Micro-Gap Discharge Phenomena in Air and SF₆ Gas

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For improvement of detection techniques on the partial discharges in gas-insulated substations, it is important to make clear the physical process of micro-gap discharge in air and in SF₆ gas.

The discharge current wave shapes and temporal variations of the emitted light were observed using a streak camera, and a simulation of spark-type discharge process in micro-gap was also performed.

The measured results show that as the gap size increases from 0.5 to 3.5 mm, front time $T_f$ and tail time $T_t$ of the discharge current wave shapes in air increase from 1 and 20 ns to 2 and 51 ns, while the current peak value $I_p$ decreases from 2.6 to 0.2 A. On the other hand, in SF₆ gas, $T_f$ and $T_t$ are shorter and $I_p$ is greater than those in air. The measured results on temporal variation of the discharge light show that there is some difference in the wave shapes between the current and the emitted light. The calculated results on the wave shapes of discharge current and emitted photons indicated clearly these characteristics.

Key words: Discharge current wave shape, Discharge light, Simulation of discharge process, Continuity equations for charged particles

1. Introduction

It is well known that partial discharges due to floating metal components and treeing in solid dielectrics may occur in gas-insulated substations and switchgear (GIS), and these discharges at last stage could lead to a serious failure in electric power system. Therefore, for maintaining a GIS it is expected to establish a reliable monitoring system for the immediate detection of partial discharges. In the recent years, the diagnostic techniques have been investigated to detect the partial discharge chemically, mechanically and electrically\(^{(1)}\). However, the properties of the partial discharges are still not completely understood because the physical process involved in partial discharge is complicated. For improvement of detection techniques of partial discharges in GIS, it is important to make clear the fundamental physical process of micro-gap discharge in air and in SF₆ gas.

The present study includes measurement of the wave shapes of discharge current in air and SF₆ gas and of the discharge light emission in the rod-to-plane electrode geometry. Moreover, a simulation of spark-type discharge process in micro-gap was also performed for understanding of the observed experimental results.

2. Experimental setup

Fig. 1 shows the layout of the experimental setup used for the measurement of discharge current wave shapes and of discharge light. It consisted of a high voltage supply, a rod-to-plane electrode geometry and an instrumentation section. The high voltage supply was composed of a battery-driven DC-DC converter and a high voltage pulse generator. The high voltage pulse had a peak value of 1.2 kV, and its front time and tail time were 0.2 and 0.5 μs.
3. Experimental results

3.1 Wave shapes of discharge currents

The electrode geometry shown in Fig. 1 was charged by DC high voltage supply, and its voltage level was set just below the spark onset voltage of the gap. When a high voltage pulse was given to the electrode geometry, the potential of upper plane electrode rose further from its DC voltage level. As the potential difference between the plane and rod electrode reached the spark onset voltage of this gap, a spark-type discharge event accompanied by the emission of discharge light took place.

Fig. 3 shows some wave shapes of discharge currents observed in several different gaps in air and SF₆ gas. In each case, the gas pressure was kept at 1 atm and the DC applied voltages were chosen to lie just below the onset levels of all gap spacings used. From these oscillograms and others, it is clearly seen that the wave shape of discharge current depended strongly on the gap size and on the gas kind.

In the case of air, as gap length was 0.5 mm, the discharge current pulse had a peak value ($I_p$) of...
2.6 A, and a very steep front time ($T_f$) and tail time ($T_t$) of 1.0 and 2.0 ns, respectively. When the gap length was increased, the peak value of current decreased sharply, and the front time and tail time extended considerably. These values were observed to become $I_p=2.1$ A, $T_f=2.5$ ns, $T_t=4.1$ ns in a 1.0 mm gap, and $I_p=0.2$ A, $T_f=19.0$ ns, $T_t=51.4$ ns in a 3.5 mm gap. As the gap length was increased further up to 4.0 mm, not only these values but also the wave shape was different from former cases (Fig. 3 (c)). It had two peaks with the time interval of about 28 ns. The reason of this distortion in large gap is thought to be due to the presence of a remarkable space charge effect. On the other hand, in the case of SF$_6$ gas, the discharge current pulse in a 1.0 mm gap had a greater peak value of about 8.3 A, a shorter front time and tail time of about 1.1 and 2.1 ns respectively, as shown in Fig. 3 (d). The difference between the wave shape of current pulse in SF$_6$ gas and that in air in the same gap can be ascribed to the large values both of inception voltage and of $d(a-\eta)/dE$ and also to the very strong electron attachment ability of SF$_6$ gas.

