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# Prebreakdown Phenomena of $SF_6$ Gas in a Non-uniform Field Disturbed by a Metallic Protrusion

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## Abstract

This paper deals with the prebreakdown phenomena of $SF_6$ gap stressed by non-oscillating and oscillating impulse voltages in a strong inhomogeneous field disturbed by a fixed needle shaped-protrusion on the earth-side electrode. The breakdown voltage-time characteristics were measured for both positive and negative polarities and over the gas pressure range of 0.1~0.5 MPa, and the temporal developments of the prebreakdown were observed by a shunt of 50 Ω. The dependence of the leader stepping time on the gas pressure were obtained. The local field enhancement due to the space charges, which is produced by the streamer corona, has influence with the electrical breakdown of the test gap. The first streamer corona is only a necessary condition for the electrical breakdown and the subsequent ionization activities launch the leader at the local field region.

## 1. Introduction

The sulphur-hexafluoride($SF_6$) is a gas of widespread use as the insulating and quenching mediums in high-voltage equipments, because of its high dielectric strength and excellent heat transfer properties.

FTOs(fast transient overvoltages) act as travelling surges originating from the disconnecting switch and have oscillation frequencies up to more than 100 MHz. The dielectric strength of $SF_6$ gas stressed by FTOs is very sensitive to the local electric field disturbed by conducting-particles. Paschen's law is not generally valid in inhomogeneous field, the anomalies arising from space charge effects are observed. Numerous experimental and theoretical investigations have been carried out on the dielectric breakdown behaviors of $SF_6$ gas for quasi-uniform electric fields and D.C or well-defined voltages. In particular, in order to improve the reliability of GIS, the understanding of the discharge phenomena of $SF_6$ gas and the detailed study for the influences of conducting particles on the discharge development are of great important[1]-[4].

Further works of the discharge phenomena of $SF_6$ gap stressed by fast transient overvoltages in inhomogeneous field caused by the conducting-particles need to be investigated. The aim of this work is to present informations on the prebreakdown phenomena of the conducting-particle initiated breakdown. The experiments have been performed by using non-oscillating and damped-oscillating impulse voltages in the simplified coaxial cylindrical electrode arrangements.

The experimental apparatus was made of a 400 kV real-sized GIS arrangement. The breakdown voltage-time characteristics and prebreakdown developments were measured. All signals were recorded by a transient digitizer having a bandwidth of 350 MHz. In addition, the prebreakdown behaviors are discussed in detail based on the waveform of corona current pulses.

## 2. Experimental

The experimental apparatus used here was designed to simulate the fast transient overvoltages that might be generated in GIS during the operation of disconnector. The voltage applied to the test gap was measured by a conical type electric field probe[5]. The test voltages were non-oscillating impulse of 1.7/44 μs and damped-oscillating impulse voltage of 400[ns]/1.14 MHz. The electric field of test gap was disturbed by a stainless steel needle-shaped protrusion on the earthside electrode. In order to minimize the displacement current, the needle-shaped protrusion was electrically isolated from the earthed electrode. Curvature radius and length of the needle-shaped protrusion are 0.3 mm, 15 mm, respectively. And the distance between the inner electrode and the tip of needle-shaped protrusion is 22 mm. The prebreakdown current was observed by a shunt of 50 Ω. All signals were recorded by an oscilloscope having a bandwidth of 350 MHz(Tek. 2440). The pressure vessel was evacuated to 0.13 Pa and then commercial grade $SF_6$ gas was filled. Fig.1 shows the cross-sectional view of the coaxial cylindrical electrode geometry. The outer and inner cylinder radii are 54 mm and 17 mm, respectively.

