# EFFECT OF WATER CONDUCTIVITY ON ITS PULSE ELECTRIC STRENGTH

Piotr Lubicki, James D. Cross, Shesha Jayaram
University of Waterloo
Electrical & Computer Engineering Department
Waterloo, Ontario, N2L 3G1 Canada

Jacek Staron, Boleslaw Mazurek
Technical University of Wroclaw
Institute of Electrotechnics and Electrotechnology
pl. Grunwaldzki 13, Wroclaw 51, Poland

Abstract: The dependence of the impulse electrical strength of water on conductivity was investigated in non-uniform electric field - point-plate electrode system. The voltage pulses, with the rise time $t_r$=1 µs, and time to half-decay $t_{1/2}$= 30 µs, were generated by a Marx bank. Conductivity was varied by the use of different $CuSO_4$ concentrations in distilled water. The voltage and current during the electrical breakdown were recorded by using a pulse voltage divider and current shunt. The dynamic resistance calculated from current and voltage waveforms during electrical breakdown, is also presented. On the basis of these waveforms, the dependencies of the time to breakdown and breakdown voltage on the conductivity for two polarizations of the point electrode are plotted. Investigations made by means of static photography were carried out. It was found that the electrical strength of water depends strongly on the polarity of point electrode and the conductivity of the water. The electrical strength of water decreases, and time to breakdown increases, as water conductivity is increased.

## INTRODUCTION

Water has been used in high voltage resistors and capacitors as a dielectric for pulse applications and as a medium for high voltage commutators with relatively low losses [1-5]. Phenomena accompanying its impulse breakdown have been used in high energy physics, and in technological processes (metal machining, generation of high intensity light, generation of acoustic waves used for hydroacoustic and hydrogeological investigations) since as early as 1950 [2]. Besides, discharges in water have been investigated as a possible means for inactivation of microorganisms in consumable liquids [6-9].

Depending on the purpose, whether breakdown is desirable or not, the high voltage properties of water under pulse application must be known [4,8,9].

The experiments described in this paper are part of the research undertaken to investigate the possibilities of developing a non-thermal sterilization technique using high voltage pulses. Any discharges in liquid (water) must be avoided in a wide range of water conductivity, as the quality of the sterilized liquid is affected by electrolysis, temperature rise, free radicals formation, injection of electrode materials and others [1,2,4,8,9]. The results described in the paper are useful to estimate the range of rise time, peak voltage, and the voltage polarity which could be applied for sterilization of consumable liquids without causing any undesirable electrical breakdowns.

## EXPERIMENTAL SETUP

The investigations were carried out in an asymmetrical point-plate electrode system (plate grounded) with electrode spacing, d = 10 mm and the radius of the point electrode, r = 0.2 mm. Such an electrode system gives an electric field ~ 1000 kV/cm.

HV pulses were generated by using a one stage modified Marx bank [4]. The generator setup is shown in Fig. 1. The water capacitor $C_2$ was used to shape the front of the pulse. A rise time of $T_n$= 1 µs, and time to half-decay, $T_{1/2}$ = 30 µs was obtained without any sample connected across the generator terminals.

Breakdown current was measured by means of the tube shunt. The dc resistance of the shunt is equal to, R=1.1 Ω. The shunt was connected by BNC socket and 1:10 measuring probe with the KIKUSUI COM7101E oscilloscope with the sampling rate 200 MS/s.

Voltage was recorded with the use of HV pulse divider with a ratio of 2000. The accuracy of the current and voltage recording is 7%. The dynamic resistance r=f(t) was calculated on the basis of current and voltage waveforms recorded during breakdown. The waveforms obtained were also used to estimate breakdown voltage and time to breakdown depending on conductivity. The breakdown voltage is defined as a point at which the resistance rapidly decreases and the current increases to its maximum. This point is referred as the beginning of breakdown. The difference between the time at which the voltage pulse is applied and the beginning of breakdown is defined as the time to breakdown. The measurements were carried out for both polarizations of the applied voltage. Conductivity of the samples was varied by varying the concentration of $CuSO_4$ dissolved in distilled water. The conductivity was measured before and after the breakdown by means of conductometer INCO N5721 with the probe type PS-27. The investigations were carried out for the solution conductivities within the range of $\gamma$=5 mS/m to 15 mS/m. This range of conductivity matches the conductivity of consumable liquids and drinking water. Additionally, the static photograph method was applied to investigate the

