High-voltage impulse surface discharge: influence on power system insulation and electro pulse boring

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Abstract. This research utilizes a unified approach to characterize high-voltage impulse surface discharge physics, providing information for three different types of materials. The study first investigates surface discharge on solid polyurethane and stone tiles materials immersed in transformer oil. By using a DC source and Marx generator, energy dissipation is quantified via current/voltage analysis. Subsequent microscopic analysis identifies degradation effects (small-cracks) crucial for insulation condition analyzation of high-voltage equipment. Based on the information obtained, the research then focused on the use of fast, sub microsecond electrical pulses for the electro pulse boring marble slab using a petal-shaped electrode drill. Characterizing the plasma channel formation and resulting high-pressure pulses is essential for optimizing pulsed power systems. Post-optimization will allow for the characterization of discharge parameters and associated morphological changes on the rock surface.

1 Introduction

The global economy's sustained dependence on the exploration and extraction of essential natural resources, including oil, natural gas, mineral deposits, and geothermal energy—continues to drive the demand for advanced drilling and excavation technologies. Conventional mechanical drilling methods, despite decades of refinement, face major limitations when operating in deep boreholes or extremely hard geological formations [1, 2]. Under such conditions, the efficiency of mechanical penetration decreases sharply, while equipment wear, operational time, and overall costs increase. These challenges have stimulated intensive research into alternative rock-disintegration techniques capable of achieving higher efficiency, reduced mechanical stress, and lower environmental impact [3].

Among non-mechanical methods, Electrical Pulsed Boring (EPB) represents one of the most promising approaches [4, 5]. EPB relies on the application of rapid, high-voltage impulses—typically with rise times below 500 ns—to initiate electrical breakdown inside the bulk of the rock rather than along its surface. This internal breakdown creates a highly conductive plasma channel, and its rapid expansion generates a strong shock wave that fractures the rock. In contrast to Electrohydraulic Disintegration (EHD), where shock waves originate in the surrounding liquid, EPB directs the electrical energy directly through the rock matrix. This leads to significantly higher fragmentation efficiency, lower specific energy consumption, and improved selectivity in mineral separation. A fundamental requirement for advancing EPB technology is a deeper understanding of high-voltage impulse physics, particularly the processes governing plasma formation, energy dissipation, and material degradation under fast, high-amplitude electrical stress. This research therefore adopts a unified experimental methodology applicable to both insulation diagnostics and pulsed rock fragmentation.

The first part of the study investigates surface discharge phenomena on polyurethane-based composite materials immersed in transformer oil, a liquid dielectric commonly employed in high-voltage equipment. A combined high-voltage system consisting of a DC power supply and a Marx generator is used to generate controlled impulse voltages [6, 7]. Analysis of the measured voltage and current waveforms enables precise determination of the discharge energy as well as its temporal evolution. Subsequent microscopic examination of the stressed samples reveals characteristic degradation features, including microcracks, carbonized tracks, and surface erosion patterns. These markers are essential for assessing long-term insulation reliability.

In the second part, the study translates these insights into the domain of electrical rock disintegration. The controlled application of sub-microsecond impulses to rock samples immersed in transformer oil enables detailed characterization of plasma channel dynamics and the associated high-pressure expansion responsible for material removal. By correlating electrical measurements with morphological changes—such as crater depth, shape, and localized melting, the research provides a foundation for optimizing pulsed power systems used in EPB [8-11].

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By integrating findings from high-voltage discharge physics, material degradation mechanisms, and pulsed rock fragmentation, this research contributes valuable insights toward a study of surface discharge on insulation systems and more efficient pulsed power technologies for drilling applications. The unified approach presented here lays a foundation for future optimization of EPB systems and enhances the understanding of failure modes in dielectric materials exposed to rapid high-voltage stress.

This article focuses specifically on the effect of surface breakdown on different samples: polyurethane, stone tiles and marble slab, immersed in transformer oil. The basis of this study is to determine the effect of discharge in transformer oil as a function of applied voltage, electrode spacing and types, and surface discharge length on the degradation of the sample material.

2 Experimental apparatus

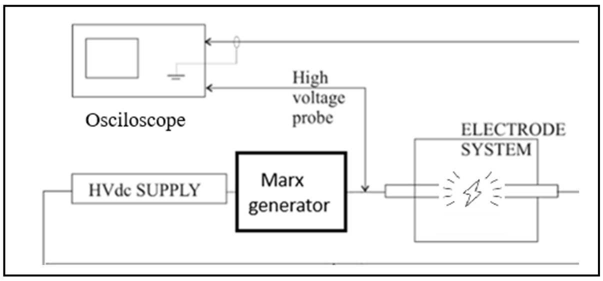

Fig. 1. The electrical scheme of setup for measurement and photo of electrode arrangement without oil.