The amount of electric charge contained in each discharge pulse was derived from the current wave shapes. The results indicated that the electric charge per discharge pulse was in the range from 10 to 20 nC both in air and in SF$_6$ gas. In air, obviously, as peak currents got smaller sharply with the increase of gap spacing, front times and tail times became longer, thus compensating the effect.

It should be noted that in the case of small gap, since a discharge event completed within several nanoseconds or less, the charging action through 5 kΩ resistor had almost no effect upon the discharge process. In this case, the end of discharge pulse depended on voltage drop of the stray capacitance of rod-to-plane electrode, because the spark-type discharge current had a high value. On the other hand, in a larger gap, the discharge duration became relatively long, and the value of current became very low. Therefore, it can be said that discharge phenomenon in the larger gap was affected strongly by the space charges generated during the discharge development and by the voltage drop of rod-to-plane stray capacitance due to flow of the electric charges.

### 3.2 Discharge light

Simultaneously, the discharge light emitted from the discharge gap was also observed with the streak camera and CCD camera. Fig. 4 shows three streak records of discharge light in the atmosphere. In the 1.0 mm gap, the discharge luminosity was found to start from the vicinity of the cathode tip and develop towards the plane electrode, as shown in Fig. 4 (a). After the luminosity crossed the entire gap in 1 ns, the light intensity decreased gradually.
with the passage of time. At the last stage, the
luminous area was restricted only to the vicinity of
the rod tip. This observation indicates that in this
gap the discharge transformed from spark-type to
corona-type at the last stage of discharge process.
But this transformation cannot be seen from the
similar corresponding discharge current wave shape in Fig.
3(b), because the current of corona-type discharge
is much smaller than that of spark-type discharge.

In a 2.0 mm gap, however, the discharge luminos-
ity over the entire gap continued for a longer time
than 3 ns, as shown in Fig. 4(b). The narrow
luminosity associated with the corona-type dis-
charge found in Fig. 4(a) at the last stage of dis-
charge process was not observed in this case. As the
gap length was raised further up to 4.0 mm, more
complicated spatiotemporal variation of the dis-
charge luminosity was observed as shown in Fig.
4(c). It is thought that this temporal variation
Corresponds to the two peaks of current wave shape
in Fig. 3(c).

By applying a digital processing to the digital
outputs of CCD camera, the integrated brightness of
the discharge luminosity over the entire gap space
were obtained as the function of time. The results
are shown in Fig. 5. The integrated brightness at a
moment is thought to be proportional to the number
of photons emitted from the discharge gap at that
time. In other words, the wave shapes of integrated
brightness in Fig. 5 represent the temporal vari-
ations of photon radiation. Obviously, the values of
front time and tail time of the integrated brightness
wave depended on the gap size. Similar to the
current wave shapes, the front times and tail times
of integrated brightness waves in large gaps were
greater than in small gaps. Moreover, in the
4.0 mm gap, as shown in Fig. 5(c), two peaks with
the time interval of about 30 ns were seen. This is
just like the discharge current wave shape in the
same gap, as shown in Fig. 3(c). Fig. 6 shows the
relation between these times and gap size for the
discharges in the atmosphere. In order to compare
with these results, T_r and T_t of current wave shapes
are also plotted in Fig. 6 with broken lines. By
comparing these curves it is found that the
difference in front time between current wave and
integrated brightness wave is smaller than that in
tail time. This fact demonstrates that the excitation
phenomena resemble closely the ionization phenom-
ena at the early stage of discharge and at the later
stage the movement of a large amount of electrons,
which are generated by the earlier ionization phe-
nomena, can only keep the external current for a
relatively long time but causes no further ionization
and excitation.

4. Simulation of discharge

For understanding of observed discharge light
and current wave shapes, a simulation of discharge
process in micro-gap was made based on the contin-
uity equations for charged particles. It was
noticed in the previous section that the duration of
the current pulses both in air and in SF_6 are within
few nanoseconds in the case of the small gaps. On the other hand, the time constant for charging gap electrodes is about 50 ns. Therefore, the discharges in these gaps may be considered independent of the high voltage charging circuit. The single discharge event, thus, can be thought as the neutralization process of electric charges stored in the stray capacitance of rod-to-plane electrode.

