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EXPERIMENTAL INVESTIGATIONS ON ELECTRICAL PLASMA CONDUCTIVITY IN A MODEL SPARK GAP FOR SURGE CURRENTS

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Abstract. In this experimental investigation the electrical conductivity of plasma is measured during surge current using potential probes. The measurements were carried out in a narrow gap arrangement based on spark gap technology. In order to investigate the electrical conductivity during surge this model is tested using 8/20 µs surge currents according to the IEC 62475. The measured behaviour of the electrical conductivity during surge and the uncertainty of these measurements are discussed.

Keywords: arc, electrical conductivity, plasma, spark gap, surge current, surge protective device.

1. Introduction

In case of current limiting switching devices in inductive circuits the voltage drop of the arc has to be higher than the the supply voltage. The arc voltage can be calculated as the sum of the electrode sheath and the plasma voltage, which can be calculated using the electrical conductivity σ, current I, length l and cross section A.

$$U_{\text{Sup}} < U_{\text{Arc}} = U_{\text{Electrode sheath}} + \frac{I * l}{A * \sigma} \qquad (1)$$

In order to design switching devices it is important to know how to influence the arc voltage. Thus following influences are possible in order to increase the arc voltage:

- Increasing of the electrode sheath voltage by using deion arc splitters
- Extending of the length
- Decreasing of the cross section
- Decreasing of the electrical conductivity

The electrode sheath voltage, length and cross section is mostly determined by the geometry and influenced easily, whereas the electrical conductivity cannot be influenced directly. In order to identify different influence possibilities the electrical conductivity has to be determined firstly.

Two ways are possible to identify the conductivity: Firstly a simulation of the device and secondly a measurement. To guarantee high quality of the results it is best to do both ways with a comparison of the results. In this experimental investigation a spark gap is tested with surge currents according to surge protective devices. The applicability of a compact measuring method is verified in pre-investigations and used to determine the electrical conductivity behaviour of plasma. Further a statement about the uncertainty of the measurement is given.

2. Experimental Set-Up

The measurements are carried out in a spark gap model using surge currents described in subsection 2.1. The electrical conductivity is measured using two potential probes introduced in subsection 2.2. In order to verify the applicability of the method some pre-investigations are presented in subsection 2.3.

2.1. Experimental Model

The spark gap model consists of a box-shaped narrow gap which is formed by two tungsten copper electrodes and surrounding chamber wall made of Polyoxymethylen. Additional two outlet ducts are mounted at the sides of the gap (Figure 1). The dimensions are: side lengths of the spark gap: 10 mm, height: 1 mm and length of the outlet duct: 20 mm. A surface discharge device is used to ignite the spark gap connected through a varistor. More details are given in [1].

As surge current the 8/20 µs impulse is used according to the IEC 62475 with amplitudes of 23 kA. The behaviour of the spark gap during impulse can be diverted into different phases (see also Plasma Propagation in section 2.3) [2]: Ignition of the spark gap, commutation of the current from varistor to plasma, high current phase and undershoot.

2.2. Measuring Method

The aim of this investigation is to measure the electrical conductivity of the plasma. One method is to use the current density and electrical field of the plasma, which is the voltage drop of the plasma divided by the length:

$$\sigma = \frac{j}{E} = \frac{j * l}{\Delta U} = \frac{I * l}{A * \Delta U} \qquad (2)$$

The current density can be calculated by using the measured current and the cross section of the spark gap. Also the length is given by the geometry whereas the voltage drop of the plasma is unknown in most

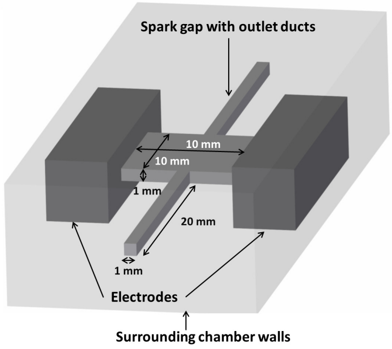

Figure 1. 3-D model of the spark gap model without SDD.

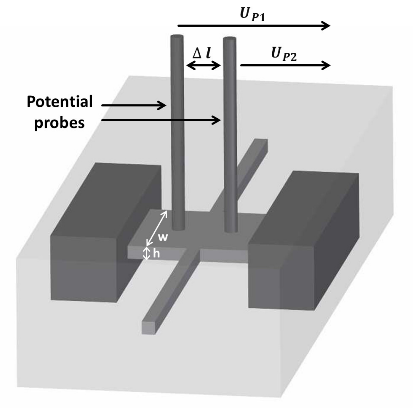

Figure 2. Measuring set-up for electrical conductivity.

cases, caused by the voltage drop of the electrode sheath. Two methods can be used to identify the voltage drop of the plasma: Firstly the voltage of the arc can be measured. In order to determine the plasma voltage the measured voltage is subtracted by the voltage drop of the electrode sheath which can be estimated based on data like in [3]. Secondly a measuring method can be used, which eliminates the voltage drop of the electrode sheath. In this paper, the second method is presented. In order to eliminate the voltage drop potential probes are used, which are already investigated like in [4]. The concept of the presented method is to use two voltages with the same voltage drop like in [5]. Thus two identical potential probes are located in the plasma with floating potential. The voltage drop between both potential probes and a reference electrode is measured (U_{P1} and U_{P2} in Figure 2).

