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Electric strength of dielectrics under influence of bipolar voltage pulses of submicrosecond duration

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The development of electric pulse technologies for the destruction of solids states (rocks) — drilling, cutting and crushing requires reduction of high pulse voltages. In this work, for the first time, studies are proposed and carried out to determine the breakdown voltages of various dielectric media (air, water, rocks) while simultaneously supplying two pulses to the electrode system by two high voltage generators of different polarity — positive and negative, which halves the operating impulse voltage each generator. In addition, experiments have shown that for all media there is a decrease in breakdown voltage in comparison with a monopolar voltage pulse, which reaches 28% — for the breakdown of sandstone, 23% — granite, 24% — water, 25% — air. A physical explanation of the discovered effect is given.

Keywords: monopolar and bipolar pulse voltage, breakdown voltage, discharge channel.

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Introduction

The discovery made in the field of dielectric strength of solid and liquid dielectrics subjected to high-voltage pulses of the submicro- and microsecond range provided an opportunity to propose new methods for destruction of solids (specifically, electropulse (EP) drilling, cutting, crushing, etc. [1,2]).

The formation of a breakdown channel and the breakdown itself are crucial for EP technology. When the time of exposure to voltage pulses decreases, the strength of solid and liquid dielectrics increases to a varying degree. As a result, the dielectric strength of liquid dielectrics exposed to voltage pulses with a rise time shorter than 10^{-6} s becomes higher than the strength of solid dielectrics and rocks [1,2]. When electrodes are positioned on one face of a solid insulating body below a liquid layer, a discharge channel develops in the solid. The energy stored in a pulsed voltage generator (PVG) is released into the discharge channel within $10^{-6}-10^{-5}$ s, thus inducing an electric explosion with ejection of a part of the solid material located above the discharge channel [2]. The EP method for rock crushing has an advantage over modern mechanical techniques for crushing of hard rocks both in efficiency and in throughput performance. These advantages have been demonstrated both in laboratory studies and in the field.

The most comprehensive reviews of scientific data on EP disintegration of materials (obtained primarily in the USSR in the latter half of the 20th century) may be found in [2,3]. Research in this field is currently ongoing in Germany [4], the United States [5], Australia [6], China [7], Russia [8], and several other countries. However, the EP technology has not found wide industrial application (with the notable exception of EP disintegration setups produced by SelFrag [9]).

The need to use high voltages of several hundred kilovolts is one of the factors slowing down the process of industrial implementation of EP technology. Several methods for reducing the operating pulsed voltage were proposed, but all of them have certain limitations [2,10]. We have outlined a way to reduce the operating pulsed voltage with the use of two PVGs that provide for simultaneous application of pulses of different polarity to the electrode system. The voltage for each PVG is then two times lower than the one corresponding to a unipolar generator. A solution of this kind has never been proposed before for EP technology, and no experiments have been performed.

The aim of the present study is to examine the possibility of application of a bipolar voltage pulse in EP technology as a means of reducing the operating voltage of an individual generator. A twofold voltage reduction contributes to a considerable increase of service life of generator components and insulation elements and structures that connect a PVG to the electrode system. This is crucial for reliable operation of EP setups.

1. Procedure

Figure 1 presents the general electric circuit of the test setup that features the following units:

