Breakdown Mechanisms in a Triggered Water Gap

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Abstract: The paper reports on an investigation into the mechanisms and development of the breakdown of a triggered water gap plane-parallel electrode system with an electrically isolated trigger pin. A fast (5000 fps) CCD camera was used to observe the gap after a voltage pulse had been applied to the trigger pin.

The optical observations obtained by the high-speed digital camera show the development and collapse of a bubble formed as a result of the (500ns) trigger pulse. Simulation results using QuickField software indicated that the magnitude of the electric field within the bubble increased after the main voltage had been applied across the water gap. Due to the lower electrical strength of water vapour, an electric avalanche was initiated within the bubble. The complete gap breaks down as a consequence of the discharge within the bubble and the subsequent streamer propagation in the water gap.

Keywords: Triggering, water, breakdown, bubble

1 Introduction

Water can exhibit a high electrical breakdown strength (~100 MVm⁻¹) when stressed using voltage pulses. Its high relative permittivity (~81) [1] results in a high-energy storage density. These properties make it a suitable medium for the dielectric in pulsed-power applications and consequently water has also been used as the dielectric medium in pulsed power switches [2-3]. There is, therefore, a considerable interest in the mechanisms that cause the water gap to breakdown [4]. The effect of the voltage triggering on the breakdown of a liquid gap has been investigated by Watson et al [5] and laser triggering of a liquid gap has been studied by Larsson et al [6].

In order to improve the performance of high-voltage, high-powered switches based on a water dielectric, the mechanism of the breakdown in a triggered water gap was investigated [7]. This paper describes the electrical measurements, optical observations and simulation results undertaken to reveal the dynamics of the breakdown in a triggered water gap. Time lags to breakdown were measured for two conditions: self-breakdown and triggered breakdown. A fast (5000 fps) CCD camera was used to observe water gap after a voltage pulse application to the trigger pin. Finally, the electric field distribution after the trigger pulse application was simulated using QuickField software in order to gain insight into the potential mechanism of breakdown.

2 Experimental Procedure

The experimental set-up is shown schematically in Figure 1. It consists of a water gap with Ekonite plane-plane electrodes. The trigger electrode is a stainless pin mounted flush with the lower earthed electrode surface, but electrically isolated from it. The trigger gap spacing between the pin tip and the earth electrode was 0.4 mm. The main voltage was applied across the water gap by the discharge of an 80nF capacitor. This was charged by a high power supply (100 kV and 3 mA) via the resistive chain of 40 MΩ. The capacitor voltage was applied by the operation of a Trigatron switch, triggered by a 100 ns pulse of magnitude of
Figure 1. Schematic of experimental system incorporating a high-speed digital camera for capturing images of gas bubble formation and pre-breakdown streamers.

1) 100kV, 3mA dc power supply. 2) 60kV, 1.5mA dc power supply. 3) 40MΩ resistor 4) 22MΩ resistor 5) 4X Blumlein trigger generator (100ns) 6) 4X Blumlein trigger generator (500ns) 7) Pull switch 8) Trigatron switch 9) 80nF capacitor 10) 1MΩ resistor 11) 200Ω resistor 12) Triggered water gap with a pin trigger electrode 15) Camera (17) Camera controller (18) PC

Figure 2 shows the triggering effect on the time lag to breakdown. The main gap spacing was 2 mm. The trigger pulse energy was 1.44 J with a trigger peak voltage of +30 kV. The main voltage polarity was positive. As Figure 2 shows, voltage triggering has decreased the time lag to breakdown and also the minimum breakdown voltage. The time lag to breakdown has decreased from ~18 µs at 25 kV non-triggered water gap to ~ 7.5 µs at triggered water gap and also the minimum breakdown voltage has decreased significantly from ~22.5 kV at non-triggered water gap to ~2 kV at triggered water gap. This means that the electric field strength of this configuration has decreased significantly from ~110 kV/cm to ~10 kV/cm.

