Investigation of Plasma Properties in a Narrow Gap for Short Time Current

Runge T.[1], Kopp T.[1], Kurrat M.[1]

[1] *Technische Universität Braunschweig, Institute for High Voltage Technology and Electrical Power Systems, Schleinitzstraße 23, 38106 Braunschweig, Germany, t.runge@tu-braunschweig.de*

In the current study an experimental model was established, in which the plasma is quenched in a defined narrow gap and tested with an 8/20 µs impulse current with an amplitude of 23 kA. The experimental model is equipped with an outlet duct of different cross sectional areas. The measured data such as arc voltage and current are used in order to estimate the plasma properties electrical conductivity and pressure.

Keywords: surge current, plasma properties, lightning protection, spark gap

1 INTRODUCTION

The use of surge protective devices (SPD) is necessary to prevent destruction of electrical components. The SPD based on spark gap technology ensure a galvanic separation between the system and the neutral conductor before the surge occurs. During surge event the spark gap ignites. Due to the arc, the surge is bypassed to the neutral conductor. The arc represents a failure which allows the flow of a failure current which is feed by the energy grid. Suppression of this current can be achieved by extinguishing the arc, which is necessary to prevent tripping of the main fuse. It is common use to quench the arc in a narrow gap which leads to a lower cross section of the arc and to an ablation of the chamber walls. Thus the current will be limited. If the limitation suffices to reach zero current, than the arc extinguishes, this ensures a galvanic separation again.

For a better understanding of the arc extinction process, it is necessary to know how the arc in the narrow gap behaves during a surge. To supress the failure current it is necessary to increase the arc voltage. In [1] and [2] it has been shown that a chamber wall ablation increases the arc voltage due to a cooling effect of the gas [3]. Furthermore, the ablation leads to an increase of the pressure in the narrow gap. To reduce the pressure the narrow gap can be equipped with small outlet ducts. The influence of different cross sections of the outlet ducts on the pressure and electrical conductivity of the arc is investigated through measurements and simplified mathematical relations in this research.

2 METHODOLOGY

In order to investigate the plasma properties in a narrow gap an experimental model was established in the laboratory. The measured arc voltages for impressed impulse currents are then implemented in a simple mathematical model in order to evaluate the plasma properties. Subsection 2.1 presents the experimental setup and 2.2 introduces the mathematical modelling.

2.1 EXPERIMETAL SET-UP

The selected test objects are rotational symmetrical spark gaps (Figure 1). Each cylindrical arc chamber consists of two tungsten copper electrodes (75 % / 25 %) with an outlet duct in the left electrode and a cylindrical shell made of polyoxymethylen (POM).

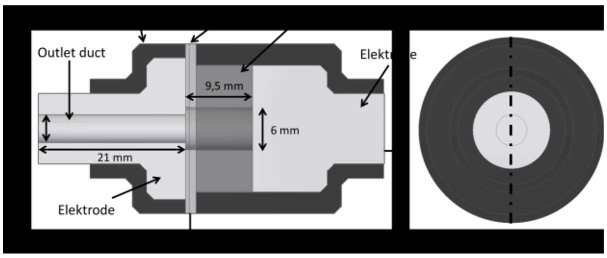

Fig.1: Top view (right) with section line for the side view (left) of the spark gap

The arc chamber has a gap length of 9.5 mm and a diameter of 6 mm. The test objects have different outlet ducts with diameters of 1 mm, 2 mm and 4 mm and a length of 21 mm. An insulating housing prevents external flashovers. Before surge the chamber is filled with air, due to wall and electrode ablation during surge the gas in the chamber is assumed to be a mixture of air, POM and copper.

Surge impulse currents (8/20 microseconds) according to IEC 62475 applied to the spark gaps ignite the arc plasma. The current amplitude is limited to 23 kA. The arc starts at the ignition aid on the left side and spreads out towards the opposite electrode. The arc plasma becomes hot and the pressurized plasma streams out through the outlet duct in the left electrode.

All test objects are subjected to several surge currents. Each impulse current and arc voltage are recorded. A typical surge current and arc voltage are shown in Figure 2. The impulse current is reasonably divided in three different phases: ignition, high current phase and undershoot due to oscillating circuit in the test setup [2].