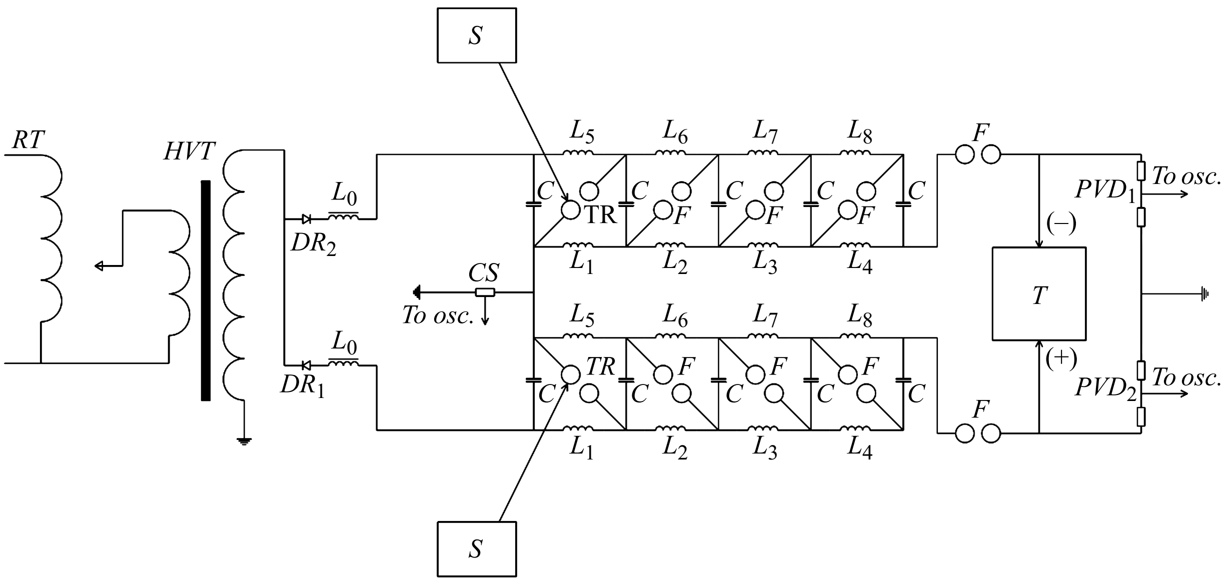

Figure 1. Electric circuit of the test setup: RT — regulating transformer, HVT — high-voltage transformer, L_0 — charging chokes, DR_1 and DR_2 — rectifiers, C — capacitance, L_1–L_8 — inductances, TR — trigatron, F — spark gap, PVD_1 and PVD_2 — potential dividers, CS — current shunt, T — discharge chamber, S — start-up generators.

– high-voltage charging device with elements for measurement of a high rectified voltage, protective devices, and a control panel; – two high pulsed voltage generators with controlled start-up devices based on trigatrons;

– units for measurement of high pulsed voltages with low-inductance Ohmic potential dividers and a current shunt to measure the breakdown current;

– test polyethylene cell for the studied rock samples that is filled with water and fitted with an electrode system.

A source with the required time and energy parameters is needed to establish the conditions for electropulse breakdown and destruction of solids. We used capacitive Arkadyev–Marx high pulsed voltage generators, which are a common choice for this role, in our experiments. Platform-type generators feature five stages. Each stage is fitted with IK-100/0.1 capacitors, where 100 is the rated operating voltage [kV] and 0.1 is the capacitance [μF]. The operating PVG voltage is adjusted by altering the distance between spark balls at each stage. The charging voltage of each PVG does not exceed 35 kV. It follows from the results of no-load operation and short-circuit tests that the rise time of pulses is $\tau_f = 0.2 \cdot 10^{-6}$ s and wave impedance $Z_w = 12.0\,\Omega$.

When load in the form of the electrode system in water is connected, the pulse parameters change: the rise time increases to $\tau_f = 0.24 \cdot 10^{-6}$ s, while the voltage pulse duration decreases due to the high capacitance between electrodes and the low resistivity of water.

Control circuits of trigatron-type discharge devices with adjustable voltage and actuation time served to synchronize the operation of two generators.

The high-voltage measurement unit featured two low-inductance Ohmic dividers for simultaneous measurement of voltages of two PVGs with positive and negative polarity. The error of measurement of parameters of a voltage pulse did not exceed 3.1% [11]. The current shunt made it possible to measure discharge currents with a magnitude no lower than 20 kA.

The test cell was a polyethylene tank 500 dm^3 in volume with the removable electrode system of two rod electrodes mounted inside (Fig. 2).

Two rod electrodes 8 mm in diameter were positioned at an angle to each other in such a way that their working tips were on the same face of a rock sample. The tips of electrodes on the sample side were bent toward each other at an angle of 30° and machined so that the electrode tip plane

