Solid State Modulator for Plasma Channel Drilling

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***Abstract*—In addition to conventional mechanical and explosive drilling and demolition, drilling based on the use of pulsed electric power has been investigated intensively and recently commercial applications begin to emerge. With this method, the demolition of the rock is either performed by sonic impulses due to pulse discharges in water or by discharges directly through the rock, called plasma channel drilling (PCD). Due to the direct impact, the PCD method is more efficient. It is based on the fact that for very fast pulse rise times (<200-500ns) the breakdown field strength of water is higher than that of rock, so that the discharge takes place in the rock.**

In the publications dealing with this topic plasma dynamics, the crack formation and the setup of the electrodes are mostly studied. There, modulators based on spark gaps either as single switch or in a Marx generator are utilised for generating the high voltage pulse. These modulators are basically able to generate high voltages and high currents at the same time. However, the PCD method requires the high voltage just for igniting the discharge. After the ignition the voltage across the arc is relatively small. Therefore, these modulators are basically oversized. Furthermore, the life time of the spark gaps and their reliability is limited.

Therefore, a solid state modulator, which generates a high voltage pulse for ignition and thereafter a high output current, is presented in this paper. This modulator consists of a single semiconductor switch, saturable inductors and a pulse transformer.

I. Introduction

In addition to conventional mechanical and explosive drilling and demolition of rocks, drilling based on the use of pulsed electric power has been investigated intensively in the last decades (starting with [1], [2]) and recently commercial applications begin to emerge [3]–[5], [7]. With this method, high voltage pulses with durations in the microsecond range are fed to electrodes, which are close to or in contact with the rock (cf. Fig. 1). There, the electrodes and the rock are usually in a liquid dielectric (often water). Due to the high pulse voltage between the electrodes a breakdown occurs, which is used for disintegration of the rock. Depending on the location of the breakdown two different effects are used for crushing/drilling of concrete/rock. With the first, a discharge in the dielectric/water outside the rock is generated. This discharge causes a sonic impulse/pressure wave, which breaks the surface of the rock/concrete [4].

The second method, called here Plasma Channel Drill (PCD), is based on the fact that for very fast pulse rise times (<200-500ns) the breakdown field strength of water increases more rapidly than the one of stone (cf. Fig. 2), so that for fast pulse edges the breakdown occurs inside the rock instead of the dielectric [1], [2]. In [6] this effect is explained by the breakdown of gas cavities inside the rock. The expanding plasma channel inside the rock causes a pressure wave in the rock, which disintegrates the material from inside. Due the direct impact, the second method is more efficient than the first one, since it is difficult to focus the sonic impulses only to the material, so that part of the pulse energy is lost.

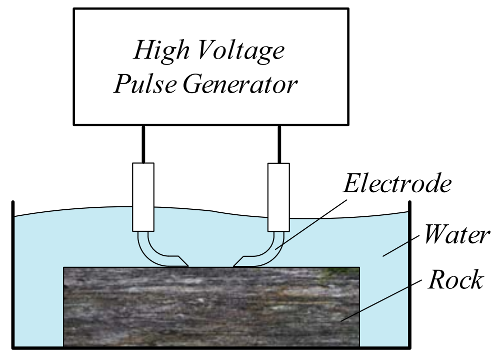

Figure 1: Basic setup for PCD-drilling consisting of a pulse modulator generating a high voltage and a high current pulse, two electrodes, a dielectric and the stone.

In [2] and other publications the discharge plasma dynamics, the crack formation and the final destruction have been studied in detail. Also different arrangements and shapes of electrodes have been proposed and experimentally tested. In [8] and in [9] for example coaxially shape electrodes are presented and in [10] rod electrodes with a L-bend are used to make a slot in a rock. The electric discharge drilling is also used in mining machines, where this method is combined with mechanical

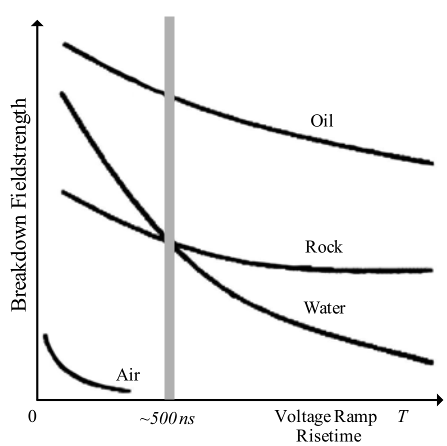

Figure 2: Breakdown voltage of water, air and rock as function of the rise time of the voltage pulse [3].

chisels [7].

