High-Voltage Pulsed Generator for Dynamic Fragmentation of Rocks

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Abstract – We present here a portable HV pulsed generator, designed for rock fragmentation, though another technological applications are possible as well. The installation consists of low voltage block, high voltage block, coaxial transmission line, fragmentation chamber, and control system block. Low voltage block of the generator, consisting of 300 μF capacitor bank and thyristor switch, stores pulse energy and transfers it to the HV block. Maximum charging voltage is +2 kV, stored energy up to 600 J. High voltage block includes high voltage pulsed step up transformer, high voltage capacitive storage, and gas switch. Technical characteristics of the pulsed generator: stored energy in HV capacitors – 500 J, – output voltage up to 300 kV, voltage rise time ~ 50 ns, current amplitude on 40 Ohm active resistor is ~ 6 kA and ~ 20 kA in discharge, typical operation regime – 1000 pulses bursts with a repetitive rate of 10 Hz. The operation process can be controlled within a wide range of parameters.

1. Introduction

There has been an issue of interest for the last several decades in the use of high-voltage pulse technology for rocks disintegration, because the electrical disintegration of rock through application of high voltage electrical pulses is one of the effective techniques in disintegration of mineral aggregates [1, 2.]. This technique is being proposed as an environment-friendly alternative to the use of explosives. It is well known that the electric breakdown strength of some liquids (including oil and water) grows faster than that of solid materials if the risetime of the voltage pulse is reduced. Therefore, there is a regime of operation where an increasing fraction of discharges is initiated through the solid, providing high efficiency of the fragmentation process.

Several designs of generators for similar purposes are known [3, 4]. Usually they are based on the Marx scheme, where large number of spark gaps is required with synchronous triggering. Presented in this paper generator contains one HV storage, charged to full voltage, and one switch. This storage (capacitor bank) is pulsed charged from the pulsed transformer. Such solution simplifies design and enhances the system reliability.

2. Design of the generator

Operation principle: Principal electrical scheme is given in Fig. 1. At command from the control system power supply *CCS*-2 charges primary storage C_1 up to preset value (up to 2 kV). After it triggering pulse U_{tr} turns on the thyristor switch VS_1 and energy from the primary storage C_1 transfers through the HV transformer *TV* on the HV capacitor bank C_2, charging it up to the required value (200÷300 kV) in ~ 80 μs. Amplitude of a current pulse from the low voltage block is ~ 11 kA with pulse duration ~ 85 μs. Circuit from diode D_1 (DCH-353-800A-3600V) and resistor R_1(0.08 Ω) is placed in parallel with the thyristors. It catches up energy of the pulse, which has not been transferred to the load due to gas switch *SG* breakdown before maximum voltage or in case when there is no breakdown and transfers it back to C_1.

At voltage close to maximum the gas switch *SG*, operating in self breakdown mode, breaks down. At this time, HV capacitor bank C_2 discharges on the load through transmission line, forming HV pulse on the fragmentation chamber electrodes. Process is repeated until acquisition of required pulse number.

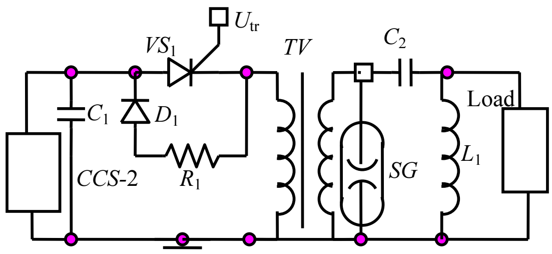

Fig. 1. Principal electrical scheme of the generator

Low voltage block incorporates HV power supply on 2 kV, primary capacitive storage C_1, thyristor switch VS_1, triggering block, demagnetization block, and automatics block.

HV power supply *CCS*-2 from General Atomics (2 kV, 8 kJ/s) provides charging of the primary capacitive storage C_1 up to (1.5÷2) kV in ~ 0.08 s.

Capacitor bank C_1 on 300 μF is assembled from 12 connected in parallel capacitors GLI-2150V-25 μF (Vishay Esta). Maximum charging voltage is +2 kV, stored energy up to 600 J.

The thyristor switch is assembled from two connected in series fast thyristors TB-353-1000A-1800V.

Automatics block incorporates power supply on 24 V, control contactors, triggering block, air conditioning system, relays and a row of safety interlocks. Triggering block forms pulse U_{tr} ~ 15 V for command to the thyristor switch and provides synchronous operation of the thyristors.

