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Analysis of phase-resolved images of partial discharges generated in compressed air at non-uniform electric field

Streszczenie. (Analiza fazowo-rozdzielczych obrazów wyładowań niezupełnych generowanych w sprężonym powietrzu w niejednorodnym polu elektrycznym). *Artykuł przedstawia wyniki badań wyładowań niezupełnych (wnz) w układzie elektrod o polu niejednorodnym przy ciśnieniu podwyższonym w zakresie do 0,6 MPa. Rejestrowano obrazy fazowo-rozdzielcze wnz dla stwierdzenia występowania formy bezimpulsowej wyładowań przy napięciu krytycznym. Mechanizm wyładowań niezupełnych przy podwyższonym ciśnieniu wykazuje cechy podobne jak przy ciśnieniu atmosferycznym, przy czym wyraźny jest wpływ ładunku przestrzennego i procesów dyfuzyjnych.*

Abstract*. The paper presents results of investigations of partial discharges (PD) in point-to-plane electrode configuration at high pressures up to 0.6 MPa. The PD phase-resolved images were registered for pulseless form of PD detection at critical voltage. Mechanism of partial discharges at higher pressures shows similar features as for normal pressure, the influence of space charge and diffusion processes are observed.*

Słowa kluczowe: wyładowania niezupełne, obrazy fazowo-rozdzielcze, sprężone powietrze, niejednorodne pole elektryczne.
Keywords: partial discharges, phase-resolved images, compressed air, non-uniform electric field.

Introduction

Compressed gasses are treated as perfect insulants in high voltage insulating systems. Application of compressed air in environmentally testing of medium voltage equipment after manufacturing process seems to be nowadays very actual topic [1].

Partial discharges in air exhibit different forms, which depend on such factors as: electrode arrangement, air conditions, and waveform of the testing voltage. The maximum breakdown voltage for electrodes arrangement can be obtained when the electrodes are profiled for reaching uniform electric field.

The breakdown voltage of uniform field gaps in the range where Townsend's mechanism is valid can be calculated from the Paschen's law (the right side of the Paschen's curve). Some empirical relations were suggested to express the breakdown voltage in uniform field for air at atmospheric pressure [2, 3].

The breakdown voltage increase linearly with pressure in uniform electric field up to about 1,5MPa and that level the curve saturates. There are some methods for calculation of breakdown voltages for uniform electric field in air at higher pressures. At the high pressures deviations from the similarity law of discharges mechanism are present. The breakdown voltage values vs. pressure at different electrode distance and uniform electric field are shown in the Figure 1.

The mechanism of partial discharges in inhomogeneous field in air at atmospheric pressure is known [2, 5-7]. At non-uniform electric field deviation from similarity law is much more significant. It is caused by deformation of electric field due to space charge and the electron emission from cathode. When point-to-plane electrode system is applied mechanism of discharges depends on testing voltage value and polarity.

The partial discharge mechanism depends strongly on the testing voltage – whether the testing voltage is only at the level of inception voltage, or whether it have much higher value [5] or just little higher then the inception voltage (e.g. U-1.5U_0; U_0 -PD inception voltage).

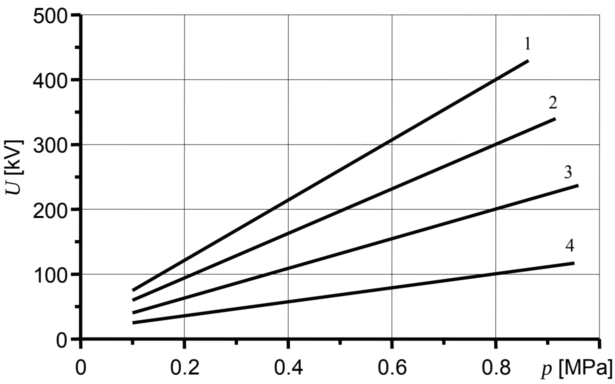

Fig.1. The breakdown voltage vs. pressure at electrode distance d equal to: 1) 5 [mm], 2) 10 [mm], 3) 15 [mm], 4) 20 [mm] (uniform electric field)

It concerns the situations when the discharges are initiated in the space surrounding a micro-sharpness in the insulating system (e.g. GIS) or outside, which results in disturbances.

