Vol. **115** (2009) *ACTA PHYSICA POLONICA A* No. 6

Proceedings of the 2nd Euro-Asian Pulsed Power Conference, Vilnius, Lithuania,September 22–26, 2008

Gas-Insulated Self-Breakdown Spark Gaps: Aspects on Low-Scattering and Long-Lifetime Switching

W. Frey*, M. Sack, R. Wuestner and G. Mueller

Forschungszentrum Karlsruhe GmbH, Inst. f. Hochleistungsimpuls- und Mikrowellentechnik (IHM)
Hermann-v-Helmholtz-Platz, 1, DE-76344 Eggenstein-Leopoldshafen, Germany

The influence of the electric field distribution between the electrodes and the seed electron generation rate on the scattering of the breakdown voltage of SF_6-insulated spark gaps was investigated. The breakdown voltage scattering considerably can be reduced by applying large-gap-volume, uniform-field electrode profiles instead of spherical shaped electrodes. Moreover, uniform field electrode profiles exhibit an uniform discharge probability in the entire gap volume and following an almost uniform erosion of electrode material along the electrode's surface. This preserves electrode shape and switching performance of the spark gap for a long maintenance-free lifetime. Breakdown voltage scattering further can be reduced by increasing the seed electron generation in the gap by an auxiliary corona discharge adjacent to the main gap. The experimental observations are discussed on the basis of the volume time law for discharge initiation.

PACS numbers: 52.75.Kq, 52.80.Mg

1. Introduction

Commercial applications of pulsed power techniques [1] demand for long lifetime switches, which are cheap, reliable and simple in construction. For industrial processes, a high pulse to pulse stability is required.

Self-breakdown spark gaps for repetitive pulse generators usually are charged by a more or less continuous voltage rise within several 10 ms to s, depending on the pulse repetition rate of the generator. A discharge between the electrodes is being initiated when the electric field strength in any volume element in the gap exceeds the DC breakdown field strength and if seed electrons are present in that volume element. At a sufficient high gas density avalanching processes lead to the formation of a streamer, which finally will bridge the gap, if the condition for streamer development, i.e. a sufficient high electron multiplication along the path of propagation, is fulfilled. After bridging, the plasma channel formed by the streamer will heat up. The gap is closed and the pulse energy can be delivered to the load.

The time lag to discharge inception, which corresponds to the scattering of the self-breakdown voltage for spark gaps charged by a continuous voltage rise, can be explained according to the volume time law, stated by Boeck in 1975 [2]:

$$\frac{\mathrm{d}N_\mathrm{e}(t)}{\mathrm{d}t} = \dot{n}_0(t) g(E(\boldsymbol{r}))\mathrm{d}V. \tag{1}$$

The number of seed-electrons $N_\mathrm{e}(t)$ per unit time $\mathrm{d}t$, which initiates gap bridging streamers, depends on the electron generation rate $\dot{n}_0(t)$ and a field-dependent weighting function $g(E)$ in a certain gap volume $\mathrm{d}V$ [3]. The weighting function depends on the electron ionization and attachment coefficients of the insulating gas and gives the probability of avalanche formation from a seed electron [4]. For a low breakdown voltage scattering the seed electron generation rate and the weighting function has to be high and at best uniform within the entire gap volume.

2. Experimental setup and conditions

All self-breakdown experiments were made on a SF_6-insulated spark gap of a 600 ns, 50 Ω transmission line pulse generator, Fig. 1. The transmission line was terminated by a cooled 50 Ω load. The voltage drop V_M across the load, measured by a calibrated Tektronix probe P6015 A, was referred to the breakdown voltage of the gap V_b as $V_\mathrm{M} = V_\mathrm{b}/2$. The pulse line was charged by a 60 kV/5 mA power supply. Prior to each experiment, the charging voltage maximum and the current were adjusted for a time of 2 s between two pulses.

The spark gap case, inner diameter 50 mm, length 160 mm, is made of PVC. All breakdown experiments were made at a SF_6 pressure of 7.0×10^4 Pa and at a gas flow of 100 Nl/h. The influence of the electrode shape on switching performance exemplarily was investigated for uniform field electrodes (asymmetric π-Broda-profile [5]) and for hemispheric electrodes. The electrodes were made of brass. Surface finishing of the electrodes was done with SiC sandpapers. Grain 4000 was

---

* corresponding author; e-mail: Wolfgang.Frey@ihm.fzk.de

used for the final polish. After polishing, electrode surface conditioning was accomplished by approximately 200 shot per mm^2 eroded area of electrode surface. In case of uniform field electrodes, after conditioning the erosion was visually uniform on the whole surface, whereas an accumulation of discharge base points near the symmetry axis on the hemispherical electrodes could be observed.