Demagnetization block converts core of the HV transformer to the initial magnetic state in pause between pulses. It supplies 100A DC current, which permanently flows through the HV transformer primary winding during operation.

Air conditioning system provides filling of the gas switch by dry air, purge during operation and air exhaust after shot burst.

The control system provides continuous remote control from personal computer (PC) of all blocks of the rock fragmentation generator and measurements of voltage and current on the treatment chamber. Control system architecture incorporates next parts: Computer + Oscilloscope – upper level control; Controller block – accepts and executes upper level commands; Interface block – input-output control device. Controller block executes commands, received from the PC computer, and sends status information about hardware of the rock fragmentation generator. Controller block interacts with operated objects and measurement sensors through the interface block. Information between controller block and interface block is transmitted through two RS-485 interfaces (fiber optic cables are used as physical link).

All elements of low voltage block, controller block and interface are mounted in metal box with dimensions $0.6 \times 0.8 \times 1.8$ m^3.

High voltage block includes high voltage pulsed transformer TV, high voltage capacitive storage C_2, capacitive voltage divider, charging inductor L_1 and gas switch *SG* (see Fig. 2). All mentioned elements are mounted in the metal tank, filled with transformer oil. HV pulsed transformer *TV* (1) is fixed on the aluminum plate. High voltage capacitive storage C_2 is installed on four support insulators (6). Charging inductor L_1 (3) is located under the high voltage capacitive storage. Charging voltage from the *TV* transformer is delivered to the electrode (4) of the high voltage capacitive storage. This electrode is connected with the HV electrode of the spark gap. Aluminum top covers close tank of the HV block. Design of the bank, all elements for voltage input and outputs of the diagnostics signals allows vacuum pumping at filling of the bank with transformer oil.

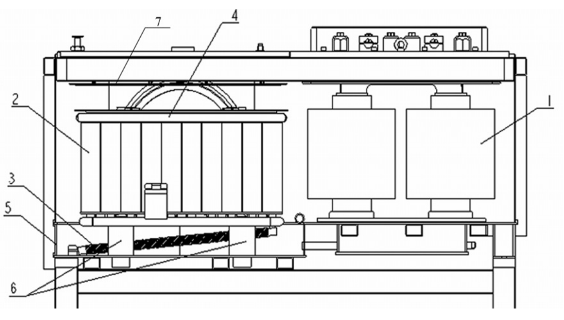

Fig. 2 HV block cross section: 1 – HV pulsed transformer; 2 – HV capacitive storage; 3 – charging inductor; 4 – electrode of the capacitive storage; 5 – tank of the HV block; 6 – support insulators; 7 – capacitive divider

High voltage capacitive storage C_2 is assembled from ceramic capacitors of type UHV-12A-1700-50 (1700 pF, 50 kV, TDK company). Capacitors are assembled in blocks with 8 caps in series and filled with epoxy compound. 48 such assemblies (i.e., 384 capacitors total) are installed between steel basement and HV electrode and fixed by two caprolon threaded rods. Total capacitance of the C_2 bank is 10.2 nF. End electrodes of the assemblies are connected with the basement and HV electrode by contact wire.

The HV pulsed transformer employs rod-type core with cut. The core is winded by strip from electrotechnical steel ET3425-0.08 mm with 110 mm width. Core cross-section is 110x92 mm^2, window dimensions 460×250 mm^2. Identical primary and secondary windings are mounted on each rod of the core. Windings are placed on fiberglass frames and connected in parallel. Primary windings – one layer with eight turns from aluminum strip 4×40 mm^2. Secondary windings of the HV transformer – multi-layered, are winded on the fiberglass frame. Total number of layers – 25. All layers except the last one are winded by the PETV-2 wire with 1 mm diameter and ~ 3.5 mm step. Last layer is winded by insulated wire (wire diameter 2 mm, insulation diameter 3 mm) turn to turn. Insulation between layers consists of layers of transformer paper with 0.1 mm thickness and mylar film also 0.1 mm. Total thickness of insulation between winding layers is ~ 2 mm. Main parameters of the transformer are the following: transformation coefficient – 170, current pulse length (half period) – 85 μs, current amplitude on the primary – 10.6 кA, current amplitude on the secondary – 60 A, maximum voltage pulse amplitude on the secondary ~ 330 kV.

