Breakdown strength and dielectric recover investigation inside a supercritical switch

BREAKDOWN STRENGTH AND DIELECTRIC RECOVER INVESTIGATION INSIDE A SUPERCRITICAL SWITCH

J. Zhang[1], E.J.M. van Heesch[1], Takao Namihira[2], F.J.C.M. Beckers[1], and A.J.M. Pemen[1],

[1] *Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands*
[2] *Graduate School of Science and Technology, Kumamoto University, Kumamoto, 860-8555, Japan*
jin.zhang@tue.nl, E.J.M.v.Heesch@tue.nl, namihira@cs.kumamoto-u.ac.jp, F.J.C.M.Beckers@tue.nl, A.J.M.Pemen@tue.nl

We present the design of a supercritical fluid insulated switch (SC switch). The dielectric recovery inside SC N_2 switch is tested with repetitive voltage source with peak voltage 30 kV and frequency up to 1 kHz. The percentage of the full recover of the SC switch is larger than 80 % within 1 ms, if the value of $pd > 18$ bar·mm, and d > 0.2 mm. With a numerical model simulating the complete discharge and recovery procedure inside a plane-plane electrode gap insulated with SC N_2, we find that the hot region of spark in SC N_2 where T > 2000 K vanishes at 1 μs after the breakdown, and the dielectric strength of the gap recovers to half of the cold breakdown value at about 5 μs.

1 Introduction

In power system networks, the popular switching medium in high voltage circuit breakers (CBs)-Sulfur hexafluoride (SF_6) demands replacement in consideration of its disadvantages: it is strong greenhouse gas, and its degradation products are toxic. It is essential to find a switching medium with excellent interrupting performance but still is environmentally harmless, as an alternative of SF_6. Supercritical fluids (SCFs), widely researched in chemistry field, have recently drawn scientists' attention to its potential in the area of electrical switching. The reason is that SCF combines the advantages of liquids and gases: high density, high heat conductivity and large mass transfer ability such as the low viscosity and the high diffusion. Existing data about breakdown voltage inside SCF proved the satisfying dielectric strength of SCF, but the dielectric recovery process after the breakdown inside SCF is still unexplored.

Aiming on the breakdown strength and dielectric recovery analysis of a SCF, plasma switches insulated with SCFs are designed and tested in our lab. SC nitrogen (SC N_2) is chosen to be the studied medium in this work, because of its relatively low critical pressure of 3.94 MPa and critical temperature of 126 K. The breakdown voltage inside SC N_2 has been proven to be convincingly high [1].

2 Experiment setup

We have designed and tested a SC plasma switch under a repetitive voltage source. The maximum pressure of the SC switch is 200 bar and the adjustable gap width varies from 0 to 1 mm. In our experiment we keep N_2 in the room temperature. Figure 1(a) gives a 3D plot of the SC nitrogen switch designed for operating up to 200 bar. Figure 1(b) gives the schematic of gas supply circuit for SC switch. Nitrogen (pure 3.0) with pressure up to 200 bar is supplied from nitrogen bottle, one air driven gas booster is used to facilitate the nitrogen flow inside the loop; pressure valves and gauges are included to ensure safe operation; a balance vessel is used to smooth out the pressure fluctuation caused by pulsed operation of the booster; a water cooled heat ex-changer keeps the SCF temperature constant at room temperature (290 K); a flow meter as well as pressure gauges are used to monitor the flow rate and pressure of SCF flowing through the SC switch. The charging circuit for the SC switch with repetition frequency up to 1 kHz (time space between two succeeding pulses 1 - 100 ms) has already been introduced by figure 2.

