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A Method to Monitor Vacuum Degree Using Capacitive Partial Discharge Coupler

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Abstract – Internal pressure of vacuum interrupter (VI) is one of the most important parameters in VI operation and may increase due to the outgassing from the materials inside VI or gas permeation through metal flange or ceramic vessel. The increase of the pressure above a certain level leads to the failures of switching or insulation. Therefore, an effective pressure check of VI is essential and an analysis of partial discharge (PD) characteristics is an effective monitoring method to identify the degree of the internal pressure of VI. This paper introduces a research work on monitoring the internal pressure of VI by analyzing PDs which were measured using a capacitive PD coupler. The authors have developed cost effective capacitive coupler based on the ceramic material that has an excellent insulation properties and the main component of the capacitive coupler is made by SrTiO3. Detectable internal pressure range and distinguishability of the internal pressure of VI were investigated. From the PD tests results, the internal pressure range, from 10^{-2} torr to 500 torr, can be monitored by PD measurements using the capacitive coupler and PD inception voltage (PDIV) follows the Paschen's law. In addition, rise time of PD pulse at 13.2kV decreases with the increase of the internal pressure of VI.

Keywords: Vacuum interrupter, Partial discharge, Capacitive coupler, Rise time

1. Introduction

Circuit breakers for medium voltage classes are mainly vacuum types. Recently, the higher interruption ability and operating voltage of a vacuum circuit breaker (VCB) have brought wider use of VCB in the field of switchgear. This situation was accelerated with the need of environment friendly power equipment [1]. The degree of vacuum in a vacuum interrupter (VI) is very important because VCB has excellent switching performance in the high degree of vacuum. However, the internal pressure of the VI may gradually increase due to the outgassing from the materials inside VI and the gas permeation through metal flange or ceramic vessel after a long period service. Switching capability and insulation performance of interpoles are the most important characteristics of VCB, and those are remarkably affected by gas pressure of VI. Therefore, a monitoring of the gas pressure of VI has been one of the effective diagnosis techniques in VCB operation [2].

Test methods such as magnetron emission current, high frequency current, interpole breakdown voltage, arc voltage type, and X-Rays have been used for measuring the gas pressure of VI [3, 4]. These off-line methods require the interruption of service for measuring the vacuum degree of VI. To overcome the disadvantage of the off-line methods, the on-line monitoring techniques are needed. Studies on the on-line monitoring the vacuum degree of VI based on the partial discharges (PDs) have been reported recently. The PDs occur between the arc shield and the closed electrodes in VI when the internal pressure of VI is increased at certain range.

Operating voltage of VI, which is applied between the closed electrodes and the earth, is divided into two distributed voltages, one is distributed between electrodes and the arc shield, and the other is applied between the arc shield and the earth. Larger voltage applied between the electrodes and the arc shield gives better sensitivity and more extensive measurable pressure range according to the PD measurements. Therefore, capacitance between the arc shield and the earth should be much bigger than the capacitance between the electrodes and the arc shield. Sensors, such as the air capacitive coupler, antenna, electric field sensor and electro optical sensor installed in the electric field between the arch shield and the earth have been used for measuring PD in VI. However, these methods are not expected to give good sensitivity and measurable pressure range because the capacitance between the arc shield and the earth is similar or smaller than that between the electrodes and the arc shield. Therefore, the capacitive coupler which has much greater capacitance than the capacitance between the electrodes and the arc shield should be inserted between the arc shield and the earth. The authors have developed a cost effective capacitive coupler using the ceramic materials. The main material of the sensor is SrTiO3.The sensor has been

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designed to have excellent insulation performances and larger capacitance comparing to the capacitance between the electrodes and the arc shield.