Design of the gas switch is shown in Fig. 3. High voltage electrode 1 of the switch is fixed in the acrylic interface insulator 2. Insulator is clutched between flanges 3 and 4 and fixed to flange 5, which is welded to wall of the HV block tank. The switch is closed by flange 7. Breakdown in the switch occurs between electrode 9, which is made as cylinder of 6 mm diameter with flat end, and electrode 8, which is fixed in the flange 7. There is a 2 mm diameter hole in the electrode 8, which supplies air flow to the discharge zone with rate ~ 1 l/s. Air exhaust is provided through hole in the flange 7. Volume of air in the switch is ~ 6 l. Switch has been tested at 9 bar pressure and maximum allowed pressure at operation is 7 bar (absolute). Flanges 3 and 4 are made of a one metal piece each without welded joints. Gap between electrodes 8 and 9 and pressure in the switch volume are adjusted depending on the operation regime. Such electrode configuration with sharp edge on HV electrode 9 and air purge during operation enabled us to get stable operation with low jitter in breakdown voltage during shot sequence.

Charging inductor is made as solenoid, winded on the frame from fiberglass rods. Solenoid is winded by copper insulated wire with diameter of the central wire ~ 2 mm, insulation diameter – 3 mm. Inductance of the charging inductor is ~ 200 μH. Solenoid outputs are soldered to the end flanges, which are connected with electrode of the HV capacitive storage and tank of the HV block.

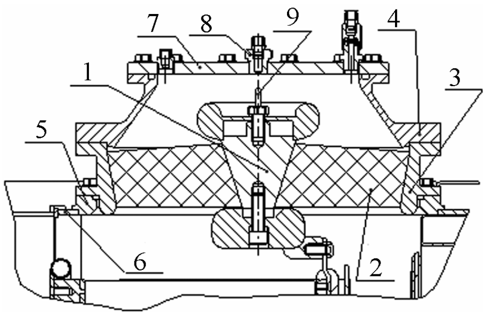

Fig. 3. Design of the gas switch: 1 – HV electrode; 2 – interface insulator; 3, 4, 5, 7 – flanges of the switch; 6 – wall of the HV block tank; 8, 9 – electrodes

Design of the transmission line is shown in Fig. 4. It is made as coaxial from stainless steel tubes. Inner conductor (1) diameter is 40 mm, outer (2) – 128 mm, line length – 2.5 m. Transmission line is fixed to the wall of the HV block tank through flange 3. Central electrode of the transmission line is fixed on the insulator (4). On the opposite end, central conductor of the transmission line is connected with current input electrode (5) of the interface insulator in the treatment chamber. Line is filled with transformer oil, wave impedance of the line is ~ 47 Ω. Transmission line oil is not connected with the HV block tank oil.

Design of the rock fragmentation chamber is shown also in Fig. 4. Treated material has to be placed in cone cavity (10) of insulator (7). Discharge occurs between electrodes (8) and (9). Vertical position of the

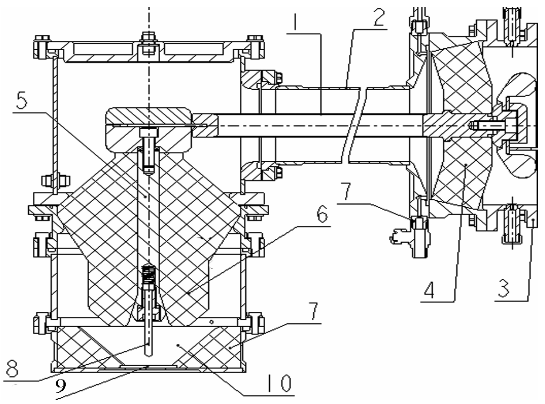

Fig. 4 Transmission line and chamber for rock fragmentation: 1, 2 – conductors of the transmission line; 3 – flange; 4 – insulator; 5 – current input electrode; 6 – interface insulator; 7 – insulator of the treatment chamber; 8, 9 – electrodes; 10 – cavity for material treatment

electrode (8) could be adjusted through the spring connection, which is placed inside current input electrode (5). All elements of the treatment chamber are made of stainless steel, except for insulator (6), which is made of polyethylene block. Treatment chamber has been tested at 3 bar pressure.

Diagnostics. Charging voltage on the HV capacitor bank is measured by capacitive voltage divider. There are following probes in the treatment chamber: capacitive voltage divider on the central electrode of the chamber; shielded inductive current probe of the treatment chamber, which is installed in the chamber body; insulated inductive current probe of the treatment chamber, which is installed in the top cover of the chamber.