So far, no investigations have been performed to optimise the power modulator for PCD and the high voltage pulse is simply generated with modulators based on spark gap switches – either as single switch or in a Marx generator in order to increase the pulse voltage. These modulators are basically able to generate high voltages and high currents at the same time. However, the PCD method requires the high voltage just for igniting the discharge. After the ignition the voltage across the load is relatively small even if the load current is high, since the resistivity of the arc is usually significantly smaller than 1Ω. This could be seen in the mentioned publications showing voltage and current waveforms for the load. Consequently, the applied pulse modulators are oversized. Furthermore, the life time of the spark gaps and the reliability is limited.

Therefore, a compact solid state modulator, which generates a high voltage pulse for ignition and thereafter a high output current, is presented in this paper. This modulator consists of a single semiconductor switch, two capacitors, two saturable inductors and a pulse transformer. The schematic and the operation principle of the proposed modulator are presented in section II. In section III follows the mechanical construction of the modulator. Finally, results for the ignition voltage at the electrodes and the current through the plasma/arc are shown in section IV.

II. Pulse Modulator

For the PCD a high pulse voltage is required for igniting the electric arc between the electrodes and then a high current must flow in order to generate a high pressure in the discharge channel for disintegrating the rock. So far, these kind of voltage and current have been generated with modulators based on spark gap switches, which basically could provide a high blocking voltage and a high current carrying capability.

Semiconductor devices offer a much lower power handling capability, i.e. either the blocking voltage is relatively low or the maximal device current is limited. Therefore, these devices either have to be connected in series or in parallel to achieve the same power handling capability as modulators based on spark gaps.

However, the PCD requires the high voltage just for a short time during the ignition of the discharge, where the current is relatively low. Thereafter, a high current must flow at a low output voltage. Consequently, the output power requirement of the modulator is much lower than the product: maximal voltage × maximal current. In Fig. 3 the schematic of the proposed solid state modulator, which is capable of generating the required high ignition voltage and the high current, is given. The proposed topology consists of an input capacitor C_1, which provides the energy for the discharge, a semiconductor switch S_1, a pulse transformer Tr_1, a decoupling capacitor C_2 and the two saturable inductors L_{HC} and L_{MPC}. Here, an IGBT is shown for S_1 but basically also a pulse thyristor could be applied, which could be used for generating higher ignition voltages and higher output currents as will be shown in section IV.

A. Operating Principle

In the following the basic operating principle of the solid state modulator for PCD is explained. At the beginning, switch

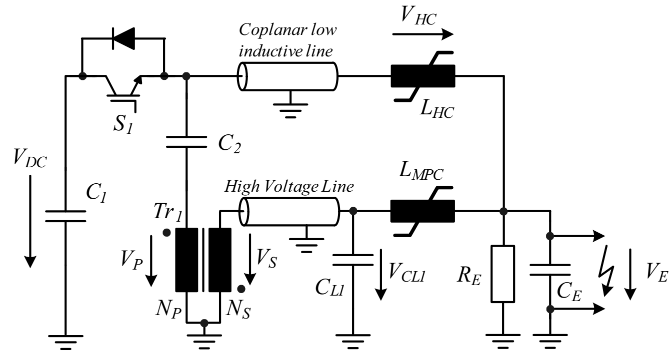

Figure 3: Schematic of the proposed pulse modulator for PCD.

S_1 is open and capacitor C_1 is charged up. Furthermore, capacitors C_2, C_{L1} and C_E are completely discharged. Capacitor C_{L1} is in the range of a few 100pF and is realised by the coaxial high voltage line. The inductance of the line is considered in combination with the leakage inductance of the transformer, which is much higher. With C_E the parasitic capacitance of the electrodes / the connection cables and with R_E the resistance of the electrodes, which is mainly determined by the water, are modelled.