The schematic diagram of experimental system is shown in Figure 1. A 50 kV STATRON was used as the HVDC supply. This source was used to generate pulsed voltage using the Marx generator. The classical Marx generator consists of 4 stages with pair capacitors (1 nF, 20 kV) connected in series. The maximum output voltage was 80 kV. A HV probe, the resistor divider and a Rogowski coil were used for measuring the development of voltage and the current waveform, respectively. RIGOL DHO 924S, 250 MHz digital oscilloscope was used for sampling waveform data.

Figure 2 shows the voltage waveforms measured on the Marx generator for 3 mm ball gap distance. The measurements were obtained in the 1st stage and the 4th (output) stage, which was connected to the measuring electrode system (Figure 3). In the 1st stage, a significant voltage drop is observed immediately after the spark, followed by a subsequent recovery towards the initial charging voltage. In the final output stage, a rapid voltage increase is evident, occurring in less than 0.1 ms. This pulse was followed by an oscillation, which was largely caused by the connection and impedance of the external electrode system. The evolution of the energy delivered to the breakdown is also shown on Fig. 2. The distance between the electrodes immersed in transformer oil (Figure 3a) was 2 mm, the input DC voltage was 7 kV, and the input energy was approximately 24 J. At this voltage the frequency of breakdown starts was 3 Hz and increases with increasing DC voltage.

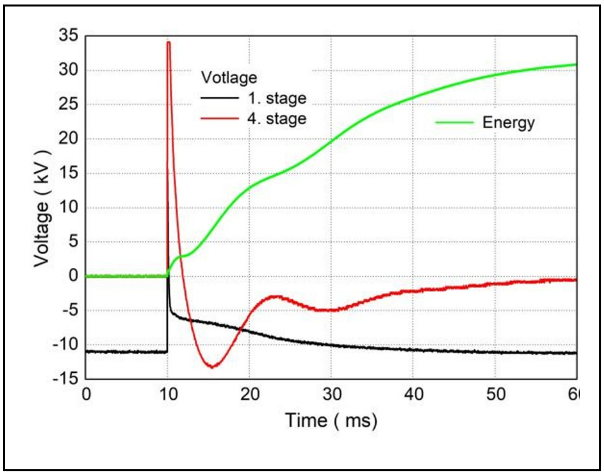

Fig. 2. The development of voltage from 1. and last stage of the Marx generator at 3 mm distance of sphere electrodes and the energy supplied to the breakdown.

The needles for generation of partial discharge were positioned at the angle 45^o on the rock at various distances (Figure 3a). This arrangement creates a strong tangential field component on the insulation surface while minimizing the vertical field component through the insulator. The petal-shaped electrode drill with an outer diameter of 5 cm was used as the electrode system for the rock-breaking experiments (Figure 3b) [12, 13].

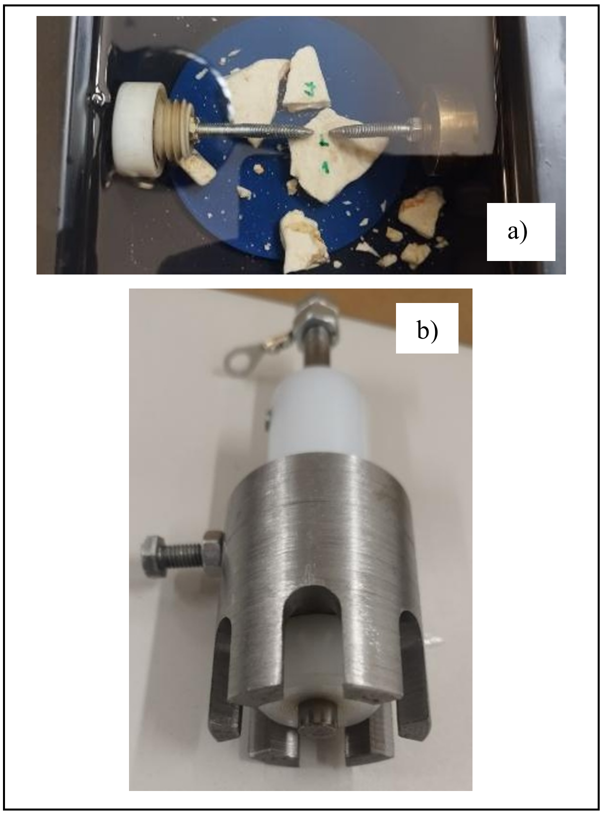

Fig. 3. The two types of electrodes systems a) two needle electrodes and b) a petal-shaped electrode drill.

