doi:10.14311/ppt.2017.2.165
Plasma Physics and Technology **4**(2):165–168, 2017

INVESTIGATION OF THE RECOVERY BEHAVIOUR OF A SMALL SWITCHING GAP AFTER CURRENT INTERRUPTION

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Abstract. The recovery behaviour of switching arcs in a small gap was investigated experimentally. Therefore a simple mechanical model switch without an arcing chamber was designed. For the investigation the current carring contacts are separated. After various arcing times, the current is interrupted by an electronic switch. At a fixed contact distance, the switching gap was tested with variable voltages to investigate the dielectric strength. Based on these results the recovery behaviour was studied using the Weibull distribution function.

Keywords: plasma temperature, switching gap, arc, current zero, reignition, Weibull distribution.

1. Introduction

Switches (e.g. grounding or disconnecting) and surge protective devices (SPD) are common as protection units, which both use gaps and arcs as switching elements[1–3]. The switching task is carried by the arc, that has to be extinguished quickley[1, 2, 4–6]. To prevent reignition of the arc, a high dielectric strength of the switching gap after current interruption is required[1–3]. Hence, the dielectric recovery behaviour of the residual gas column in the switching gap is of importance. Based on the breakdown mechanims in ionized gases, a first treatment on the recovery behaviour of low voltage switches is done in [1, 2, 7–10]. During the recovery process positive residual volume charges are left in front of the cathode of the switching gap. In the residual gas column a region with low ionization probability is established. The dielectric breakdown behaviour of this region can be characterized by the Townsend Mechanism[7–9]. The ionization of the residual gas column depends on the temperature and the electric field[1, 2, 7–10]. Within a temprature range of 300 K to 3000 K of the residual gas column, the density decreases and the effective ionization coefficient rises mainly dependent on dissociation processes[11, 12]. Regarding to the recovery behaviour this can be associated with a higher reignition probability. Especially the recovery behaviour of switching gaps with metal contacts can be modeled as a dielectric breakdown in high ionized gases[13]. Therefore the properties and behaviour of the residual gas column in the switching gap are important for an understanding of the recovery behaviour. Towards first investigations on the recovery behaviour of low voltage switches the dielectric strength of a switching gap is studied in this paper.

2. Measurement Setup

In this section, the designed measurement setup for the basic investigation of the recovery behaviour of the switching gap will be presented.

2.1. Electrical Test Circuit

In order to investigate the dielectric strength of a switching gap after various arcing times T_{Libo}, a test circuit, that is shwon in Figure 1 was developed. The 18 mF capacitor $\mathrm{C_C}$ provides the desired test current, which is adjusted by the resistor R roughly. It can be fine-tuned by varying the charging voltage $\mathrm{U_C}$ and the charging resistor $\mathrm{R_L} = 300\,\mathrm{k\Omega}$. To reduce the influence of the arc on the load current, the voltage of $\mathrm{C_C}$ is only adjusted within the range of 1 kV to 1.6 kV. The test voltage $\mathrm{U_V}$ is stabilized by a 40 µF capacitor $\mathrm{C_V}$ which can prevent any significant voltage drop when the voltage is applied onto the switching gap. Since the capacitor $\mathrm{C_V}$ and parasitic inductances may cause some oscillations the 140 Ω damping resistor $\mathrm{R_D}$ is added to the electrical test circuit. $\mathrm{R_D}$ also limits the current in case of a re-ignition of the arc. The archived slew rate of the test voltage is 2.5 kV/µs.

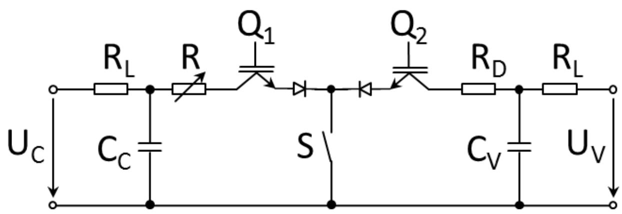

Figure 1. Electrical test circuit to investigate the dielectric strength of the switching gap

2.2. Mechanical Model Switch

The model mechanical switch consists of two contacts which are shown in Figure 2. The contacts are separated using a linear motion. The contact arrangement is placed in an open setup and is only surrounded by two sidewalls. The switching medium is air at atmospheric pressure. The contact plates with (4x3) mm^2 are sligthly spherical. The contact material is Ag/SnO_2. To minimize the influence of contact wear onto the measurements the contact plates were replaced after several switching processes. Quenching units are not implemented to ensure fast pressure equalization.

