Recovery of Water Switches

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Abstract

The recovery of a water switch has been studied by means of Schlieren diagnostics. It was found that a vapor bubble which begins to expand 2 μs after the electrical breakdown and decays after 1 ms determines the recovery time of the switch. The recovery time, defined as the time required to reach the full voltage across the gap after a previous switch event, was measured for two different electrode geometries by means of a pulse-probe (double pulse) system. The first pulse generated the water breakdown. The second pulse served as a probe pulse. The degree of recovery was defined as the ratio of the breakdown voltage obtained with the second pulse to that of the first pulse. Full recovery was achieved for a switch in static water with an energy deposition of 0.6 J per cm gap length after 2 ms corresponding to a repetition rate of 500 Hz. This rate could be increased to 1 kHz by flowing the water. An all-water pulse generator consisting of a water switch and a pulse forming network with water as dielectric was built and tested. This pulse generator produced 14 kV, 10 ns pulses into a 15 Ω load with a current rise of 4×10^{11} A/s.

1. Introduction

Water has been used in pulsed power systems because of its high dielectric strength, self-healing ability and high dielectric constant. For distilled water, a dielectric strength on the order of MV/cm was measured [1]. The breakdown process in water is very fast. The rate of current rise was measured as 3×10^{11} A/s [2]. These properties make water a good candidate as switching medium in a high power switch [3].

For high power water switching, the recovery time of water determines the repetition rate. In this paper, we report the results of experimental studies on the recovery behavior of a water switch. Schlieren photographs of static water after breakdown show the successive phases of the recovery: plasma decay, shockwaves and the expansion of a vapor bubble. This process takes milliseconds. The bubble expansion and decay process dominate the recovery phase of the water switch. By flowing the water through the switch, we can shorten the recovery time and operate the water switch at a higher repetition rate.

Since water has a high dielectric constant (ε=80), it can be used as the energy storage medium for a pulse forming line (PFL) in a compact pulsed power system. By combining a water switch and a water Blumlein PFL, we have built an all-water system that is compact and triggerable.

2. Recovery Measurements (Optical)

Schlieren diagnostics was used to study the post-breakdown phase of a water switch. Schlieren diagnostics allow us to obtain the information on the gradient of the index of refraction [4]. The experimental setup is shown in Fig. 1. A discharge cell with pin-plane electrodes (stainless steel, pin diameter 1.7 mm) and a gap distance of 200 μm is charged by a Blumlein line generator (50 Ω), which provides a 200 ns pulse. The maximum voltage is 60 kV. A CCD camera with 200 ps resolution is triggered by a pickup signal from the spark gap of the Blumlein line pulser. This trigger signal for the CCD camera could be delayed by a delay generator, and consequently allows us to observe the temporal development of the density gradient after water breakdown .

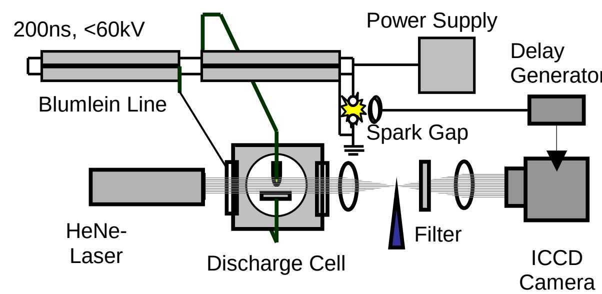

Fig. 1. Experimental Setup.

The Schlieren photowgraphs of the postbreakdown phase are shown in Fig. 2. The gap distance is 200 μm and the exposure time is 50 ns. The time shown on the photographs is the time between the application of voltage and the trigger signal of the CCD camera. The jitter is ~100 ns. The electrical breakdown and the formation of a spark plasma cause shockwaves. The shockwaves are traveling symmetrically along the pin electrode at the speed of 1.5 km/s. 50 μs after breakdown they are no longer observed in the viewing area. It can be seen that 2 μs after the breakdown opaque volume (bubble) originates from the region between the two electrodes. This volume continues to expand for 200 μs. After that, it decays within 1 ms. This opaque volume can be explained as a vapor bubble. This assumption is based on the opacity of the volume, which is due to the large difference in dielectric constant of vapor (ε=1) and surrounding water (ε=80). The change in refraction index from water to air inside the bubble results in the scattering of the laser beam light as shown in Fig 3.a. Also, as shown in Fig. 4, the radial expansion of the volume ($R(t) \propto t^{0.4}$) is in agreement with a bubble theory [5], which shows the radius of the bubble is determined by the kinetic energy of the water surrounding the bubble:

$$R=R_0 + (25W_k/8\pi\rho)^{1/5}t^{0.4}$$

where ρ is the mass density of water, R_0 is the initial radius of the bubble, and W_k is the kinetic energy of the water surrounding the bubble. Fig. 3.b shows the velocity vector that is caused by the vapor pressure along the bubble-water surface qualitatively [6]. When the pressure inside the bubble has decreased to the value of the pressure of the surrounding water, expansion stops and collapse begins.