With the assumption that the voltage drops of the electrode sheaths of both measured voltages are similar it can be subtracted by calculating the difference between them. Thus the electrical conductivity can be estimated using (3).

$$\sigma = \frac{I * \Delta l}{A * (U_{P1} - U_{P2})} \tag{3}$$

But due to the ablation of the chamber wall a thin cold gas layer is located at the chamber wall which height is about 20 % of the spark gap height [6]. This layer does not make a contribution to the current flow. Thus about 80 % is filled with plasma in which current flow occurs. Therefore the spark gap height (h) multiplied with the width (w) and 80 % has to be used to calculate the conductivity (4).

$$\sigma = \frac{I * \Delta l}{0.8 * w * h * (U_{\mathrm{P1}} - U_{\mathrm{P2}})} \tag{4}$$

The inserting of the probes in the plasma caused electrical and thermic influences which disturbs the plasma properties. Thus in order to minimise these influences following requirements for the used probes have to be fulfilled [5, 7, 8]: Firstly the ablation of the probes has to be minimised to reduce the thermic influence. Secondly cylindrical probes with small diameter have to be used to reduce the influence on the plasma flux. And thirdly the current through the probes has to be negligible compared with the current in the plasma. These requirements are fulfilled by using cylindrical probes made of pure wolfram with a diameter of 0.4 mm and voltage probes with high resistance.

2.3. Pre-Investigations

Before the method is applied at the spark gap three questions must be attempted: The influence of the probes on the plasma, the inducted voltages in the measurement and the propagation of the plasma during surge.

Influence of the potential probes on plasma
A huge challenge of measurement is that the measurement itself is not allowed to influence the result excessively. Thus in this case the electrical conductivity has to be the same with and without measurement setup. In order to approve this, the voltage of the arc (plasma with arc root voltage) is measured and compared with and without measurement setup (Figure 3). The comparison reveals a voltage within the standard deviation in both cases especially in the high current phase. Thus it can be assumed that the electrical conductivity is not influenced by the measuring setup.

Induced Voltage
Another challenge to deal with is the voltage measurement. Due to the high di/dt values caused by the surge current induced voltages occur in the measurement. These voltages are measured for U_{P1} and U_{P2}. In this case the spark gap is filled with copper, thus a short circuit occurs and the measured voltages have to be near zero due to the negligible resistance of copper. In Figure 4 the measured induced voltages are presented, which is maximal about 110 V in U_{P1} and thus not negligible. Due to the predefined current the induced voltages are similar during the cases of short circuit and plasma. Using the same geometry setup the induced voltages will

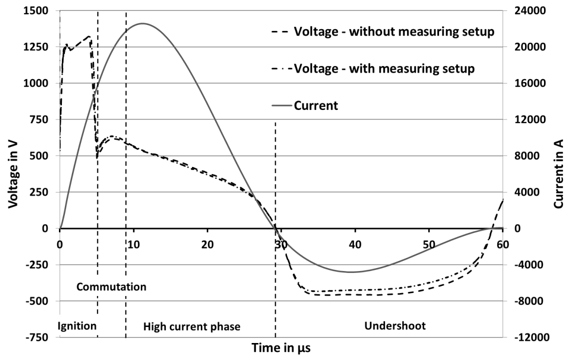

Figure 3. Influence of the measuring setup on plasma.

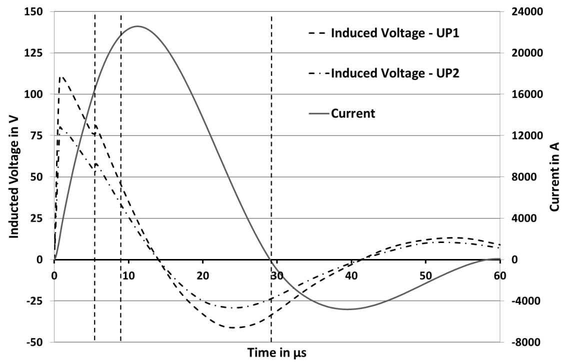

Figure 4. Induced voltages during surge current.

remain equal and can be subtracted in the calculation.