The high-voltage electrode is separated from the grounded electrode by a nylon insulator, chosen for its high dielectric strength and ability to ensure that the discharge occurs only at the front end of the drill. The primary goal of the electric rock-breaking setup is to initiate the discharge inside the rock rather than on its surface. To maintain stable discharge conditions and ensure repeated breakdown within the rock volume, mechanical pressure was applied to the drill head to keep the electrode tip in firm contact with the rock.

3 Results and discussion

At small separations between the spherical spark gaps of the Marx generator, the surface discharge in transformer oil - under the electrode configuration shown in Figure 3a - was predominantly confined to the immediate vicinity of the electrodes. The discharge was characterized by the formation of narrow, well-defined surface channels developing in regions of locally enhanced electric field intensity. These channels originate from streamer propagation along the polymer surface, followed by localized thermal effects (Figure 4a). The energy deposited during each impulse induces thermal and partially chemical degradation of the material, leading to progressive deterioration of the surface layer.

The polymer surface undergoes a complex process of localized degradation in which recurrent plasma channels preferentially propagate through regions of reduced electrical strength and accumulated residual heat. This interaction establishes an erosion mechanism that progressively compromises the structural integrity of the material. With increasing impulse number, individual microchannels coalesce into a single dominant, deeply penetrating erosion track as the polymer matrix is locally decomposed due to discharge duration (Figure 4b, Table. 1).

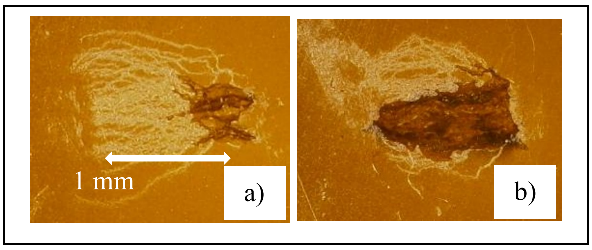

Fig. 4. Influence of surface discharge on polyurethanes during a) 10 s and b) 30 s at 1 mm distance of electrodes at DC input voltage 13 kV.

At small electrode spacing, strong local field enhancement and rapid voltage rise result in highly concentrated energy deposition - surface discharge, subjecting the polymer to severe thermo-mechanical stress that exceeds its intrinsic strength limits. Transient plasma temperatures reaching several thousand kelvins induce progressive delamination, localized melting, and thermochemical degradation, ultimately leading to the loss of surface load-bearing capacity and structural integrity. The combined action of shock-wave-induced pressure and surface discharge activity promotes predominantly surface degradation, frequently culminating in perforation manifested as a narrow conductive path. The number of such paths depends on electrode spacing, impulse amplitude and waveform (particularly pulse duration), and overall discharge duration (Table I., polyurethane). These findings are essential for evaluating the impulse withstand capability of polymeric insulating materials and for optimizing electrode configurations in applications where controlled surface discharge propagation and minimized degradation are required.

Table 1. The effect of different discharge times on the degradation effects on the investigated surfaces (N - number of paths, l/d - length/depth in mm, D/d - diameter/depth in mm).

Type	param	1 s	5 s	10 s	30 s
Polyurethane	N	5±2	10±3	40±10	1
Stone tile	l/d	1.5/0.1	3/0.1	3/0.2	3/0.6
Marble slab	D/d	1/1	5/1	10/2	15/4

The second investigated material consisted of stone tiles exposed to the same surface discharge conditions as the polymer samples. The tiles are primarily composed of feldspar and quartz and are characterized by a dense crystalline microstructure that provides high mechanical strength and abrasion resistance. Owing to their significantly greater hardness, density, and thermal stability compared with polymers, the extent of discharge-induced degradation was substantially lower.

To induce measurable surface damage, a larger spacing between the spherical spark gaps was employed in combination with an input DC voltage of 16 kV. Under these conditions, the surface discharge produced a narrow, highly localized erosion channel [14]. Although the channel width remained limited, repeated impulse loading led to progressive and clearly observable deepening of the affected region (Figure 5a). The dependence of crack length and width on discharge duration is summarized in Table I. (Stone tile). The dominant degradation mechanisms include localized heating, microcrack formation within the surface layer, and partial vitrification along the discharge path. These effects remain strongly confined due to the material’s rigidity and high melting temperature. A three-dimensional surface profile obtained by confocal microscopy (Figure 5b) confirms the formation of a steep, narrow channel and demonstrates that, unlike polymeric materials, degradation in stone is highly localized with minimal lateral surface deformation. This behavior reflects the distinct interaction between impulse discharges and hard inorganic insulators, where energy deposition promotes preferential penetration into the bulk rather than lateral surface propagation. At higher voltages (>25 kV), the discharge energy increases significantly, and high-energy impulses have been observed to induce macroscopic cracking of the stone surface (Figure 3a).

