High Voltage Pulsed Power Systems

From Solid-State SiC Switching and Insulation Diagnostics to Electro-Pulse Boring

Marián Janek, Jozef Kúdelčík, Štefan Hardoň, Jakub Donoval

V4 EnergyNet – Online Workshop 2 · 9 November 2026

Department of Physics, Faculty of Electrical Engineering and Information Technology
University of Žilina, Slovakia

Research roadmap

I. Solid-state SiC switching

- 10 kV stack of series SiC MOSFETs
- 1 µs to 10 µs switching
- Static & dynamic voltage balancing
- LTspice verification

II. Insulation diagnostics

- Marx generator, up to 120 kV
- Surface discharge in transformer oil
- Polyurethane & ceramic samples
- Microscopy & 3D profilometry

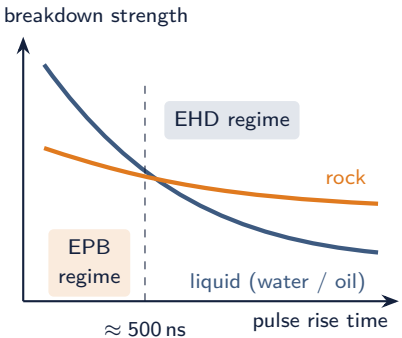
III. Electro-pulse boring (EPB)

- Petal-shaped electrode drill
- Marble slab, 25 kV DC input
- Crater morphology vs. energy
- Path to a full pulsed-power drill

A unified experimental methodology: the same impulse physics governs insulation ageing in HV equipment and rock disintegration in pulsed drilling.

Motivation: why pulsed power for rock disintegration?

- Mechanical drilling loses efficiency in deep boreholes and hard formations: tool wear, time and cost rise sharply.
- **Electro-Pulse Boring (EPB)**: impulses with rise time $< 500\,\text{ns}$ make the rock break down *before* the surrounding liquid.
- The plasma channel forms *inside* the rock, then its expansion launches a shock wave that fractures along grain boundaries.
- Compared with electro-hydraulic disintegration (EHD): higher efficiency, lower specific energy, better mineral selectivity.



Schematic: for fast impulses the rock becomes the weaker dielectric.

The switch: the heart of every pulsed-power system

Requirements for rock fragmentation

- Voltage 10 kV to 200 kV
- Peak currents of several kA
- Switching times of the order of µs
- Repeatability and precise timing

Spark gaps & thyratrons

Simple and high-voltage capable, **but**: limited repetition rate, electrode erosion, timing jitter.

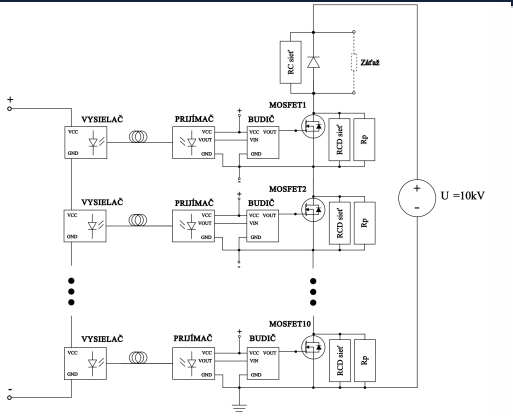
Why SiC MOSFETs?

- Higher breakdown field per unit thickness
- Low $R_{\mathrm{DS(on)}}$, fast switching
- Superior thermal conductivity
- Modular: series stacking to reach kV

Number of series devices:

$$N = \left\lceil \frac{V_{\mathrm{total}}}{V_{\mathrm{BR}}\, k_{\mathrm{sf}}} \right\rceil = \frac{10\,\mathrm{kV}}{1200\,\mathrm{V} \cdot 0.7} \approx 12$$

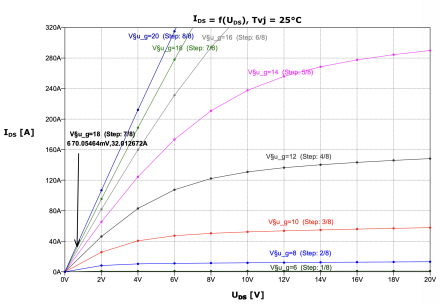
Modular 10 kV switch topology



Series SiC MOSFET stack with isolated gate drivers (transmitter – receiver – driver per stage), RC/RCD balancing and $U = 10\,\mathrm{kV}$ supply.