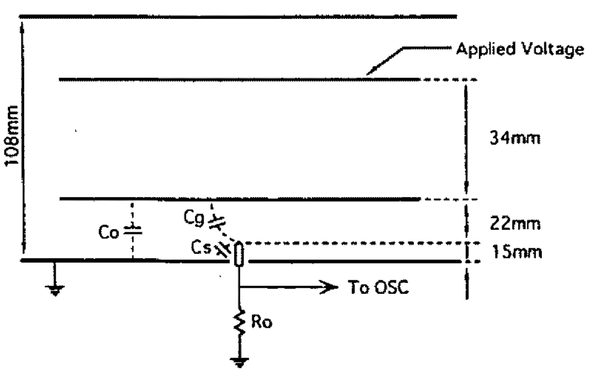



Fig.1 Cross-sectional view of the coaxial cylindrical electrode geometry

## 3. Results and Discussion

The prebreakdown developments strongly depend on the applied voltage waveform, which affects the leader propagation across the test gap. In particular, in the presence of the negative polarity the time to breakdown of oscillating impulse voltage is noticeably longer than that of non-oscillating impulse voltage. Also, the time-lag of electrical breakdown on the wave tail is mainly subject to the field stabilization due to streamer corona space charges[6]. An electrical breakdown at the falling part of wave tail and/or trough part of oscillation can only take place if the leader overcomes the reduction of electric field caused by the variation of the applied voltage and space charges. The prebreakdown development is interrupted as the electric field strength is decreased by an oscillation of applied voltage. The consequence brings on a long time-lag between the leader steps. However, the prebreakdown development for non-oscillating impulse voltage is continuous and leads to an electrical breakdown in the short time.

Fig.2 shows the applied voltage and prebreakdown current waveforms in the positive and negative non-oscillating impulse voltages for a gas pressure of 0.2 MPa. Also the prebreakdown developments mainly depend on the gas pressure and the applied voltage waveform. A prebreakdown development is initiated by the first streamer corona from the tip of a needle-shaped protrusion and is propagated by a stepwise leader regime. The first streamer corona for lower gas pressure is started by a pronounced pulselike current, and it was gradually decreased with increasing the gas pressure.

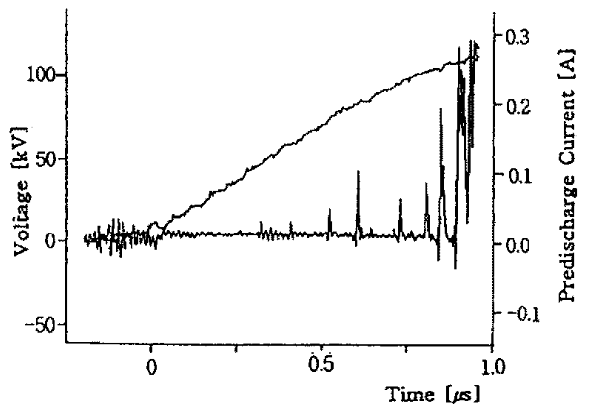
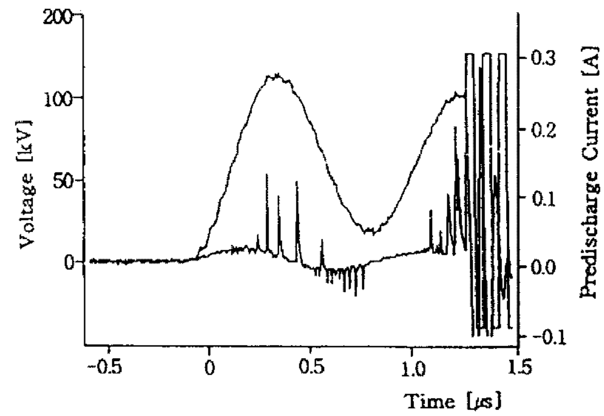


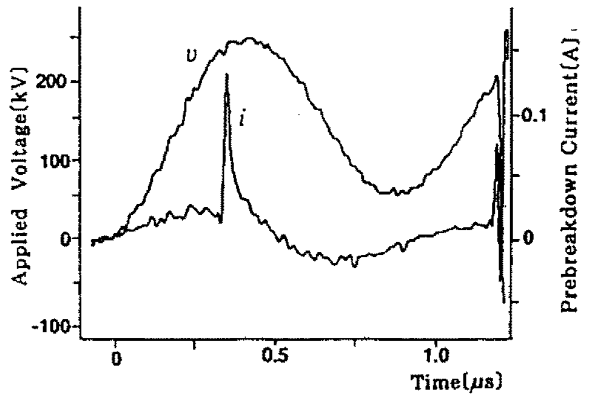

Fig.2 Applied voltage and prebreakdown current waveforms for non-oscillating impulse voltages

Also the weakly conductive plasma channel then is formed by streamer corona in front of the needle-shape protrusion at which the electric field becomes quasi-uniform. The streamer to leader transition for higher gas pressure is formed and the leader propagates with stepwise into the gap. The electrical breakdown takes place as the leader jumps across the gas gap. That is, it is inferred that the breakdown would take place by streamer corona sequences at the tip of the conductive plasma channel.

Fig.3 shows the voltage and prebreakdown current waveforms for the positive and negative oscillating impulse voltages. Comparing breakdown voltages between the data for the non-oscillating and oscillating impulse voltages, there is little difference, but the different regimes of the prebreakdown developments were observed.




