Influence of gas composition on the pulse form of partial discharge current

R. Kozakov[1], M. Bogaczyk[1], S. Gorchakov[1], S. Arumugam[2]

[1] *INP Greifswald, Felix-Hausdorff-Str. 2, Greifswald 17489 Germany*
[2]*Faculty of Electrotechnics, Rostock University, Tannenbergstr. 10, Rostock, Germany*

The shape of the current pulse of a single partial discharge (PD) in dependency on different gas mixtures has been investigated by modelling und experiment.. The model of PDs is based on the self-consistent description which includes a solution of the Boltzmann equation and a system of rate equations for plasma species. Measurements on the real power cables are made. Problem of the current pulse form reconstruction from the data measured with limited frequency band is addressed.

1. Introduction

Diagnostics of partial discharges is a commonly accepted procedure in the evaluation of the status of an electro-technical apparatus. The frequently applied technique is the phase resolved partial discharge (PRPD) diagrams. These diagrams represent phase resolved statistics on the apparent charge transferred in the single PD event. Different defects in the apparatus like voids in dielectric etc. favour the appearance of corona discharges, surface discharges, giving rise to different patterns in the PRPD diagrams. Based on the reference measurements the trained personal can identify the type of the defects in the apparatus.

Measurements of the apparent charge are standardised [1] and do not require the knowledge of the current waveform of a single discharge. Due to extremely short rise times of the current pulse, typically of the order of sub-nanoseconds, their detection and assessment is a challenge. Nevertheless such information can give additional insights in the nature of the partial discharges and provide an additional powerful tool in commissioning of electro-technical apparatus.

The present contribution examines the waveform of the single PD current pulse for a void type defect. The modelling of the single discharge phenomenon is performed in different gas mixtures at various pressures. The obtained results are compared with the measurements of PD current waveforms in the power cables.

2. Model of the PD

For the description of a single cable defect a global model of a single filamentary discharge was applied.

2.1. Assumptions

The model considers a discharge in a form of a single cylindrical filament (Fig.1) with a radius R. The filament length is defined by the distance d between two charged layers (electrodes). The layer material is a cross-linked polyethylene (XLPE). The plasma is assumed to be axially homogeneous along the z axis, radially inhomogeneous with a given radial profile $g(r)$ and rotationally symmetric. In the frames of the present model the radial profiles $g(r)$ for all excited species and electrons have been chosen to coincide with Bessel functions of zeroth-order. For the temperature distribution in radial direction a Gaussian profile was assumed.

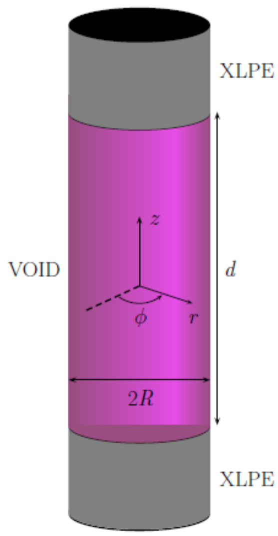

Fig. 1 Schematic picture of discharge geometry.

The plasma is produced by a homogeneous axially distributed electric field $E_z(t)$ which was self-consistently determined in the model.

2.2. Equations system

The radially averaged treatment of the discharge plasma comprises the solution of the time-dependent Boltzmann equation for the electron component, of the system of balance equations for heavy particles and of the circuit equations. The time-dependent Boltzmann equation of the electrons, radially averaged over the cross section of the filamentary plasma, is treated on the basis of the conventional two-term approximation of the electron velocity distribution function. Besides the influence of the electric field it includes elastic collisions, exciting, de-exciting and ionizing electron-heavy particle collision processes, chemo-ionization processes, recombination and the electron-electron interaction. Furthermore, the electron loss by ambipolar diffusion to the tube walls has been approximately taken into consideration by a lifetime term. Details of the electron kinetics and the coupling between the different systems of equations can be found in the literature [1].

For the determination of the densities of plasma species the fluid description has been used. The balance equations for the axial particle densities N_j after simplifications result in

$$\frac{\partial N_j \overline{g(r)}}{\partial t} - D_j N_j \overline{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial g(r)}{\partial r}\right)} = Z(r,t) \qquad (1)$$

where D_j is the diffusion coefficient (ambipolar diffusion for charged particles and particle diffusion for neutral species) and $Z(r,t)$ is the effective production rate in collisional and radiative processes.