- $12 \times$ **1200 V SiC MOSFET**, $R_{\mathrm{DS(on)}} \approx 80\,\mathrm{m\Omega}$, $I_D > 30\,\mathrm{A}$
- Each device has its own floating gate driver
- Galvanic isolation: optocouplers / digital isolators + isolated DC–DC supplies
- Gate drive $20\,\mathrm{V}$ / $-5\,\mathrm{V}$: robust turn-off, no Miller-induced parasitic turn-on
- All gate signals must arrive within a window of $< 50\,\mathrm{ns}$

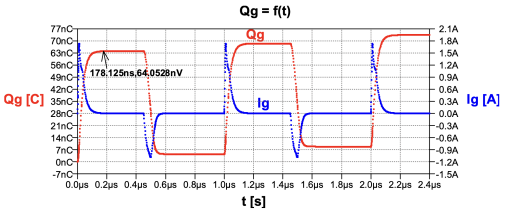
SiC MOSFET model: output characteristics and gate charge



$I_D = f(V_{DS})$ for several V_{GS} (SPICE model).

Linear-region slope at $V_{GS} = 20\,\mathrm{V}$ gives

$R_{\mathrm{DS(on)}} \approx 80\,\mathrm{m\Omega}$; knee at 3 V to 5 V.



Gate charge profile during turn-on: $V_{\mathrm{th}} \rightarrow$ Miller plateau $\rightarrow$ full drive. $Q_g \approx 100\,\mathrm{nC}$ to $150\,\mathrm{nC}$.

Required peak gate current for $t_{\mathrm{sw}} = 1\,\mu\mathrm{s}$: $I_{g,\mathrm{peak}} = Q_g / t_{\mathrm{sw}} = 150\,\mathrm{nC}/1\,\mu\mathrm{s} = 150\,\mathrm{mA}$ – well within commercial driver ICs.

Voltage balancing: static resistors and RCD snubbers

Static balancing (off-state)

Leakage-current spread ΔI_{DSS} causes unequal sharing $\Rightarrow$ R_{bal} across each device, $I_{\mathrm{bal}} \approx (5\text{–}10)\,\Delta I_{\mathrm{DSS}}$.

$$R_{\mathrm{bal}} = \frac{V_{\mathrm{DS,max}}}{I_{\mathrm{bal}}} = \frac{830\,\mathrm{V}}{1\,\mathrm{mA}} = 830\,\mathrm{k\Omega}$$

$$P_{\mathrm{bal}} = \frac{V_{\mathrm{DS,max}}^2}{R_{\mathrm{bal}}} \approx 0.83\,\mathrm{W}$$

Dynamic balancing (transients)

Faster devices block first and see overvoltage $\Rightarrow$ RCD snubber limits $\mathrm{d}V/\mathrm{d}t$.

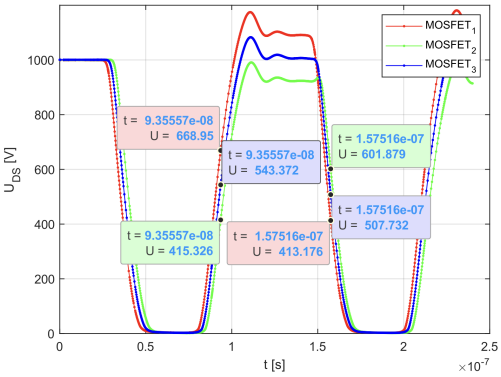
$$C_s = \frac{I_{\mathrm{load}}\,\Delta t_{\mathrm{sw}}}{\Delta V_{\mathrm{max}}}, \qquad R_s = \frac{t_{\mathrm{on}}}{5\,C_s}$$

Factor 5 $\Rightarrow > 99\,\%$ discharge of C_s within t_{on}.

Link to insulation diagnostics

Balancing networks see the same issues as HV insulation: conductivity and losses depend strongly on **moisture, material condition and temperature**.