This paper introduces a research work on the monitoring the vacuum degree in VI using the capacitive coupler. The sensor is electrically connected between the arc shield and the earth. Voltage distribution between the electrode and the arc shield in VI according to the existence of the sensor was carried out for considering the effects of the sensor capacitance to the voltage distribution in VI. The PD inception voltages and PDs at 13.2kV with various vacuum degrees inside VI were measured using the capacitive PD coupler. In addition, the trend of rise time of PD pulses was obtained through the PD tests. The results of the above tests prove that the detectable pressure range in VI using the capacitive coupler was approximately from 10^{-2} torr to 500 torr and the rise time of PD pulse could be a good indicator to estimate the internal pressure of VI.

2. Specification of capacitive coupler PD sensor

The on-line PD test has become a popular test for insulation condition assessments. Many different types of sensors such as capacitive coupler, inductive coupler, and current transformer have been developed for detecting PD pulses. The epoxy mica capacitive coupler (EMC) developed in North America has been extensively used for on-line PD detection in electric machines. The EMC has excellent electrical properties because it has sufficient layers of epoxy impregnated mica. However, the fabrication of EMC is difficult and this results in more production cost. The authors have developed a cost effective capacitive coupler based on ceramic material that has a simple manufacturing process and excellent insulation properties. Fig. 1 shows the structure of the developed sensor. Main component of the sensor is SrTiO3 and the sensor consists of several cylindrical types of blocks those are electrically connected in series. Various performance test were carried out and given in Table 1. The insulation performances such as power frequency and lightening impulse voltage indicate that the sensor have enough insulation levels to meet the withstand voltages of medium voltage class VI [5].

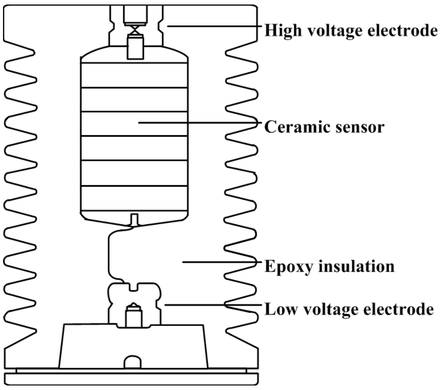


Fig. 1. Structure of capacitive coupler

Table 1. Incipient electrical characteristics of capacitive coupler

Test Items	Electrical Characteristics
PD inception voltage	more than AC 30kV
Dielectric loss	0.03% at 20kV, room temperature
Dielectric loss at high temperature	0.69% at 20kV, at 130°C
AC Dry flashover voltage	101.9kV rms
Lightening impulse flashover voltage	191.4kVp(positive), 223.8kVp(negative)
Lightening impulse withstand voltage	110kVp/±15

3. Voltage distribution in VI

3.1 Numerical analysis

Fig. 2 represents structure and equivalent circuit of VI. Voltage distribution forced on electrodes and arc shield in VI can be express as

$$V_a = \frac{C_s}{C_a + C_s} V_0 , \quad V_s = \frac{C_a}{C_a + C_s} V_0 \tag{1}$$

where V_a is the distributed voltage between the electrodes and the arc shield, C_a is the capacitance between the electrodes and the arc shield, V_s is the distributed voltage between the arc shield and the earth, C_s is the capacitance between the arc shield and the earth and V_0 is the applied voltage between the electrodes and the earth. Since C_a is greater than C_s during the normal operation of VI without capacitive coupler, the distributed voltage between electrodes and arc shield is smaller than that of voltage between arc shield and earth. The small distributed voltages can prevent the occurrence of PD even if the internal pressure of VI increases. In addition, this can reduce magnitudes of PD even if the PDs were occurred. Therefore, monitoring the vacuum degree in VI based on the PD measurements without capacitive coupler has low satisfaction. However, if a capacitive coupler which has greater capacitance comparing to C_a is connected in parallel with C_s , Eq. (1) can be modified as Eq. (2) and the capacitance between the arc shield and the earth becomes $C_s + C_c$.

$$V_a = \frac{C_s + C_c}{C_a + C_s + C_c} V_0 , \quad V_s = \frac{C_a}{C_a + C_s + C_c} V_0 \tag{2}$$

where C_c is the capacitance of the capacitive coupler. Therefore, the distributed voltage between the electrodes and arc shield becomes much greater than the voltage between the arc shield and the earth. This makes the occurrence of PD when V_a becomes equal or greater than the partial discharge inception voltage (PDIV) and improves sensitivity for measuring PD.

