Enhancement of Breakdown Strength by Microdischarge under Impulse Voltage Applications in Vacuum

Keita Aoki[1], Ryouki Nishimura[1], Hiroki Kojima[1], Mitsutaka Homma[2], Tetsu Shioiri[2], Hitoshi Okubo[1]

[1] Nagoya University, Nagoya, Japan

[2] Toshiba Corporation, Fuchu, Japan

***Abstract*- An investigation of charge behavior such as microdischarge under high electric field in vacuum is very important in order to enhance the electrical insulation performance of vacuum circuit breakers and vacuum interrupters (VCB/VI). This paper discusses the enhancement characteristics of breakdown strength by microdischarge under applying impulse voltage repeatedly and changing vacuum pressure. As a result, microdischarge which had pulsed current waveform became smaller with repeated constant peak voltage applications under 10^{-6} Pa vacuum. In addition, microdischarge generation had the electrode conditioning effect to raise the breakdown voltage by reducing adsorption gas of the electrodes. Microdischarge having very small charge compared with that of breakdown has a possibility of drastic enhancement of breakdown strength in vacuum, as the non-breakdown conditioning technique.**

I. INTRODUCTION

Recently, vacuum circuit breakers and vacuum interrupters (VCB/VI) require development into higher voltage level and reliability [1,2]. In order to enhance the operational voltage and reliability of VCB/VI, it is necessary to understand the dielectric phenomenon under high electric field close to breakdown in vacuum. However, the mechanism of charge behavior such as pre-breakdown and microdischarge under high electric field in vacuum is not well clarified [3]-[6].

It is said that microdischarge can be observed at spark conditioning process [6]-[8]. Microdischarge starts at a high level of several ampere and falls off with the conditioning process. Although the microdischarge would play a critical role of pre-breakdown process, the characteristics and conditioning effect of microdischarge are not clear.

In this paper, we measured microdischarge under repetitive impulse voltage applications in vacuum. We discussed the characteristics and conditioning effect of microdischarge.

II. EXPERIMENTS

Figure 1 shows an electrode configuration for experiments. We used parallel plane electrodes with the gap length d=10 mm. For the experiment, these electrodes were OFHC Cu made by mechanical finish.

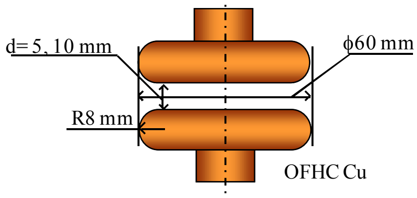

Fig. 1. Configuration of parallel plane electrodes with quasi uniform field.

Before the experiment, electrodes were treated by an ultrasonic washing in ethanol.

Negative impulse voltage (-30/100μs) was repeatedly applied to the upper electrode. The voltage waveforms were measured by universal voltage divider. The current waveforms were measured by a high frequency CT. The vacuum pressure in the chamber was kept at the order of 10^{-6} Pa.

A. *Microdischarge at conditioning process*

Figure 2 shows applied voltage and microdischarge waveforms we measured. Microdischarge which has pulsed current waveform begins to generate from 34 μsec.

Figure 3 shows light emission image of microdischarge taken by using digital camera with image intensifier (I.I.). From Figure 3, it is considered that microcischarge is generated at the wide region of electrodes.

Figure 4 shows the history of applied voltage and microdischarge during conditioning process. In this figure, gray vertical line means the occurrence of the breakdown. The method of voltage application is as follows. From V=16.8 kV, we repeatedly applied the constant peak impulse voltage. Then, if microdischarge less than 30 mA continued three times, we raised the voltage step. On the other hand, if breakdown occurred, we lowered the voltage step. The voltage step ΔV was 5.6 kV. Regardless of the occurrence of breakdown, microdischarge becomes smaller with repeated constant voltage applications. This will be the conditioning effect of microdischarge to improve condition of electrodes surface. In addition, microdischarge becomes large when applied voltage is raised. It is considered that this result is due to the increase of field emission current and energy of charged particles by raising applied voltage.