Simulated switching performance (LTspice)



U_{DS} of series MOSFETs during switching transients with the RCD snubber network (±10 % parameter mismatch, 20 ns driver skew).

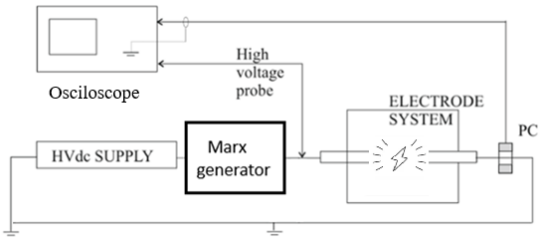
Parameter	Value
Total blocking voltage	10 kV
Series MOSFETs	12
Turn-on / turn-off time	1.2 µs / 0.8 µs
Static imbalance	$< 3\,\%$
Dynamic imbalance	$< 8\,\%$
Peak drain current	35 A
Total on-state resistance	$\approx 1\,\Omega$

$> 25\,\%$ without balancing

$< 8\,\%$ with RCD snubbers

- Driver delay mismatch (20 ns) is the dominant source of dynamic imbalance.
- $E_{\mathrm{cond}} = I^2 R\, t = 35^2 \cdot 1 \cdot 10\,\mu\mathrm{s} \approx 12.25\,\mathrm{mJ}$ per pulse – negligible.

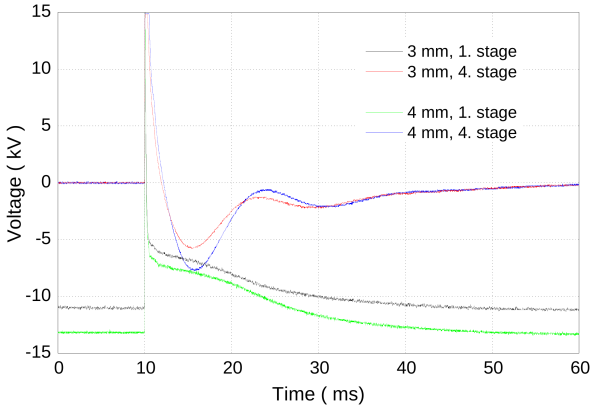
Experimental apparatus



HVDC supply → Marx generator → electrode system in transformer oil; HV probe, Rogowski coil, oscilloscope, PC.

- **HVDC source:** 50 kV STATRON
- **Marx generator:** 4 stages, capacitor pairs 1 nF/20 kV, max. output 120 kV
- **Voltage:** resistive HV divider probe
- **Current:** Rogowski coil
- **Acquisition:** RIGOL DHO924S, 250 MHz
- Energy dissipation quantified from recorded $u(t)$, $i(t)$ waveforms

Marx generator waveforms



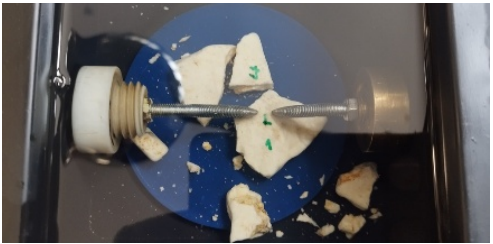
Voltage at the 1st and the 4th (output) stage for sphere-gap distances of 3 mm and 4 mm.

- Sphere-gap distance sets the spark breakdown threshold
- **1st stage:** sharp drop at breakdown, then recovery to the charging voltage
- **Output stage:** rapid rise followed by oscillation, governed by the external electrode impedance

Example operating point

2 mm oil gap, 1.5 mm Marx gaps, 4 kV DC in $\rightarrow$ 15 kV out, $\approx$20 J; breakdowns from 30 Hz, rising with DC voltage.

Two electrode systems



a) Two needle electrodes at 45° on the sample – strong tangential field along the surface, minimal normal component.

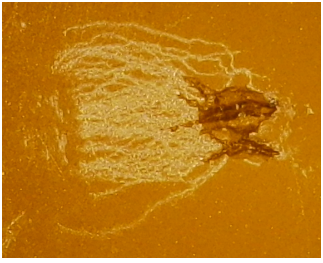


b) Petal-shaped electrode drill, outer diameter 5 cm.