When a high voltage is applied across the short trigger gap, a very high electric field in the range of a few hundred kV/cm would be established in this gap. This electric field would lead to the initial breakdown in the trigger gap in a few hundred nanoseconds. The breakdown would cause the deposition of the Blumlein generator energy into the trigger gap. A fraction of this energy might result in water vaporisation and bubble generation.

3 Results

3.1 Triggering Effect on Time lag to Breakdown

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3.2 Bubble Images by High-Speed Digital Camera

The energy available from the trigger discharge is deposited in <500ns. Water vapour will form at a high temperature and pressure and produces a gas bubble that will expand rapidly. The expansion decreases both the internal gas pressure and gas temperature. When the external hydrostatic pressure is greater than the internal pressure the bubble collapses. To observe the processes after the trigger pulse application, a high-speed digital camera was employed. Figure 3 shows images of the electrode gap in the region of the trigger pin captured by the high-speed digital camera at 5000 fps, with 200µs between frames. For clarity these have been presented as negatives with increased contrast. The images show the development of a gas bubble, generated at the trigger pin by the trigger voltage. The bubble is approximately hemispherical and grows into the electrode gap and then collapses. In the original (positive) images the bubble appears opaque. For comparison an air bubble was injected into the electrode gap using a hypodermic syringe. This results in a transparent bubble with a partly reflective interface between the gas and water giving a low contrast image. The differences in the appearance between the two types of bubble suggests either that the surface of the bubble formed by the discharge is not smooth but is multifaceted, thus causing multiple reflections to give the diffuse appearance or that there is an internal structure to the bubble.

Figure 3. Successive frames at times of 200, 400, 600, and 800 µs showing the development of a bubble produced in the electrode gap after the application of a trigger pulse, energy 2.56J

3.3 Electric Field Enhancement in the Bubble

When a high voltage is applied across the main gap, due to the relative permittivity differences in the gas ($\varepsilon_r \approx 1$) and water ($\varepsilon_r \approx 80$) the applied field will be redistributed with the field in the gaseous and the bubble being greater than in the liquid. As the gas bubble expands the field magnitudes in both liquid and gas will decrease. Figure 4 shows the electric field distribution for a hemispherical gas bubble between two plane parallel electrodes as simulated using axial symmetry and QuickField 2d software package. The field was determined perpendicular to the electrode surface along a line passing through the trigger pin position, the planar face of the bubble contacting the electrode.

The electric field magnitude in the bubble was 200% of the field present in the absence of the bubble and in the liquid region was ~50% of the original value. When the bubble expands the fields in both the gas and liquid reduce, so that liquid initiated breakdown is unlikely.

Figure 4. The electric field across a water gap containing a hemispherical gas bubble in contact with the centre of the earthed electrode. E/E0 is the ratio of the electric field strength to the strength in the gap without the bubble present.

3.3 Streamer Propagation in the Water Gap

Since the dielectric strength of the gas is lower than in the liquid where the field is greater, the electric field enhancement would cause an electron avalanche initiation within the bubble. For electric avalanche initiation in the bubble, there must be an available electron and the probability of this increases with bubble expansion and its internal pressure decreasing. If the electric field intensity
were sufficient, the avalanche would be transformed into a streamer. Streamer establishment within the bubble would redistribute the electric field distribution in the water gap. The electric field distribution in the water gap was simulated using QuickField for the case when a streamer was established in the generated bubble. The streamer was simulated by a conductive channel in the bubble. The electric field intensity in the water gap after the establishment of the streamer within the bubble on an axis perpendicular to the electrodes surface along a line passing the trigger pin is shown in Figure 5. The Figure shows that the field intensity in the main gap is intensified after the initiation of the discharge in the bubble and the establishment of a conductive channel in the bubble. The electric field intensification factor increased with increasing size of the hemispherical bubble, changing from ~ 4.5 for the R/D of 0.5 and ~ 2.2 for R/D of 0.2, where R/D is the ratio of bubble radius over the electrode gap spacing. The increasing electric field at the streamer’s tip, would increase the energy available to vaporise water in front of the streamer and would allow the electric streamer to propagate in a vapour channel, rather than in the liquid. An image of the streamer propagation in the water gap, captured by the high-speed digital camera, is shown in Figure 6. It can be concluded that an electron avalanche was initiated within the bubble and transformed to a streamer.