As the comparison basis partial discharge phase-resolved distributions and charge-amplitude distributions registered for testing voltages from 1.2U_0 to 3.0U_0 have been used.

The measuring method and experimental setup

The laboratory measurements in the model electrode arrangement with distance 20 mm in the point-to-plane configuration and with a needle electrode tip radii of 185μm has been performed.

The electric stress along the axis of the needle-to-plane configuration can be calculated by following equation:

$$E(\xi) = \frac{2U}{\ln(4a/r)} \cdot \frac{1}{2\xi + r - \xi^2 / a} \qquad (1)$$

where ξ is the distance from the needle tip, the distance between needle and plane electrodes and r is the radius of the needle tip.

The inception electric stress E_0 at the needle radii of 185μm was about 16kVmm^{-1}, but the space charge effect was not taken into account.

Experiments described in the paper were performed in specially projected and constructed high voltage and high pressure gas chamber. The tested model electrode arrangement was placed inside the chamber.

The pressure in the tank has been controlled using compressor and manometer. The pressure levels have been varied from normal atmospheric value (0.1 MPa) up to 0.6 MPa.

For partial discharge detection and measurements the classical measurement system with wideband detection circuit described in IEC60270 standard [8] has been applied (Fig. 2). Measuring impedance Z_m was connected in series to electrode system placed inside high pressure chamber.

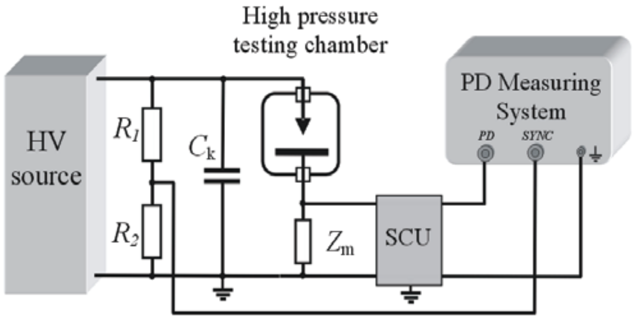

Fig. 2. Experimental setup: R_1/R_2 – high voltage divider; C_k – coupling capacitor, Z_m – measuring impedance; SCU – signal conditioning unit.

Measurement results

Characteristics of inception voltage U_0 and breakdown voltage U_p vs. pressure for point-to-plane electrode system (and as reference for sphere-to-sphere electrode system) are shown at the Figure 3.

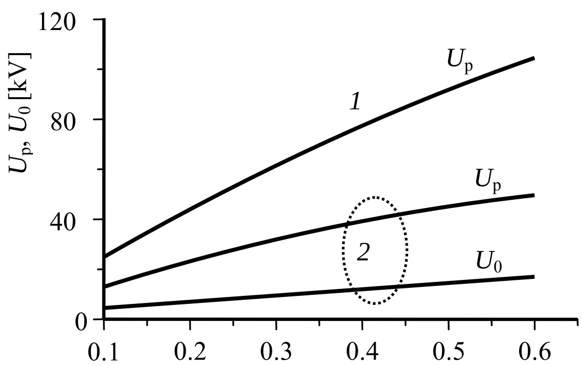

Fig. 3: The PD inception voltage U_0 and breakdown voltage U_p vs. pressure for two electrode configurations, (electrodes distance ξ=20mm); 1) sphere electrode system, 2) point-to-plane system

The PD-phase distributions were registered for testing voltages up to (3÷4)U_0. Selected distributions collected for atmospheric air are shown in Figure 4.

Observed partial discharges in point-to--plane electrode configuration are Trichel-like discharges in negative half of ac cycle. These pulse-type discharges are caused by the periodic reduction of the electric stress near the cathode due to the presence of a space charge.

