Fields and Streamers in Water with Near Electrode Conductive Layers

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***Abstract*—Deionized water is the most suitable media for pulse storage systems due to high dielectric permittivity, high pulse electric strength, non-toxicity and non-flammability. Here it is attempt to study prebreakdown processes in case of conductive layers near electrodes. The results of experimental studies of the electric field strength distribution in the gap with modified electrodes in water is presented. Pulse electric strength is increased, nonelectrode and postbreakdown streamers are registered. The nonelectrode streamers develop in the form of cathode and anode semistreamers initiated at the same point.**

Keywords— Streamers; electrical strength; pulsed power; water; Kerr fringes, screening, modifyed electrodes.

I. INTRODUCTION

Water as dielectric liquid has application in pulsed power system because of high dielectric permittivity and high pulse electric strength. Power of pulse systems could be increased if electric field will be increased. In our opinion the initiation is the key control factor of pulse electrical strength. That is why an influence upon initiation is most evident way to increase pulse electrical strength of water. Breakdown initiation on electrodes surface limits the pulse electric strength. There are a lot of attempts to increase pulse electrical strength of liquids, polar liquids especially.

The initiation requires strong electric field, therefore the decrease at the place of streamer initiation should lead to electrical strength increase. Two successful attempts were based on electrodes screening. To eliminate the influence of microscopic whiskers on electrodes it was proposed in the paper [1] to create near electrode diffusion conductive layers in water. The implementation of this method has been carried out by slow forcing the electrolyte solutions through the porous electrodes. Inner part of gap is clean water, near-electrode regions contain electrolyte that provide the high conductivity of near-electrode layers. Under the action of pulse voltage, its conductivity leads to formation of space charges which, in turn, decreases the electric field at electrode surfaces and increases in the inner part of gap. Pulse electrical strength was increased in 3÷4 times in comparison with conductive layers absence.

The other method of conductive layer preparation consists of pulse heating of electrodes in case of glycerol based liquid insulation [2]. Heat transfer from electrodes into liquid leads to temperature increase in the near electrodes layers which size Δx is approximately equal $\Delta x \sim (\mathbf{a}\cdot\mathbf{t})^{0.5}$. Here **a** - thermal diffusivity coefficient, **t** – time duration from pulse heating beginning up to voltage action. Strong increase of conductivity due to strong viscosity decrease at high temperature leads to formation of transient conductive near - electrodes layers. It performed to decrease electric field strength in the places of breakdown initiation and to increase the pulse electric strength of water insulation [1, 2]. In our experiments, the pulse electrical strength of glycerol increased no less than two times in comparison with strength of gap with cold electrodes.

Other method of near electrodes field decrease was proposed in [3, 4]. There water and water/glycol mixtures were used. Bipolar homocharge injection due to choice of electrode pair (brass, steel, aluminium etc) lead to the electric field decrease at both charge-injecting electrodes. The space-charge shielding at the electrodes increased the voltage breakdown strength by up to 40% in water.

Nevertheless these excellent results didn’t find application in pulsed power systems. In our opinion the reason is technological complications with layers creation and maintenance, as well as dielectric media recovery after each shot.

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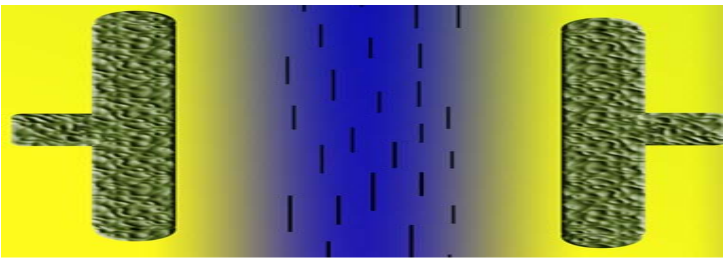

Figure 1. The pattern of the interelectrode gap with the conductive layers. Central blue zone is dielectric core, yellow near-electrode zone – conductive layers.