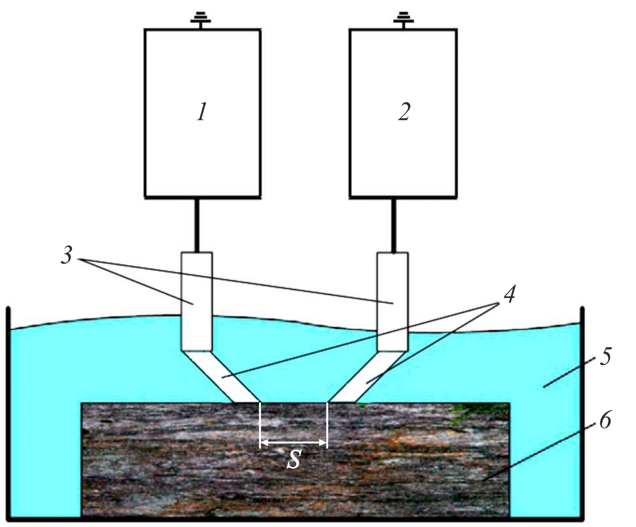

Figure 2. Diagram of positioning of the electrode system on the sample: *1, 2* — pulsed voltage generators, *3* — insulation, *4* — electrodes, *5* — liquid, *6* — rock, *S* — interelectrode distance.

was parallel to the sample surface (see Fig. 2). The contact pressure between the sample surface and the electrodes was produced by their own weight only. Each electrode was connected to its own PVG by an insulated wire. The interelectrode distance was adjusted in accordance with the plan of experiments. The polyethylene tank was filled with tap water with resistivity $\rho = (3.6–4.2) \cdot 10^3\,\Omega{\cdot}\mathrm{cm}$ in the initial state, since water is the working liquid of choice for EP technology. The resistivity of water was monitored in the process of operation. When ρ dropped below $10^3\,\Omega{\cdot}\mathrm{cm}$, the tank was refilled with water.

Sandstone (hardness $f = 6$ on the Protodyakonov scale) and granite ($f = 14$) samples were chosen to be tested as rocks that are the most abundant in nature [12,13]. Samples $150 \times 100 \times 50$ mm in size were cut out from granite and sandstone blocks. The breakdown voltage of water was also examined with exposure time $\tau = 0.24 \cdot 10^{-6}$ s and the same electrode system as the one used for rocks. Breakdown of air was initiated in a weakly nonuniform field between spark balls 12.5 cm in diameter. International tables of variation of breakdown voltages with distance between balls and polarity of the potential electrode are available for such electrodes. It is known that breakdown voltages corresponding to the positive polarity of the potential electrode are somewhat lower than the ones for the negative polarity [11]. In the present study, the breakdown voltages for bipolar operation were compared to the breakdown voltages determined for the positive polarity of the potential electrode. Spark balls were positioned horizontally on support insulators. Each electrode was connected to a separate generator. The number of breakdowns observed in the preset conditions was no lower than 50 (for water and air) and 30 (for rocks). The scatter of breakdown voltages for rocks did not exceed 10%.

Since the EP effect is observed at submicrosecond durations of voltage application, the essential requirement for comparative studies is that the breakdown voltages should be determined at equal (or close) times to breakdown. This is important due to the fact that the breakdown voltage for all dielectrics increases (at different rates [2]) as the time to breakdown decreases.

Depending on the dielectric strength of the dielectric material and the interelectrode distance, breakdown may occur at the leading edge, within the amplitude part, or at the trailing edge of a voltage pulse with a given amplitude. The breakdown voltage in all our experiments was determined as the maximum amplitude of a voltage pulse [10], and the time to breakdown was determined based on the oscilloscope record of current (Fig. 3).

2. Physical aspects of breakdown of solid and liquid dielectrics

In the context of the EP technology, researchers are mostly interested in breakdown processes in relation to the polarity of voltage applied to solid and liquid dielectric materials (with rocks being one example of such materials).

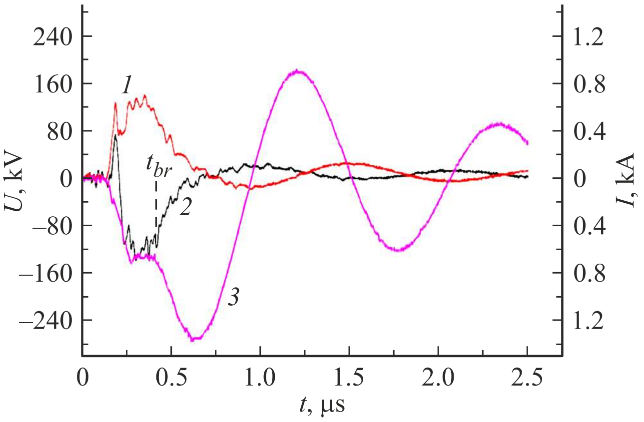

Figure 3. Oscilloscope record of current and voltage: *1* — positive-polarity voltage pulse, *2* — negative-polarity voltage pulse, *3* — current in the circuit, t_{br} — time to breakdown.

