ISBN _______________ XXIIth Int. Symp. on Discharges and Electrical Insulation in Vacuum-Matsue-2006

Pulse forming technology on crowbar circuit of two parallel-connected triggered vacuum gaps

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***Abstract-* Triggered vacuum gaps (TVGs) can work for large current and high voltage in comparison with semiconductor devices, and have advantageous that are shown good switching characteristics for the wide working voltage range with no adjustment of the gap length. However, a switching time of TVG is strongly influenced by the main voltage polarity. It is called polarity effect.**

We found that a circuit of two parallel-connected TVGs generated a crowbar current automatically. When two TVGs used as a start switch and a crowbar switch, respectively, characteristics of the crowbar circuit of two parallel-connected TVGs was examined experimentally.

In this paper, the pulse forming technology in the crowbar circuit which employing two TVGs is examined experimentally. It is clarified that the time to half value of the crowbar current is controlled by inserting a resistor or a capacitor. And the characteristics of the crowbar current are measured.

I. INTRODUCTION

Triggered vacuum gaps (TVGs) are one of switches for high voltage and large current control, and have the following advantages compared with other gap switches [1,2].

(i) Good switching properties are obtained without adjusting the gap length for a wide- voltage range from several kV to tens kV.

(ii) The withstand voltage is high, the electrical discharge space can be miniaturized, and the stray inductance of the switch can be decreased. As a result, high voltage device can be miniaturized.

(iii) Arc voltage is about 20 V and the dissipation is low.

(iv) The insulation recovery after arc discharge is fast.

(v) No audio noise or shock wave is generated.

On the other hand, the switching time that is time difference from triggering to main current flowing is influenced greatly by the voltage polarity of main electrode, as a disadvantage [2]. It is called polarity effect of the switching characteristic [2-4].

If TVGs are applied for unknown voltage polarity, TVGs might not work well as protection devices. One of methods for polarity effect decreasing is parallel connection of two TVGs with reverse polarity of the main electrode [4]. In other words, one of two TVGs works on any polarity surge voltage. And the switching characteristic almost similar to a good polarity effect of single TVG is obtained.

Crowbar current [5,6] circularly flows in the parallel connection circuit, when a coil is inserted in it. This crowbar circuit is simpler than conventional one because it doesn't need delay circuit. We study the crowbar circuit using the polarity effect of TVGs by the simultaneous trigger.

In this paper, the pulse forming technology in the crowbar circuit employing two TVGs is examined experimentally. It is clarified that the time to half value [7] of the crowbar current is controlled by inserting an interruptive resistor or capacitor. And the characteristics of the crowbar current are measured.

II. SWITCHING TIME OF TRIGGERED VACUUM GAP

Schematic diagram of a sealed-off TVG is shown in Fig. 1. Each main electrode is a cylindrical rod of 30mm in diameter, and it is made of the alloy of silver-tungsten-carbide (Ag-WC). One of main electrodes has a central hole of 8mm in diameter. Molybdenum (Mo) trigger pin (trigger electrode) of 6mm in diameter is mounted in this hole. And the holed main electrode and the trigger electrode are insulated in an alumina ceramic (Al_2O_3) tube. The cylindrical insulation chamber is also made from alumina ceramic of 83mm in outer diameter and 200mm in length. The gap distance of two main electrodes can be adjusted up to 20 mm according to changing the position of the non-hole electrode by the help of bellows. The pressure inside vacuum chamber is kept about 1.3×10^{-5} Pa.

The operation process of TVG is thought as follows. A high voltage is applied to main electrodes, and a suitable trigger pulse is applied to the trigger electrode. Trigger discharge generates between a trigger electrode and a holed main electrode. Trigger plasma diffuses between main electrodes by electric field and the density gradient and grows. As the result, the dielectric breakdown of main electrode is caused, and a main current flows. After the main current disappears, insulation of the main electrodes recovers again.