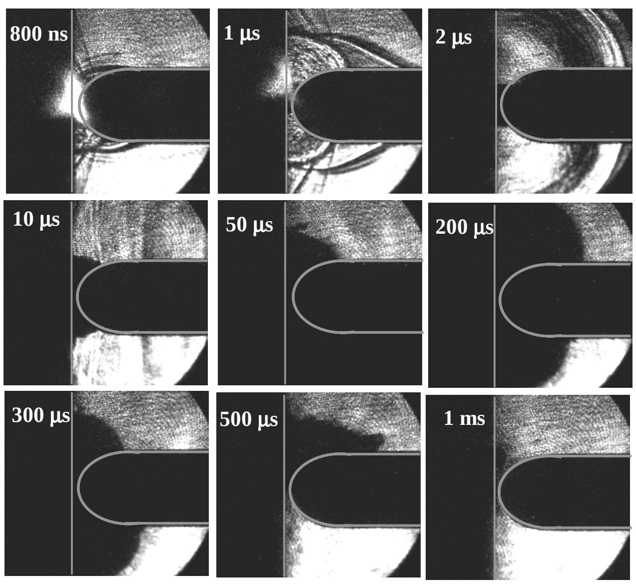

Fig. 2. Schlieren photographs in the post-breakdown phase.

The expansion and decay phase of the bubble can be shortened by flushing the gap to remove the bubble mechanically.

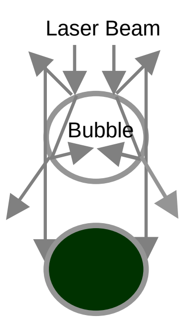

Fig. 3a. Light scattering of vapor bubble.

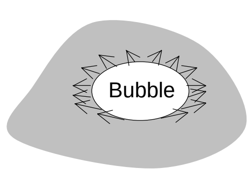

Fig. 3b. Velocity vector along the bubble-water interface [5].

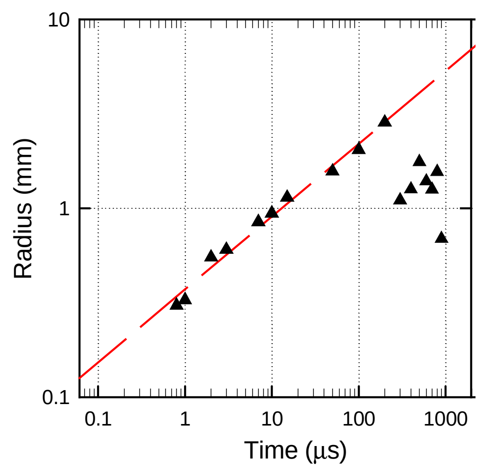

Fig. 4. Temporal development of bubble radius. The fitting curve for the radius expansion is $R(t) \propto t^{0.4}$.

3. Recovery Measurements (Electrical)

The bubble expansion and decay determines the recovery time. By flowing the water these processes can be shortened in time. There were two types of flowing systems (electrode geometries) investigated, shown in Fig. 5. One is designed to flow water transversely and the other to flow water axially through a hollow tube electrode. It can be expected that axial flow will produce a higher efficiency than transverse flow because of a shorter flow length required to remove the bubble. (For example, in a 100 µm wide gap, an axial water flow of 1 m/s can bridge the gap within 1 µs.)