Yu.N. Vershinin has developed a modern novel theory of breakdown of solid dielectrics by voltage pulses [14,15]. This theory is the basis for our reasoning. The electric field induces the passage of current in dielectrics. If the case of application of a high voltage sufficient for breakdown, the current before the breakdown is called the prebreakdown one. This prebreakdown current in a (solid) dielectric is the sum of electron and hole currents flowing in one direction in the conduction band and the valence band. Both types of charge carriers (electrons and holes) are involved in the process of formation of a discharge. However, one type of carriers only alter the potential distribution pattern and bend the energy bands in the discharge gap, while carriers of the other type are responsible for breakdown. In order to stress their functional differences, these charge carriers are called minority and majority ones, respectively. If the electrode has a positive polarity, holes are minority carriers and electrons are majority carriers. If the electrode has a negative polarity, holes are majority carriers and electrons are minority carriers [15].

When the discharge is initiated at the anode, electrons are the carriers responsible for breakdown. The discharge propagation rate is then

$$V^+ = V_n = \mu_n E(U).$$

When the discharge is initiated at the cathode, holes are the carriers responsible for breakdown, and the discharge propagation rate is

$$V^- = V_p = \mu_p E(U),$$

where V_n, V_p are the velocities of diffusion of electrons and holes, respectively, and μ_n, μ_p are the mobilities of electrons and holes.

At $E = \text{const}$, where E is the electric-field intensity at electrodes,

$$\frac{V^+}{V^-} = \frac{V_n}{V_p} = \frac{\mu_n}{\mu_p}.$$

The mobility of electrons in solid dielectrics is higher than the mobility of holes. Therefore, $V^+ > V^-$.

In view of this, the breakdown voltage at the positive pulse polarity is lower than the one at the negative polarity; i.e., $U^+ < U^-$ at $\mu_n > \mu_p$ [14].

Electrons are more active than holes in the ionization of the breakdown channel within the dielectric structure. This also contributes to a reduction in the breakdown voltage at a positive electrode polarity and to an increase in V^+.

The discharge formation time in solid dielectrics is a function of mobility of majority carriers:

$$t_p = \frac{d}{\mu E_{br}}, \tag{1}$$

where d is the thickness of the dielectric material at the site of breakdown and E_{br} is the electric-field intensity at breakdown. It follows from (1) that the discharge formation time

1) increases with d;

2) decreases as the overvoltage increases;

3) at a positive electrode polarity is lower than at a negative polarity, since $\mu_n > \mu_p$ [14].

Another two factors exerting an influence on the polarity effect should be added to this explanation:

1) probability P_n of production of primary electrons is higher than probability P_p of production of primary holes; i.e., $P_n > P_p$;

2) electron impact-ionization rate α is higher than hole impact-ionization rate β; i.e., $\alpha = 3\beta$ [14].

The combined influence of these two factors ($p_n > p_p$ and $\alpha > \beta$) results in $E^+_{br} < E^-_{br}$ [14].

The thermal physical nature of initiation of the primary discharge channel at the anode and the cathode is the same. The difference consists in the fact that intrinsic electrons from the lower donor levels of the dielectric are involved in the formation of a discharge at the anode, while a discharge at the cathode is formed primarily by electrons injected from the cathode.

With a positive polarity of the potential electrode, a discharge in a highly nonuniform field is initiated at the potential electrode at the minimum breakdown voltage and terminates even before the emergence of discharges at the grounded (negative) electrode. The breakdown voltage and time are minimized. With a negative polarity of the potential electrode, a discharge is initiated with a certain delay, and the breakdown voltage is considerably higher than the one corresponding to the positive polarity [2].

The simultaneous application of voltages of both polarities to the electrode system leads to an increase in the electric-field intensity at the electrode that would be otherwise grounded (due to the lack of the „earth"effect [2]). This contributes to a reduction of the interelectrode breakdown voltage. In addition, the development of two antiparallel discharge channels at both electrodes (even with a certain time delay and a lower propagation rate at the negative electrode) contributes to an increase in intensity between the channels in the process of their development and facilitates breakdown of the entire interelectrode gap, which occurs earlier and at a lower voltage in this case. In view of the above, the breakdown voltage in a system of two potential rod electrodes (highly nonuniform field) should decrease compared to the voltage in a system with one grounded electrode.

