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# Empirical analysis of picosecond breakdown in sulfur hexafluoride

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ABSTRACT

Using state of the art equipment and multiple simultaneous data acquisition systems, breakdown in sulfur hexafluoride ($SF_6$) is examined in high resolution. Recorded risetimes can be as fast as 50 ps. Influential parameters of breakdown are identified, recorded, and categorized. Methods for removing the impact of the measurement system are implemented in efforts to distinguish the physical phenomenon from influential external factors. Observed waveforms and breakdown characteristics are categorized into three types. Each type is particular to a specific parameter range – i.e. electric field *E/p* or the product of pressure and distance *pd*.



## 1. Introduction

Due to its electronegative nature and excellent arc-extinguishing properties, sulfur hexafluoride ($SF_6$) provides high dielectric strength and enables significant reductions in equipment size [1]. The dielectric strength of $SF_6$ under DC-stress and homogenous electric field conditions is 89 V/m Pa [2]. When this critical value is exceeded, electric breakdown occurs. During breakdown, $SF_6$ loses its insulating properties and a highly ionized conductive channel is formed bridging the electrodes and equalizing the potential over the gap as current is allowed to flow. As gases are self-restoring dielectric media, following the extinction of discharge, $SF_6$ regains its insulating properties and returns to its prior stable state.

The ionization (breakdown) process is influenced by a vast range of variables such as gas properties, pressure, temperature, electrode material and configuration thereby making the breakdown process difficult to predict and model. Overall, two theories have been generally accepted in the scientific society for explaining breakdown in gas – the Townsend theory and the Streamer mechanism.

The Townsend theory predicts the formation of an electron avalanche initiating from a primary electron with sufficient ionization energy to progress across a gap to bridge the electrodes. Secondary emission of electrons is required to maintain the avalanche growth for breakdown to be complete. In contrast, the Streamer mechanism predicts that the distribution of electrons and slower positive ions (products of collisional ionization) distort the electric field at the tip of the advancing avalanche. This enhanced field may generate photo-ionization which in turn can trigger additional electron avalanches which are then bridged by weakly conducting streamers to form a highly conductive discharge channel [1,2].

Paschen's law expresses Townsend's breakdown criteria in terms of voltage (or electric field) making its practical interpretation easier. Essentially, breakdown voltage $U_b$ is a function of pressure $p$ and inter-electrode distance $d$. Each individual gas has a specific curve with a finite minimum value $(pd)_{min}$. Below this minimum value, electrons may cross the gap without a single ionizing collision and therefore require a larger voltage stress to achieve breakdown [2]. The $pd$ range investigated in this research spans $21 < pd < 2736$ Pa m and remains above the $(pd)_{min}$ value for $SF_6$ (0.35 Pa m).

Several limitations and deviations from theory have been experimentally derived. For example, Paschen's law is valid up to a certain $pd$ value for static breakdown where voltage stress gradients are low. For applied impulse voltages, this $pd$ value decreases with increasing stress gradient [1]. To account for this, breakdown voltage as a function of applied impulse voltage steepness is assessed (Section 3).

Divergence from Paschen's law not only occurs for excessively high pressures, but also for sufficiently low pressures where the

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laws of vacuum breakdown are dominated by electrode material [1,2]. Applied pressures in this research do not fall below 0.1 MPa.

In addition, dielectric strength has also been found to depend on inter-electrode distance and does not remain constant. In very short gaps, ionization mechanisms do not have sufficient time to operate resulting in increased field strength of the insulation gas [1]. In large gaps, higher breakdown voltages are observed for a given *pd* value due to the loss of electrons in the gap as a result of diffusion [3]. The inter-electrode distances in this research remain under 1 mm.

Numerous authors have also developed equations for calculating the risetime of breakdown in insulating gases [4–7]. Typically, risetime is presented in relation to electric field, gas pressure (or density), characteristic impedance, and distance. Depicted relationships and dominating parameters are quite varying and are confined to restricted ranges and conditions. There is an overall lack of uniformity and universal application.

Accurate measurement of the breakdown process is difficult. In efforts to improve recorded data integrity steps were taken to design an appropriate test device, widen the range of influential variables, improve sampling resolution, and remove the impact of the measurement system from results.

## 2. Test setup

Measurements were conducted using two alternative systems and multiple recording instruments to study the reproducibility of the observed phenomena. Two different test spark gaps were designed using FEM (Finite Element Method) simulation and theoretical analysis. The first spark gap, which is used in this text as a comparison and not discussed in detail, has a coaxial structure with biconical electrodes [8]. The second spark gap has a conical design. Both gaps have electrode profiles designed to produce a homogenous electric field in the breakdown region.