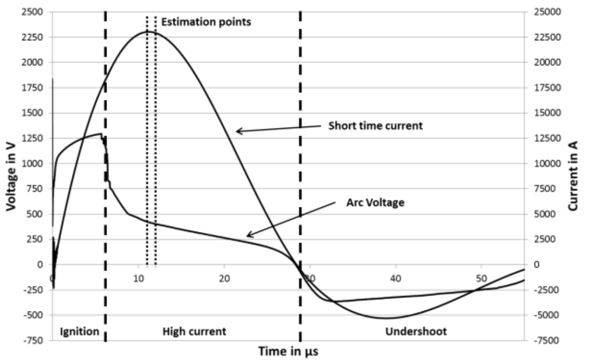

Fig.2: Typical surge current and arc voltage of a spark gap with 4 mm outlet duct diameter

The arc voltage of the hot plasma after current peak yields a decreasing plasma conductance within the high current phase. The electrical conductance depends on the geometrical current flow and plasma conductivity, which is assumed as a state variable. The gradient of the decreasing plasma conductivity is important for the current interruption capability of a spark gap. Plasma temperature and pressure determine the electrical conductivity. The tested various outlet duct diameters cause different pressure values. Therefore different arc voltages are measured.

2.2 MATHEMATICAL MODEL

The measured parameters are used in simplified relations to calculate the plasma properties. These properties are investigated for two different time points, at maximum current at 11 µs and 1 µs after maximum current (Figure 2).

For the electrical conductivity it is assumed, that the spark gap between the electrodes is completely filled with homogeneous plasma [4], while the outlet duct is neglected.

The voltage drop over the arc root is assumed to be constant with 16.5 V [5]. Based on these assumptions the el. conductivity can be calculated using Equation (1) with the current i and the arc voltage u_{arc}:

$$\sigma = \frac{i * length}{(u_{arc} - 16.5\,V) * \pi * \left(diameter/_2\right)^2} \qquad (1)$$

In order to estimate the temperature and pressure the calculation of the electrical conductivity of air in [6] can be used (Figure 3). In this experimental model the nature of the gas is not pure air but a mixture of air, POM and copper. The deviations of pure air and a POM-air mixture in the electrical conductivity can be neglected [7]. Also the influence of copper vapour can be neglected at high temperatures [8]. Using these results the needed pressure at different temperatures can be calculated to get the estimated electrical conductivity.

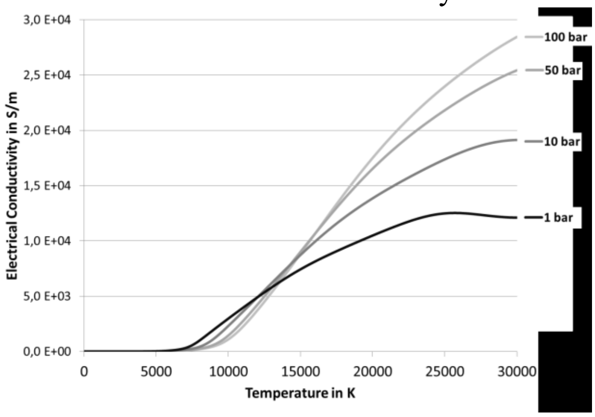

Fig.3: Electrical conductivity of air as a function of the temperature and pressure up to 100 bar and 30000 K [6]

Another method to estimate the temperature and pressure is to use the radiation of the plasma. Therefor the radiated power has to be known. An assumption is that the radiated power is a constant proportion of the input energy. With a radiation model like the net emission coefficient (NEC) the needed pressure at different temperatures can be calculated to get the estimated radiation power. The published results in [9] of the NEC of air for optical thin mediums in Figure 4 could be used. The deviations caused by the POM in the gas can be neglected again whereas the influence of copper vapour cannot be neglected [10].