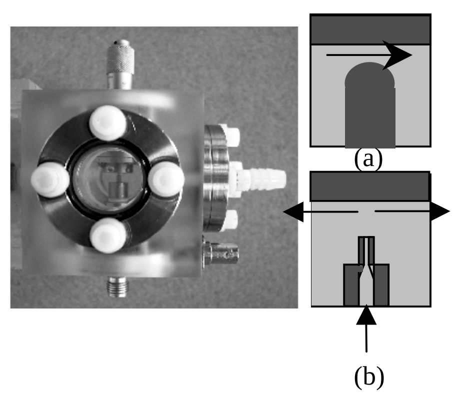

Fig. 5. Discharge cell and water flow for two different electrode geometries.
(a) transverse flow (b) axial flow

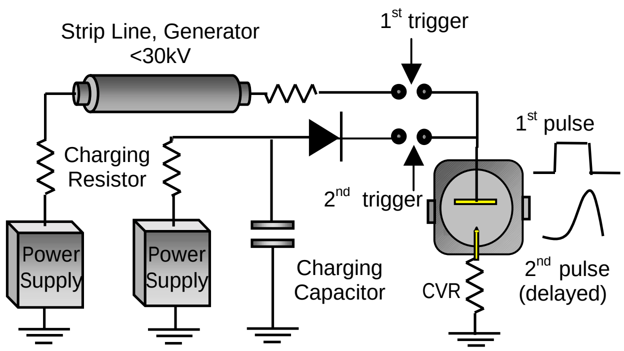

Fig. 6. Pulse-probe system.

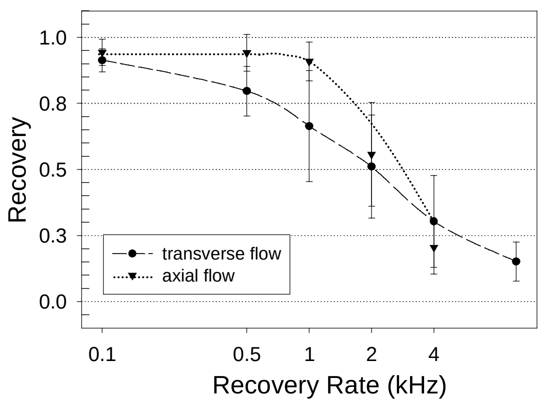

Fig. 7. Recovery of switch with transverse flow and axial flow.

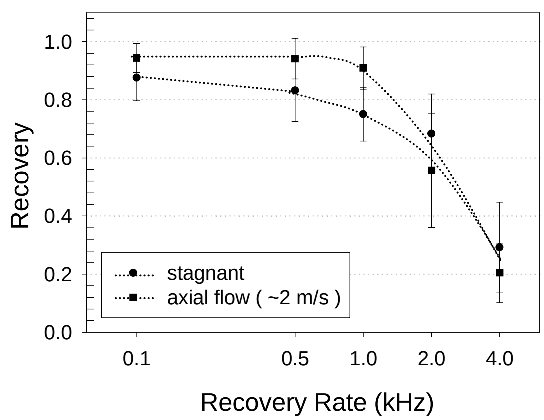

Fig. 8. Recovery of switch in stagnant water and axially flowing water.

A pulse-probe system (double pulse generator [7]) (shown in Fig. 6) was built to study the recovery behavior of the water switch. The first pulse, generated by a stripline provides a rectangular pulse and causes water breakdown. The energy deposited into the water can be adjusted by changing the impedance of the strip line. The second pulse, which is serving as a probe, has the same magnitude as the first pulse but a longer risetime. It was applied with a delay time of 250 µs to 10 ms, and the magnitude of the voltage across the gap was measured. The degree of recovery is defined as the ratio of the breakdown voltage of the second pulse to the breakdown voltage of the fully recovered water switch.

A comparison of the degree of recovery for axial flow and transverse flow for a 100 µm gap is given in Fig. 7. The average energy deposited into the water gap is 0.6 J per cm gap length. For transverse flow, the velocity is 0.25 m/s and for axial flow it is 2 m/s. An average degree of recovery of 75% at 1 kHz can be reached with transverse flow. However, with axial flow, the average degree of recovery increases up to 90%. This latter case was also compared with the recovery of stagnant water, as given in Fig. 8. It can be seen that without flowing the water, the average degree of the recovery is only 70% at 1 kHz.

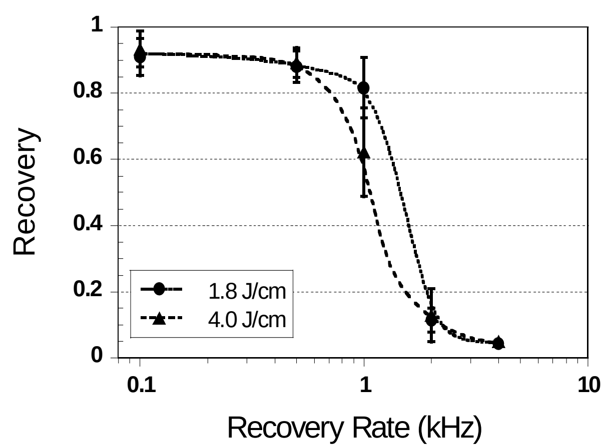

Fig. 9. Recovery dependence on energy deposition.