(a) Positive



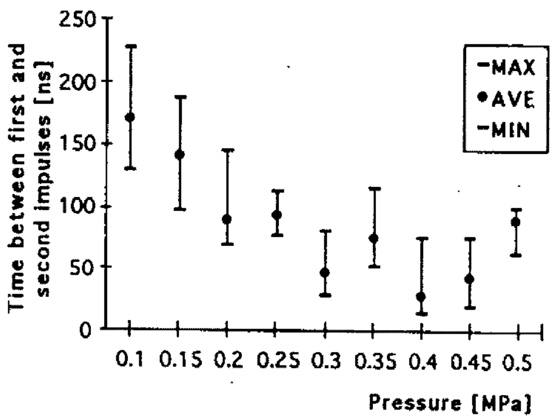

(b) Negative

Fig.3 Applied voltage and prebreakdown current waveforms in the positive and negative oscillating impulse voltages for a gas pressure of 0.2 MPa

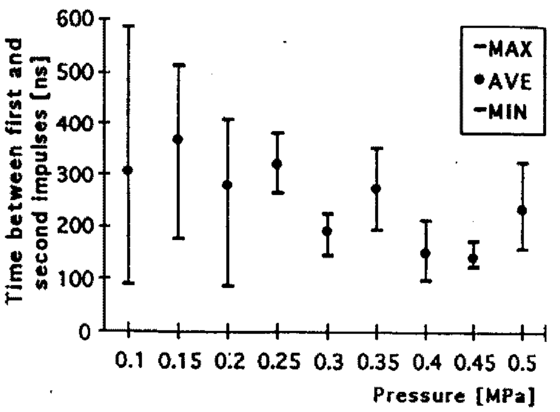
The prebreakdown currents in the positive polarity are bipolar corresponding to the oscillation of applied voltage. Similar observations of the prebreakdown developments were reported by S. Matsumoto et al.[8]. The first corona at the rising part of positive applied voltage takes place in front of the needle-shape protrusion and forms positive ion space charges. The positive leader then propagates with stepwise toward the opposite electrode. When the potential of the needle-shaped protrusion is decreased by the oscillation of applied voltage, there exists the potential difference between the needle-shaped protrusion and the positive space charges. This process reforms an electric field in the direction opposite to the leader development, and then the negative pulselike current flows. The implication is that the backward prebreakdown processes develop toward the needle-shaped protrusion. If the variation rate of applied voltage is slower than the diffusing time of positive space charges, the unidirectional prebreakdown current flows. The diffusing time of positive space charges determines whether a bipolar current flows or not.

The bipolar prebreakdown current is mainly related to the oscillation frequency of applied voltage, gas pressure and gap geometry. The negative prebreakdown development is started by the first streamer corona, which is a very small at the front part of oscillation wave. The prebreakdown development pattern is essentially similar to the positive prebreakdown current waveform. The accompanying current pulse is extremely larger than that of the first corona current. But after the appearance of strong corona current pulse, the leader is stopped, and a bipolar current is fainter than that for the positive polarity.

Fig.4 shows the dependence of the first streamer corona to leader transient time on the gas pressure under the non-oscillating impulse voltages. The vertical lines indicate the range of the first streamer corona to leader transient times which were not constant, and were determined from the data of more than 5. The time interval between the first and second streamer corona pulses in the positive and negative polarities gives a decreasing trend of $T_1$ with gas pressure and results in somewhat of an increase for a gas pressure of 0.5 [MPa]. In the presence of the same gas pressure, the most frequent values for the time intervals $T_1$ in the negative polarity are approximately twice that compared to those in the positive polarity. In particular, the deviation of the time intervals $T_1$ in the negative polarity is appreciably pronounced for lower gas pressure and it might be related to the statistics of inception of an effective shielding streamer corona. The reduced time interval $T_1$ with increasing gas pressure means that the leader should be more rapidly launched and developed through a stepwise process.




(a) Positive



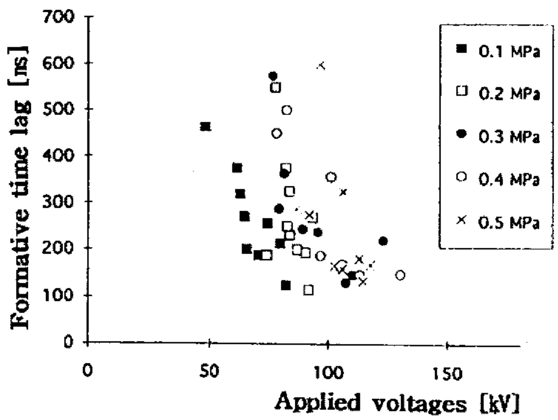

(b) Negative

Fig.4 Dependence of the first streamer to leader transition time on the gas pressure.