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Our experiments [5,6] with screened electrodes applied the same idea, but conductive layers in water were formed by application of the special modified electrodes. The effect of the pulse electrical strength increase was obtained too. According to electrooptical measurements, the maximal electric field in the center of the gap was 1 MV/cm, and the electric field near electrodes was 400 kV/cm. The mean electric field strength was 700 kV/cm. If we take into account that the breakdown field strength of the gap without conductive layers was 400 kV/cm, then the pulse breakdown strength in these experiments was increased approximately by 1.7 times. The goal of the paper is a demonstration of new events that take place in case of screened electrodes.

II. EXPERIMENTAL SETUP AND RESULTS

Experimental setup and measurement technique are described early in [6, 7]. The experiments were performed with using voltage pulses with characteristic rise time $\tau_f \approx 0.6$ µs and amplitude U up to 200 kV. There were used spherical electrodes 35 mm in diameter and the gap between them was d = 3.5 mm usually. Modification of metal electrodes was carried out by cation- and anion-exchange membranes which are pre-soaked in electrolyte solutions of KCl, KOH, HCl at a concentration of 1 mol / liter. Deionized water with the specific conductivity $\sigma \sim 10^{-7}$ $(\mathrm{Ohm \cdot cm})^{-1}$ went into the cell from water purifier closed loop. The registration of prebreakdown and breakdown processes was performed with the help of the shadow and Kerr methods by application a semiconductor laser with wavelength of λ = 0.61 µm and pulse duration at half-height of 3 ns. The photo registration was made with the digital camera with resolution of 10 µm in the mode of open diaphragm. The electrooptical scheme of measurements was adjusted for minimum light transmission in the absence of the electric field. Therefore, the radiation of breakdown processes was also registered by the camera and it was superimposed on the image of the Kerr fringes. Besides, electric field in central part of the gap was additionally measured with second Kerr system consisted of laser, polarizer, analyzer and photomultiplier. Typical results concerned electric field inhomogeneity inside the gap in case of screened electrodes illustrated by Fig. 2

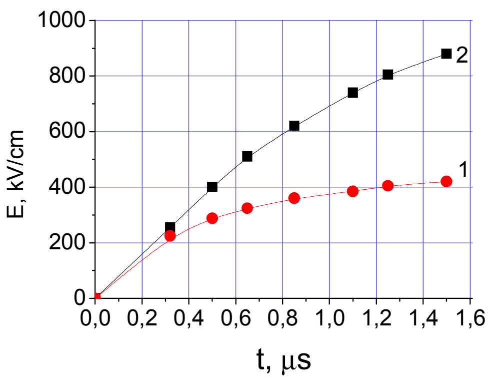


Figure 2. Dependence of the average electric field intensity (1) and the maximal on (2) versus time for the conditions [5,6].

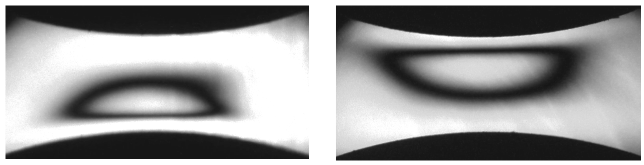
It follows from Fig. 2. that an increase in the electric field intensity at the center of the gap, and, consequently, a decrease in the vicinity of the electrodes, is recorded from the time t≈ 0.4 µs.

As the first approximation, the electric field strength close to the electrode surface can be estimated by the expression given in [1]:

$$E(t)_e \approx (U/d)\cdot((\tau_f/\tau_r) - 1)^{-1}\cdot[\exp(-t/\tau_f) - \exp(-t/\tau_r)], \quad (1)$$

where τ_f – characteristic time of voltage rise, $\tau_r \approx \varepsilon\cdot\varepsilon_0/\sigma$ - Maxwell time of electric field relaxation in the media with dielectric permittivity ε and specific conductivity σ.