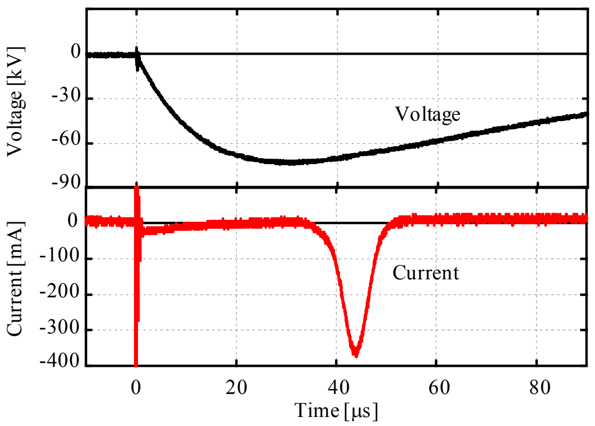

Fig. 2. Applied voltage and microdischarge current waveforms.

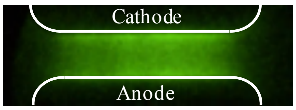

Fig. 3. Light emission image of microdischarge in electrode gap.

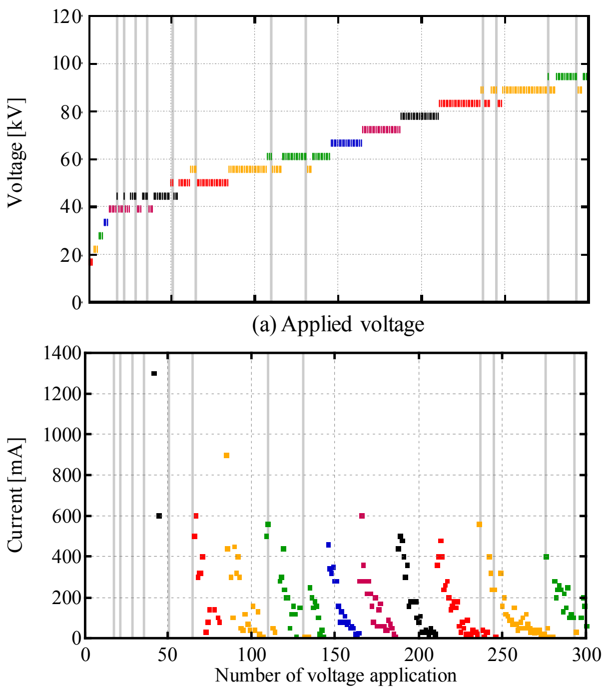

Fig. 4. History of applied voltage and microdischarge current during conditioning process.

B. *Vacuum pressure dependence of microdischarge*

The time of microdischarge peak is not corresponding to that of voltage peak in Figure 2, and microdischarge current is up to more than 1 A in Figure 4. Accordingly, microdischarge would be generated by the multiplication of field emission current with adsorption gas of electrodes. In order to investigate the relation of microdischarge and adsorption gas of electrodes, we changed the vacuum pressure from 10^{-6} Pa into 10^{-2} Pa. We measured the transition of microdischarge behavior by changing the vacuum pressure.

Negative impulse voltage was applied to the electrode shown in Figure 1 under 10^{-6} Pa and 10^{-2} Pa. First, electrode conditioning was conducted by repeatedly applying impulse voltage to the electrode to generate microdischarge under 10^{-6} Pa vacuum. At this time, adsorption gas of electrodes will decrease. Next, we changed vacuum pressure from 10^{-6} Pa into 10^{-2} Pa, and repeatedly applied impulse voltage under 10^{-2} Pa low vacuum. There were three kinds of voltage application intervals, that is, 1 min, 1.5 min, and 2 min.