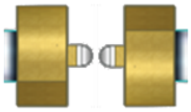

Figure 2. Contact arrangement

The switch is designed to be normally closed and the contact pressure is provided by a coil spring. A pneumatic drive is used to actuate the moving contact. Therefore the switching speed can be adjusted by varying the operating pressure.

3. Measurements and Results

The measurement procedure is described briefly and the results are shown. Based on the evaluated test parameters the analysis of the recovery behaviour is addressed using the Weibull distribution function.

3.1. Measurement Procedure

The measurement procedure is shown in Figure 3. The test circuit setup is to generate a load current of 100 A. The switch is in the closed position when the IGBT Q1 is turned on. The current flows for approximately 5 ms until the contacts are separated. The occurring arc voltage is detected by a separate triggering unit which starts the digital sequence control system. The digital sequence control system ensures exactly the same time sequence for each series of measurement. Depending on the series of measurement the arc burns for $T_{\mathrm{Libo}} = [0.1,\ 0.5,\ 1,\ 1.5]$ ms until the current is interrupted by the IGBT Q1. Exactly 2 ms after contact separation, the IGBT Q2 is turned on which applies the test voltage onto the switching gap.

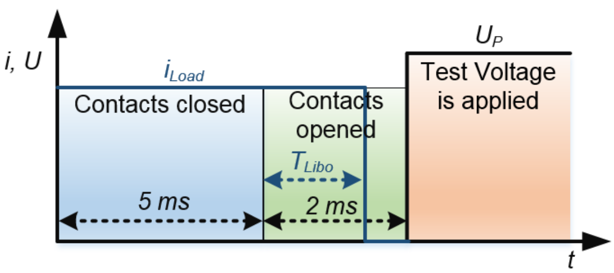

Figure 3. Schematic of the measurement procedure

This time and the operating pressure of the pneumatic system is kept constant to ensure exactly the same contact distance during all series of measurement. The contact distance could not be measured but is estimated to be in the 200 µm range. When the test voltage is applied the contacts are opened. The test voltage U_P was varied in the range of 400 V to 1800 V and 20 tests have been done at each chosen voltage. Depending on the breakdown probability of the last measured step, the voltage was reduced or raised in order to generate the reference points for the Weibull distribution.

3.2. Weibull-Estimation

For the investigation of the recovery-behaviour in the small switching gap a statistical approach based on the Weibull distribution is considered as appropriate[2, 14, 15]. The Weibull distribution function is described by the equation

$$F(U_P) = 1 - e^{-\left(\frac{U_P - U_{P0\%}}{U_{P63.2\%} - U_{P0\%}}\right)^{\beta}} \tag{1}$$

U_P is the test voltage, $U_{P0\%}$ the withstand voltage and $U_{P63.2\%}$ the breakdown voltage. $F(U_P)$ is calculated using the Matlab function *wblfit* and based on the measured data. Due to the fact, that a monotonously increasing behaviour of the input data is requiered the following steps in the calculation procedure are necassery. Assuming that the Weibull distribution function $F(U_P)$ is almost linear within the range of 0.3 to 0.9, only these values (pair of $F(U_P)$ and U_P) in the frequency distribution of the measured data are taken into account [14, 15]. With the selected data pairs, the 63.2 % breakdown-voltage-probability ($U_{P63.2\%}$) is caluclated using the fitting tool *fit* in Matlab in the first step. Based on the approach of linear regression the shape parameter β of the Weibull distribution function is caluclated using the same fitting tool in Matlab in the second step. In the last step the withstand voltage $U_{P0\%}$ of the switching gap is calculated using the Weibull chart.

3.3. Results

Calculation results of the Weibull parameter for a load current of $I_p = 100$ A are given in table 1. Both, U_P and β show a dependency on the arcing time. With a decreasing arcing time the shape paramter β shows a decreasing behaviour. The 63.2 % breakdown-voltage show for an increase of T_{Libo} from 0.1 ms to 0.5 ms and from 1 ms to 1.5 ms no significant change. Whereas for a time step of T_{Libo} from 0.5 ms to 1 ms the 63.2 % breakdown-voltage is reduced. An increase of the arcing time leads to a reduction of the withstand voltage $U_{P0\%}$. Considering the Weibull parameters, calculation results of the Weibull distribution functions are shown in Figure 4. For each function the associated reference points are highlighted as points in the same colour. It can be observed, that an increase of T_{Libo} leads to a shift of the weibull distribution function along the x-axis and hence to a reduction of the dielectric strength of the switching gap. For $T_{\mathrm{Libo}} =$ 1.5 ms the selected reference points show a maximum scattering, whereas for $T_{\mathrm{Libo}} = 1\,\mathrm{ms}$ the scattering is the lowest.