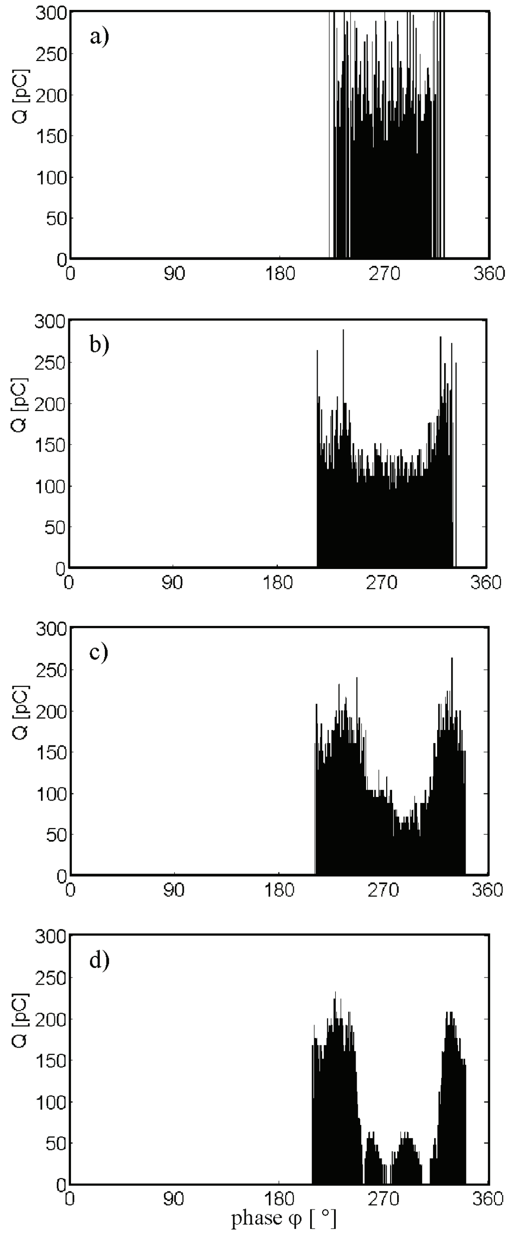

Fig. 4. The PD-phase distributions at U/U_0: a) 1.25; b) 2.0; c) 2.5; d) 3.0 (pressure p = 0.1 MPa)

Here appears the influence of testing voltage on:

- number of pulses N;
- phase range z_φ of pulses in half of cycle;
- maximal pulse charge Q_m and also on the shape of PD-pulse distributions.

In PD mechanism in strongly inhomogeneous electric field in air one may notice the characteristic value of voltage – critical voltage U_{cr} [7]. At this value of testing voltage transition from pulse to pulseless form of discharges is starting. Pulse-height distributions are normal-like type (Gaussian) (Fig.5a) only up to certain voltage.

At the critical voltage, pulse-height distribution shows two groups of PD pulses (Fig. 5b), corresponding to changes in PD-phase distribution (Fig. 4d).

This effect influences on the repetition rate N of PD pulses – namely – repetition rate N increases up to the critical voltage U_{cr} above which the discharge frequency decreases to a few pulses per half-cycle (Fig.6). Decreasing of the PD repetition rate above U_{cr} is accompanied by the change from pulse-type discharges to the partially pulse-less discharges.

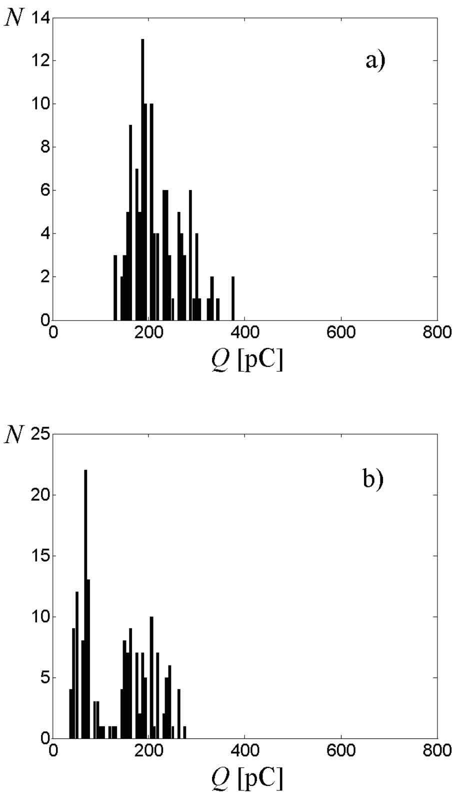

Fig. 5. Pulse-height distributions at U/U_0 equal to: a) 1.25; b) 3.0 (pressure p = 0.1MPa)