Figure 5 shows the transition of applied voltage and microdischarge behavior when vacuum pressure is changed. In this figure, microdischarge became smaller with repeated voltage applications under 10^{-6} Pa vacuum. On the other hand, under 10^{-2} Pa low vacuum after microdischarge conditioning, microdischarge became bigger with time by applying the constant voltage repeatedly.

Now, the flux Γ of gas molecules against surface of material is obtained by equation (1),

$$\Gamma = \frac{nv}{4} \tag{1}$$

where n is the gas molecule density and v is the mean velocity of the gas molecules. Since the vacuum pressure is proportional to n, Γ becomes big by changing the vacuum pressure from 10^{-6} Pa into 10^{-2} Pa. Namely, the amount of gas which absorbs the electrodes per unit time increases. Here, we compare "decrease of the adsorption gas of the electrodes by generating microdischarge" with "increase of the adsorption gas by the gas molecule flux to the electrodes in the vacuum tank ". Under 10^{-6} Pa vacuum, the former is greater than the latter. Under 10^{-2} Pa low vacuum, the latter is greater than the former. Therefore, by applying the repeated constant voltage, it is considered that microdischarge current decreased under 10^{-6} Pa vacuum, and increased under 10^{-2} Pa low vacuum as shown in Figure 5.

Figure 6 shows the transition of microdischarge to the number of voltage applications in each case of the voltage application interval (1 min, 1.5 min, and 2 min) under 10^{-2} Pa low vacuum. In Figure 6, time is

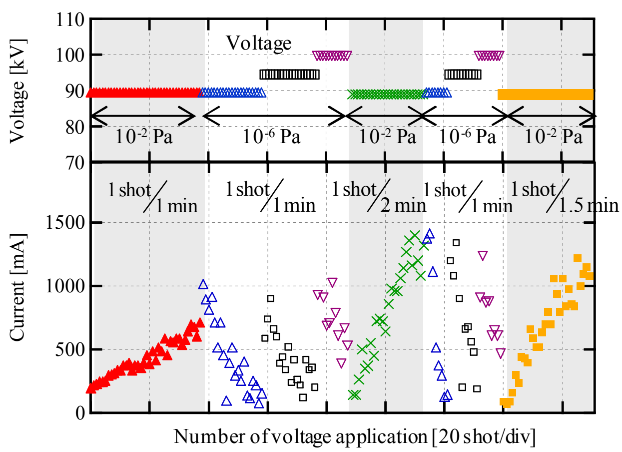

Fig. 5. Transition of applied voltage and microdischarge when vacuum pressure is changed.

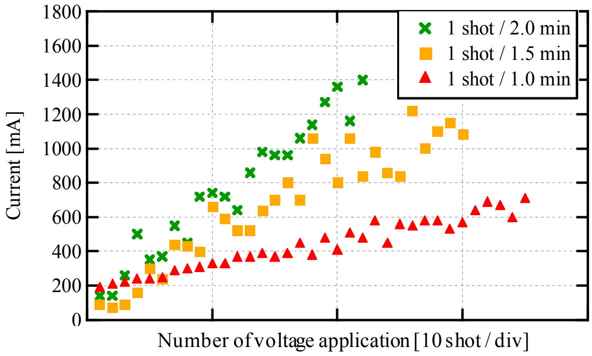

Fig. 6. Microdischarge characteristic to the number of voltage applications for different voltage application interval under 10^{-2} Pa low vacuum (voltage:89 kV).

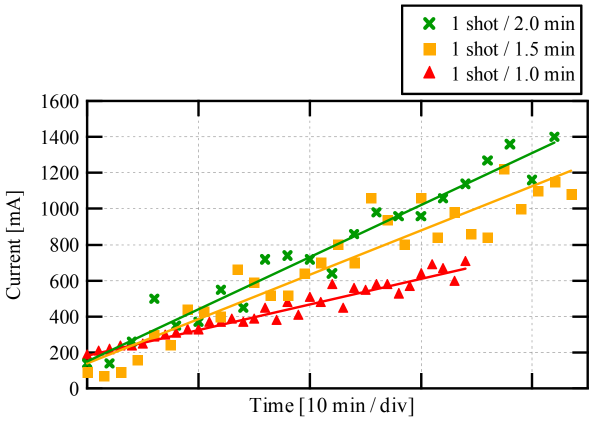

Fig. 7. Microdischarge characteristic to time for different voltage application interval under 10^{-2} Pa low vacuum (voltage:89 kV).