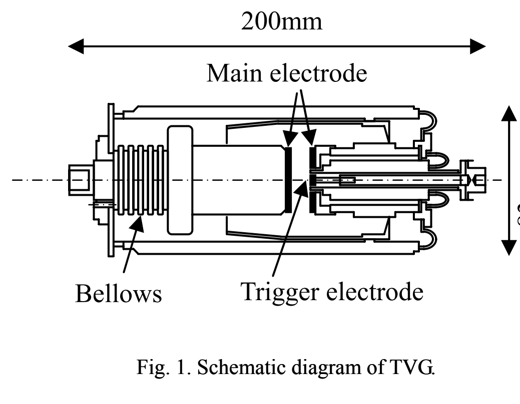

Fig. 1. Schematic diagram of TVG.

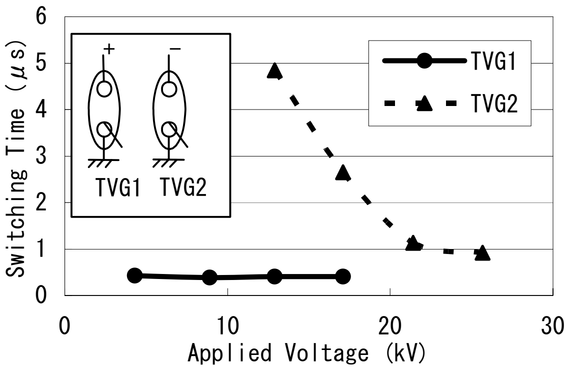

Fig. 2. Switching time of TVG.

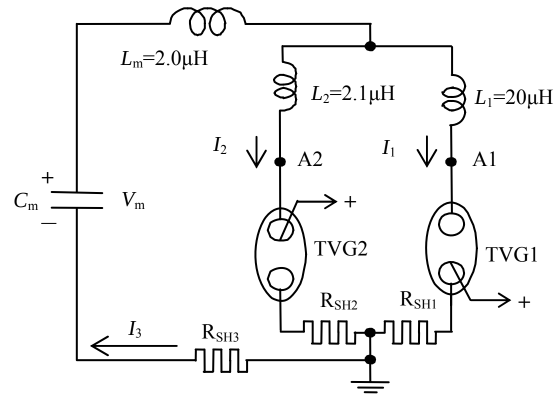

Fig. 3. Experimental circuit.

If the non-hole electrode is positive polarity (M+ mode), trigger plasma expands from cathode with ambipolar diffusion. The diffusion speed of M+ mode is faster than M- mode. Oppositely, M- mode makes the formation delay of the electrical discharge channel between main electrodes. Therefore, in case of M- mode, the switching time from the trigger discharge to main current flowing is late. This is a factor to cause the polarity effect.

A characteristic model of the switching time of TVG is shown in Fig. 2. TVG1 shown a good starting property for a certain applied voltage operates, though TVG2 doesn't operate. When the voltage polarity reverses to M+ mode, TVG2 operates.

III. Pulse Forming for the Crowbar Circuit

A. Experimental circuit and method

The experimental circuit is shown in Fig. 3, and is composed a main capacitor C_m, a load inductance L_1, and two TVGs (TVG1 and TVG2). The inductance L_m = 2.0 μH and L_2 = 2.1 μH in Fig. 3 are stray inductance of the circuit and the TVGs. The currents flowing into two TVGs and the main current are measured by three shunt resistors R_{SH1}, R_{SH2}, and R_{SH3}, as currents I_1, I_2, and I_3, respectively.

The trigger current is detected by a Rogowski coil, and observed with an oscilloscope. The waveform is sinusoidal wave with period of 11 μs.

Period T of the main current I_3 is given by following equation.

$$T \approx 2\pi\sqrt{(L_m + L_1)C_m} \tag{1}$$

First, the main capacitor C_m is charged up to voltage of V_m. Next, TVG1 and TVG2 are triggered at the same time. When TVG1 (M+ mode) and TVG2 (M- mode) connected parallel with a reverse-polarity each other are given the same applied voltage, TVG1 shown good starting characteristic operates. Current flows from positive terminal of C_m through L_1 and TVG1 to negative terminal of C_m.