Analysis of data, presented in Fig.2 with the help of expression (1) could perform to estimate conductivities of near electrode layers. Value τ_r could be estimated from Fig.2 as $\tau_r \approx 0.4$ µs, hence conductivity of near-electrode layer is $\sigma \approx \varepsilon\cdot\varepsilon_0/\tau_r \approx 1.8\cdot10^{-5}$ $(\mathrm{Ohm\ cm})^{-1}$, and charge carrier concentration $n = \sigma/2\cdot e\cdot\mu \approx 1.6\cdot10^{16}$ cm^{-3} (here mobility $\mu \approx 3.5\cdot10^{-3}$ $\mathrm{cm}^2/\mathrm{V\ s}$). The electric field strength on the surface of the electrodes increases with time, and then, reaching a maximum, decreases. The maximum value of the electric field strength reaches at a time $t_m = (\tau_f\cdot\tau_p/(\tau_f - \tau_p))\cdot\ln(\tau_f/\tau_r)$, which can lead to breakdown initiation on the electrode surface. Spatial kerrograms for different ways of creating layers are shown In Fig. 3.. The kerrograms were obtained at the moment of 50-100 ns before the sharp drop in voltage. The phase shift equal to π (the first dark band from the electrodes) corresponds to the mean electric field strength E ≈510 kV/cm. The characteristic size of the layers δ can be estimated from the distance from the surface of the electrodes to the darkening along the axis of the gap. So in the case of Fig. 3. a cathode layer size is δk = 0.6 mm, anode layer size is δa = 2 mm, and for Fig. 3.b δ δk = 1.5 mm, δa = 0.6 mm.



a

a b

Figure 3 Kerr fringes for two variants of layer creation.

The sizes and conductivities of the near-cathode or near-anode conductive layers could be modified with the purpose of breakdown initiation control. Usually the anode is the place of breakdown initiation that is why anode screening is most preferable way of electrode modification.

In experiments two new events were registered. The first one is nonelectrode streamers. The images of early stages of nonelectrode streamer in water are presented early [5, 8]. This kind of streamers sometimes appears in case of screened anode or both cathode and anode. In our experiments non-electrode streamers didn't bring to total breakdown. That is why it is a kind of partial discharges [9].

Figure 4 shows the shadow photo of the nonelectrode streamer in the case of a screened anode creating increased

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electric conduction near the anode and a lot of anode directed streamers initiated on cathode. The point of the initiation of a characteristic single nonelectrode streamer propagating simultaneously to the anode and cathode in the form of "half_streamers" is seen at the distance $\delta A \approx 1$ mm from its surface. Cathode directed "half streamer" has supersonic velocity and anode directed one has subsonic velocity. More large nonelecrtode streamer is shown in Fig.4 in case of electrooptical regisration. One could see electric field increase before the head of anode directed semistreamer. Besides, breakdown channel wasn't initiated by this nonelectrode streamer!

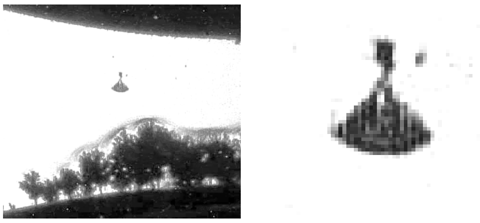


Figure 3 Shadow photo (a): top- modified anode; bottom - metallic cathode; U =142 kV, d = 3 mm, t = 2.05 μs; (b) enlarged part of the interelectrode gap with the nonelectrode streamer [6].

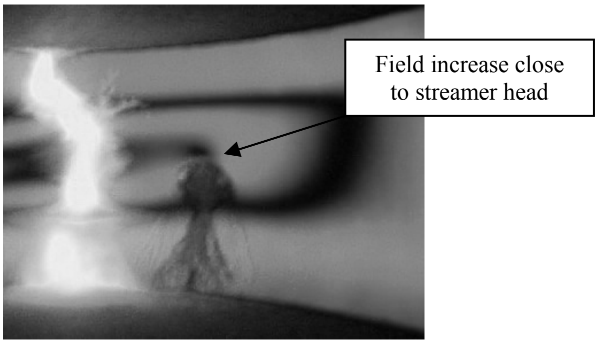
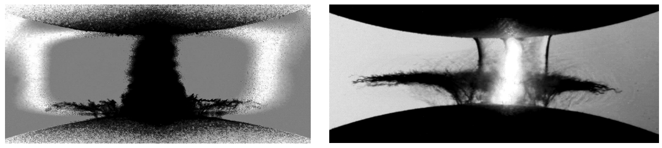


Figure 4 Kerrogram and inherent glow of discharge. Voltage U= 132 kV, gap d= 3.5 mm. The moments of Kerr picture and breakdown were the same tl ≈ tb = 1.4 μsec. Electric field strength at the centre of the gap E ≈ 720 kV/cm.