To generate an output pulse, switch S_1 is closed and the input voltage V_{DC} is applied to the primary winding of transformer Tr_1, since capacitor C_2 is discharged. On the secondary side the primary voltage V_P multiplied by N_S/N_P occurs. There, the leakage inductance L_σ of the transformer forms a LC-circuit with the parasitic capacitor C_{L1} of the line, so that voltage V_{CL1} starts to resonate to maximally twice the value of $N_S/N_P \times V_P$ if any parasitic effects are neglected. During this time the saturable inductor L_{HC} is not saturated yet, i.e. the LC-circuit is approximately unloaded/undamped.

Saturable inductor L_{MPC} is used in combination with the parasitic capacitor C_E to perform a magnetic pulse compression, so that the rise time of the electrode voltage V_E is decreased. There, the value of C_E is adjusted by the connecting cables between the saturable inductors and the electrode aa well as by the shape of the electrode. With

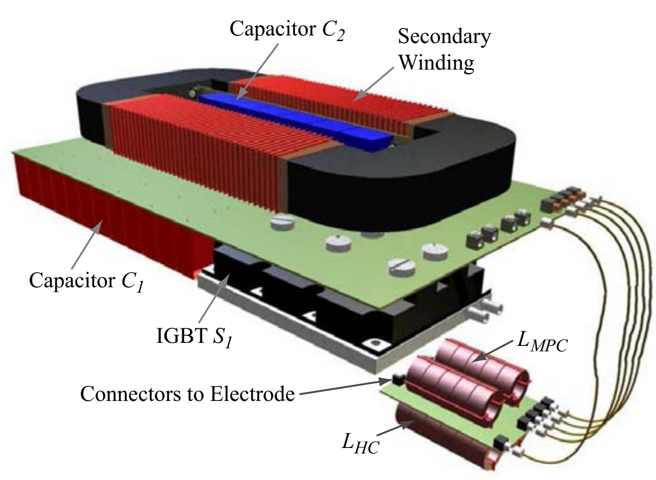

Figure 4: 3D mechanical drawing of the solid state modulator.

the resonance of L_σ and C_{L1} as well as with the magnetic pulse compression voltage V_E rises rapidly until a breakdown occurs. Ideally, L_{MPC} saturates when V_{CL1} is maximal, what results in a minimal rise time and a maximal voltage V_E.

Due to the winding direction of transformer Tr_1 voltage V_E starts to rise in the negative direction, so that the voltage V_{HC} across inductor L_{HC} is positive and its core is magnetised in positive direction. The saturation current respectively the maximal possible flux of L_{HC} must be chosen so, that L_{MPC} saturates before L_{HC}, i.e. L_{HC} must saturate shortly after the breakdown. During the rise of V_E until the breakdown, inductor L_{HC} blocks the high pulse voltage and the coplanar low inductive connection line between the switch S_1 and L_{HC} is approximately just charged up to the input voltage V_{DC}.

With the breakdown the voltage V_E rapidly decreases and a thermal plasma is created by the current flowing from the transformer and the stored energy in C_{L1} and C_E. The voltage across L_{HC} is still positive, so that the core is further magnetised in positive direction. This is very important in order to achieve a short time between the breakdown and the saturation of L_{HC} and to avoid extinguishing of the arc. Consequently, shortly after the breakdown, inductor L_{HC} saturates and connects the input capacitor C_1 via switch S_1 to the electrodes, what results in an inversion of V_E and the arc current. Due to the relatively large time constants of the charge in the plasma, the arc is not extinguishing during the rapid inversion.

The connection between S_1 and L_{HC} is made of low inductive coplanar conductors, so that the current to the electrodes can rise rapidly. In order to minimise the parasitic capacitance of the electrodes, which must be charged by the high voltage ignition pulse, inductors L_{HC} and L_{MPC} are placed as close as possible to the electrodes and the parasitic capacitance of the two saturable inductors is minimised. The arrangement of the electrodes/modulator is shown in section III, where the 3D setup of the modulator is explained.

After L_{HC} saturated the energy stored in C_1, C_2 and C_{L1} is transferred to the arc and the plasma channel is rapidly expanding due to the increasing temperatures. As soon as the energy is transferred to the output and the capacitors are discharged, switch S_1 is opened and input capacitor C_1 is charged again, so that the modulator is ready for the next pulse.

III. Test Setup

In order to validate the simulation results presented in section IV a prototype with the components given in Table I is built. A 3D mechanical construction of the hardware is shown in Fig. 4. The modulator has a size of 50cm×30cm×12cm and the saturable inductors approximately of 100mm×100mm×120mm. To minimise the capacitance which must be charged up to the high ignition voltage, the inductors are placed as close as possible to the electrodes.