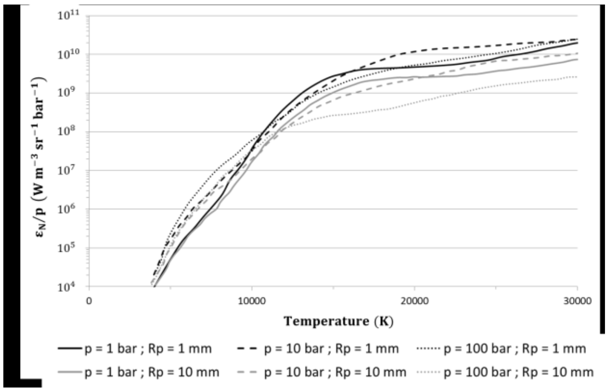

Fig.4: Reduced NEC of air plasma for different values of the radius and pressure [9]

A targeted comparison between both methods to get a more precise estimation of the pressure and temperature cannot be done due to the unknown radiated power and exact mixture of gas in the chamber.

However, in order to get a first assumption of the pressure in the chamber a pressure range can be estimated. Therefore the calculated electrical conductivity of the plasma and the results of [6] are used. The temperature is assumed to be in a range from 25000 K up to 30000 K. From these extreme values two values of the pressure can be deduced and a pressure range can be given.

3 RESULTS AND DISCUSSION

The applied surge impulse current is predefined by the generator according to IEC 62475 and varies only negligible with the device under test. At 11 µs the current reaches its maximum with 23000 A in the next microsecond the current is decreasing about 200 A to 22800 A. Like the current the voltage drop is decreasing over the investigated time (Figure 5). In contrast to the current the voltage varies with different outlet duct diameter and is increasing with increasing diameter. The differences between an outlet duct diameter of 1 mm and 2 mm are only small at both time points, whereas the voltage is about 40 V to 50 V higher at 4 mm. Because of same current flow through the plasma the different voltages using different outlet duct diameters has to be determined by the electrical conductivity, which is also decreasing with increasing diameter of the outlet duct (Figure 6).

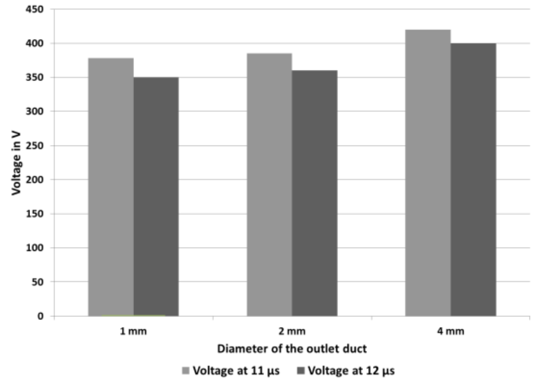

Fig.5: Voltage of the investigated spark gap with different outlet duct diameters at different time points

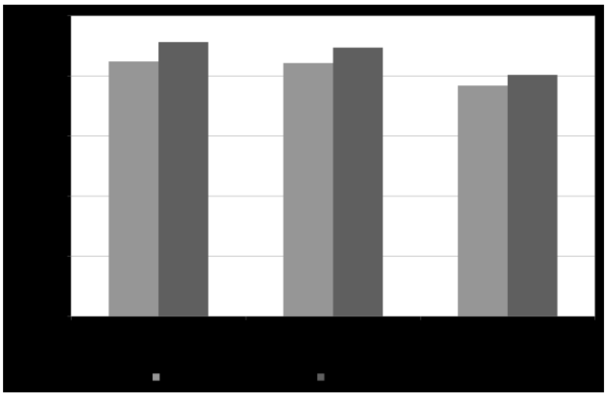

Fig.6: Electrical conductivity of the plasma in the investigated spark gap with different outlet duct diameters at different time points

Due to decreasing current over time a first assumption is that the electrical conductivity decreases as well. In this case, caused by faster decreasing arc voltage compared to a slower declining current, it can be ascertained that the electrical conductivity has to be increasing.

An increasing electrical conductivity is caused by an increasing temperature, pressure or a combination of both. Due to unknown exact temperature the pressure cannot be calculated. Instead, a temperature and pressure range can be given. The estimated pressure ranges of the plasma at different outlet duct diameters over the time are shown in Figure 7.