The kerrogram that perform to estimate cathode streamer conductivity is presented in Fig.4. Here it is several branches of cathode directed half-streamer that reach the cathode. Electric field near the head of anode directed half-streamer is slightly increased, but macroscopic field near cathode directed part isn't changed. In all registered non-electrode streamers (it were obtained more than twenty events) Kerr fringes change shows that electric field before the head of anode directed half streamer has more increased level. As for as anode directed half streamers Kerr fringes change wasn't registered. It means that in part of anode directed half streamer space charge was redistributed and negative charge carriers are situated near the head of streamer. Positive charge carriers didn't concentrate at the tips of cathode directed streamer. These data may point out to more high conductivity of anode directed half-streamer than cathode directed one.

Second new event in case of screened electrodes is postbreakdown streamer appearance [8] (Fig.5).



a b

Figure 7.Postbreakdown streamers. a – the negative of prebreakdown kerrogram (U = 214 kV, d = 4 mm, t_b = 1.4 μs, t_l = 1.35 μs); b – the shadow photo of afterbreakdown phenomena (U=108 kV, d = 3 mm, t_b = 1.0 μs , t_l = 1.65 μs). The upper electrode is anode.

Figure 7a presents the negative of kerrogram registered ≈ 50 ns before the breakdown (t_b is breakdown time, t_l is the time moment of laser exposition). A light closed oval corresponds to the average field strength E ≈ 510 kV/cm along the beam path, the field strength in the central part is E ≈ 620 kV/cm, and the average field strength in the gap is E = U/d ≈ 530 kV/cm. The Kerr electrooptical scheme of measurements was adjusted for minimum light transmission when the electric field is absent. The radiation of secondary ionization processes after the breakdown was also registered by the camera and it was superimposed on the image of the Kerr fringes. "Branches" near the cathode propagate generally in radial direction from the discharge channel. The length of "branches" from the center of discharge channel reaches 5 mm and their thickness is ≤ 0.1mm. They are situated in the region of the enhanced field gradient.

The evaluation of of radial branch velocity gives value ≈ 10 km/s, therefore they are supersonic streamers.

III. DISCUSSION

The electrical characteristics of a layer depend on relation of Maxwell time τ_r and characteristic time of voltage rise τ_f. For $\tau_f << \tau_r$ the layer is a capacitor, and for $\tau_f >> \tau_r$ the layer is a resistor. The layer is efficient for breakdown initiation suppression if electric field close to electrode is decreased. From the Poisson equation it follows that the gradient of the electric field strength in the gap caused by the conductivity gradient leads to the space charge appearance with density $\rho(x) \approx \varepsilon \cdot \varepsilon_0 \cdot (dE/dx)$. Thus, the electric field intensity in the gap is a superposition of the external field and the field of space charges. The electric field of space charge is the reason both for breakdown strength increase and nonelectrode streamers appearance and postbreakdown streamers appearance. Pulse electric strength is increased due to decrease of electric field close to the electrodes at the stage of voltage rise. As for as the energy storage and release, this fact inevitably leads to an increase in the energy stored in the capacitor. However, when the capacitor is rapidly discharged to the load with time much less than τ_f , the energy of the external field is released in the load, and the energy due to the charge field remains in the gap and dissipates in time τ_r. Therefore, to reduce energy losses, the conductive layer must be much smaller than the interelectrode gap.

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High electric field in the core part of the gap leads to nonelectrode streamer initiation. The immediate cause of such streamer emergence is small particles inside the bulk of liquid.

Space charge couldn't disappear instantly and after fast breakdown with short circuit this space charge leads to form extremely high electric field which excites streamers from breakdown channel to space charge region.

IV. CONCLUSION

In case of screened electrodes nonelectrode streamers appearance takes place. Anode directed half streamer has subsonic velocity and high conductivity. Cathode directed half streamer has supersonic velocity and low conductivity. Second new event is postbreakdown streamers. The reason both of non-electrode and postbreakdown streamers is space charge formation in near-electrode region. con

Pulse electric strength and energy storage are increased due to decrease of electric field close to the electrodes at the stage of voltage rise.

ACKNOWLEDGEMENTS

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