Inductor L_{HC} is made of two parallel saturable inductors, which are made of 6 stacked T60006-W424 toroidal cores and two turns of litz wire. The overall dimensions of this setup is 100mm×50mm×100mm. For L_{MPC} two series connected inductors made of 5 stacked T60006-W424 cores, each with 5 turns are used, which results in a total size of 100mm×50mm×120mm for L_{MPC}. For the pulse transformer a core made of 2605SA1 made by Metglas is used, which has the dimension 41cm×27mm×9.5cm. This core is slightly oversized, but has been chosen in order to reduce losses.

Table I: Components and system parameters of proposed pulse modulator for PCD.

Switch S_1	FZ3600R17KE3_B2 IGBT 3.6kA/1.7kV, Eupec
Capacitor C_1	57μF / 1600V FKP4 (WIMA)
Capacitor C_2	2μF / 2000V FKP1 (WIMA)
Pulse Transformer	1:50 / 2605SA1 (Metglas) L_σ = 40μH
Inductor L_{HC}	2 turns on 2 parallel 6 stacked T60006-L2040-W424 (VAC)
Inductor L_{HC}	5 turns on 2 series 5 stacked T60006-L2040-W424 (VAC)
Parasitic R_E	$\geq$400Ω
Parasitic C_E	$\leq$90pF

IV. Load Voltage/Current

With the 3D construction given in section III the parasitic elements of the modulator system have been calculated and a simulation including the influence of the parasitic elements has be performed. There, the leakage inductance and parasitic winding capacitance of the pulse transformer and the interconnection as well as parasitic resistors have been included. Moreover, the parasitic inductances and resistances of switch S_1 and of the two capacitors C_1 and C_2 have been considered.

The simulated voltage and current waveforms at the load are given in Fig. 5, where it has been assumed that a breakdown occurs at 50kV. The rise time for the 50kV is approximately

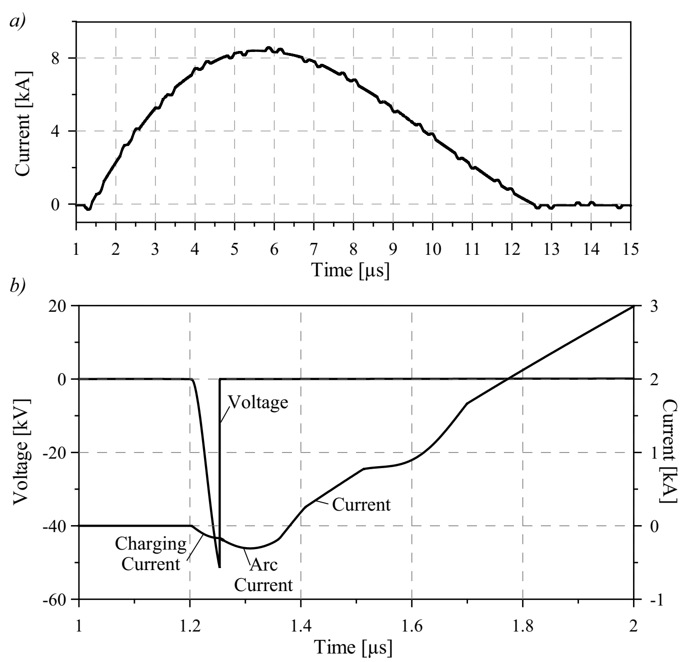

Figure 5: Output current of the modulator based on the components listed in Table I. In b) a zoomed view of the current around the breakdown is shown, where also the load voltage is included.

Table II: Loss energy distribution of the solid state modulator for a single pulse.