influence of conductivity on the development of impulse breakdown in water. In this case, the Pentacon sixTL camera was used.
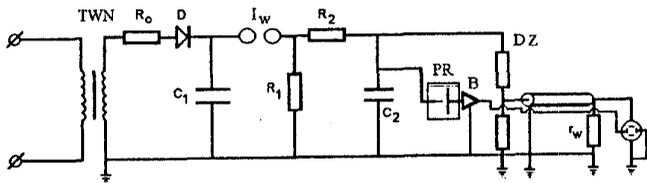
conductivity $\gamma=2\times10^{-2}$ S/m. The voltagewaveform allows to estimate the value of breakdown voltage $U_b=42$ kV. The time to breakdown in this case equals to $T_b=0.9$ μs.

Figure 1. Experimental setup used for measurements of breakdown voltages and currents. TWN - high voltage transformer, $I_w$ - spark gap, PR - sample, B - current shunt, DZ - voltage divider, $C_2$ - water capacitor C=3.7 nF, $r_w$ - terminating resistor.

## RESULTS

Figures 2-4 present the typical waveforms of current and voltage obtained for impulse breakdown of water with different conductivities for positively polarized point electrode. Figure 2a shows the waveforms obtained for water with conductivity $\gamma=2\times10^{-3}$ S/m. Breakdown voltage is approximately equal to $U_b=37$ kV. Time to breakdown is $T_b=0.7$ μs with respect to the origin of voltage waveform. The current and voltage waveforms were used to calculate the resistance-time dependence which is presented in Fig. 2b. The resistance rapidly decreases after the time of t=0.8 μs with respect to the origin of voltage waveform.
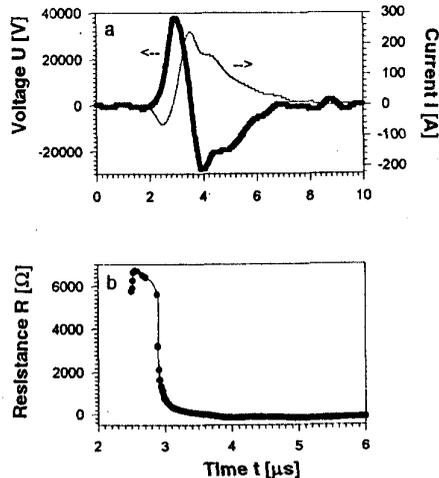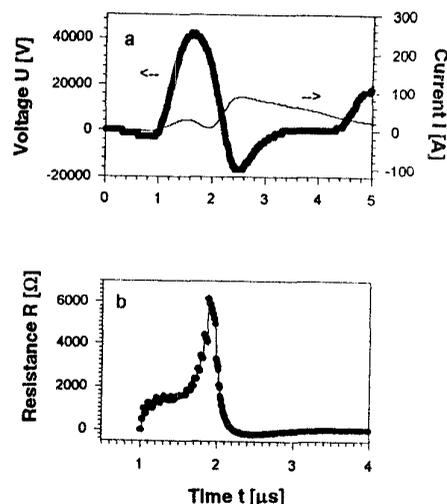
Figure 2. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of CuSO₄ water solution with conductivity $\gamma=2\times10^{-3}$ S/m, positive polarization of the point electrode.

Fig. 3 shows current and voltage and dynamic changes of resistance during the breakdown of the water solution with

Figure 3. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of CuSO₄ water solution with conductivity $\gamma=2\times10^{-2}$ S/m, positive polarization of the point electrode.