proportional to the number of voltage applications since each voltage application interval is constant. Thus, microdischarge current increases in proportion to time because microdischarge current increases in proportion to the number of voltage applications. Moreover, the longer the voltage application interval is, the greater the increment of microdischarge current between applied impulse voltages is. These may be because the adsorption gas of the electrodes increases in proportion to time, and the longer the voltage application interval is, the greater the increment of the adsorption gas of the electrodes between applied impulse voltages is.

Figure 7 shows the transition of microdischarge to time in each case of the voltage application interval (1 min, 1.5 min, and 2 min) under 10^{-2} Pa low vacuum. In Figure 7, each gradient of approximate line representing the degree of an increase of microdischarge to time is different. These may be because the number of voltage applications per time is different. Namely, decrease of the adsorption gas of the electrodes is different. The more the number of voltage applications per time is, the greater decrease of the adsorption gas of the electrodes is.

We conclude that the amount of the adsorption gas of the electrodes is one of the parameters affecting the amplitude of microdischarge. In other words, since the adsorption gas of the electrodes decreases by generating microdischarge, microdischarge current decreases when the constant impulse voltage is repeatedly applied.

C. Electrode conditioning effect by microdischarge

We found that microdischarge generation reduces the adsorption gas of the electrodes. In order to understand the electrode conditioning effect by microdischarge, we compare spark conditioning with microdischarge conditioning.

For spark conditioning procedure we used up-down method. From V=16.8 kV we change the voltage as voltage step ΔV = 5.6 kV. The method of microdischarge conditioning is as follows. From V=16.8 kV we applied the constant voltage repeatedly. Then, if microdischarge did not appear three times continuously, we raised the voltage. If breakdown occurred, we lowered the voltage. The voltage step ΔV was 2.8 kV in order to avoid the occurrence of the breakdown. We used parallel plane electrodes shown by Figure 1 with the gap length d=5 mm for both experiments.

Figure 8 shows the history of spark conditioning by up-down method. Here, we found that breakdown voltage was enhanced from 28.0 kV to 89.6 kV in the conditioning process.

Figure 9 shows the history of microdischarge conditioning. Here, we found that breakdown voltage was enhanced to 78.4 kV.

The initial breakdown voltage at microdischarge conditioning (53.2 kV) is higher than that at spark conditioning (28.0 kV). These results clearly show that generating microdischarge has the electrode conditioning effect to raise the breakdown voltage.

The electrode surface before and after conditioning was observed with a digital microscope (×500). As a result, in case of before conditioning, we found the certain roughness by mechanical finish of the electrode. In addition, in case of microdischarge conditioning, we could not find any change of electrode surface. On the other hand, discharge traces could be seen by breakdown discharge after spark conditioning. From these electrode surface changes, it is considered that in spark conditioning, the breakdown voltage is raised by mainly reduction of defects such as microprojections due to melting of electrode surface at spark conditioning. On the other hand, microdischarge scarcely melts

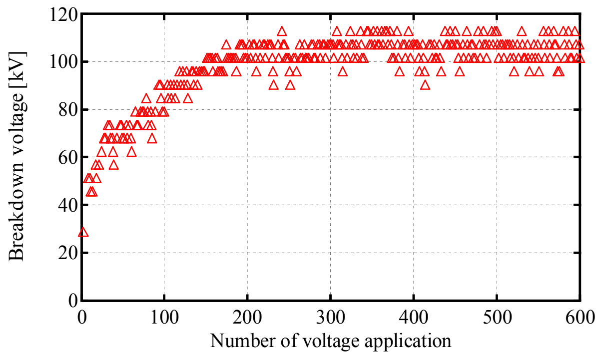

Fig. 8. History of spark conditioning by up-down method.

