Potential Distribution Measurement of Surface Discharge Developing on Insulating Material

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A new method is developed for measuring the transient potential distribution of surface discharge. The measuring system consists of a BGO Pockels crystal, an Ar ion laser, a beam expander, a streak camera and a CCD camera. The potential profile of a stepwise surface discharge along a linear path of 50 mm in length is measured with high space and time resolution: 0.1 mm and 2 ns in minimum resolution.

The electric field component parallel to the direction x of the streamer propagation (E_x) is easily computed from the potential profile. E_x near the tip of a negative surface streamer is around 24 kV/cm. There is no significant difference between the profiles of the potential and E_x around the tip of a feather-shape streamer and those of a sector-shape streamer.

Keywords: Pockels, surface discharge, potential distribution

1. Introduction

There are some methods for measuring electrical potential and electric field. In them, a Pockels sensor is based on an electro-optic effect and has the following advantages: (1) it needs no metallic component in itself and scarcely affects the measured space, (2) information on electric field is communicated optically and the method is robust to electromagnetic disturbances, and (3) it has a broad frequency response in the range of dc to GHz.

Surface discharge developing on a dielectric material has a great influence on the insulating performance of electrical apparatuses and electronics devices. Many researchers have measured the propagation characteristics of the surface discharge such as developing length, velocity, inception voltage and flashover voltage⁽¹⁾⁽²⁾. Information on the potential and the field profile along the surface discharge has been required for quantitatively discussing and clarifying the propagation mechanism.

Sensing techniques with a Pockels crystal have been applied to the space charge measurement of electrical discharge⁽³⁾. The techniques are expected to make it possible to directly measure the distribution of potential and electric field of a surface streamer^{(4)~(6)}.

In this paper, a new CCD camera system connected to the streak camera with optical fibers is used and the measurement error caused by the instrumental property is minimized. In addition by squeezing the width of the observing line-area with a cylindrical lens, the space resolution of the measurement system is increased. The transient change of potential distribution with a stepwise surface discharge in air is measured with high space and time resolution.

2. Measurement System

Fig. 1 shows the schematic diagram of the measurement system. The linearly polarized light beam emitting from an Ar ion laser (514.5 nm in wavelength, 50 mW in power, 1.5 mm ϕ in laser diameter) is expanded to 50 mm width with a cylindrical beam expander and squeezed to 0.2 mm thickness with a cylindrical lens, and then is put into a $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO, 16 in relative permittivity ϵ_r) crystal disk (50 mm in diameter, 1 mm in thickness). The BGO crystal has the Pockels effect and the polarization of the light transmitted in it is changed.

Fig. 1. Experimental setup.

Fig. 2. BGO sensor device.

One side of the BGO crystal is grounded and the reverse side has a dielectric-mirror coating as shown in Fig. 2. The laser beam is reflected back by the dielectric mirror on the crystal, and only the x-axis component of it is detected through a polarized beam splitter PBS by a streak camera system. The detected light intensity I_{out} is given by

$$I_{out} = \frac{I_{in}}{2} (1 - \cos k \cdot V_{BGO}) \quad (1)$$

The temporal change in the beam intensity distribution is observed with a streak camera, which is connected to a CCD camera in order to digitize the output light intensity. The connection part between the streak and CCD cameras is composed of not a relay-lens but coupled optical fibers. With this connection system, the infection of the scattered light is eliminated. The minimum space and time resolutions of the measurement system reach up to 0.1 mm and 2-3 ns, respectively.

Equation (1) shows that the detected light intensity changes as a cosine function of a potential difference applied to the crystal V_{BGO} . This relation also shows that there is a limited range in the measured potential difference for holding a single-value relationship between the detected light intensity and the potential difference. This limit is defined as a half wavelength voltage V_{π} . The value V_{π} for this BGO device is 14.5kV.

To calibrate an exact potential value on the BGO, a plate electrode is attached on the BGO and the light intensities are measured for all points on the measured surface of the plate while changing the voltage applied to the plate electrode. From these data, an experimental equation showing the relationship between the output light intensity and the potential on the BGO is derived for all 512 points along the measured path of 50 mm.

3. Experimental Results

3.1 Transient Response Characteristics The transient response characteristic of the sensor system is examined by applying an impulse voltage of 75ns in

Fig. 3. Response waveform for impulse voltage.

Fig. 4. Standard deviation of measured potential.

risetime to the plane electrode that is set on the BGO. The output waveform of the streak system at center of the BGO is compared with the applied impulse voltage as shown in Fig. 3. The system responds well to the applied voltage.