Switch S_1	< 0.45J
Inductor L_{MPC}	< 0.5J
Inductor L_{HC}	< 0.1J
Pulse transformer Tr_1	< 0.2J

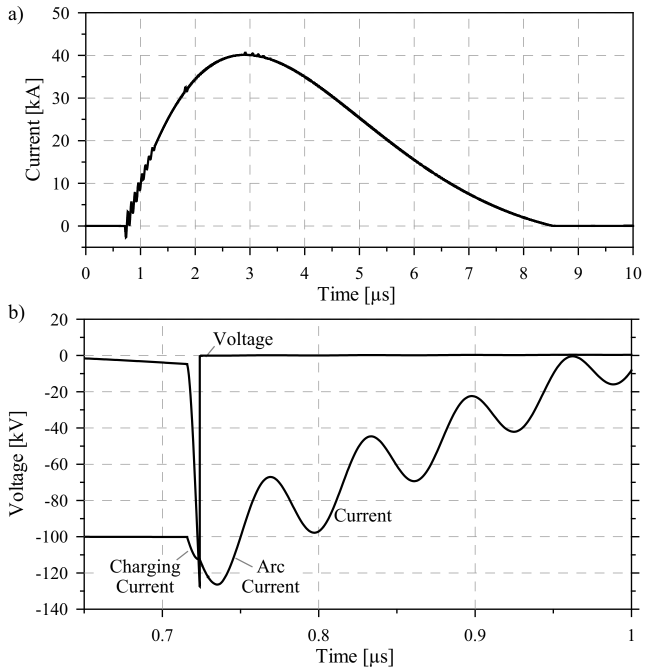

Figure 6: Output current of the modulator based on a pulse thyristor (e.g. 5SPR 26L4506 made by ABB). In b) the zoomed view of the voltage and current waveforms around the breakdown are shown.

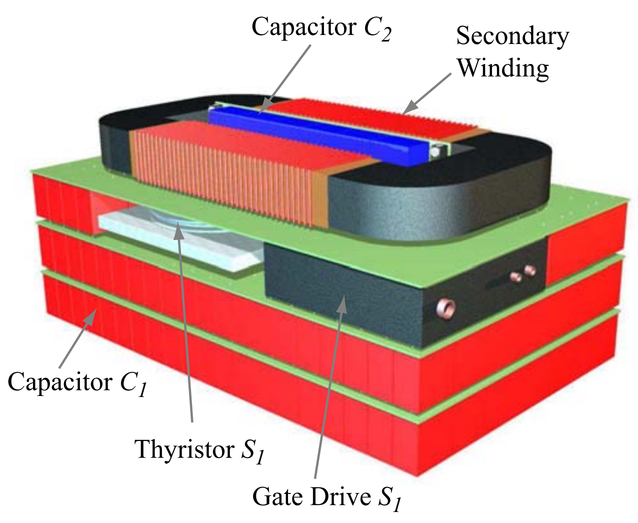

Figure 7: 3D mechanical drawing of the solid state modulator based on the pulse thyristor 5SPR 26L4506.

50ns, what can be seen in Fig. 5b), and the peak current through the arc is 8kA.

At the beginning of the voltage rise the parasitic capacitance C_E is charged first and then, after the breakdown, C_E discharges via the arc and the current flows through the plasma. In the first pulse approximately 75% of the energy stored in C_1 are transferred to the arc.

In order to generate higher output voltages for igniting the discharge, a 4.5kV pulse thyristor could be used instead of the IGBT. With this device the maximal input voltage is 2.8kV and the maximal achieveable ignition voltage with the considered pulse transformer is higher than 130kV. The peak output current is 40kA as could be seen in Fig. 6, where the simulation results for the thyristor modulator and a zoomed view around the breakdown, which is assumed to happen at 130kV, are depicted. Due to the larger charging current respectively the increased input voltage the rise time up to 130kV reduces to 20ns. A 3D mechanical drawing of the modulator based on the pulse thyristor 5SPR 26L4506 made by ABB is shown in Fig. 6. The overall dimensions are 50cm×30cm×20cm.

V. Conclusion

In this paper a solid state modulator, which generates ignition voltages up to 50kV and thereafter a peak output current of 8kA, for application in plasma channel drilling is presented. This modulator is based on a single semiconductor switch, two capacitors, two saturable inductors and a pulse transformer. Besides the operating principle and the design criteria of the pulse modulator also the mechanical construction of a prototype is explained in detail. Furthermore, simulation results for the ignition voltage at the electrodes and the current through the plasma are shown and the efficiency and the loss distribution of the system are determined. In the next step a prototype is built and the simulation/calculation results are validated in a PCD application.

In order to generate higher output voltages and currents for larger PCD units, a second modulator utilising a pulse thyristor is presented. This modulator is capable of generating ignition voltages up to 130kV and peak output currents in the range of 40kA.

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