The second electrode configuration, a petal-shaped drilling electrode (Figure 3b), more closely replicates practical electric drilling conditions. In this arrangement, a higher DC input voltage of 25 kV was applied to generate a sufficiently intense discharge within the rock. A 3 cm thick marble slab served as the test specimen to evaluate the effects of high-energy surface and subsurface discharges on a mechanically robust natural stone.

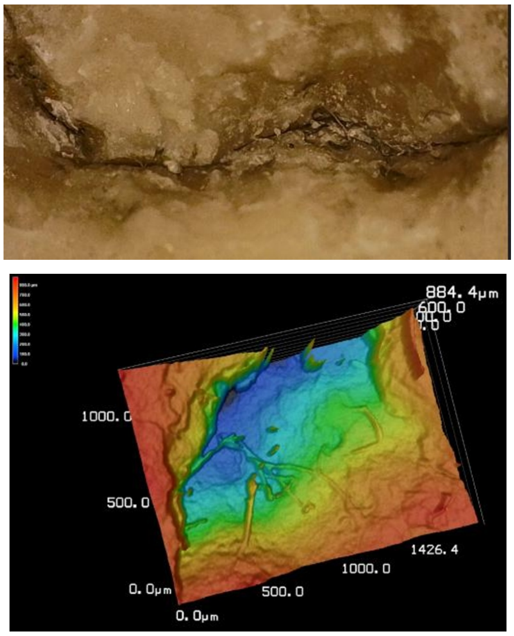

Fig. 5. Influence of surface discharge on stone tile during a) 30 s at 3 mm distance of electrodes at DC input voltage 16 kV. b) 3D scan of evaporated surface of stone tile.

Breakdown initiation occurred predominantly in the vicinity of the central high-voltage electrode and subsequently propagated toward the surrounding grounded segments of the petal-shaped structure. Compared with previous experiments using needle electrodes, the discharge intensity was significantly higher, resulting in rapid and clearly observable surface degradation of the marble within approximately 30 s. The dependence of crater diameter (D) and depth (d) on exposure time is summarized in Table I. (Marble slab). The dominant erosion mechanisms included intense localized heating, partial melting, and rapid microcrack propagation near the energized electrode. After a certain operating period, discharge activity gradually decreased. This reduction was primarily attributed to material removal and vaporization beneath the high-voltage tip, which diminished the effective electrical coupling between the electrode and the rock. As material recession progressed, the local electric field distribution was altered, reducing discharge stability and ultimately preventing the formation of a sustained plasma channel.

Despite these limitations, the results demonstrate that the petal-shaped electrode can produce a highly localized electrical breakdown capable of removing substantial material within a short time. Future investigations will employ a higher-energy Marx generator to increase the delivered impulse energy and improve discharge stability. The discharge characteristics were found to depend strongly on the applied voltage amplitude as well as on the mineral composition and microstructure of the marble. Further optimization will require adjustments to electrode geometry and contact pressure to enhance energy transfer into the rock and ensure stable and repeatable discharge operation.

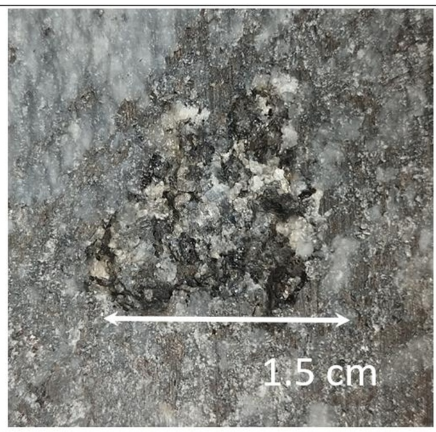

Fig. 6. Influence of surface discharge on marble slab generated using the petal-shaped electrode drill at DC input voltage 25 kV

4 Conclusions

This study investigated the electrical breakdown behavior of selected insulating and geological materials subjected to impulse voltages generated by a Marx generator, with emphasis on the initiation and evolution of surface and subsurface discharges. Microscopic and three-dimensional topographical analyses identified characteristic degradation features, including erosion channels, microcracks, craters, and localized melting or vitrification, whose morphology and extent were governed by the intrinsic physical and mechanical properties of the materials. Polymeric samples exhibited rapid surface erosion and progressive channel coalescence, ceramic-based materials developed narrow but deeply penetrating erosion tracks, and marble showed substantial material removal under intensified discharge conditions produced by the petal-shaped drilling electrode. The use of transformer oil provided controlled dielectric conditions representative of practical insulation systems and electro-impulse drilling environments.

Overall, the results provide a detailed understanding of the interaction between high-voltage impulse discharges and solid materials and establish a basis for optimizing electrode configurations and scaling impulse energy in future rock-fracturing and material-processing applications employing higher-energy Marx generators.

Acknowledgements: This work was supported by project VEGA 1/0622/24.

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