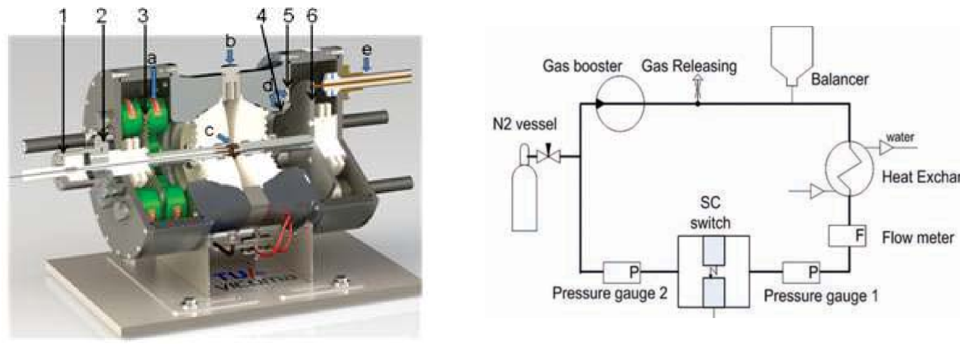

Figure 1: (a). Versatile supercritical medium switch and the schematic of its setup a. integrated capacitor; b. optical sight plug; c. adjustable gap width; d. embedded voltage and current sensor; e. 4-stage TLT voltage amplifier; 1. Adjusting knob for trigger electrode; 2. Adjusting knob for main electrode; 3. Flexible aluminum disk for gap width adjustment; 4. Rogowski coil; 5. Copper plate for voltage sensor; 6. Stainless steel plate for voltage sensor. (b). Schematic of gas loop of SC switch.

The SC switch under goes breakdown when the trigger gap fires under the RLC [2] triggering system. The voltage is measured on the main anode of the SC switch with a voltage probe North Star 5.0. A signal turn rogowski coil mounted on the cathode side measures the arc current. The typical voltage and current waveform are shown in figure 3. From figure 3 we can find that the measured spark current $i(t)$ has a second peak at time about 150 ns. This is due to the reflection from the unmatched transmission line transformer (TLT) mounted behind the SC switch.

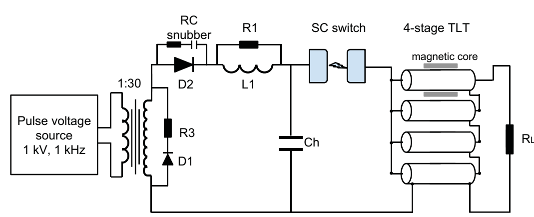

Figure 2: Schematic of charging circuit for SC switch. C_h-high voltage capacitor; L_1-inductance for resonant charging circuit for C_h; TLT-transmission line transformer; R_L-resistive load the match the impedance of TLT.

3 Experiment Results

Back

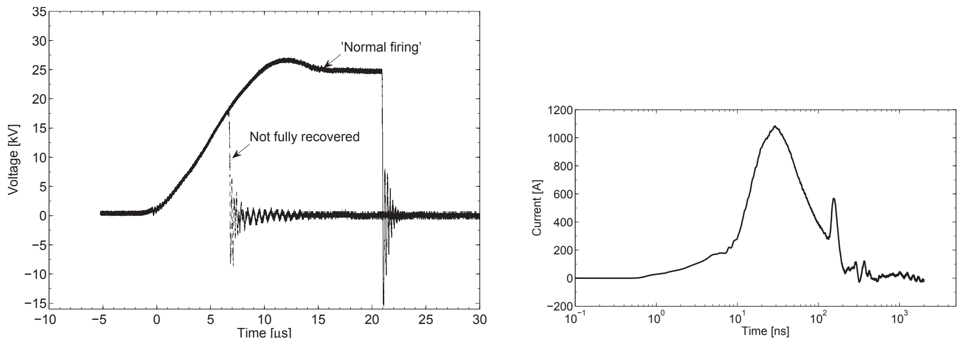

Figure 3: (a) Example of voltage waveform measured on the anode of the SC N_2 switch under breakdown of fully recovered and not fully recovered. (b) Current measured through the gap with Rogoeski coil. The pressure of SC N_2 is 80 bar, the gap width 0.3 mm, and the temperature 300 K.

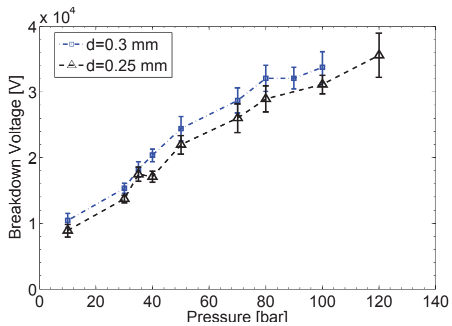

Figure 4: Breakdown voltage of the SC switch versus pressure at gap width of 0.25 mm and 0.3 mm.