![Figure 5](image.png)  
Figure 5. The electric field across a water gap containing a hemispherical gas bubble in contact with the centre of the earthed electrode. E/E0 is the ratio of the electric field strength to the strength in the gap without the bubble present.

Figure 6. Pre-breakdown streamer at the plane-plane triggered water gap with a trigger pin, the main gap spacing=8.7mm and the main voltage=16kV, trigger pulse energy=1.44J

When the streamer bridges the main electrodes, final breakdown would take place and the remaining potential energy stored in the capacitor supply would be discharged in the main water gap and any resistance in series with the water gap. This energy would provide an expanding conductive vapour channel.

4 Discussion

When a high voltage trigger pulse is applied to the trigger gap, a high electric field is established in the trigger gap. This field would cause the initial breakdown in the trigger gap in a time of a few hundred nanoseconds. The trigger current would pass through the trigger gap and some of the energy from Blumlein pulse generator would be deposited into the gap. As a result, water in the trigger gap would be vaporised and a bubble would be generated, as can be seen in the images shown in Figures 3. As reported in [7], the bubble would expand into the main gap to a maximum radius and then it would contract and finally collapses. When a voltage is applied across the gap electrodes, due to the relative permittivity differences in the gas ($\varepsilon_r \sim 1$) and the water ($\varepsilon_r \sim 80$), the applied field will be redistributed with the field in the gaseous bubble being greater than in the liquid. The electric field magnitude in the bubble was 200% of the field present in the absence of the bubble where as in the liquid region it was ~50% of the original value. When the bubble expands, the fields in both the gas and liquid reduce, so that liquid initiated breakdown is unlikely. The dielectric strength of the gas is lower than in the liquid where the field is greater; thus an electron avalanche can be initiated within the bubble. If the electric field were sufficient, the electron avalanche would develop into a streamer. The streamer would traverse the bubble and
subsequently propagate in the main water gap, as shown in Figure 6.
Streamer establishment within the bubble would redistribute the electric field distribution in the water gap. The electric field intensity in the main gap is intensified after the initiation of the discharge in the bubble and the establishment of a conductive channel in the bubble, as shown in Figure 5. The electric field intensification factor increased with increasing size of the hemispherical bubble. The increasing electric field at the streamer's tip, would increase the energy available to vaporise water in front of the streamer and would allow the electric streamer to propagate in a vapour channel, rather than in the liquid.
Final breakdown would take place after the streamer propagating in the water gap, bridged the main electrodes.
Voltage triggering causes the water gap to breakdown much earlier than for the non-triggered water gap. Thus, the time lag to breakdown would be decreased in the triggered water gap, as can be seen from Figure 2. Also the minimum breakdown voltage is reduced in the case of the triggered breakdown.

5 Conclusion

In a triggered water gap, the application of the trigger pulse causes the initial breakdown to take place between the trigger electrode and the earthed electrode. A bubble is then generated as a result of the deposition of some of the trigger pulse potential energy into the trigger gap. Due to the great difference between the water permittivity ($\varepsilon=81$) and water vapour permittivity ($\varepsilon\approx1$), the electric field intensity is intensified in the gas bubble after a high voltage is applied across the main gap. Afterwards, if the main voltage is sufficient, an avalanche is initiated in the water vapour because of much lower electric field strength of the water vapour relative to liquid water. As a consequence, a streamer can form from the avalanche and thus traverses the bubble and subsequently propagates through the main gap until the main electrodes are bridged. This results in the final breakdown of the gap.

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References