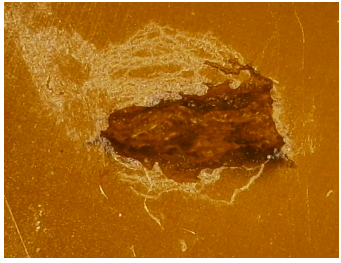
Petal drill

- HV and ground electrodes separated by a **nylon** insulator
- Discharge only at the drill front
- Pressure keeps the tip in contact → breakdown *inside* the rock

Polyurethane composite: progressive surface degradation



a) 10 s exposure



b) 30 s exposure

1 mm electrode spacing,
13 kV **DC input**

- Narrow channels along regions of enhanced field (streamers + local heating)
- After tens of impulses: channels widen and merge
- A dominant burned-through channel forms – a self-reinforcing process

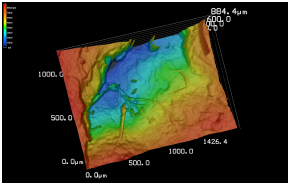
Mechanism

Fast voltage rise → surface discharge before bulk oil ionisation → highly localised, energy-concentrated plasma (hundreds to thousands of K within µs) → thermal stress + shock-wave pressure → delamination, melt-like deformation, perforation.

Ceramic floor tile: narrow and deep erosion



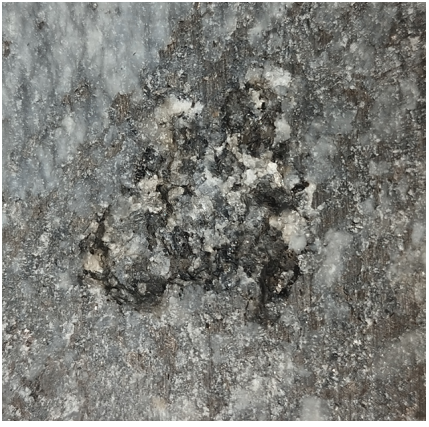
a) 30 s exposure, 3 mm electrode spacing, 16 kV DC input.



b) 3D confocal scan of the evaporated surface (depth scale up to ≈880 µm).

- Sintered silicate matrix: hard, dense, low porosity
- Narrow, concentrated channel that deepens with every impulse
- Local heating, micro-fracturing, partial vitrification
- Minimal lateral deformation – unlike polymers

Petal-shaped drill on a marble slab



Crater in a 3 cm marble slab after ≈30 s of discharges (≈ 1.5 cm × 1.2 cm).

- 25 kV DC input – much stronger discharge than with planar electrodes
- Discharge starts at the central HV electrode and propagates to the grounded petals
- Strong local heating, partial melting, fast micro-crack growth → substantial material removal

Observed limitation

Activity decays over time: material under the HV tip evaporates, coupling drops, the field redistributes and a stable plasma channel is lost.

Next steps

Higher-energy Marx generator, optimised electrode geometry and contact pressure for consistent discharge paths.

Conclusions and outlook

- **SiC switch:** 12 series MOSFETs, 10 kV, 1 µs to 10 µs; static imbalance $< 3\,\%$, dynamic $< 8\,\%$ under worst-case mismatch.
- **Insulation diagnostics:** damage morphology (channels, cracks, pits, melting) is set by the material – fast erosion in polymers, narrow deep channels in ceramics.
- **EPB:** the petal-shaped drill removes marble efficiently; discharge stability is the next challenge.

Outlook

- SiC switch prototype, thermal management, integration with the drill system
- Real-time $u(t)$, $i(t)$ diagnostics of switch health; higher-energy Marx generator

Open for cooperation

We warmly welcome collaboration with colleagues from the V4 EnergyNet consortium and beyond – joint experiments, shared measurements, student and PhD exchanges, and joint project proposals in pulsed power, HV insulation diagnostics and electropulse drilling.

Let us talk!

Thank you for your attention

Marián Janek

marian.janek@uniza.sk

Department of Physics, FEEIT, University of Žilina

Univerzitná 8215/1, 010 26 Žilina, Slovakia

Questions, ideas and collaboration proposals are very welcome.