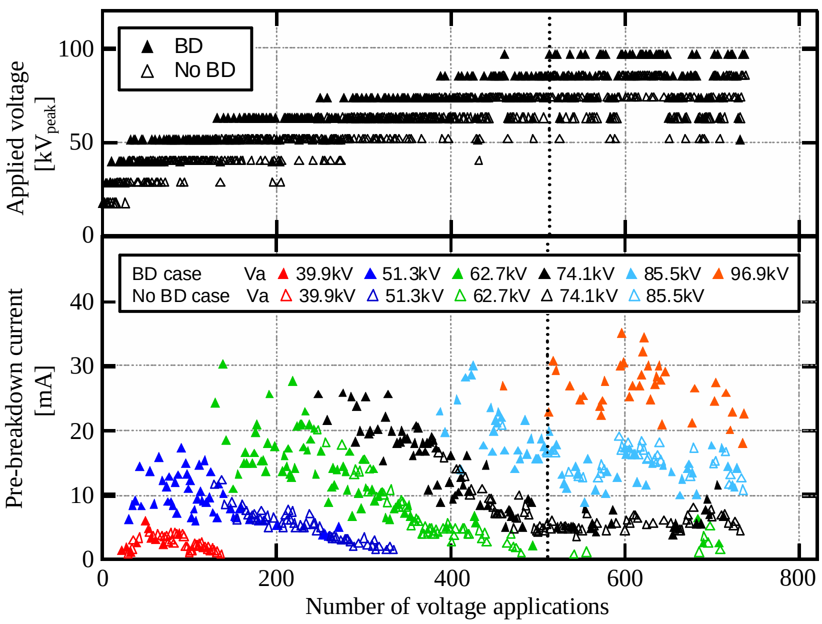


Fig.4. Transition of pre-breakdown current during conditioning.

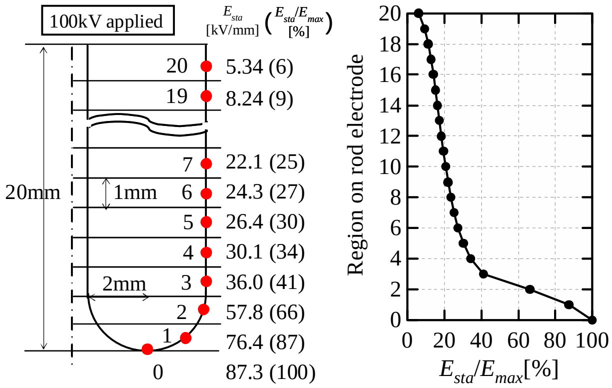
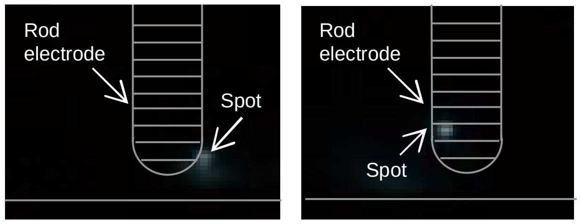


Fig.5. Electric field distribution on rod electrode



(a) Region 2 (shot 270) (b) Region 3 (shot 492)

Fig.6. Illumination of breakdown spot (d=2mm, R=2mm).

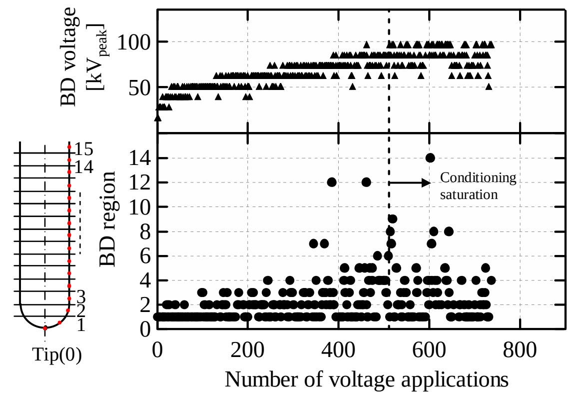


Fig.7. Transition of BD region during conditioning.