The fluctuation of signal due to various kinds of noise occurring in the laser and the CCD camera is observed on profiles of measured potentials. It is found to depend on the detected light intensity corresponding to the measured potential. The relationship between the standard deviation σ of the fluctuation and the instantaneous measured potential V is estimated based on the experimental data and an example of them is shown in Fig. 4.

In this figure, the value of σ increases with V . In the case of $V = -5$ kV and -10 kV, σ is 0.17 kV (3.4 %) and 0.46 kV (4.6 %), respectively.

3.2 Potential Distribution near Rod Electrode

The potential distribution near a rod electrode is measured to examine the potential calibration method mentioned at the previous section. The 5 mm ϕ rod electrode

Fig. 5. Potential distribution near rod electrode.

is set parallel to the y-axis on the BGO surface in an insulating oil pool to suppress the occurrence of surface discharge. Fig. 5 shows the potential distribution obtained at the moment when the potential of -6.0 kV is applied to the rod electrode. The error bar is added to the potential profile using the relationship shown in Fig. 4.

The theoretical potential is also shown in Fig. 5. It is obtained on the basis of numerical computation using the charge simulation method. The experimental result agrees well with the theoretical one.

3.3 Potential Distribution along a Negative Surface Discharge The potential distribution along a negative surface discharge developing on the BGO is measured using this Pockels sensor system.

When a thread is put on an insulating material, a negative surface discharge on the material propagates along it. A thread (silk or hair, 50 μm in diameter) is put on the BGO crystal as shown in Fig. 2 to control the propagating direction of surface discharge.

By observing the Lichtenberg figure pattern of the surface streamer, which occurs first from a sphere electrode and propagates radially, it is confirmed that the thread has no effect on the figure pattern and the development length of a streamer. It can be considered that the thread hardly has influence on the electric field

Fig. 6. Voltage and current profiles.

distribution inside the propagating streamer.

3.3.1 Overview and Experimental Condition

Negative impulse voltage shown in Fig. 6 is applied to a 6 mm ϕ circular cone electrode. The divergence angle of its tip is 30 degree. Figs. 7 and 8 show the still photograph of the surface discharge and the potential distribution change with the propagation of the surface discharge on the BGO, respectively. The cone electrode is set just on the position of $x = 0$ mm, and the impulse voltage is stressed at $t = -200$ ns. The streak camera observing the potential distribution starts at $t = 0$ ns and ends at 348 ns.

Fig. 9 represents the distribution of E_x , that is, the propagating component of the electric field. This figure is derived from Fig. 8 by considering its gradient.

The first surface streamer (stage "I" in Figs. 6 and 7) occurs around $t = -40$ ns and propagates radially from the cone electrode. As it has been reported the profiles

Fig. 7. Still photograph of negative surface discharge.

Fig. 8. Potential distribution of negative surface discharge

Fig. 9. E_x distribution of negative surface discharge

of potential distribution, electric field distribution and charge density distribution of a surface streamer that occurs first from a sphere electrode⁽⁶⁾, the further discussion about this first streamer properties is omitted in this report.

The surface discharge propagates one more step in the direction of the left (stage "II") and two more steps in the direction of the left (stages "III" and "IV"). Current pulses appear simultaneously in Fig. 6 with the inceptions and the subsequent propagation of these steps. The high potential region also expands in Fig. 8 simultaneously with these steps.

There is an obvious difference in the shape of the streamer at stage II and those at III and IV. At stage II, the streamer propagates in the shape of a feather. On the other hand, at steps III and IV streamer forms in sectors and propagates regularly. The shape of streamer is influenced greatly by many experimental conditions such as the shape of electrode, the power circuit, applied voltage waveforms, the thickness and material of the insulating plate and the guiding method. In general, when a thin plate is used as an insulating plate, and is scratched or partially covered with a thin film as the direction guide for the surface discharge, surface discharge easily propagates in a feather shape.

3.3.2 Steps in Sector Shape The temporal change in the potential distribution with the streamer propagation at stage III is closed up as shown in the bottom part of Fig. 10. These characteristic curves are derived from Fig. 8 by considering cross sections that are vertical to the t -axis. These curves are derived at 10 ns time intervals. When the potential distribution changes rapidly these curves are sparsely spaced, and when it changes slowly they are densely spaced.

Since there is little change between the potential distribution profiles of $t=t_6$ and $t=t_7$, it is natural to say the streamer stops around $t=180$ ns.

The propagation direction components of the electric field E_x can be calculated from the slope of these potential distribution profiles, and the temporal change in its distribution are shown in the top part of Fig. 10. At each time, the distribution of E_x has a triangular profile.