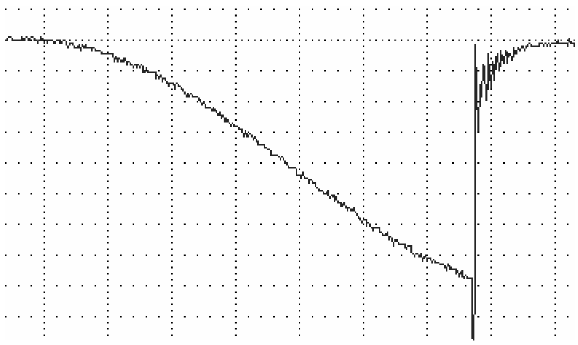

Fig. 5 Voltage waveform on the HV capacitive storage – 30 kV/div, 10 μs/div, 1.5 kV charging voltage

3. Experimental results

The generator was tested in two regimes, namely in regime with an active load equivalent and regime of rock fragmentation.

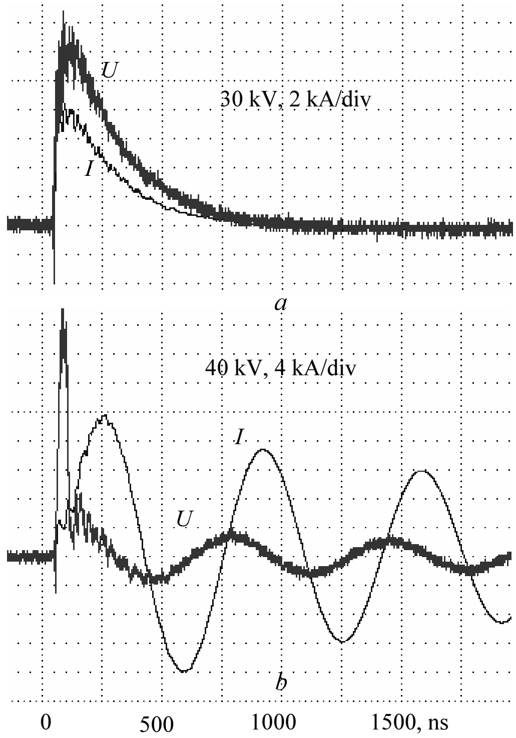

Fig. 6. – Load voltage U and current I at operation on the load equivalent (a) and in rock fragmentation regime (b) (charging voltage 1.5 kV)

Active load equivalent. Load resistance in this regime is formed by water column between HV electrode and grounded flange of the fragmentation chamber. Dimensions of the electrodes and insulator are adjusted in order to get load resistance ~ 40 Ω.

Gap between HV electrode and chamber bottom is equal to 41.5 mm. Appearance of the electrodes in the treatment chamber in the material fragmentation regime is shown in Fig. 4. In this case gap between HV electrode (8) and electrode (9) is equal to 10 mm. Tests of the generator have been performed at charging voltages 1.5 kV and 1.8 kV by 1000 shots bursts with 10 Hz frequency. At charging voltage 1.5 kV gap distance in the gas switch between electrodes 8 and 9

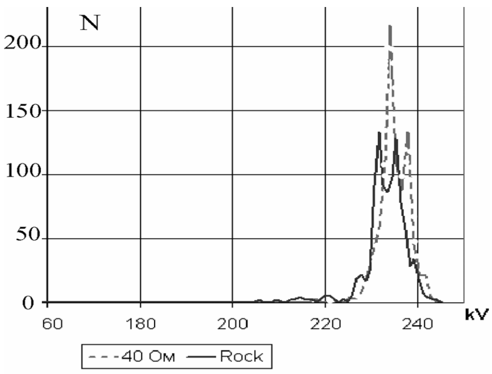

Fig. 7 Statistical distribution of the spark gap breakdown voltage

(Fig. 3) is equal to 15 mm, pressure in the switch volume is equal to 5.8 bar (absolute value). Charging voltage waveform on the HV capacitive storage is shown in Fig. 5. Traces of the load current and voltage are given in Fig. 6, *a*, *b* for operation on load equivalent and in rock fragmentation regime. Statistical distribution of breakdown voltage in series of shots for the gas switch is given in Fig. 7. Jitter around average value is about 5%, which satisfies well to technical requirements.

4. Summary

An innovative design of repetitive pulse generator has been successfully developed. Compact design, high efficiency, complete remote control over all installation, easy maintenance allow one to employ such generator both for laboratory investigations and commercial applications.

References

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