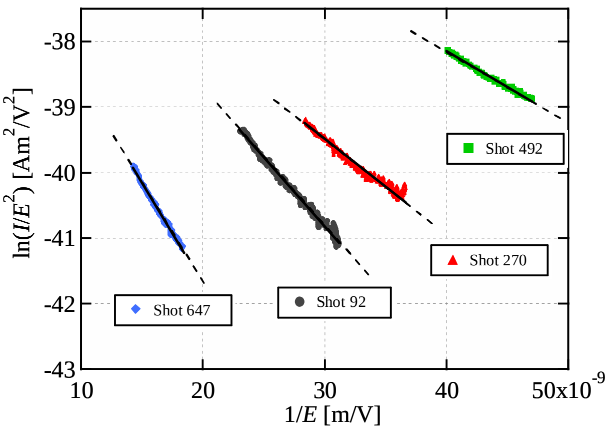


Fig.8. F-N plots

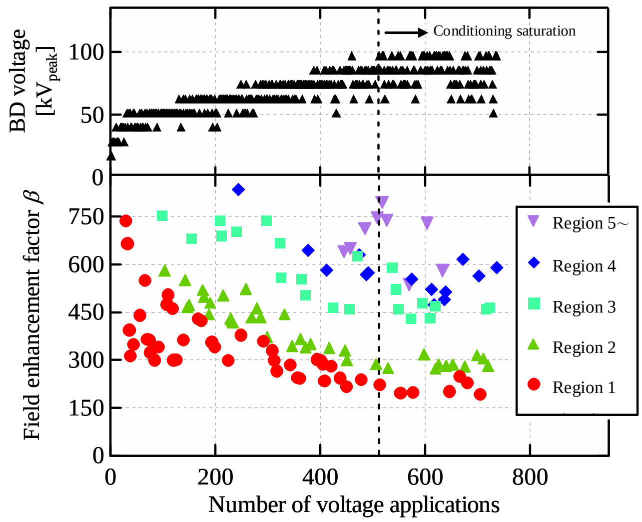


Fig.9. Field enhancement factor β at each rod electrode region during conditioning.

As a result, a lot of BDs could occur even at region 5 and upper, which corresponded to as low electric field region as 30% of maximum field strength.

Here, we assumed that the field emission could occur at the same point of BD illumination spot. Under such assumption, we related the pre-breakdown current with the field strength at each region. The relationships are shown as F-N plots in Figure 8. We found that the F-N plots became linear lines, so it clarified that pre-breakdown current we measured was based on field emission mechanism. From F-N plots, we calculated the field enhancement factor β for each BD.

Figure 9 shows field enhancement factor β at each rod electrode region during conditioning. We found that β at each region of rod electrode started from 700~750 and gradually decreased. After BD voltage was saturated, β was also saturated. The result can be interpreted that conditioning BD removed the protrusions and impurities on the rod electrode surface.

After conditioning, β was 195 at Region 1, 276 at Region 2, 434 at Region 3, 575 at Region 4, we found that β was inversely proportioned to the field strength at each region on rod electrode. That is, the stronger the electric field, the better conditioned surface can be obtained. However, the final value of β after conditioning depends on material of electrode and energy of applied impulse voltage etc., so more discussion would be needed.

Figure 10 shows effective field strength β×E during the conditioning. We found that β×E was nearly constant during the conditioning, and the value of β×E after the conditioning was about 1×10^{10}[V/m]. It was slightly higher than the value 3×10^{9}[V/m], inception field of field emission by Fowler-Nordheim equation.

C. Model of conditioning mechanism under non-uniform electric field

Figure 11 shows a model of electrode conditioning mechanism under non-uniform field. This model shows extension of BD region on rod electrode, transition of β, E, and βE.

At Stage 1, at the initial condition, surface condition of all region of rod electrode is uniform, that is to say, β is uniform. Because βE depends on only E, BD can occur at the tip of electrode.

At Stage 2, β at the tip of electrode decrease because of conditioning. Therefore, BD voltage is increase, and BD can occur even at the upper region of electrode.

At Stage 3, BD voltage increases more, region of BD extends upward, and βE decreases compared to Stage 1.

After conditioning, at Stage 4, β at each region of electrode is in the inverse with E, and βE is overall constant, so BD is generated at all region of electrode.