The recovery rate is also dependent on the energy deposited into the water during breakdown. In order to explore the effect of the energy deposition, the impedance of the stripline was changed from 10 Ω to 5 Ω. These values correspond to an energy density of 1.8 J per cm gap-length and 4.0 J per cm gap length, respectively. For an energy of 1.8 J per cm gap length (300 µm gap length), the recovery rate was approximately 1 kHz. It was reduced for an energy of 4.0 J per cm gap length to about 600 Hz.

4. All-Water Pulse Generator

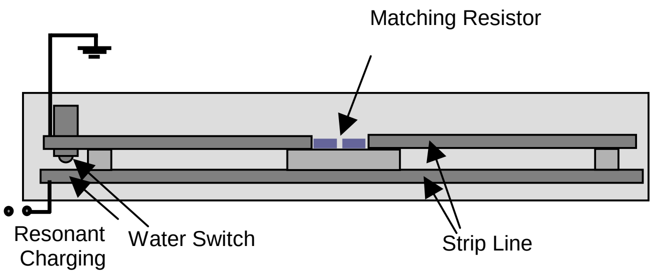

Fig. 10. Sketch of an all-water pulse generator.

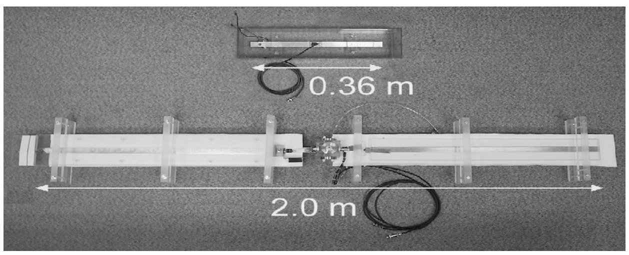

Fig. 11. A comparison of two 10 ns pulse generators.
Upper: all-water system
Lower: pulse generator with Teflon as dielectric

We have combined the water switch and a PFN with water as dielectric to build a 10 ns, 15 Ω pulse generator. The Blumlein line structure is 36 cm long. The cross section is shown in Fig. 10. The whole system was placed into a water tank and was charged with a resonant charging circuit. Compared to a common Blumlein line where the dielectric is Teflon, the all-water system is more than 5 times shorter (Fig. 11). Besides the reduced size, such a pulse generator offers the opportunity to vary the impedance by changing the distance between the strip line plates.

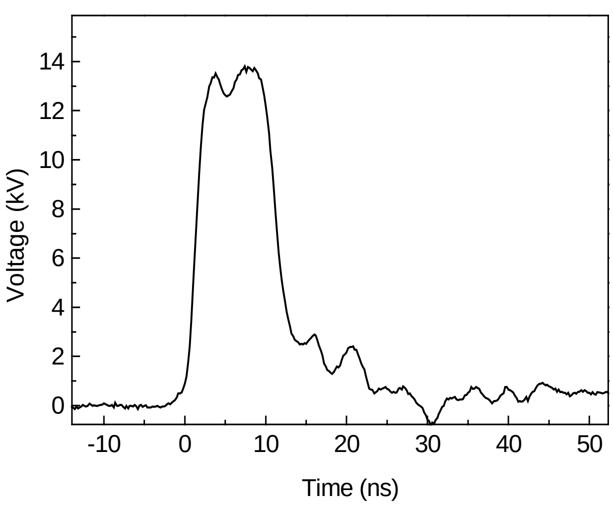

Fig. 12. A typical voltage pulse generated by the all-water system.

A typical 10 ns voltage pulse with rise time < 2 ns is shown in Fig. 12. The rate of the current rise is 4×10^{11}A/s. This pulse provides an energy of 0.1 J to a matched load.

5. Conclusion

After the electrical breakdown of a water switch, the vaporized water expands in form of a bubble within hundreds of microsecond to milliseconds. Expansion and decay of the vapor bubble determines the recovery of the water. Flow of water through the switch volume causes a reduction in recovery time and consequently an increase in recovery rate. For a switch with an energy deposition of 0.6 J per cm gap length and an axial water flow, a recovery rate of 1 kHz was achieved. An all-water pulse generator was built which provides the same pulse as a pulse generator consisting of a PFN with solid dielectric and a gaseous switch, but at a much reduced size.

Acknowledgement

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