Fig. 4a shows current and voltage waveforms for positive polarization of point electrode during electrical impulse breakdown of the water solution with conductivity $\gamma=5\times10^{-2}$ S/m.
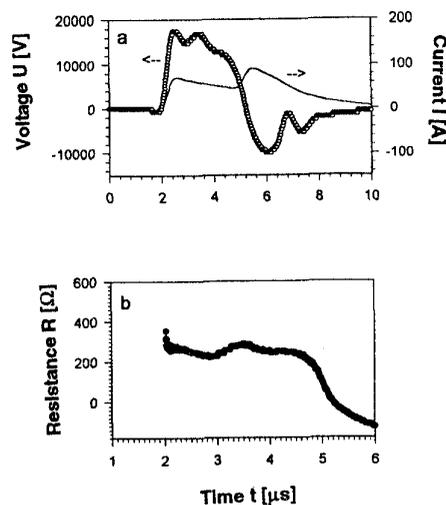
Figure 4. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of CuSO₄ water solution with conductivity $\gamma=5\times10^{-2}$ S/m, positive polarization of the point electrode.

The breakdown voltage is significantly lower than in previously described cases $U_b=7.5$ kV, and the time to breakdown is remarkably longer $T_b=2.9$ µs. The current waveform differs from previous ones. The dependence r=f(t) (Fig. 4b) shows that the time to minimum value of resistance is equal to 4 µs.

Fig. 5 shows the photographs taken during the impulse breakdown of $CuSO_4$ water solutions with conductivity equal to $\gamma=2x10^{-3}$ and $5x10^{-2}$ S/m for positive polarization of the point electrode. Branched and complicated preliminary discharges and few main channels coming to plate electrode are visible (Fig. 5). The discharge channels are thin and long. This is the evidence that in this case the collision ionization processes are very fast.
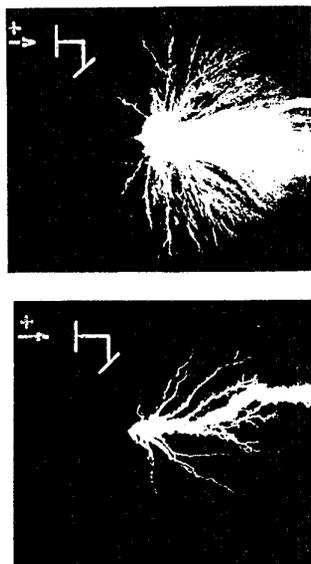


Figure 5. Photographs of electrical breakdown of $CuSO_4$ water solution with conductivity: a) $\gamma=2x10^{-3}$ S/m, b.) $5x10^{-2}$ S/m, for positive polarization of point electrode.

The second series of experiments were carried out for negatively polarized point electrode. The voltage and current waveforms and the dynamic resistance characteristics for impulse breakdown of $CuSO_4$ solutions with conductivity respectively $\gamma=2x10^{-3}$, $9x10^{-3}$, and $2x10^{-2}$ S/m for negative polarization of point electrode are shown in Fig. 6-8. The breakdown voltage decreases with an increase in conductivity. This voltage is equal to $U_b=28.6$ kV for water with $\gamma=2x10^{-3}$ S/m (Fig. 6a), and it decreases to $U_b=3.6$ kV for water with $\gamma=2x10^{-2}$ S/m (Fig. 8a). Time to breakdown is much longer than that in the case of positive polarization of point electrode. The breakdown occurs during the decay of the HV pulse. Time to breakdown is $T_b=8.4$ µs for water with conductivity $\gamma=2x10^{-3}$ S/m, and $T_b=17.1$ µs for conductivity of

the solution $\gamma=2x10^{-2}$ S/m (Fig. 6-8). The dynamic resistance characteristics (Fig. 6b-8b) differ from those obtained for positive polarization of the point electrode.

The photographs of discharges in water solutions with conductivity equal to respectively $\gamma=10^{-3}$ and $5x10^{-3}$ S/m for negative polarization of the point electrode are presented in Fig. 9. The discharge channels are bigger. Branches of those channels are filled with a material displaying a different light deflection coefficient from the water solution sample. It is most likely that this is a gas phase.