Since the polarity effect is zero in a system of two symmetrical potential electrodes of the same shape and size, the breakdown voltages are compared for unipolar gaps with a positive polarity of the potential electrode and the grounded electrode.

3. Experimental results

Experiments were performed in three fundamentally different media (gas, liquid, and solid) to reveal the expected breakdown voltage reduction in all these media. There is all the more reason for this as the EP effect is implemented in a combined (solid−liquid) medium. The summary of results of all experiments is presented in the table.

3.1. Sandstone

Sandstone is a sedimentary rock with its physical and mechanical characteristics varying within a very wide range [12,13]. The studied rock had a relatively low breakdown voltage $U_{br\Sigma}$ (see the table). When the interelectrode distance increased by a factor of 1.5, $U_{br\Sigma}$ remained almost unchanged, which is due primarily to the variation of the time to breakdown: it occurred practically within the amplitude part of the voltage pulse at $S = 20$ mm and at the trailing pulse edge at 30 mm. This agrees closely with the variation of the voltage–time curve. The pulsed breakdown voltage is assumed to be equal to the pulse amplitude if breakdown occurs at the trailing edge. The breakdown voltages given in literature for close experimental conditions with a unipolar PVG and sandstone with similar characteristics are $U_{br} = 234$ kV at $S = 20$ mm and $U_{br} = 263$ kV at $S = 30$ mm. The table demonstrates that the $U_{br\Sigma}$ reduction relative to literature data is as high as 28% [16].

It should be noted that the process of formation of a discharge channel in a solid (especially rocks) in EP experiments is stochastic and probabilistic in nature; the penetration depth and the length of a channel vary greatly from one discharge to another, and this has an effect on the breakdown voltage data [17]. However, one may still state that the breakdown voltage for sandstone in experiments with two potential electrodes is lower than the voltage determined with one potential electrode and one grounded electrode (with the above-mentioned scatter taken into account).

Characteristics of breakdown in different media under the influence of a bipolar voltage pulse

Material	S, mm	$U_{br\Sigma}$, kV	t_{br}, μs	U_{br}, kV	$U_{br}/U_{br\Sigma}$	Scatter, %
Sandstone	20 30	206 205	0.19 0.31	234 [16] 263 [16]	1.18 1.28	10–20 [3]
Granite	20 30 50	248 290 320	0.24 0.39 1.8	306 [16] 316 [17] 362 [17]	1.23 1.1 1.14	
Water	15	290	0.38	360 [15]	1.24	8 [3]
Air	64 75 97	172 219 236	0.15 0.18 0.19	216 [11] 244 [18] 270 [18]	1.25 1.12 1.14	3–3.16 [19,20]

Note . S is the interelectrode distance, $U_{br\Sigma}$ is the overall breakdown voltage at electrodes with positive and negative polarities, t_{br} is the time to breakdown, U_{br} is the breakdown voltage with a unipolar positive electrode (taken from literature data) in the conditions corresponding to our experiments, $U_{br}/U_{br\Sigma}$ is the relative reduction in breakdown voltages with unipolar U_{br} and bipolar $U_{br\Sigma}$ voltage pulses.

3.2. Granite

Granite is an igneous rock with its physical and mechanical characteristics varying within a wide range; for example, its hardness on the Protodyakonov scale varies from 6 to 19 [12]. The dielectric strength of rocks is correlated with their hardness [16]. As was demonstrated above, the hardness of the studied granite samples is fairly high (14). Since the dielectric strength of granite is higher than that of sandstone, the pulsed voltage generator needs to be adjusted accordingly (especially when the interelectrode distance increases).

It can be seen from the table that breakdown voltage U_{br} with a unipolar pulse is higher [16,17] than the voltage corresponding to a bipolar pulse. It should be noted that the data for comparison for a unipolar pulse were taken from different sources: experimental data from [16] were used at $S = 20$ mm, and the results of calculations in accordance with the formula from [17] were used at $S = 30, 50$ mm. I can be seen that, although breakdown occurred both at the leading edge and the trailing edge of a voltage pulse, the overall breakdown voltage also decreases by as much as 23% when bipolar voltage pulses were applied to granite samples. This exceeds the scatter of breakdown voltages of various rocks (see the table) [3].