For the determination of the axial electric field the following approach has been used. The cable specimen is loaded with sinusoidal voltage U_{gen} with the voltage amplitude of 18 kV. The void and the XLPE layer present the capacitive divider with corresponding capacitances C_{XLPE} and C_{void}. The mean external electric field strength E_z is determined from the relation of capacitances and void length:

$$E_z = \frac{U_{void}}{d} = \frac{U_{gen}}{d}\frac{C_{void}}{C_{void}+C_{XLPE}} \qquad (2)$$

In addition an initial field E_{mem} caused by surface charges with the density (σ) is added.

$$E_{mem} = U_{mem}/d = \frac{(\sigma_+ + \sigma_-)A}{C_{void}\, d} \qquad (3)$$

The positive and negative surface charge density σ_+ and σ_- are distributed on the electrode surfaces A with given spatial profile. The density corresponds to a typical critical level of 5 pC. During the discharge the fluxes of charged particles provides annihilation of deposited surface charges and accumulation of new charges with opposite polarity in such a way, that the resulting internal field in the void (E_z-E_{mem}) is below the breakdown threshold value. The temporal evolution of the surface charge density has been determined from the charged particle fluxes J_+ and J_- according to

$$\frac{d\sigma_\pm}{dt} = J_\pm \qquad (4)$$

In order to study the influence of the chemical composition on the current pulse properties the discharge in N_2, O_2, H_2O and C_2H_4 has been simulated. The corresponding reaction kinetics schemes can be found in references [2-5]. The pressure inside the void has been assumed to be equal to 1 or 2 bar.

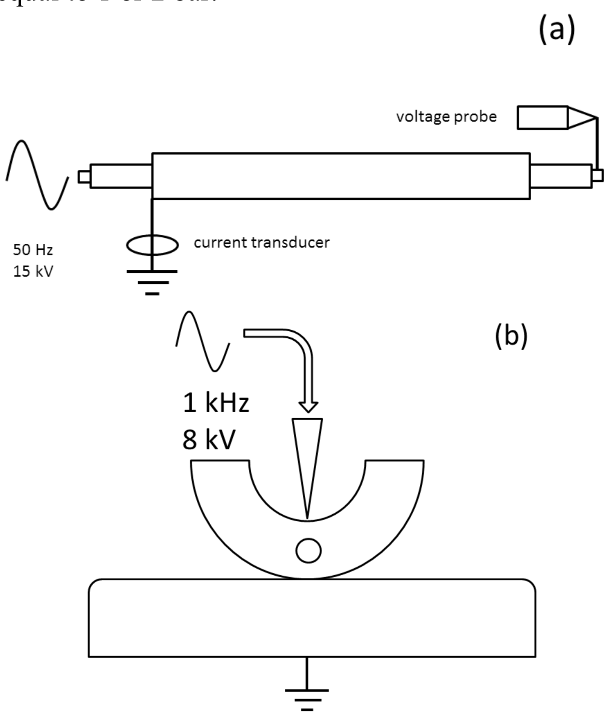

Fig. 2. Experimental setup for tests on cable section (a), and cable piece (b).

3. PD diagnostics

3.1. Experimental setup

Figure 2 shows the schematic view of experimental setup. Two configurations have been used for investigations. In the first case (Fig. 2a) the test object was a 1 m long piece of a 20 kV power cable. The sinusoidal voltage (frequency 50 Hz) was applied to the one end of the cable. The voltage amplitude was varied from 500V to 20 kV. The shielding of the cable was connected to the ground electrode. Due to the isolation material between the central lead and the shielding only the displacement current was observed in the absence of PD. Starting at certain voltage amplitude typical patterns of partial discharges could be detected in the current waveforms. The voltage was measured with a high voltage probe Tektronix P6015A (bandwidth 75 MHz). The current signal was acquired with a current transducer Tektronix TCP202 (bandwidth 50 MHz). An example of obtained waveform for one period of the applied voltage is shown in Figure 3.

While the first experimental arrangement allows for registration of sequences of PD from different possible locations, second arrangement (Fig 2b) was used to study a single PD event. Here, the semi-circular XPLE isolation of the power cable (thickness of the cable section is 1 cm) is pierced by a hole with a fix diameter in order to simulate a partial discharge of a void type. The width of dielectric was 5 mm. The lead was replaced by a tip made of stainless steel. The applied voltage was in this case 8 kV at an operation frequency of 1 kHz. The current is measured by a differential voltage probe TDP0500 (bandwidth 500 MHz) connected in parallel to measuring resistor (300 Ω).