With the propagation of streamer, the outline of E_x profile changes. In the case of $t = t_1$ (130 ns, the streamer starts at this time), E_x has its maximum (23.9 kV/cm) at $x = 3.3$ mm and decreases down to the half value at $x = 4.6$ mm. In the case of $t = t_3$ (150 ns, the streamer is propagating at this time), E_x has its maximum (26.4 kV/cm) at $x = 4.5$ mm and decreases down to the half value at $x = 5.5$ mm. In the case of $t = t_6$ (180 ns, the streamer has already stopped at this time), E_x has its maximum (22.8 kV/cm) at $x = 6.1$ mm and decreases down to the half value at $x = 7.3$ mm.

The E_x profiles of t_1 and t_6 show similar curves. Considering E_x profiles of t_1 shifted the streamer development length (equals to 2.7 mm) along the x -axis, it coincides well with that of t_6 around the tip of streamer. It can be said that the potential distribution around the tip of the surface streamer forms similar profile regard-

less of the order of occurrence when the surface streamer stops.

On the other hand, the maximum value of E_x varies around 24 kV/cm during the propagation. The profiles of $|E|$ along the surface streamer which occurs first and propagates radially from the electrode have been already calculated with charge simulation method⁽⁶⁾. In the neighbor of the tip of the streamer, the intensity of $|E|$ exceeds 25 kV/cm. It is possible to say $|E|$ near the tip of streamer keeps its value around electric-field ionization intensity whether the streamer propagates or stops for a while. The propagation of the surface discharge is affected by not only electric-field ionization but also other factors such as photoionization. To define the strict stop condition for the surface discharge propagation, it is necessary to consider the three dimensional profile of $|E|$ and other parameters such as the emission of light.

During the propagation of the streamer at stage III, the leader is being formed inside streamer. For example, the value of E_x at $x = 2.7$ mm decreases from 21.1 kV/cm (at $t = t_1$) to less than 5 kV/cm (at $t = t_4$). At the time $t=t_6$, the value of E_x in the region of $x = 0 \sim$

Fig. 10. Temporal change in potential and electric field distribution.

Fig. 11. Temporal change in potential at position x along surface discharge.

3.2 mm is below 5 kV/cm.

Fig. 11 shows the temporal change in the potential at position x along the surface discharge. This figure is derived from Fig. 8 by considering cross sections that are vertical to the x -axis. The potential at $x = 6$ mm increases gradually after $t = 180$ ns (at this time, step III stops its propagation). After the propagation stops, charges inside the streamer drifts to the head of streamer and the potential near the head of the streamer is increased.

3.3.3 Step in a Feather Shape The transient changes in the potential and E_x distributions with the streamer propagation at stage II are shown in Fig. 12. These curves are also derived at 10 ns time intervals. Fig. 13 shows the temporal change in potential at position x along surface discharge. As the streamer propagates over the observed line area, the potential and E_x profiles during the propagation are shown in Fig. 12. As these profiles lie at approximately equal spaces, the streamer propagates without stagnation at stage II.

The distribution of E_x has a triangular profile whose size is similar to that at stage III.

The maximum value varies around 24 kV/cm during

Fig. 12. Temporal change in potential and electric field distribution.

Fig. 13. Temporal change in potential at position x along surface discharge.

the propagation like that at stage III. Considering the movement of the high E_x region shown in Fig. 9, the streamer propagates at the velocity of the same order as at stage III.

During the propagation of the streamer, there is no significant difference between the profiles of the potential and E_x around the tip of the streamer at stage II and those at stage III. Taking the final shape as shown in Fig. 7 into account, the curvature radius of the streamer at stage II is estimated smaller than that at stages III and IV. It is possible to say that at stage II the electric field $|E|$ around the streamer tip is bigger than that at stage III, and it is easier to maintain the streamer propagation.

4. Conclusions

An optical method was developed for measuring the transient potential distribution of surface discharge using Pockels effect. The potential profile of a surface discharge along a linear path of 50 mm in length was measured in the range of $0 \sim \pm 14.5$ kV. The space and time resolutions of this system reach 2 ns and 0.1 mm, respectively.

The experimental results obtained from the potential distribution measurement of negative surface discharge are summarized as follows: The electric field near the tip of a negative surface streamer is around 24 kV/cm. When the stepwise surface streamer stops its propagation, the potential distribution around the tip of it forms similar profiles regardless of the order of occurrence. There is no significant difference between the profiles of the potential and E_x around the tip of a feather-shape streamer and those of a sector-shape streamer. To define the strict stop condition for the surface discharge propagation, it is necessary to consider the three dimensional profile of $|E|$ and other parameters such as the emission of light.

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