Plasma Propagation

In order to calculate the conductivity the current density respectively the cross section of the current has to be known. It can be assumed as the plasma propagation. In [9] it is shown that plasma during surge is spreading. Using a much smaller volume than [9] it is assumed that in this case the plasma fills out the spark gap completely. In order to verify this assumption the plasma propagation in the spark gap was recorded using a high speed camera and neutral density filters as shown in [10] (Figure 5):

During ignition phase, the spark gap ignites at the SDD at the right electrode and the plasma spreads towards the left electrode. The SDD is connected by a varistor, thus in this phase the current flows through a varistor until the plasma reaches the opposite electrode and a breakdown of the spark gap occurs. Afterwards the current commutates from the varistor to the spark gap. In high current and undershoot phases current flows through the plasma which fills the chamber nearly homogenous and completely. Further due to high pressure, the plasma steams out through the outlet ducts. Thus the assumption of homogenous plasma propagation in the spark gap is verified.

3. Uncertainty of Measurement

For the interpretation of the measurement results a statement about the relative uncertainty is necessary.

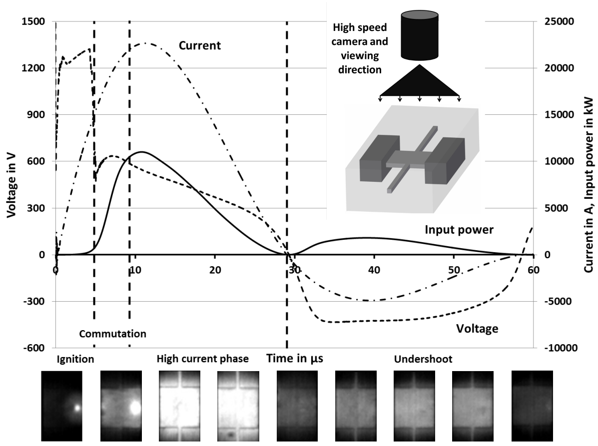

Figure 5. Plasma propagation during surge current.

Thus an estimation of the uncertainty u using the Guide to the Expression of Uncertainty in Measurement (GUM) is presented using the data at maximum electrical conductivity.

Due to the calculation of the electrical conductivity using different values the uncertainty is a geometrical addition of the uncertainties of these values (5). Thus uncertainty of current and voltage measurements have to be determined together with the uncertainty in the distance of the probes and cross section of current.

$$u_{\sigma,r} = \sqrt[2]{(\frac{u_I}{\bar{I}})^2 + (\frac{u_{\Delta U}}{\bar{\Delta U}})^2 + (\frac{u_{\Delta l}}{\bar{\Delta l}})^2 + (\frac{u_A}{\bar{A}})^2} \quad (5)$$

The uncertainty of the current respectively of the voltage is the sum of the variation with different measurements and the uncertainty of the measurement setup. For both (current and voltage measurement) the uncertainty of the measurement setup can be assumed to 2.5 %. Thus for the total uncertainty of the current this calculation reveals 2.52 % and 2.8 % for the voltage including the influence of variation in the inducted voltage at confidence interval of 68 %.

To determine the uncertainty of the distance of probes and cross section of current another method has to be used. In these cases it is assumed that the probability of these values is a Gaussian distribution. Further a most probably value is estimated with boundaries in whose area the real value is located with a probability of 99 %. Thus the standard deviation can be calculated which is used as the uncertainty of these values.

The probe distance should be 4 mm due to the design drawing. Thus this is the most probable value. Caused by tolerances in the manufacturing and slightly movements during surge the mentioned boundaries are estimated to be 3.9 mm and 4.1 mm, same procedure for the cross section: the most probable value is estimated to be 8 mm^2 (see 2B). The boundaries are estimated to be about ± 20 % of this value and thus about 6.5 mm^2 and 9.5 mm^2 (Figure 6). This yields into a relative uncertainty of 0.97 % for the

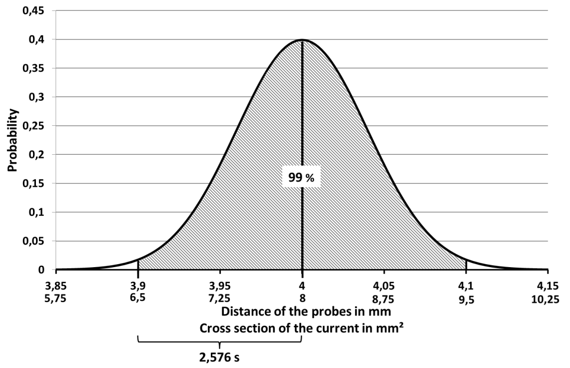

Figure 6. Gaussian distribution of the probe distance and cross section.