When the current is the maximum at $t_1 = T/4$, the voltage polarity of the main capacitor C_m reverses, and TVG2 become the good starting characteristic at this time. After the time of t_1, a circulation current, i.e. a crowbar current, flows in the closed circuit composed of L_1, TVG1, and TVG2. The crowbar current attenuates gradually by internal resistance r which is in the circuit including the arc resistance of two TVGs. That is, a crowbar circuit without any delay circuits can be composed by using polarity effect of two TVGs with simultaneous triggering.

Circuit conditions are assumed to be the main capacitor C_m = 0.5 μF and the applied voltage V_m = 8.9 kV. Waveform of main current I_1 is observed with using a digital storage oscilloscope, and the time to half value is measured. For pulse forming, an interruptive resistor R_i = 0.25-2 Ω or capacitor C_i = 17-150 μF is inserted in point A1 or point A2 in Fig. 3.

B. Pulse forming by resistor

When the resistor R_i is inserted at A2 in Fig. 3, current I_1 is obtained by following two equations. After the main current flows, I_1 is expressed by next equation until $t = t_1 = T/4$, where the internal resistance r is neglected for the simplification.

$$I_1(t) = V_m\sqrt{\frac{C_m}{(L_1 + L_m)}} \cdot \sin\frac{1}{\sqrt{(L_1 + L_m)C_m}}t \tag{2}$$

Afterwards ($t > t_1$), I_1 is decreasing exponentially by a time constant of $L_1/(R_i+r)$, where I_m is the maximum value of I_1 at $t = t_1$.

$$I_1(t) = I_m e^{-\frac{R_i + r}{L_1}(t - t_1)} \tag{3}$$

Therefore, in case of inserting resistor, the time to half value T_R is expressed by

$$T_R = t_1 + t_2$$

$$= \frac{T}{4} + \frac{L_1}{R_i + r} \cdot \log_e 2 \qquad (4)$$

where t_2 is time different from peak of I_1 to half value after t_1.

In case inserting the resistor R_i at A1, the time to half value T_R is the same equation as (4).

C. Pulse forming by capacitor

When the capacitor C_i is inserted at A2 in Fig. 3, current I_1 is obtained by following two equations. After the main current flows, I_1 is also expressed by the same equation as (2) until $t = t_1 = T/4$, where the internal resistance r is also neglected for the simplification. Afterwards ($t > t_1$), I_1 flows in the closed circuit composed by a series connection of L_1, TVG1, TVG2, C_i, and the internal resistance r. I_1 is expressed by the next equation,

$$I_1(t) = I_m \{ e^{-\alpha(t-t_1)} \cos\omega(t - t_1) - \frac{r}{2L_1}\frac{1}{\omega} e^{-\alpha(t-t_1)} \sin\omega(t - t_1) \} \qquad (5)$$

where $\alpha = \frac{r}{2L_1}$, $\omega = \sqrt{\frac{1}{L_1 C_i} - \left(\frac{r}{2L_1}\right)^2}$.

When the value of current I_1 is zero, the insulation of TVG is recovered and I_1 is interrupted.

When the capacitor C_i is at A1, the time t_1 is modified t_1' expressed by

$$t_1' = \frac{T'}{4} = \frac{2\pi}{4}\sqrt{(L_1 + L_m)(C_m + C_i)} \qquad (6)$$

where T ' is a modified period of the circuit. Using (5), we can solve the time t_2' that is time difference from peak of I_1 to half value. But we calculate t_2', i.e. the time to half value T_C, by numerical calculation.

On the other hand, the impedance of the capacitor C_i is small at the initiation of current I_1 rise, because the rate of current rise dI_1/dt is very large. Therefore, C_i is not influenced in the initiation of current I_1 rise. However, after TVG2 works, C_i absorbs the energy of the crowbar current and is charged.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Current waveforms are shown in Fig.4. Waveform (a) is a crowbar current without *R*i and *C*i. In the cases of waveforms (b) and (c), *R*i or *C*i is inserted at point A1, respectively. T_0, T_R, and T_C show the time to half value of waveforms (a), (b), and (c), respectively. The internal resistance r obtained by the dumping curve of waveform (a) in Fig. 4 as the dumping time constant of r/L_1 uses to calculate (3), (4), and (5).