The breakdown voltage of the SC switch is recorded under various gap width and medium pressure. Figure 4 gives the breakdown voltage as function of pressure under 0.25 mm and 0.3 mm gap width. The breakdown voltage of N_2 increases with higher pressure and larger gap width. The scattering of the breakdown voltage increases at higher pressure.

Due to the *LC* resonant charging circuit, the rise time of the voltage from 0 to its peak value is constant. Under repetitive operation, if the dielectric strength of the switch recovers completely from the previous breakdown, the switch undergoes a 'normal firing'. On the other hand, if the SC switch is not fully recovered, the gap will break down before the voltage reaches the peak value. Figure 3(a) has given the example voltage waveform under normal firing and not fully recovered situation.

With the criterion of normal firing defined, the ratio of the number of shots undergoing normal firing (fully charged waveform) to the number of total shots, denoted as δ, is recorded as the recovery percentage of the switch. Figure 5 shows the recovery percentage of the SC N_2 estimated from our definition, as a function of pd under 1 kHz repetitive source. From the figure we can see that the recovery percent of the SC switch is larger than 80% within 1 ms, if the value of $pd \geq 18$ bar $\cdot$ mm, and $d > 0.2$ mm. The disparity of recovery rate caused by the gap width becomes less significant in larger value of pd.

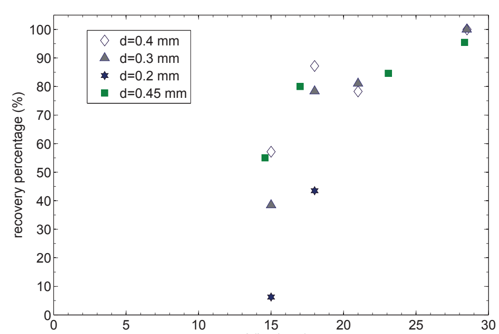

Figure 5: The recovery percentage of SC N_2 switch under 1 kHz repetitive source.

4 Physical modeling

The discharge and recovery process of a gas after breakdown can be theoretically analysed using mathematical modeling. Recent modeling works focus on different discharge stages: avalanche-to-streamer stage [3, 4]; streamer-to-spark transition stage [5]; and Discharge & post-discharge stage [6–9]. However, none of them have combined the modeling of theses stages and simulated the complete discharge process inside the gas. We have developed a physical model to study the complete recovery characteristic of a SCF. We have simulated the streamer-to-spark transition and the discharge & post-discharge phase inside the SC N_2 breakdown, as can be seen in the diagram of simulating stages in figure 6. The model and its details are published is [10].

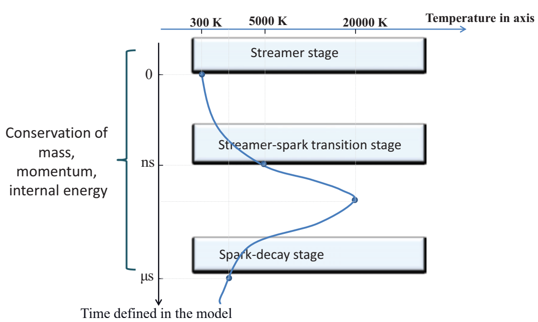

Figure 6: Simulation stages and the estimated temperature on the axis of the spark channel in SC N_2.

When electric field are applied across the gas, streamers propagates and conducting channel forms in the gap between electrodes. Energy are transferred from external source to the medium. The electric field wave shape is taken from the experimental data (measured current and circuit equations). The governing equations in the model are conservation of mass, conservation of momentum, and conservation of energy. During the streamer stage, not all the energy from external source contributes to the gas heating, but a large part is transferred and stored in the excited energy levels such as translational level, vibrational excited level and electronic excited level. Hence the equation of energy conservation includes the evolution of neutral gas energy, vibrational and electronic excited energy.