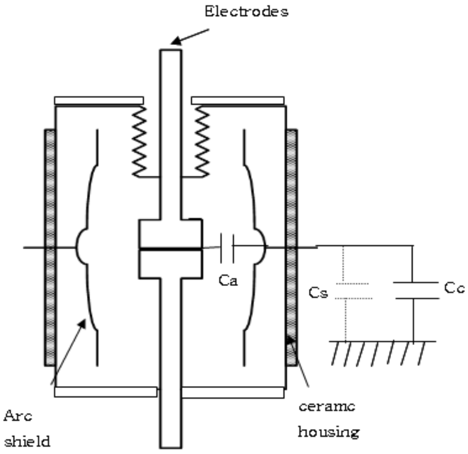
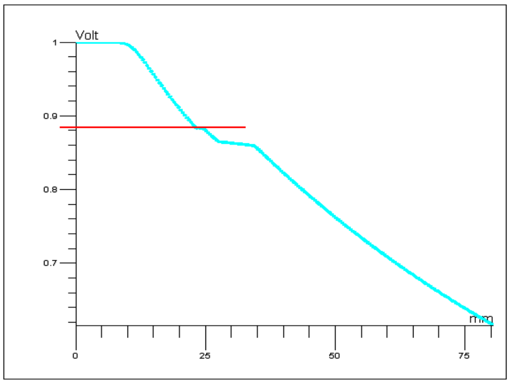


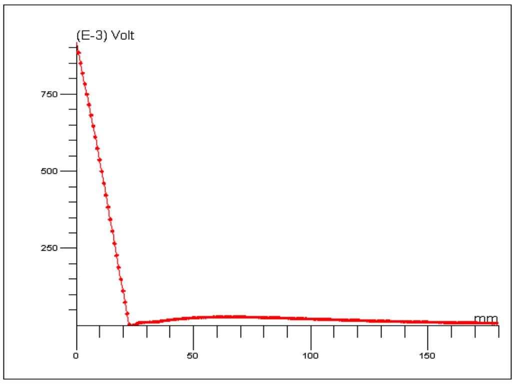
Fig. 2. VI structure and equivalent circuit

3.2 Computer simulation results

Analysis results of voltage distributions in VI according to the existence of the sensor are represented in Fig. 3 using Flux 2D program. Fig. 3 also shows that the voltage without capacitive coupler is 12% of the applied voltage and the voltage with capacitive coupler is 98% of the applied voltage. Hence, as same as the numerical analysis, the voltage between the electrodes and the arc shield becomes large when the capacitive coupler is connected in parallel with the capacitance between the arc shield and the earth.



(a) without sensor



(b) with sensor

Fig. 3. Voltage distribution analysis around VI

4. Partial discharge tests

4.1 Pattern analysis of PD

PDIV tests were performed into two types of VIs those have the same rated voltage, 25.8kV, and different rated interrupting currents, 25kA and 40kA. Fig. 4 depicts the diagram of the experimental setup for measuring PD according to the various vacuum degrees in VI. A vacuum pump is connected with VI to control the vacuum degree in VI and its control range is from 10^{-5} torr to 750 torr. PDIVs are measured for AC 60Hz and the maximum applied voltage corresponds to 13.2kV on the rated phase to earth voltage. The effect of the background noise is negligible because the magnitude of PD at the PDIV is larger than that of the background noise. Fig. 5 shows PD patterns at the PDIVs and the PDs in the patterns were measured by an oscilloscope during 100 cycles. Fig. 6 represents the PDIV characteristics of two types of VI according to the internal pressure of VI and each test was performed two times. As shown in Fig. 6, PDIVs can be detected in pressure ranges of 10^{-2} torr ~ 500 torr and have similar pattern by following the Paschen's law regardless of interrupting capacity. Meanwhile, it has been reported that PDIV with CT was only detectable in the pressure range of 2 ~ 50 torr at 13.2kV basis [6]. This indicates that the method with capacitive coupler has high sensitivity for measuring PD comparing to the conventional method.