## DISCUSSION AND CONCLUSIONS

The results presented (Fig. 2-9) illustrate an electrical breakdown process of $CuSO_4$ water solution depending on its conductivity for both polarizations of the HV pulses applied. Because the breakdown takes place under microsecond regime, it should be thought that the bubble mechanism is the cause for the electrical breakdown in both cases of the point electrode polarization [1,2,10-11]. It was observed in works [1] and [2] that the gas bubbles in electrical impulse breakdown of water are formed in the vicinity of point electrode for its positive polarization as well as for negative one.
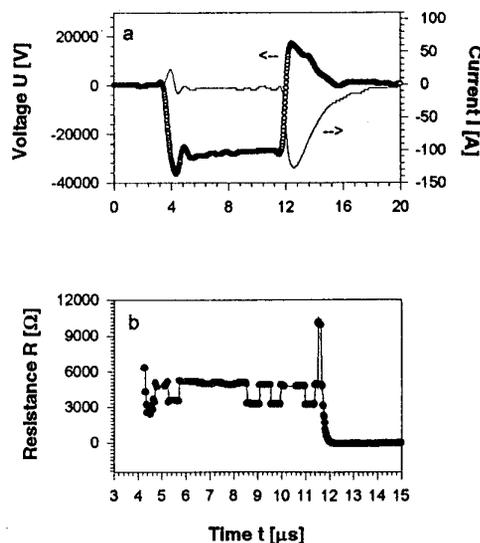


Figure 6. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of $CuSO_4$ water solution with conductivity $\gamma=2x10^{-3}$ S/m, negative polarization of the point electrode.

A phase transition liquid-gas must take place for electrical breakdown to occur. Energetic interaction between charged particles (in the case of short duration HV pulses - mainly electrons) and bulk liquid causes energy dissipation,

local heating and vaporization. In this way, the gas bubbles are created. The ionization processes well known from the
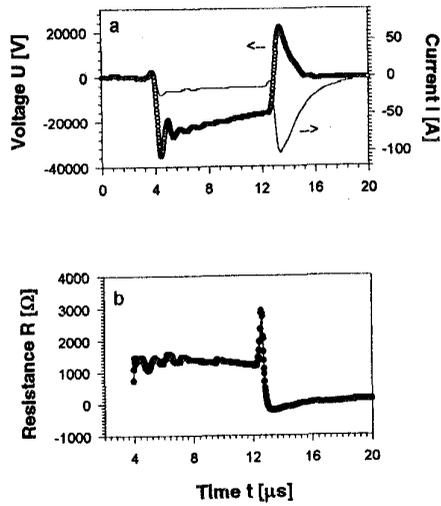




Figure 7. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of CuSO$_4$ water solution with conductivity $\gamma=9\times10^{-3}$ S/m, negative polarization of the point electrode.
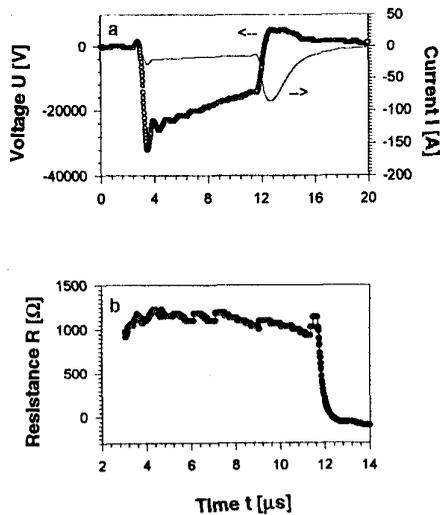




Figure 8. a) Current and voltage waveforms, b) resistance vs. time for impulse breakdown of CuSO$_4$ water solution with conductivity $\gamma=2\times10^{-2}$ S/m, negative polarization of the point electrode.

theory of electrical breakdown in gases take place in those gaseous bubbles. Those areas are filled with a space charge polarization which depends on polarization of electrodes. The

space charge plays a major role in discharge development, because it creates a new electric field distribution.