A steep negative impulse was applied over the spark gap. One electrode was grounded while the other was fed increasing voltage until breakdown in the insulating gas occurred. The breakdown voltage level was recorded by a resistive voltage divider and the resulting breakdown waveform in the spark gap was measured using *D*-dot probes.

### 2.1. Measurement system

The measurement system (Fig. 1) includes the test gap, an impulse generator (Haefely MTS), a resistive voltage divider for measuring the breakdown voltage level (up to 400 kV, experimental response time $T_N = 10.6$ ns, partial response time $T_\alpha = 11$ ns, overshoot $\beta = 8.5\%$, settling time $t_s = 90$ ns, divider ratio 1:10,809, traceable to national standard), coupling cables (Sucoflex 106), attenuators, and recording digitizers (digitizer details shown in Table 1).

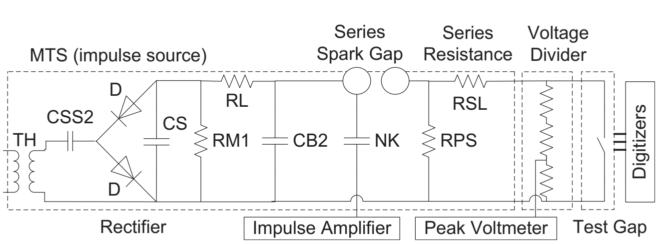


**Fig. 1.** Measurement setup – impulse source (Haefely Multi Test Set, MTS), divider, test gap, and digitizers.

**Table 1**
Digitizer list.

| Digitizer | Analog bandwidth | Risetime | Samples (S) |
|---|---|---|---|
| *Coaxial test gap* | | | |
| Tektronix DSA72004 (retail) | 16 GHz | 22.5 ps | 50 GS/s |
| Tektronix DSA72004 (prototype) | 20 GHz[a] | 22.5 ps | 50 GS/s |
| Tektronix TDS8200/80E01 | 50 GHz[b] | <7 ps | 500 S/waveform |
| *Conical test gap* | | | |
| LeCroy WaveMaster 8600A | 6 GHz | 75 ps | 20 GS/s |
| LeCroy SDA 11000 | 11 GHz | 40 ps | 40 GS/s |
| LeCroy SDA 830Zi | 30 GHz | 15.5 ps | 80 GS/s |

[a] 16 GHz analog bandwidth extended to 20 GHz using DSP. This feature could not be disabled in the prototype
[b] Series sampling oscilloscope with 80E01 sampling module.

To avoid coupling of interference into the measured signal, sensitive recording instruments were situated in the neighboring high voltage hall separated from the test gap and impulse generator by a 100 mm thick grounded steel door. The floor of the measurement area was covered by a copper sheet. Measurement cables were passed under this sheet to the digitizers. All equipment was grounded at a single point.

### 2.2. Conical test gap

The main motivation behind the construction of the conical test gap (Fig. 2) was to maximize acquired data integrity. By adopting a design principle [9] where the impedance of a conical transmission line remains constant for a fixed angle, the impact of superimposed signals affecting the measured data is minimized. The dimensions of the structure were designed so that the propagating breakdown signal is allowed to travel sufficiently far before reflecting back to the sensors. The duration of measured waveforms varied up to 1 ns. Thus, a conical transmission line length of 155 mm allows for a delay of approximately 1 ns before a major reflection from the end of the conical electrode returns to the measurement sensors. The height of the structure was selected to avoid discharge in any regions other than the intended breakdown area at the tip of the conical electrode. The fiberglass chamber containing the pressurized insulation gas offers sufficient mechanical and electrical support to separate the grounded electrode plate from the high voltage conical electrode. Modified composite insulators provide mechanical sealing and strength to withstand imposed pressures (maximum load 70 kN per insulator).

Four standard (hermitically sealed) SMA jacks located 20 mm from the spark gap center point and displaced 90° from each other were used as *D*-dot probes (Fig. 3). The center conductor of the SMA connector was cut close to the level of the insulation and mounted

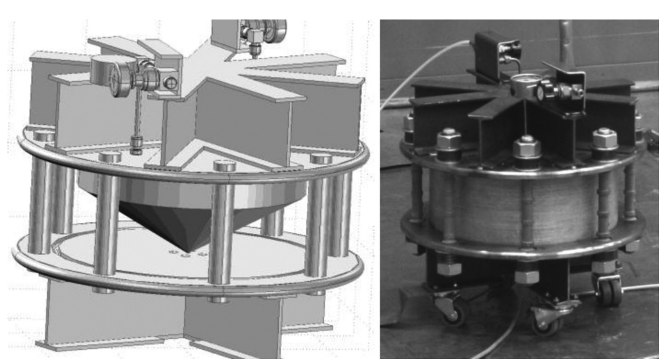

**Fig. 2.** Conical test gap. Left – interior view of conical electrode (fiberglass chamber removed). Right – exterior view including all components.