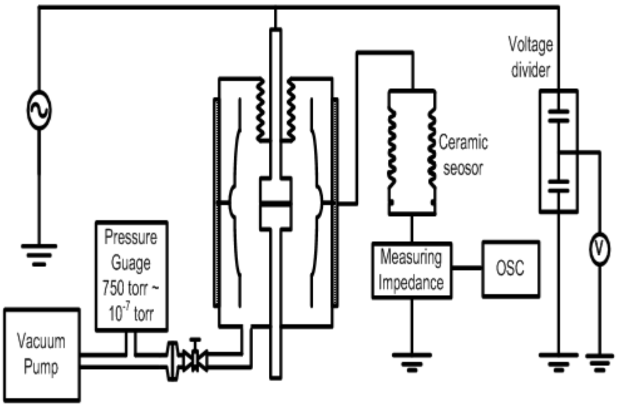
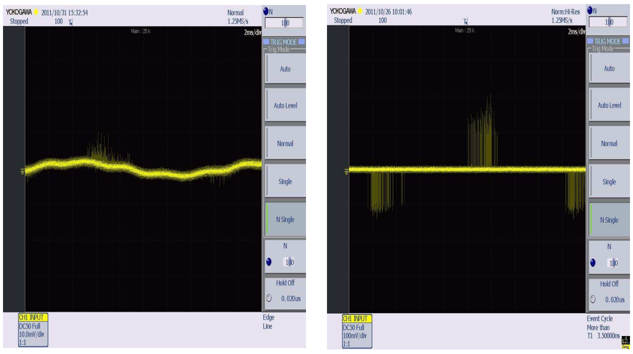
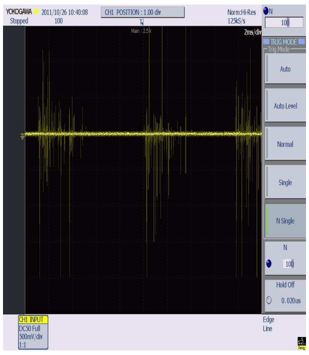


Fig. 4. Diagram of the experimental setup



(a) 2x10^{-2} torr (b) 1 torr



(c) 500 torr

Fig. 5. PD patterns at the PDIVs

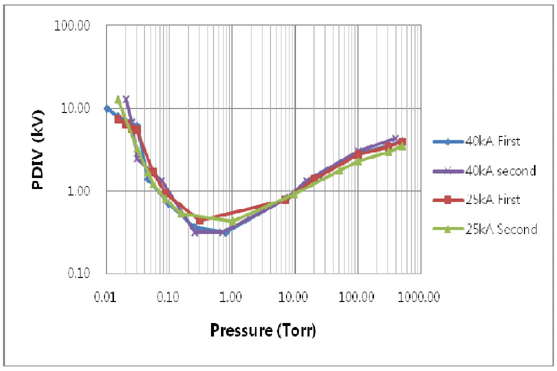
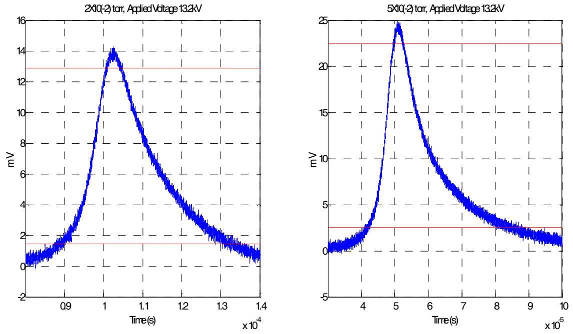