WB.-Param.	T_{Libo} in ms 0.1	0.5	1	1.5
$U_{P63\%}$	1222	1239	944	950
$U_{P0\%}$	739	572	431	227
β	9.14	5.96	5.87	3.21

Table 1. Weibull parameters for different arcing times

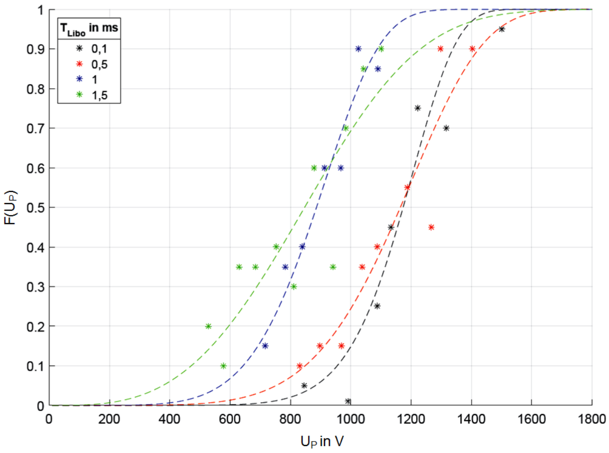

Figure 4. Weibull Distribution functions and reference points

3.4. Discussion

Based on the results the influence of the arcing time on the breakdown behaviour of the switching gap can be observed. Comparing the two time steps of T_{Libo} from 0.1 ms to 0.5 ms and from 1 ms to 1.5 ms, an increase of the arcing time does not reduce the breakdown strength of the switching gap. However comparing the results of $T_{\mathrm{Libo}} = 0.5\,\mathrm{ms}$ and 1 ms, it is obvious that an increased arcing time leads to a reduction of $U_{P0\%}$ and $U_{P63.2\%}$.

Due to the longer arc duration erosion and thereby irregularities on the contact surface are increased. This causes higher local electric fields which decrease the electric strength of the switching gap [3]. But after current interruption a pollution layer is formed onto the contacts which may have the opposite effect. A longer arc duration may cause a thicker pollution layer which even increases the electric strength. The contact surface and the forming process of the pollution layer after current interruption may be of interest for further investigations to estimate the leverage of these two effects on the dielectric strength.

Another influencing factor is the remaining conductivity of the residual gas column. The differential equations of Mayr and Cassie [1, 2, 7] can be used for an estimation. If the dielectric recovery time is several tens larger than the arc time constant of the mechanical model switch the remaining conductivity is negligible. This may be the case with arcing times of 0.1 ms and 0.5 ms and leads to the assumption that those breakdowns where dielectric only. Consequently the dielectric strength of the switching gap with $T_{\mathrm{Libo}} = 1.5\,\mathrm{ms}$ should be significant lower compared to $T_{\mathrm{Libo}} = 1\,\mathrm{ms}$. This assumption is supported by the differential equations which predict that the conductivity decreases exponentially after current interruption. But the test results show a different behaviour. The dielectric strength of the switching gap with $T_{\mathrm{Libo}} = 1\,\mathrm{ms}$ and 1.5 ms are almost identical. Either the arc time constant of the model mechanical switch is exceptional higher or the differential equations cannot be used in this case. This motivates further investigations on the conductivity of the residual gas column.

4. Conclusions

A measurement setup for the investigation of the recovery behaviour of switching gaps is presented. The recovery behaviour is studied basing on the dielectric strength of the switching gap for four different arcing times. Using the Weibull distribution function a statstical analysis of the dielectric strength and the influence of the arcing time is presented and discussed. Furthermore the erosion of the contact surface and the remaining conductivity of the residual gas column are discussed to explain the influence of the arcing time on the dielectric strength. Based on the results further investigations on the recovery behaviour of switching gaps are motivated.

Acknowledgements

The authors would like to thank Robin Schrader for his commitment and support of this work during his master thesis.

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