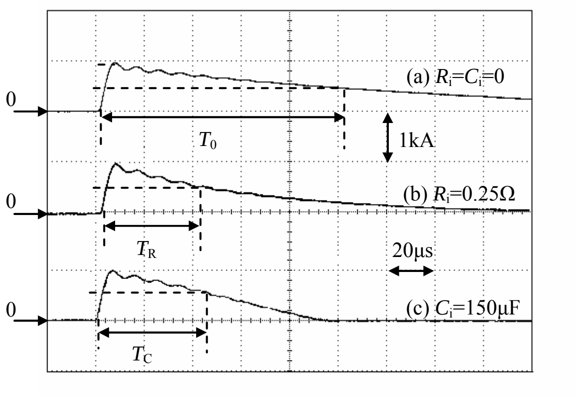

Fig. 4. Crowbar current waveforms.

Figures 5 and 6 show the relation between the time to half value and R_i or C_i. Using (4) and numerical calculation with (6), we can get the theoretical curves of the time to half value T_R and T_C depicted in Figs. 5 and 6. The solid line or dashed line in Figs. 5 and 6 shows at inserting place A1 or A2, respectively. The plotted experimental results fit on the theoretical curves.

In the pulse forming by inserted resistor R_i, the value of time to half value decreases as a function of R_i by the time constant $L_1/(R_i+r)$. Though, there is no influence by the difference of the place A1 or A2 where R_i is inserted.

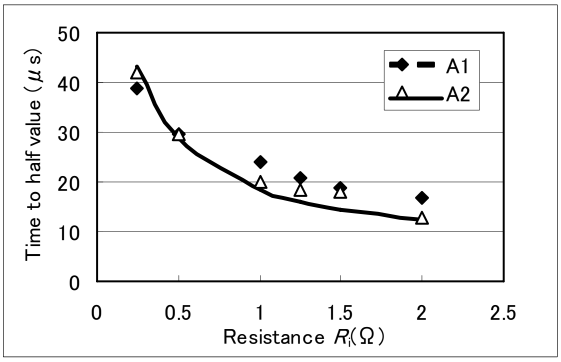

Fig. 5. Time to half value T_R for inserted resister R_i.

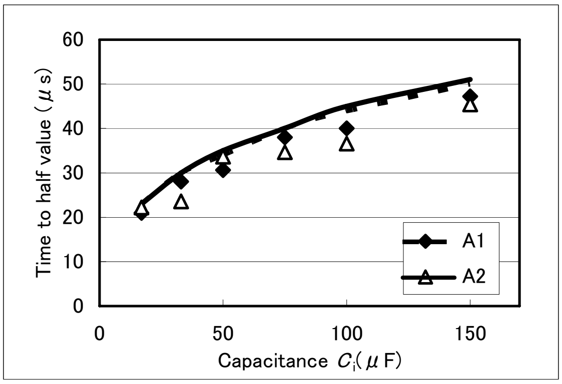

Fig. 6. Time to half value T_C for inserted capacitor C_i.

In the pulse forming by inserted capacitor C_i, the value of time to half value increases as a function of C_i. There is a little influence by the inserting place A1 or A2. The difference causes t_1' from (6).

Therefore, by an inserting resistor or capacitor, the pulse length of the crowbar current that is obtained using two TVGs with simultaneous triggering can be changed.

V. CONCLUSIONS

The crowbar current was obtained using two TVGs with simultaneous triggering. The pulse forming, i.e. the time to half value controlling, was possible by inserting a resistor or a capacitor in the parallel connection of two TVGs with reverse polarity.

Experimental results of the time to half value corresponded with theoretical curves obtained from (4) and (6) well. In the case of inserting a capacitor, there is a little time difference by the inserting place.

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