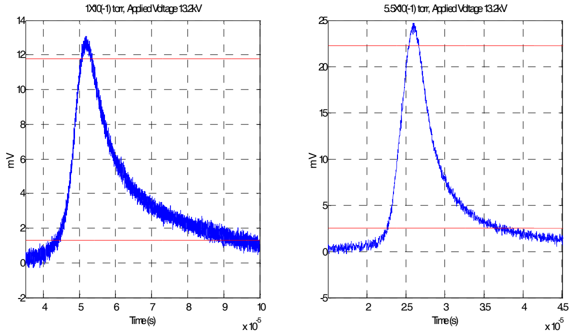
Fig. 6. PDIV as a function of the internal pressure of VI

4.2 Waveform analysis of PD

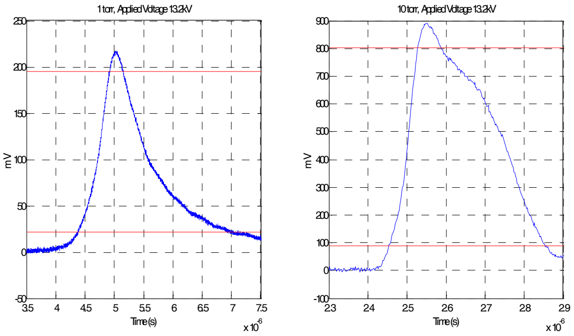
The analysis of present pressure inside VI is important for estimation of residual life of VI pressure increase. In this study, relations between characteristics of PD waveform and VI pressures were investigated. The waveform of PD pulse is known to be changed according to the vacuum degree [7]. Fig. 7 represents waveforms of PD pulses according to the internal pressure of 40kA VI. The measurement results indicate that waveforms of PD pulses change with the change of the internal pressure. The waveforms can be characterized by rise time, decay time, width and amplitude of the pulse. Accordingly, analysis of



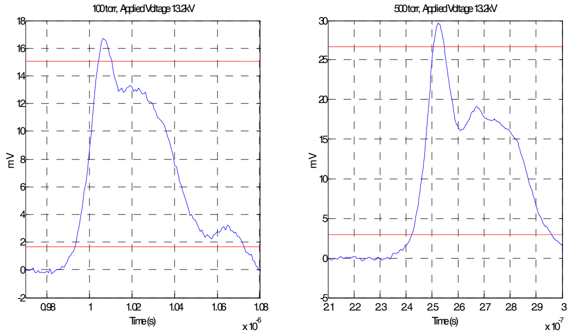
(a) 2x10^{-2} torr (b) 5x10^{-2} torr



(c) 1x10^{-1} torr (d) 5.5x10^{-1} torr



(e) 1 torr (f) 10 torr



(g) 100 torr (h) 500 torr

Fig. 7. Waveforms of PD pulses according to the internal pressure of 40kA VI

the waveform characteristics was performed to estimate the internal pressure. On the other hand, as shown in Fig. 5, since there are many PD pulses those have different pulse magnitudes at the same internal pressure, pulses magnitude is not proper in the waveform analysis. So, that was excluded in the waveform analysis. The each definitions of PD waveform are given in Fig. 8. Fig. 9 shows the trend of rise time, decay time, and pulse width of PD pulses with the change of the internal pressure obtained from Fig. 7. The results reveal that the PD pulses measured below the 0.55 torr have gradual rise time due to townsend like discharge while the PD pulses above the 0.55 torr have sharp rise time due to streamer-like discharge [2] and the rise times steadily decrease with VI pressures over the whole test pressure ranges. In case of the decay time and the pulse width, they are almost stationary below the 0.1 torr. In addition, as shown in Fig. 7(f), (g) and (h), they can be measured incorrectly at the high internal pressure area due to the oscillation in wave tail which is affected by stray reactance. From these results, the rise times have high detectable sensitivity comparing to the decay time and the pulse width and the rise time can be a good parameter to estimate the internal pressure of VI.