The simulated results for the temperature of the discharge channel as a function of time and space is depicted in figure 7. Further results of the numerical model show, for SC N_2 with parameters of p=80 bar and T=300 K, that within ns duration the spark fully develops. For pulsed power waveform of 100 ns width it takes about 5 microseconds, after spark formation, for the temperature on axis of the spark channel to decay to a value under 2000 K. At this time, the dielectric strength of the gap has recovered to about half of the cold breakdown voltage.

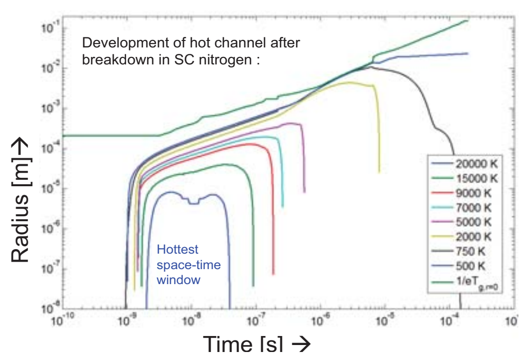

Figure 7: Space-time plot of the arc temperature calculated by the model.

5 Conclusion

The experiment results of the SC switch under repetitive pulses with time lag of 1 ms proves that the breakdown voltage and the recovery rate of SCF increases with higher *pd*. For the same value of *pd*, larger gap width *d* contributes to higher breakdown voltage and larger recover rate. In order to achieve higher repetition rate, we need larger *d* when the value of *pd* is small. But in

Back

larger value of pd, as long as $d \geq 0.3$ mm, the recovery rate of the SC switch is higher than 80 %.

For SC nitrogen with undisturbed parameters of p =80 bar and T=300 K, the simulation results show that within several *ns* after the streamer bridges the switch gap, the spark is fully developed, and this time depends on the applied electric field between electrodes. About 5 μs after the spark formation, temperature in the axis of the spark channel decays to value under 2000 K, and the dielectric strength pf the gap recovery to 2/3 of the cold breakdown voltage.

Acknowledgements

This research is supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs. The research is also supported by the Dutch IOP-EMVT program and by the companies Antea Group, HMVT, ABB and Siemens.

References

[1] J. Zhang, E.J.M. Heesch, F. Beckers, T. Huiskamp, and G. Pemen, *IEEE Transactions on Plasma Science*, VOL. 42, NO. 2, 2014.

[2] K. Yan, E.J.M. van Heesch, A.J.M. Pemen, P.A.H.J. Huijbrechts, and P.C.T. van der Laan. A 10 kW high-voltage pulse generator for corona plasma generation. *Review of Scientific Instruments*, 72(5), 2443-2447, 2001.

[3] N. Y. Babaeva and G. V. Naidis. Two-dimensional modelling of positive streamer dynamics in non-uniform electric fields in air. *J. Phys. D*, 29:2423, 1996.

[4] A. B. Sun, J. Teunissen, and U. Ebert. Why isolated streamer discharges hardly exist above the breakdown field in atmospheric air. *Geophysical Research Letters*, 40(10):2417–2422, 2013.

[5] J. A. Riousset, V. P. Pasko, and A. Bourdon. Air-density-dependent model for analysis of air heating associated with streamers, leaders, and transient luminous events. *J. Geophys. Res. (Space Phys)*, 115:12321, 2010.

[6] M. N. Plooster. Numerical Simulation of Spark Discharges in Air. *Physics of Fluids*, 14:2111, 1971.

[7] M. Akram and E. Lundgren. The evolution of spark discharges in gases: I. macroscopic models. *Journal of Physics D: Applied Physics*, 29(8):2129, 1996.

[8] M. Akram. The evolution of spark discharges in gases: Ii. numerical solution of one-dimensional models. *Journal of Physics D: Applied Physics*, 29(8):2137, 1996.

[9] H. L. Brode. Numerical solutions of spherical blast waves. *Journal of Applied Physics*, 26(6), 1955.

[10] J. Zhang, A.H. Markosyan, M. Seeger, E.M. van Veldhuizen, E.J.M. van Heesch, U. Ebert. *Numerical and experimental investigation of dielectric recovery in supercritical* N_2. Submitted to Plasma Sources Sci. Technol.