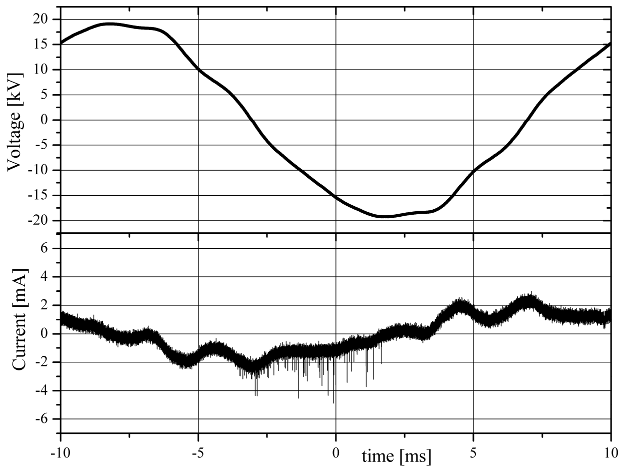

Fig. 3. Example voltage (top) and current (bottom) waveform.

4. Results and discussion

The void in the model is assumed to have a length of 0.1 mm and a radius of 0.1 mm. The discharge starts always at the same value of the voltage.

Figure 4 shows the temporal evolution of a PD current for different gases in case of a pressure of 1 bar. Despite the similar initial conditions predicted pulses show different behaviour. Distinct differences in the pulse shape are obvious. In case of oxygen and water the discharge starts earlier but the duration of the pulse is much shorter than in case of nitrogen or ethylene. Such behaviour is typical for electro-negative gases, where the attachment processes have a significant contribution to the electron loss processes. The current rise time in case of water is slightly smaller than in case of oxygen. Nitrogen shows the longest rise time and the pulse duration. The decay of the plasma is also dependent on the gas type and pressure. The longest decay is predicted for nitrogen and ethylene.

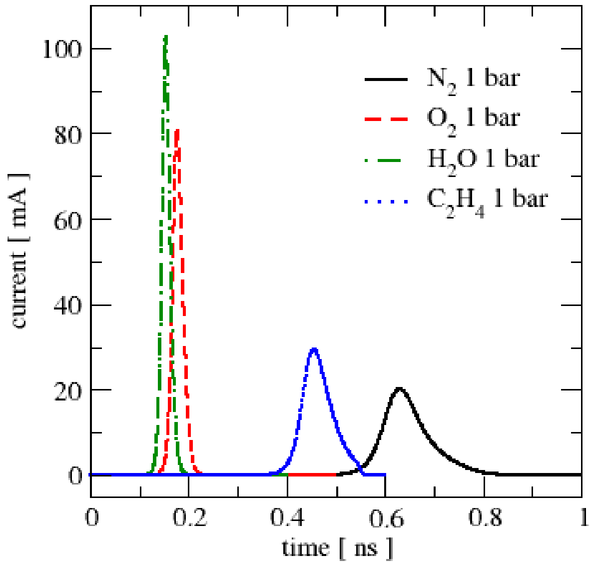

Fig. 4. Calculated form of the current pulses for different gases at 1 bar.

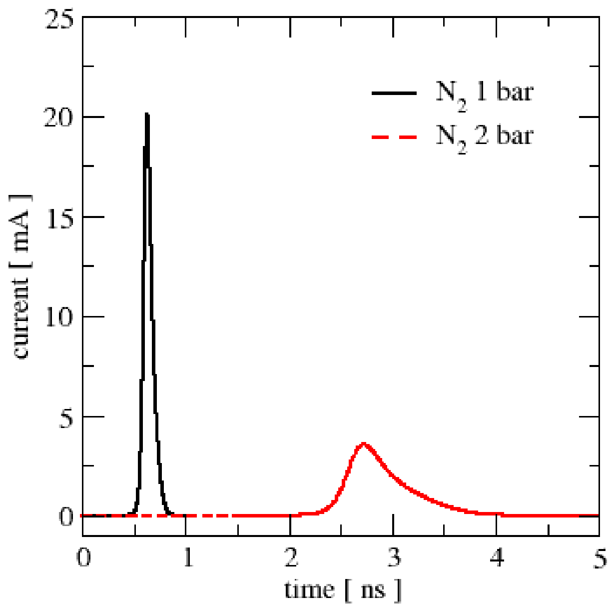

Fig. 5. Same as Fig.4 but for varying pressure and nitrogen discharge.

An increase of the gas pressure causes an additional delay in the discharge ignition (Fig. 5). Furthermore, the pulse duration also increases. Thus, the form of the current shape is also pressure dependent.