For positive polarization of point electrode, electrons (displaying higher mobility than ions) can be found in its vicinity. This causes an increase of electric field in this area. The higher the electric field, the faster the development of the electrical breakdown, and the lower the breakdown voltage. Microchannels surrounding the positive point electrode presented in Fig. 5 are filled with a gas formed by an interaction of electrons accelerated in electric field with insulation medium. The light from main breakdown channel lighting up the area of the discharge is diffracted on liquid-gas interfaces and makes it possible to take a photograph of the breakdown process. An increase of conductivity of the medium is connected with a higher concentration of CuSO$_4$ which dissociates in water into ions of Cu$^{2+}$ and SO$_4^{2-}$. An increase of the positive ion concentration causes a decrease in
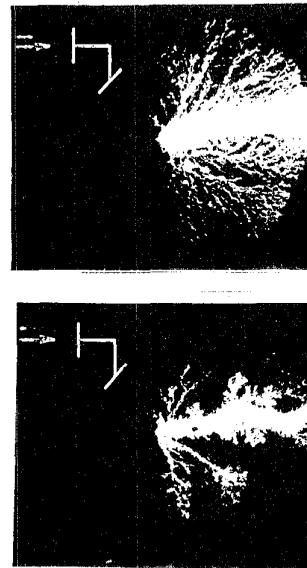


Figure 9. Photographs of electrical breakdown of CuSO$_4$ water solution with conductivity: a) $\gamma=1\times10^{-3}$ S/m, b), $5\times10^{-3}$ S/m, for positive polarization of point electrode.

a number of free electrons, and that is why the number of the breakdown microchannels decrease and an influence of a space charge on the electric field distribution is lowered with an increase of conductivity of the CuSO$_4$ water solution. At the same time the time to breakdown increases with an increase of conductivity (Fig. 2-4), and a vaporization process of gas bubble formation is intensified by electrolysis processes [1,2] - the number of channels decreases, but their diameters are greater (Fig. 5c).

The breakdown process also begins in the vicinity of point electrode for its negative polarization (Fig. 9), but the movement of electrons takes place towards positive plate electrode. The interaction between electrons and liquid cause an energy dissipation and formation of gas bubbles. For negative polarization of point electrode, the electrical breakdown takes place during the HV pulse decay (Fig. 6-8). This means that the impulse electric strength of water for the pulse duration being less than 4 μs and for negative polarization of point electrode is higher than the impulse electric strength in the case of positive polarization of the point electrode (Fig. 10). At the same time, as it is shown in Fig. 10, the time to breakdown is much longer than that for positive point (5-20 μs).
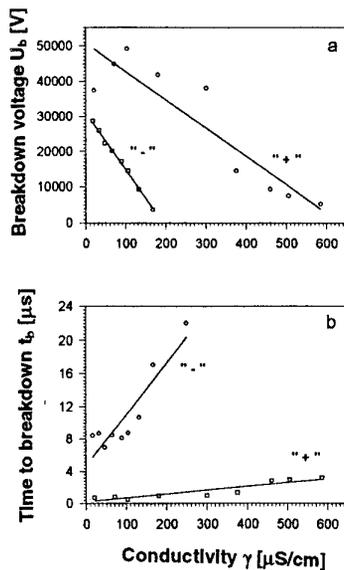


Figure 10. a.) Breakdown voltage, and b.) time to breakdown for $CuSO_4$ water solution vs. its conductivity for both polarizations of point electrode.

The photographs show that the development of breakdown for negative point is accompanied by formation of a disturbance area which can be identified as a concentration of gas microchannels and gas microbubbles (Fig. 9). This area filled with a space negative charge is "screening" the point electrode and causes the more homogeneous electric field distribution [1,2]. This is most likely to be the reason of a more difficult development of electrical breakdown for negative point electrode polarization.

Time to breakdown for positive point is significantly shorter that that for negative point. In the case of negative point, time to breakdown remarkably increases even with a slight increase of conductivity. For both polarizations of the

point electrode, the impulse electrical strength of $CuSO_4$ water solution decreases with an increase of its conductivity.

The typical range of conductivity of drinking water sources and consumable liquids is $10^2$-$10^3$ μS/cm [4]. On the basis of the presented results of the impulse electrical strength investigations, it can be concluded that HV pulses used for drinking water disinfection and for consumable liquids sterilization should be negatively polarized, and the duration of the pulse should not exceed 4 μs. Then the breakdown risk is lowered and, as a consequence, the degradation of the quality of a sterilized liquid can be avoided even for a very high electric field.

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