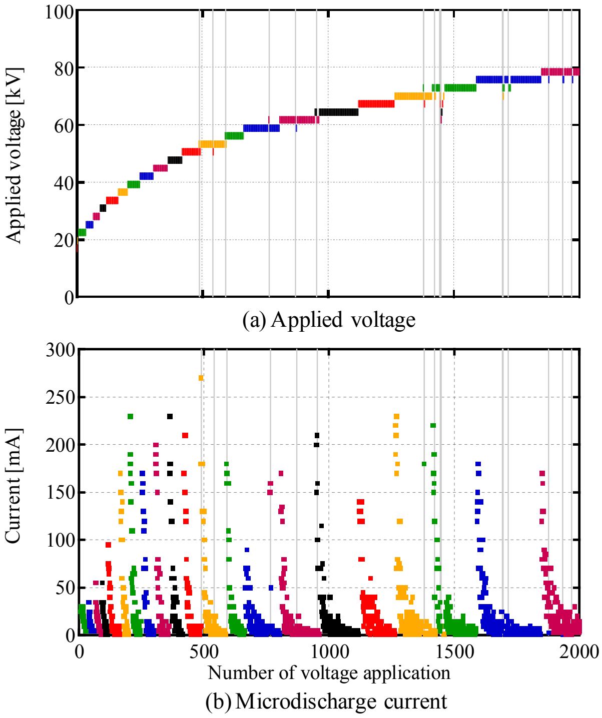

Fig. 9. History of applied voltage and microdischarge current during microdischarge conditioning process.

electrode surface. Therefore, in the case of microdischarge conditioning it is considered that the breakdown voltage is raised by mainly eliminating adsorption gas of the electrodes. The model of changing breakdown voltage in these conditioning processes is shown in Figure 10.

According to Ref [9], injected energy into electrode by breakdown discharge could contribute not only for improving but also damaging the electrode surface, and breakdown voltage after spark conditioning is higher when the injected energy is smaller. In view of this result, microdischarge having very small energy compared with breakdown has a possibility of non-breakdown conditioning technique. However, in this experiment injected energy to electrodes by microdischarge is too small to improve electrodes itself. As a result, the breakdown voltage after microdischarge conditioning might be limited at the lower value than that after spark conditioning.

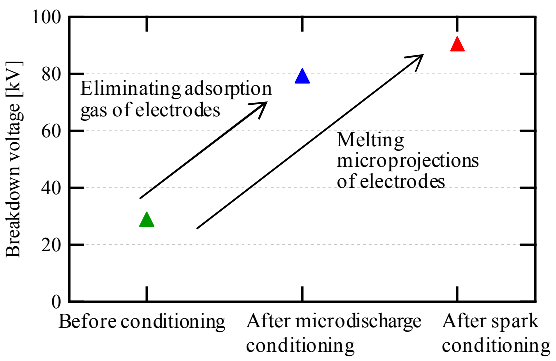

Fig. 10. Model of changing breakdown voltage in different conditioning process.

III. CONCLUSIONS

We investigated the enhancement of breakdown strength by microdischarge under impulse voltage applications in vacuum. The results are summarized as follows.

1. When negative impulse voltage (-30/100µs) was applied to the parallel plane electrode, microdischarge which had pulsed current waveform was generated at the wide region of plane electrodes.
2. The amount of the adsorption gas of the electrodes is one of the parameters affecting the amplitude of microdischarge. It was clarified by changing vacuum pressure that the greater the adsorption gas of the electrodes was, the larger microdischarge current was.
3. Microdischarge generation has the electrode conditioning effect to raise the breakdown voltage. It is mainly due to the reduction of adsorption gas of the electrodes.

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E-mail of authors: aoki@okubo.nuee.nagoya-u.ac.jp