4.1 Simulation method

The micro-gap discharge process under an applied electric field can be described by the equations for the spatiotemporal variation of charged particle density including electrons, positive and negative ions.

It is known that the drift velocities of both positive and negative ions are negligible in comparison with that of electrons under same electric field ($v_p$, $v_n << v_e$), and that the diffusion effect of the charged particles can be ignored for the simulation of discharge phenomena for short times in the order of nanoseconds. In this case, the continuity equation for particles can be written as follows:

$$\frac{\partial n_e}{\partial t} + v_e \frac{\partial n_e}{\partial x} = (a - \eta) n_e v_e + n_e^*$$  \hspace{1cm} (1)
$$= a n_e v_e + n_e^*$$ \hspace{1cm} (2)
$$= \eta n_e v_e$$ \hspace{1cm} (3)

where $n$, $v$ are particle density and drift velocity, and the subscripts of $e$, $p$ and $n$ represent electrons, positive ions and negative ions, respectively. Here, $a$ is the first Townsend ionization coefficient and $\eta$ is electron attachment coefficient. $n_e^*$ is the electron generation term exclusive of ionization due to electron impact.

It is considered that in the micro-gap discharge the electron generation term ($n_e^*$) depends mainly on the photoelectric emission effect at the surface of the cathode. Therefore, it can be written in the form

$$n_e^* = \gamma \int_0^G n_{ph} g e^{-\mu x} dx$$  at cathode tip
$$\hspace{1cm} \gamma \int_0^G$$  \hspace{1cm} (4)

where $\gamma$ is photoionization efficiency on the cathode surface, $n_{ph}$ is photon density at point $x$, $g$ is geometry factor and $\mu$ is photon absorption coefficient.

Fig. 7. Partition of gap space for simulation of discharge process.

Here $a$, $\eta$, $v_e$ and other discharge parameters are the functions of electric field strength, and their values vary within wide range due to the drop of rod-to-plane voltage. In order to simplify the calculation, the discharge space was assumed to be restricted within an axisymmetrical cylinder and the cylinder was divided into equiligird disc elements, as shown in Fig. 7. The density of space charges in each disc element was assumed to be uniformly distributed. Based on these assumptions, therefore, the differential Eqs. (1) ~ (3) can be described as follows:

$$n_e(x + \Delta x, t + \Delta t)$$
$$= n_e(x, t)(1 + a_e(x, t) n_e(x, t) \Delta t)$$
$$\times v_e(x, t) \Delta t / \Delta x + n_e(x + \Delta x, t)$$
$$\times (1 - a_e(x + \Delta x, t) n_e(x + \Delta x, t) \Delta x)$$
$$\times (1 - n_e(x + \Delta x, t) \Delta t / \Delta x)$$
$$+ n_e^*(x, t + \Delta t) \Delta t$$  \hspace{1cm} (5)

$$n_p(x + \Delta t)$$
$$= n_p(x, t) + a(x, t) \eta n_e(x, t) \Delta t$$  \hspace{1cm} (6)

$$n_n(x + \Delta t)$$
$$= n_n(x, t) + \epsilon(x, t) n_e(x, t) \Delta t$$  \hspace{1cm} (7)

where $a_e$ is effective ionization coefficient ($a - \eta$), $\Delta x$ and $\Delta t$ are the distance element in axial direction and the time-step, respectively.

Moreover, the numbers of excited molecules decrease with time due to their lifetime. The density of excited molecules at time $t + \Delta t$, $n_{ex}(x, t + \Delta t)$, is determined by

$$n_{ex}(x, t + \Delta t)$$
$$= n_{ex}(x, t) e^{-\delta(x, t) \Delta t} + \delta(x, t) n_e(x, t) \Delta t$$  \hspace{1cm} (8)

$$\times v_e(x, t) \Delta t$$
where $\tau$ and $\delta$ are mean lifetime of excited molecules and excitation coefficient. The second term on the right hand side represents new excited molecules produced by the excitation between $t$ and $t + dt$. Consequently, the photon density, $n_{ph}(x, t)$ can be expressed by

$$n_{ph}(x, t) = n_{at}(x, t)(1 - e^{-\delta t}) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS...
that in the case of air, the photon density goes down to zero from its peak point more rapidly than does the electron density at the same position. The time needed for the photon density at every position to reach its peak point is about 2 ns, very close to the observed result in Fig. 4.