A consideration of the time dependence of the plasma pressure shows an overlapping of the pressure ranges. Due to this the time depended behaviour cannot be ascertained, but with the assumption that temperature is not fast increasing, but rather slightly decreasing, it can be predicted that plasma pressure increases further after current maximum. Considering the ideal gas law at constant volume, pressure is proportional to the product of mass and temperature. Thus, in order to get an increasing pressure the mass has to increase. An increasing mass of the plasma in the spark gap should be caused by the ablation of the chamber wall, which is investigated in other publications as [1] and [2]. This ablation has to be greater than the mass loss due to mass flow through the outlet duct to increase the mass of the plasma.

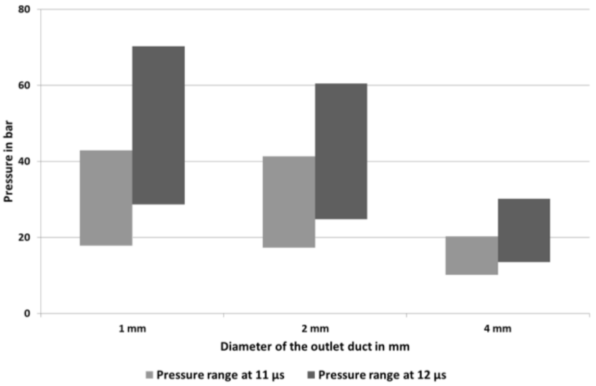

Fig.7: Plasma pressure range in the investigated spark gap with different outlet duct diameters at different time points

Considering the influence of the outlet duct diameter on the pressure a clear tendency cannot be ascertained due to overlapping ranges. But with the assumption that temperature is nearly constant over the investigated outlet duct diameter range, it can be predicted that pressure decreases with increasing outlet duct diameter. Again considering the ideal gas law the mass has to decrease as well. This should be caused by a greater mass flow through the outlet duct due to a greater cross sectional area with increasing diameter.

4 CONCLUSION

A first estimation of plasma properties in a spark model with different outlet ducts at 23 kA surge impulse currents was achieved. The results give a first overview about the possible pressure ranges. Due to overlapping ranges no tendency of pressure can be ascertained. But with the assumptions that temperature is rather slightly decreasing than increasing over the investigated time and nearly constant over the investigated outlet duct diameter range a prediction of the pressure behaviour is given.

The plasma pressure seems to be still increasing shortly after current maximum. This leads to a higher electrical conductivity. As a consequence of the combination of increasing electrical conductivity and decreasing current the voltage is decreasing. The investigation of the influences of enlarged outlet duct diameters predicts a decreasing pressure. Consequentially the electrical conductivity declines and the voltage rises.

In order to supress the failure current it is necessary to raise the arc voltage, which is determined by the electrical conductivity. To obtain a declining electrical conductivity the temperature and pressure has to be controlled. One method to control the plasma pressure is the modification of the outlet duct like it is shown in this investigation.

REFERENCES

[1] Schottel B, Kurrat M, In: International Conference on Phenomena in Ionized Gases, Granada 2013, PS2-013.

[2] Schottel B, Kurrat M, In: International Conference of Gas Discharges and Their Application, Beijing, 2012, p. 226-229.

[3] Pospiech J, Ein neues Prinzip für Blitzstromableiter im Niederspannungsnetz, Books on Demand, 2001.

[4] Schottel B et al, In: International Conference on Lightning Protection, Shanghai, 2014, p. 1400-1404.

[5] Yokomizu Y et al, J. Phys. D: Appl. Phys. 29 (1996) 1260-1267.

[6] Murphy A B, Plasma Chemistry and Plasma Processing 15 (1995) 279-307.

[7] Ma Q et al, IEEE Transactions on Plasma Science 37 (2009) 261-269.

[8] Cressault Y et al, In: International Conference on Gas Discharges and Their Applications, Xi'an, 2006, p. 133-136.

[9] Peyrou B et al, J. Phys. D: Appl. Phys. 45 (2012) 455203.

[10] Kloc P et al, J. Phys. D: Appl. Phys. 48 (2015) 055208.