Subsequent pulse wave forms were acquired by a 1 GSample, 500 MHz oscilloscope. The pulse voltage amplitude V_{M} was calculated by averaging all data points in the time range 60 ns $< t <$ 260 ns after the leading edge of the pulse, Fig. 1. A sample size of $N = 200$ was chosen for each breakdown-voltage distribution. For corona pre-ionization of the spark gap, a stainless steel needle with a tip radius of 140 μm was located at a distance of 10 mm from the edge of the electrode, Fig. 1, right. In all cases, the gap distance between the main electrodes was 3 mm.

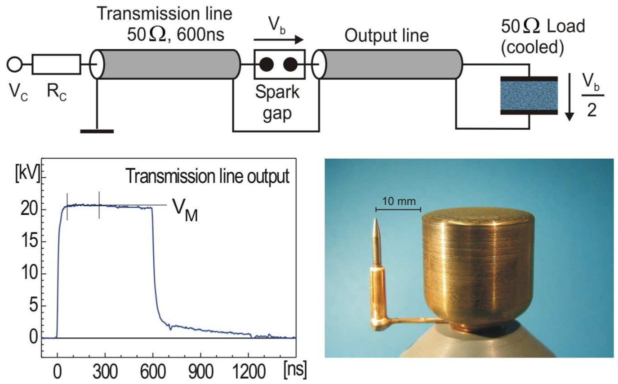

Fig. 1. Schematic diagram and output voltage of the transmission line generator. The corona pre-ionization electrode arrangement is shown in the photograph on the right.