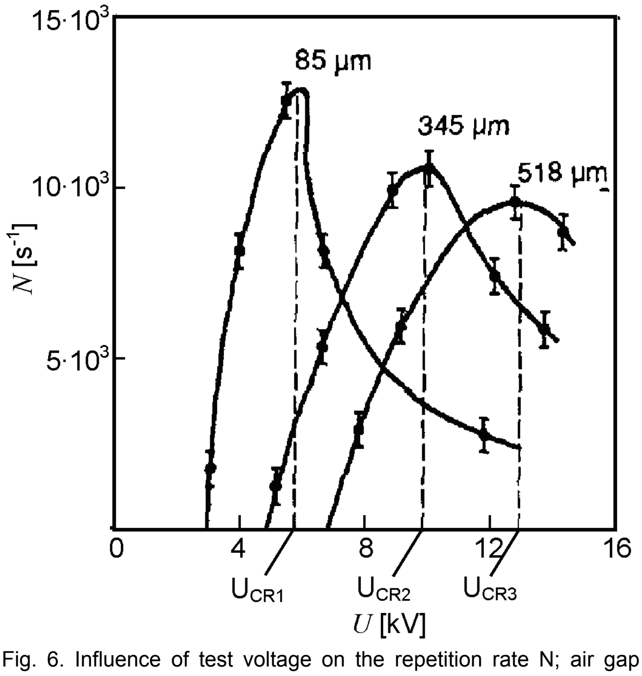

Fig. 6. Influence of test voltage on the repetition rate N; air gap 15mm; tip needle: 85μm, 345μm, 518μm

At higher pressures mechanism of discharges in strongly inhomogeneous field manifests significant changes. Difference between inception voltage U_0 and breakdown voltage U_p increases (Fig. 3) up to pressure about 0.6 MPa stable discharges initiated near the needle electrode are present. Such a situation is not occurring in a weak inhomogeneous electric field, where inception voltage U_0 is approximately equal to breakdown voltage. The PD-phase distributions at 0.4 MPa and 0.6 MPa are presented in figures 7 and 8 respectively.

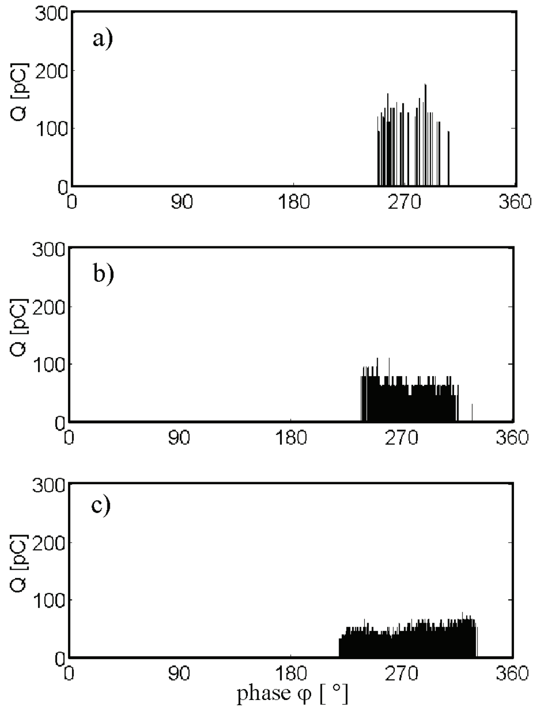

Fig. 7. PD-phase distributions at U/U_0 equal to: a) 1.25; b) 2.0; c) 3.0; (pressure p = 0.4MPa)

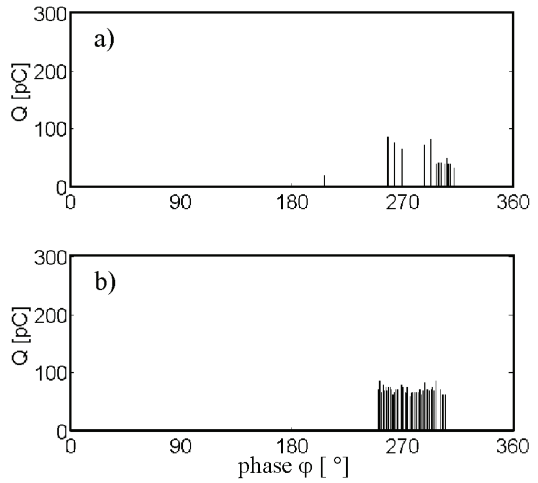

Fig. 8. PD-phase distributions at U/U_0 equal to: a) 1.25; b) 2.0; (pressure p=0.6MPa)