An example of detailed recordings of the individual PD current pulses in XLPE cable is shown in Figure 6. Two typical pulses with different amplitudes are presented. The amplitude in first maximum are 30 mA and 15 mA, respectively. It can be observed that the pulse shape is independent from the amplitude. Actually all detailed measurements of the current waveform revealed the same time profile with different amplitudes. Based on the data of simulations, where typical times of the current waveforms in the sub-nanosecond range are predicted, one can state that the measured data presented in Figure 6 show the instrumental profile of the current transducer obtained as a response of the measurement system to the delta-like pulses of PD. The measured waveform $S_{meas}(t)$ can be presented as the convolution of the real current waveform $S_{real}(t)$ with the instrumental profile $I(t)$ of the transducer:

$$S_{meas}(t) = \int S_{real}(t) I(t-\tau) d\tau \ . \quad (5)$$

In case of a broad instrumental profile the reconstruction of the real current signal becomes quite difficult task.

Measurements in the laboratory setup, shown in Figure 7 reveal similar picture on the different time scale. In contrast to XLPE cable measurements where the pulse width was approx. 100 ns long, the pulse duration in the laboratory setup was about 10 ns.

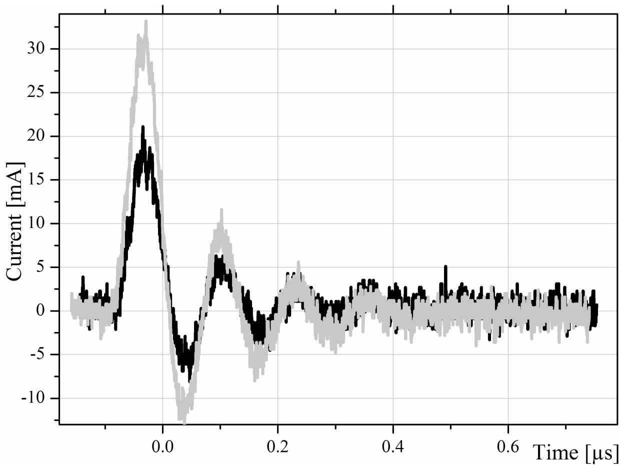

Fig. 6. Example of the detailed current waveform of two individual PD pulses measured in XLPE cable (Fig 2(a)).

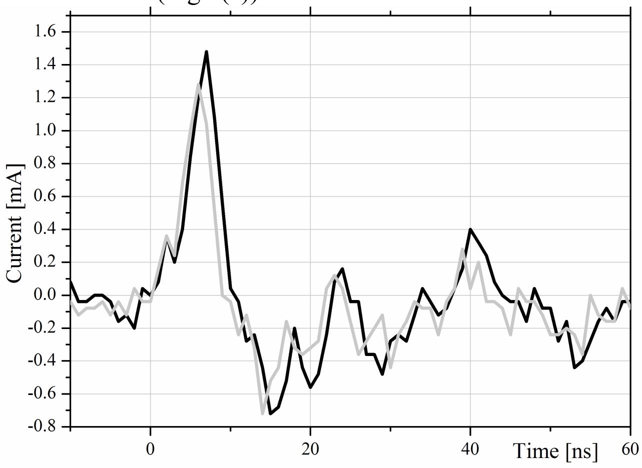

Fig. 7. Example of the detailed current waveform of two individual PD pulses measured in model setup (Fig 2(b)).

The experimental form of the current pulse cannot be assessed using the applied experimental setup. Due to the limited bandwidth of the devices only current superposed by the instrumental profile of the set-up could be recorded. In order to extract the real current pulse forms and to perform comparison with the model more detailed measurements are required. Thus, a higher bandwidth is required for better temporal resolution of current signal. The response of the setup on electrical pulses must be studied in detailed to get information about the real current shape.

4. Summary and outlook

Modelling of the current pulse forms for different gas composition was performed. Depending on the gas type and pressure the current pulses with pronounced differences in the signal shape are predicted. Comparison with the experiment was not possible due to the limited bandwidth of the experimental setup. Detailed measurements with a higher bandwidth are planned in the future.

5. References

[1] Norm DIN EN 60270:2001-08; VDE 0434:2001-08 High-voltage test techniques - Partial discharge measurement, IEC (2000).

[2] T. Braeuer, S. Gortchakov, D. Loffhagen, S. Pfau and R. Winkler, *J. Phys. D: Appl. Phys.* **30** (1997) 3223.

[3] U. Kogelschatz U., Advanced Ozone Generation, in *Process technologies for water treatment*, Editor S. Stucki, Plenum Publishing Corporation, (1998).

[4] D. L. Baulch et al, *J. Phys. Chem Ref. Data* **34** (2005) 757.

[5] J.-C. Legrand, A.-M. Diamy, R. Hrach V. Hrachova, *Contrib. Plasma Phys.* **37** (1997) 521.

[6] D. A. Alman, D. N. Ruzic, J. N. Brooks, *Physics of Plasmas* **7** (2000) 1421.