The wave shapes of discharge current and photon corresponding to Figs 8, 9 are shown in Fig. 10. The front time and tail time of discharge current in SF₆ gas are about 0.6 and 0.9 ns, smaller than those of air (2.0 and 4.3 ns). Fig. 10 also indicates that the pulse of photon is remarkably narrower than discharge current pulse in air, and almost equal to each other in SF₆ gas. These calculated results agree well with the experimental findings as shown in Figs 3, 5.

These calculated results indicate that in the case of SF₆ gas a high intensity negative ion cloud is produced very near the tip of rod electrode in shorter time than 4.2 ns after the generation of a trigger electron, and it has strong effect of restricting the growth of the electron avalanche. On the other hand, the negative ion cloud generated in the case of air has low density, and it needs more time to cause same suppression of the discharge in air. This is the reason why the discharge current wave shapes are narrower in SF₆ gas and wider in air, as shown in Fig. 3.

Fig. 11 shows the calculated wave shapes of discharge current and photon in three different gaps in air, while the effect of applied voltage (V) upon the calculated wave shapes is give in Fig. 12.

From Fig. 11 it is found that the peak value of discharge current gets smaller and the duration of discharge pulse gets wider as the gap length is increased. The front times of photon pulses are almost same as those of corresponding current pulses, but the tail times of photon pulses are clearly shorter than those of the current pulses. These tendencies are similar to the experimental results of Figs 5, 6.

Fig. 12 shows the variation of wave shapes of discharge current and photon number as the applied voltage varies from 4.7 to 5.1 kV with the interval of 0.1 kV. The results indicate that the peak value of both discharge current and photon number get sensitively larger, and the shapes become narrower with the increase of applied voltage. This tendency
on discharge current agrees with the experimental results reported in a previous paper\textsuperscript{3)\(5\).}

5. Conclusions

Discharge current wave shapes and discharge light both in air and SF\textsubscript{6} gas were observed. A simulation of spark-type discharge process in micro-gap was also performed. The main results can be summarized as follows.

In the case of air, the spark-type discharge current wave shapes and peak values are affected by the gap spacings. As the gap size increases from 0.5 to 3.5 mm, the front and tail times increase from 1.0 and 2.0 ns to 19.0 and 51.4 ns, respectively, while the current peak value decreases from 2.6 to 0.2 A. The calculated results on the simulation of discharge process show the same tendency. The discharge current in gap larger than 4.0 mm has more complicated shape due to the presence of a remarkable space charge effect.

The discharge current wave shape in SF\textsubscript{6} gas is remarkably different from that in air. For example, in a 1.0 mm gap the current pulse has a peak value of 8.3 A, a front time and tail time of 1.1 and 2.1 ns in SF\textsubscript{6} gas, but these value are 2.1 A in current, 2.5 and 4.1 ns in front time and tail time respectively in air. The simulation results indicate that in the case of SF\textsubscript{6} gas, a high intensity negative ion cloud is formed very near the tip of rod electrode in a time shorter than 4.2 ns after the generation of a trigger electron, and the discharge process is strongly suppressed by these negative ions. However, in the case of air, the negative ion cloud has much lower density and it takes more time to cause the suppression effect.

The observation on the discharge light indicates that in the gaps smaller than 1.0 mm in air, corona-type discharge appears after the end of the spark-type discharge, but it does not appear in large gaps. This phenomena cannot be seen from the measurement of current wave shapes, because the current of corona-type discharge is much smaller than that of spark-type discharge.

There is some difference between the current wave shapes and discharge brightness wave shapes. Their front times are very similar, but the difference in tail time is remarkably large. This suggests that at the later stage of a discharge process the movement of a large amount of electrons can keep the external discharge current, but does not cause new ionization and excitation. The similar tendency are also shown by the calculated results.

The present simulation method is available for calculation of the discharge process in micro-gaps. The calculated characteristics of discharge current and discharge light emission are close to the experimental findings.

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