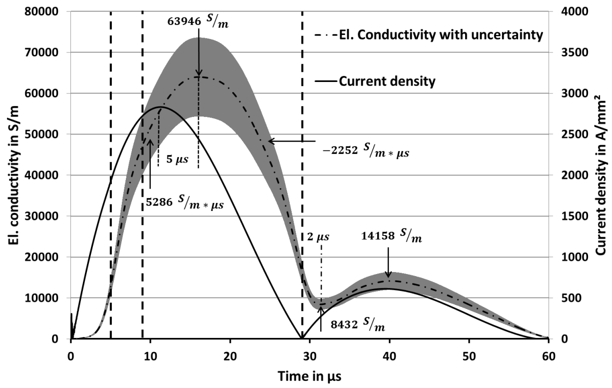

Figure 7. Behaviour of electrical conductivity during surge current.

probe distance and 7.28 % for the cross section (68 % confidence interval).

The combination of these different uncertainties in (5) yields into a relative uncertainty of the electrical conductivity of 15 % with an increased confidence interval to 90 %. This uncertainty is mostly determined by the uncertainty of the cross section. For example a reduction of the boundaries in the crosssection to ± 10 % (instead of ± 20 %) yields into a relative uncertainty of the electrical conductivity of 10 %.

4. Results

The electrical conductivity is shown in Figure 7 together with the current density. Due to the influence of the ignition using a SDD, commutation behaviour of current and unspecified propagation of the plasma in the ignition and commutation phase the electrical conductivity is an assumption during both phases. Afterwards the electrical conductivity is calculated using the measurement data.

The presented slopes are calculated as the linear increasing respectively decreasing between the 60 % and 80 % value of the maximum. The conductivity has a slope of about 5300 S per m and µs at the rising edge respectively 2250 S per m and µs at falling edge and a maximum of 64000 S per m. A comparison of the conductivity and current density reveals a similar behaviour with a time delay between the maxima of about 5 µs.

5. Conclusion and Outlook

A method to determine the electrical conductivity of plasma in spark gaps is applied at surge currents using two potential probes. The most important conclusions can be summarised as follows:

Firstly the investigations on influence of the probes on plasma, induced voltages and plasma propagation yield into the applicability of the method. Secondly the uncertainty of the result is estimated to 15 % at a confidence interval of 90 %. And thirdly the electrical conductivity during surge current was determined.

This method can be used in order to characterize the electrical conductivity in dependence of different boundary conditions like the current density and dimensions of the spark gap.

Furthermore measurements with follow current will help to get a more detailed knowledge about transition behaviour between surge and follow current like described in [10] in order to determine the current limiting behaviour.

References

[1] T. Runge, T. H. Kopp, and M. Kurrat. Experimental investigation on plasma pressure in an narrow gap for short time currents. In *Int. Conf. on Electrica Contacts*, Edinburgh, Great Britain, 2016.

[2] B. Schottel and M. Kurrat. Experimental investigation of short-time arc-wall interaction. In *Int. Conf. on Gas Disch. and Their Appl.*, Bejing, China, 2012.

[3] M. S. Benilov and A. Marotta. A model of the cathode region of atmospheric pressure arcs. *J. Phys. D: Appl. Phys.*, 28(9):1869–1882, 1995. doi:10.1088/0022-3727/28/9/015.

[4] H. M. Mott-Smith and I. Langmuir. The theory of collectors in gaseous discharges. *Phys. Rev.*, 28(4):727–763, 1926. doi:10.1103/PhysRev.28.727.

[5] G. R. Jones. *High pressure arcs in industrial devices.* Cambridge University Press, 1988.

[6] E. Z. Ibrahim. The ablation dominated polymethylmethacrylat arc. *J. Phys. D: Appl. Phys.*, 13(11):2045–2065, 1980. doi:10.1088/0022-3727/13/11/015.

[7] V. Bergmann. Untersuchungen zur anwendbarkeit elektrischer sondenmessungen im hochstromlichtbogen. PhD Thesis, 1987.

[8] G. Hertz and R. Rompe. *Einfürhung in die Plasmaphysik und ihre technischen Anwendungen.* Akademie Verlag, 1986.

[9] B. Schottel, T. H. Kopp, T. Runge, and M. Kurrat. Experimental investigations of short-time plasma propagation recorded by high speed camera. In *Int. Conf. on Gas Disch. and their Appl.*, Orleans, France, 2014.

[10] T. H. Kopp, T. Runge, and M. Kurrat. Investigation of arc interruption behavior of a model spark gap after surge current. In *Int. Conf. on Electric Contacts*, Edinburgh, Great Britain, 2016.