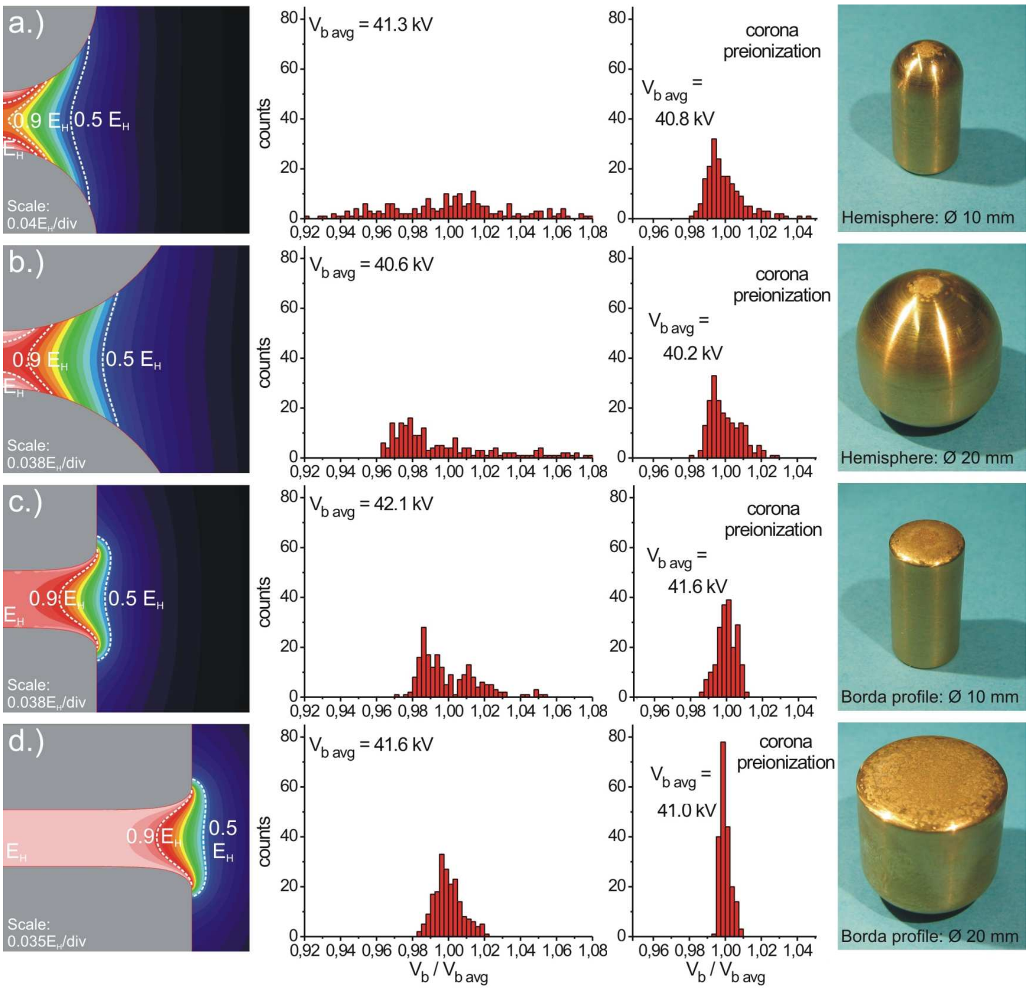

Fig. 2. Comparison of the breakdown voltage distributions of different electrode surface profiles with and without corona pre-ionization, middle columns. The distributions are normalized on the average breakdown voltage V_{bavg}. The electric field distribution of the corresponding profiles, calculated with Charge Simulation Programm CSP [6], are shown on the left. Erosion patterns are shown on the photographs on the right.

3. Results and discussion

Major sources for seed-electron generation in SF_6 insulated spark-gaps can be divided into volume based mechanisms, like ionization by natural radiation and electron detachment from negative SF_6 ions, and a surface bound effect, i.e. field emission from the cathode. The results, shown in Fig. 2, reveal the correlation between the electric field distribution in the gap and the scattering of the breakdown voltage. The lowest scattering could be obtained for the large volume uniform field profile, Fig. 2d. Irrespective of its origin, in this case, a comparable large number of seed electrons is available and the probability for streamer initiation and propagation $g(E)$ is uniform in the entire gap volume. Once a streamer is launched, it most probably will bridge the gap. Smaller volumes with sufficient high electric field strength for streamer propagation, illustrated by the dashed 0.9 E_H border lines, Fig. 2a–c, result in a higher scattering of the breakdown voltage. The gap between hemispherical electrodes exhibits the smallest volume with sufficient high electric field for streamer initiation and propagation. Additionally, the probability $g(E)$ decreases towards the middle of the gap, amplifying the tendency to a higher breakdown voltage scattering for the hemispherical profiles. A streamer, starting from the high-field region near by the electrode surface, might stop at half the gap distance, if electron attachment prevails. Enhanced seed-electron generation by corona pre-ionization in all cases further reduces the self-breakdown voltage scattering, Fig. 2.

Based on the experimental results, a clear determination of the most probable seed electron generation mechanism is difficult, since the volume with a high probability $g(E)$, the number of available seed electrons $\int \dot{n}_0 \mathrm{d}V$ and the surface area similarly increase. The fact that the discharge base point density is not increased on the surface area nearby the corona discharge electrode supports a volume based seed-electron generation, e.g. photoionization, photodetachment, in case of corona pre-ionization. A discharge initiation in the main gap by electrons from a positive polarity corona discharge directly connected to anode potential can be excluded.

Erosion patterns on the surfaces of the electrodes clearly indicate a uniform discharge base point distribution in case of uniform field electrode profiles, Fig. 2. Assuming a constant loss of electrode material after a finite number of discharges, a large diameter uniform field profile exhibits the lowest variation of electrode length, which preserves constant switching characteristics for a long time interval.

4. Conclusions

Conditions for low breakdown voltage scattering spark gaps, a high seed-electron generation rate and a constant probability for streamer initiation and propagation in the entire gap volume, can be fulfilled by large diameter, uniform field Borda profiles and corona pre-ionization. Uniform field electrode profiles provide uniform electrode erosion, preserving electrode shape and switching performance for a comparable long maintenance free lifetime.

References

[1] M. Sack, C. Schultheiss, H. Bluhm, *IEEE Trans. Ind. Appl.* **41**, 707 (2005).

[2] W. Boeck, *Elekt. Zeitschrift A* **96**, 300 (1975).

[3] P. Osmokrovic, B. Loncar, M. Gajic-Kvascev, *IEEE Trans. Plasma Sci.* **33**, 1677 (2005).

[4] M. Finkel, W. Boeck, in: *Conf. on Electric Instruments and Dielectric Phenomena*, IEEE Dielectrics and Insulation Society, 2001, p. 436.

[5] H. Prinz, *Hochspannungsfelder*, R. Oldenbourg Verlag, München 1969.

[6] P.L. Levin, A.J. Hansen, D. Beatovic, H. Gan, J.H. Petrangelo, *IEEE Trans. El. Ins.* **28**, 161 (1993).