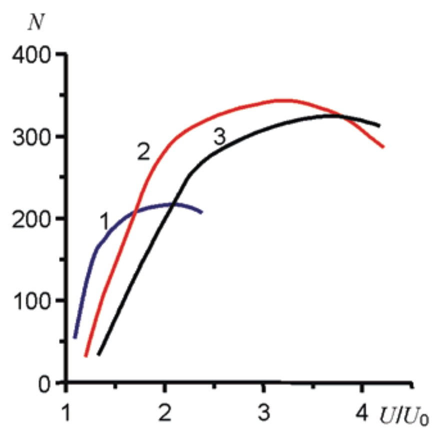

Fig. 9. Repetition rate N vs. relative testing voltage U/U_0 at the pressures: 1) 0.2 MPa, 2) 0.4 MPa, 3) 0.6 MPa

The effect of critical voltage on the repetition rate at the high pressure is similar to effect at 0.1 MPa (Fig.9).

At high pressure, due to attenuation of diffusion process, the local space charge density can be substantial and the development of discharges may be hindered. In the considered range of pressure changes from 0.1 to 0.6 MPa, the PD inception voltage has increased approximately 3 times.

The comparison of changes of maximal charge Q_m and phase range z_φ in the pressure range 0.1, 0.4 and 0.6 MPa (Fig. 10) yields information about the physical mechanism.

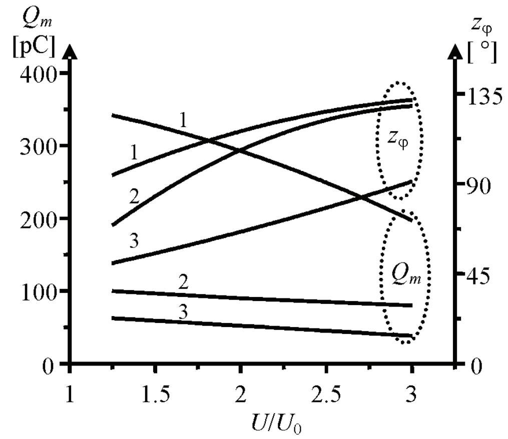

Fig. 10. The maximal charge Q_m and phase range z_φ vs. relative voltage U/U_0 at different values of pressure: 1) 0.1 MPa; 2) 0.4 MPa; 3) 0.6 MPa

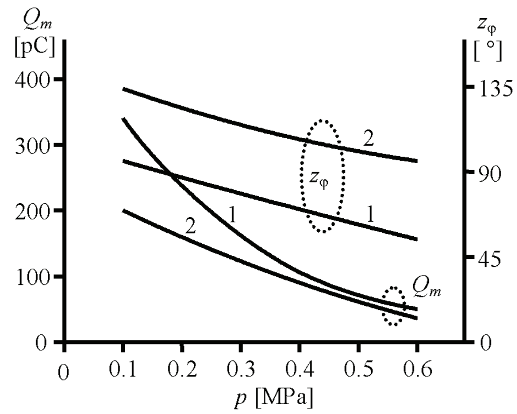

Fig. 11. Maximal charge Q_m and phase range z_φ vs pressure p 1) U=U_o, 2) U=3U_o

Conclusions

In model investigations of partial discharges in strong non-uniform field in air, the PD inception voltage is a non-linear function of pressure. The influence of pressure of compressed air on the value of maximal charge Q_m and the mechanism of discharges has been shown (Fig. 11).

The maximal charge is decreasing while increasing the pressure. However, the most dynamic range is up to 0.3 MPa, and then the Q_m value is almost constant. The PD-phase distributions confirm the presence of pulseless form of discharges, but at the much lower value of maximal charge. One may conclude that the PD mechanism at higher pressure in non-uniform field will demonstrate the distinct PD forms than at atmospheric pressure.

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