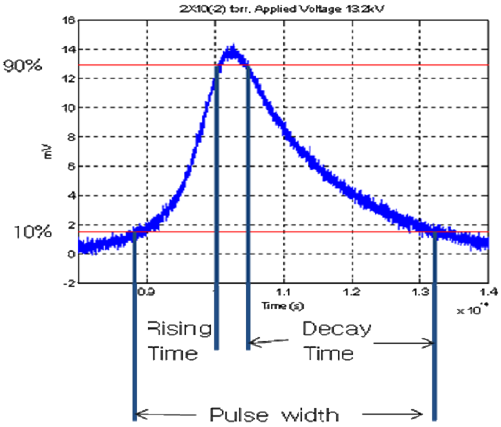


Fig. 8. Definitions of PD waveform

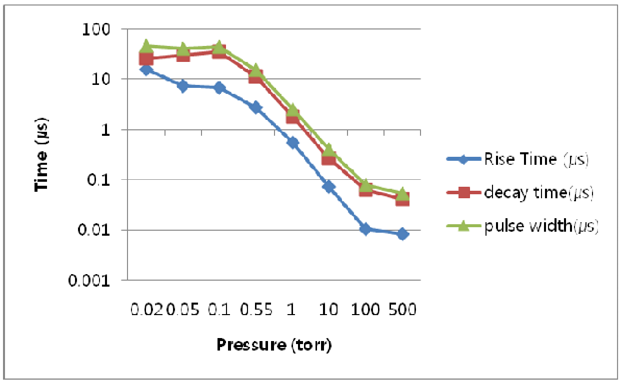


Fig. 9. Trends of rise time, decay time and pulse width of PD pulses

5. Conclusion

In this study, the partial discharges according to the internal pressures of VI were measured by using a capacitive PD coupler. The sensor was designed to have a simple manufacturing process and excellent insulation properties. From the experimental results, the following conclusions were obtained.

Electrical connection of capacitive coupler between the arc shield and the earth increases the applied voltage between the electrodes and the arc shield from 12% to 98%. The increase of the voltage is expected to be able to improve detectable range of internal pressure of VI.

Partial discharge test results indicate that the internal pressure range of VI, from 10^{-2} torr to 500 torr, can be monitored by PD measurements using the capacitive coupler and PD inception voltages follow the Paschen's law

Waveform parameters such as rise time, decay time, and pulse width decrease with the increase of internal pressure of VI. The rise time among these parameters steadily decreases with the increase of the pressure over the whole test pressure range. From this analysis result, the rise time seems to be the best parameter to estimate the internal pressure of VI.

For practical application of the proposed method in the industrial field, additional studies have to be carried out to identify the insulation performance and switching capability of VCB adapted with this kind of the capacitive coupler.

References

[1] Y. Matsui et. al., "Development and technology of high voltage ACBs; brief history and state art: ", *XXIInd Int. Symp. On Discharge and Electrical Insulation in Vacuum-Mastue,* 2006.

[2] H. Saitou et. al., "Determination of Gas Pressure in Vacuum Interrupter Based on Partial Discharge", *IEEE Trans. On DEI* Vol. 14, No. 3, June, 2007.

[3] F. R. Frontzek et. al., "Methods for internal pressure diagnostic of vacuum circuit breakers", *18th international symposium on discharge and electrical insulation in vacuum*, 1988.

[4] L. Falkingham, "Vacuum life assessment of a sample of long service vacuum interrupters", *20th CIRED*, Prague, June, 2009.

[5] IEC 62271-1, "High-voltage switchgear and control gear – Part 1: Common specifications".

[6] M. Kamarol et. al., "Diagnosis of vacuum degree in vacuum interrupter based on partial discharge", *XXIInd Int. Symp. On Discharge and Electrical Insulation in Vacuum-Matsue*, 2006.

[7] D. F. Grosjean, "Development of procedures for partial discharge measurements at low pressures in air,

argon, helium", *IEEE Trans. On DEI* Vol. 15, No. 6 , 2008.

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