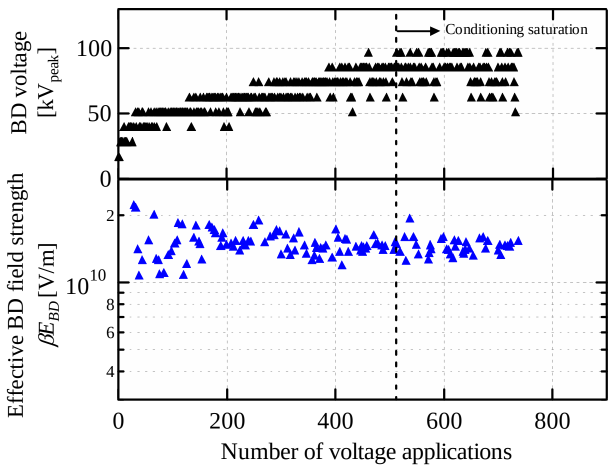


Fig.10. Effective field strength βE during conditioning.

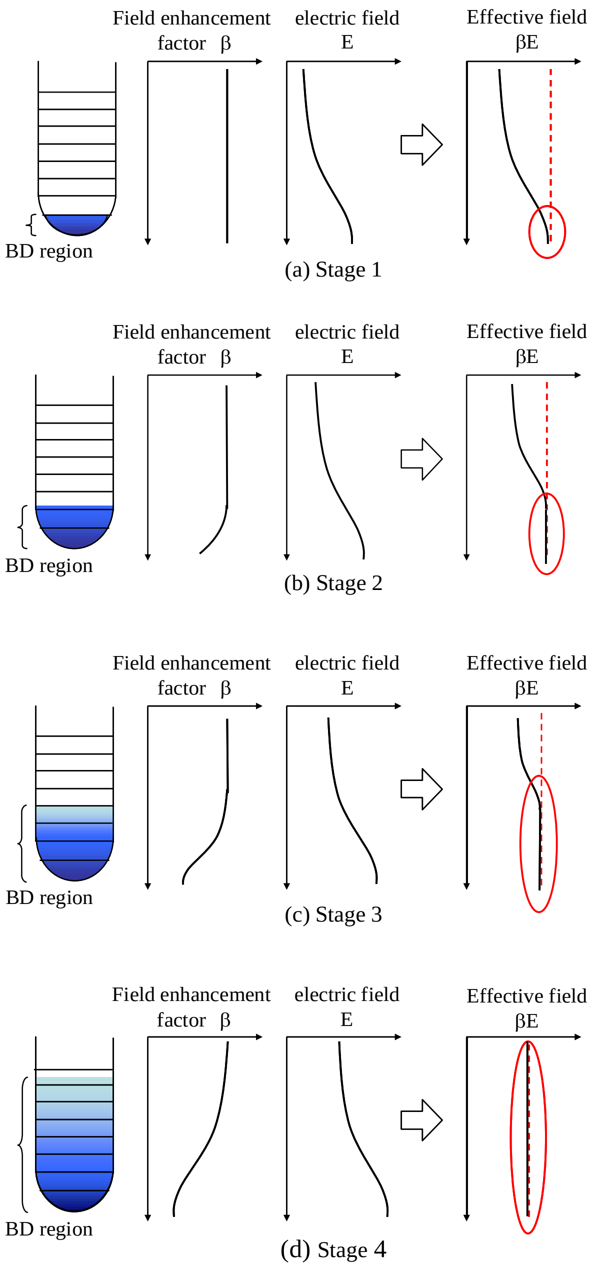


Fig. 11. Model of electrode conditioning mechanism under non-uniform field

IV. Conclusions

In this paper, we investigated conditioning mechanism focused on the pre-breakdown current under non-uniform electric field in vacuum. From experimental results, we evaluated pre-breakdown current based on F-N equation. As a result, we could found the following characteristics of conditioning.

1. We calculated F-N plots under non-uniform electric field. In the result, F-N plots were on a straight line, so pre-breakdown current we measured was clarified to be field emission current.

2. During conditioning, field enhancement factor β at each region on the electrode gradually decreased along with increase of BD voltage, and after BD voltage was saturated, β was also saturated. It shows that in this experiment, field emission was main factor of BD occurrence.

3. During conditioning under non-uniform electric field, β was distributed in the inverse with field strength E at electrode surface.

4. Effective field strength βE was nearly constant during conditioning. The value of βE was about 1×10^{10}[V/m].

5. We proposed the model of electrode conditioning mechanism under non-uniform field based on transition of β and transition of BD region during conditioning.

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