3.3. Water

The dielectric strength of water at submicrosecond durations of pulsed voltage application is significantly higher than the dielectric strength of rocks and is close to the strength of transformer oil [2]. Therefore, the interelectrode distance was adjusted to $S = 15$ mm. Even in these conditions, breakdown occurs at the trailing edge of a voltage pulse (as in granite at $S = 30$ and 50 mm; see the table).

The dielectric strength of water was studied in [21] in a wide range of distances $S = 10-90$ mm. The value of U_{br} for a unipolar positive pulse given in the table corresponds to the results of these studies.

It follows from the comparison of the obtained data that the breakdown voltage decreases by as much as 24% if a bipolar pulse is applied. This value exceeds considerably the scatter of breakdown voltages of water (see the table) [3]. Therefore, the effect of breakdown voltage reduction under the influence of a bipolar pulse persists in a liquid medium.

3.4. Air

Breakdown of air was initiated in a quasi-uniform ball–ball field with the transition to a weakly nonuniform field at distances exceeding 64 mm. The breakdown voltages for spark balls of different diameters and for different distances between balls are listed in tables provided by the International Electrotechnical Commission [11]. However, these tables are limited to a voltage pulse duration of $1.2/50\,\mu$s; a correction is required for shorter pulses, since the breakdown voltage increases. This correction is introduced in the form of „pulse coefficient" (β), which may reach $(\beta) \geq 2.2$ as the duration of voltage application decreases to 10^{-8} s (or even lower values) [18,22]. Coefficient (β) increases when the electric field uniformity is disturbed at interelectrode distances exceeding half the ball diameter [22]. In the conditions of our experiment, $(\beta) = 1.4$ [3]. It is demonstrated in the table that if a bipolar voltage pulse is applied, the breakdown voltage decreases by as much as 25% (relative to a unipolar pulse). This value exceeds considerably the scatter of breakdown voltages of air (see the table) [19,20].

Conclusion

The presented results suggest that the application of a bipolar voltage pulse to a two-electrode system in experimental conditions enabling the observation of the EP effect results in a reduction in the breakdown voltage (relative to the one corresponding to a unipolar pulse) in all the studied types of media: solid, liquid, and gas.

With a positive polarity of the potential electrode and a unipolar pulse, a discharge fails to be initiated and start developing at the grounded electrode within the pulse duration, since the potential of the grounded electrode is relatively low and the „earth"exerts a screening effect; i.e., the „earth"effect reduces the electric-field intensity at the grounded electrode. This inhibits the initiation and development of a discharge channel at this electrode [14].

With two potential electrodes of different polarity (no „earth") and equal potentials at these electrodes, the electric-field intensity is defined exclusively by the geometric parameters and the shape of electrodes.

If the electrodes are symmetrical and have the same configuration and size, the field intensities at them are equal. The initiation of a discharge channel at each electrode is then governed by the initiation mechanism, which depends on the electrode polarity. Compared to the processes at the electrode with a positive polarity, a discharge channel at the electrode with a negative polarity is initiated with a certain delay and evolves at a lower rate. A discharge in a solid body at the positive electrode is initiated at a lower voltage and propagates at a significantly higher rate ($V_a = (14.1{-}26.7) \cdot 10^6$ cm/s is the propagation rate of a discharge channel from the anode, and $V_c = (0.26{-}7.2) \cdot 10^6$ cm/s is the propagation rate of a discharge channel from the cathode [2,15]). The factor governing the propagation rate of a discharge channel is the electric-field intensity at the tips of discharge channels, and this intensity depends, in turn, on the voltage applied to electrodes and the distance between antiparallel channels from electrodes of positive and negative polarities. This contributes to a considerable increase in the intensity in the gap between the tips (heads) of channels, enhances the rate of their propagation between electrodes, and, consequently, reduces the breakdown voltage. Therefore, the breakdown voltage in experiments with a bipolar pulse cannot be higher than the breakdown voltage corresponding to a positive unipolar pulse.

The experiments preformed in the present study demonstrated that the effect of reduction of the breakdown voltage in the case of application of a bipolar voltage pulse is common to all types of dielectric media (gas, liquid, solid). The implementation of this effect in the EP technology should allow one to reduce significantly (by a factor of more than two) the operating voltages of both pulse generators and high-voltage insulating transmission systems connecting generators to the load (electrode systems), which may be spaced, if we take drilling operations as an example, several hundred or even thousand meters apart.

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Conflict of interest

The authors declare that they have no conflict of interest.

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