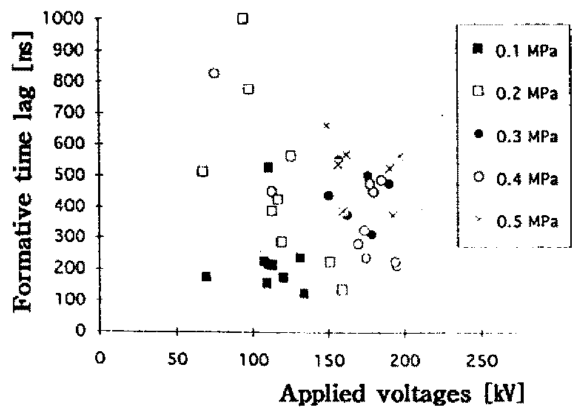
Fig.5 shows the formative time-lag to breakdown, which is inversely proportional to the applied voltage. The formative time-lags for the minimum breakdown voltage in the positive polarity are on the whole shorter than those recorded in the negative polarity. Since the leader in the positive polarity is developed by the avalanches due to the electrons produced by the detatchment from the negative ions of $SF_6$ gas, the electrical breakdown must be formed for a short time. The considerable differance between the positive and negative formative time-lags originates from the prebreakdown process.

The stem mechanism has only been observed under the negative polarity where it occurs together with the precursor mechanism. But the precursor mechanism is the only leader inception mechanism active under the positive polarity, and the dominant one under the negative polarity. As a result, the corona stabilization is more effective in case of the negative polarity.

The leader stepping time, which is the pause time between steps, is required to create a new leader precursor or stem and is strongly dependent on the gas pressure.




(a) Positive




(b) Negative

Fig.5 Formative time-lag to breakdown.

Fig. 6 shows the relationship between the leader stepping time and the gas pressure in the positive polarity under the oscillating impulse voltage stress. The leader stepping time $T_S$ is determined from the oscillogram of the prebreakdown current waveforms. The vertical lines and the circle marks indicate the variation range of the leader stepping time $T_S$ and the average values, respectively. The leader stepping time $T_S$ decreases with increasing the gas pressure and its change is insignificant for gas pressure of more than 0.3 MPa.

Irregularity of the leader stepping time $T_S$ is prominent for lower gas pressures and it exhibits a declining tendency as the gas pressure increases. It was observed that the streamer corona current for lower gas pressures is more intensive and the probability of direct breakdown, which indicates a space charge controlled streamer breakdown, is increased. Because the applied voltage is a damped oscillating impulse voltage, it is not obvious whether the fluctuation of the leader stepping time $T_S$ is dominantly caused by the effect of corona space charges with a gas pressure or by the variation of applied voltage level. The leader propagation for a low gas pressure seems to be markedly influenced by the space charges effect due to streamer corona current level. As the gas pressure increases, the attachment coefficient of $SF_6$ gas is increased and the radial development of the streamer corona sheath is reduced, the stepwise leader is frequently propagated.

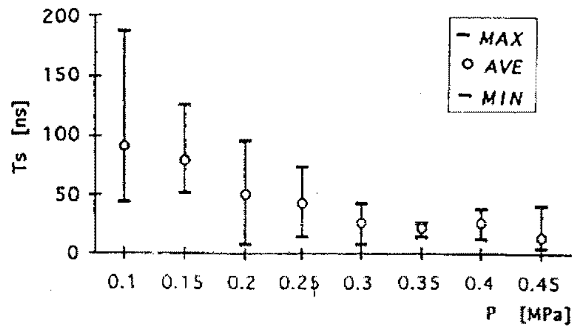



Fig.6 Leader stepping time plotted as a function of the gas pressure.

## 4. Conclusions

To obtain the information on the breakdown mechanism of $SF_6$ gas caused by fast transient overvoltages, the prebreakdown phenomena of $SF_6$ gas under non-oscillating and oscillating impulse voltages were investigated using a actual-sized GIS modeling apparatus. As a consequence, a single avalanche alone in inhomogeneous field contaminated by a conducting-particle is too weak to give rise to the electrical breakdown of the gas gap, and some other criteria such as the streamer to leader transition and the critical volume formation of space charges are necessary to bridge the test gap. The breakdown voltages of $SF_6$ gas in inhomogeneous field are noticeably influenced by the waveform and polarity of applied voltage. It was found that the outstanding difference between temporal pre-breakdown developments for the non-oscillating and oscillating impulse voltages mainly results from the space charge effects. Bipolar prebreakdown currents were observed when the test gap was stressed by the oscillating impulse voltage.

## 5. References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