THE IMPROVEMENT OF EDM PULSE GENERATOR PERFORMANCES BY USE OF THE NEWS SILICON-CARBIDE MOS TRANSISTORS

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ABSTRACT: In the first part of this article the authors make a short presentation of the resistive current limitations technique used in Controlled Pulses Generators for die Sinker Electrical Discharge Machining. In the second part, the inductive current limitations technique and schematic principia of EDM Pulses Generator based on Buck Converter are also presented. The results of circumstantial simulation for basic Buck Converters using different electronic power devices, presented in the third part, gives in evidence the superiority of SiC MOS Buck Converters in terms of electrical efficiency. An electrical schema for the gap emulation is conceived for use in simulation. The behaviour of SiC MOS Full Bridge EDM Pulses Generator is simulated using electrical schema presented in the fifth part, where the peak current limiting technique was used. The possibility to achieve bipolar ignition voltage, for reducing the ignition time, was indicated in presented example. A good electrical efficiency for switching frequency at high values permits to obtain EDM pulses of short duration. In the final part an electrical schema was conceived for simulation, using interleaved technique for achieve high value of positive current discharge for roughing machining. A desired profile of discharge current pulse can be easy obtained and this permits to minimise the electrode tool wear.

KEY WORDS: Synchronous Buck Converter, Full SiC-MOS H Bridge, Bipolar Pulses of Voltage Ignition, peak current control.

1. INTRODUCTION

In electrical discharge machining (EDM) pulsed arc discharges occur in the gap between electrode tool (ET) and work piece (WP). The gap is filled with an insulating medium, usually a dielectric liquid like hydrocarbon oil or de-ionized (de-mineralized) water. In die Sinker EDM process, the electrode shape is copied with an offset equal to the gap size (g = 10 - 100 μm) [3, 4].

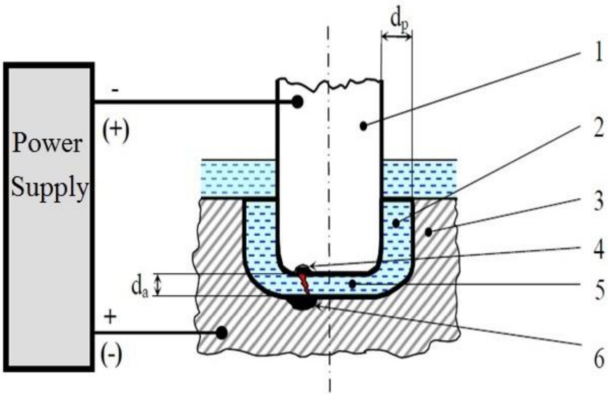

Figure 1. Die Sinker EDM Principle

In the discharge state, the gap haves a typical drop voltage in range of 20...30 V. The low values of equivalent resistance for gap required the current limiting. In figure 2 is presented the resistive current limiting principle. [4].

The amplitude of current pulse is:

$$i_d = \frac{U_0 - u_d}{R} \cong const \tag{1}$$

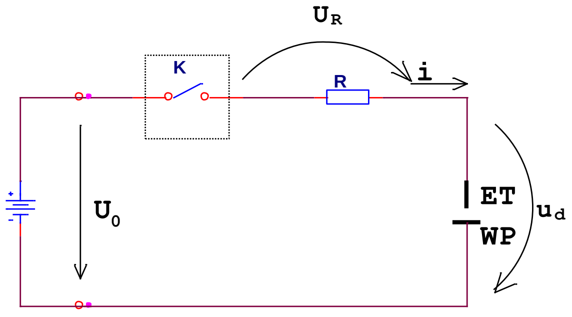

Figure 2. Resistive current limiting technique for controlled pulses generator

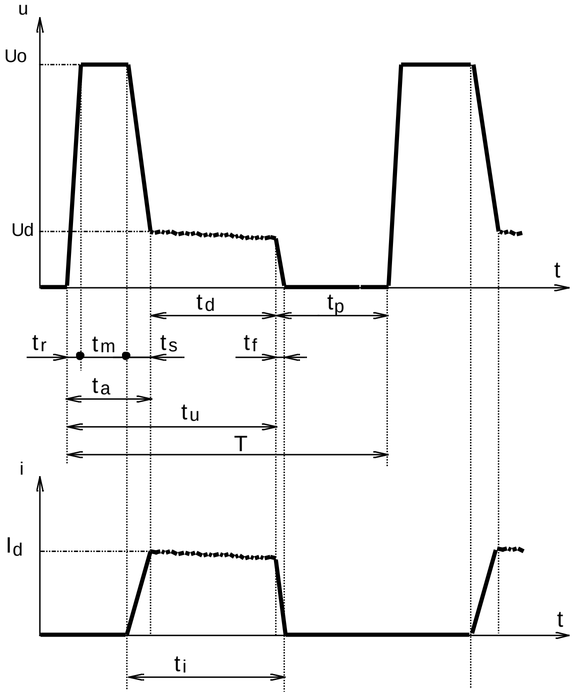

Figure 3. Resistive current limiting Pulses Generator typically chronogram for normal discharge

Figure 3 shows the chronograms of voltage pulses applied to the gap and the current in normal conditions. The controlled switch K is an electronic power device like Bipolar Junction Transistor (BJT), Insulated Gate Bipolar Transistor (IGBT) or Metal Oxide Semiconductor Field Effect Transistor (MOSFET).

Considering ideal switch (K), the power dissipated on the resistor is:

$$p_d = (U_0 - u_d) \cdot i_d \tag{2}$$

The consumed power is:

$$P_c = U_0 \cdot i_d \tag{3}$$

The utile power is:

$$p_u = u_d \cdot i_d \tag{4}$$

It results the electrical efficiency of Pulse Generator:

$$\eta = \frac{P_u}{P_c} = \frac{u_d}{U_0} \tag{5}$$

For a small difference between ignition voltage U_0 and gap voltage U_d, the efficiency can be acceptable (eq. U_d=24V; U_0=60V, the efficiency is 40%). But for high ignition voltage the efficiency is very poor (eq. U_d=24V; U_0=300V, the efficiency is 8%).

2. EDM PULSE GENERATOR BASED ON BUCK CONVERTER

For increase the electrical efficiency is necessary to replace the limiting current resistor R by a non dissipative element, a coil with inductance L, like is showed in figure 4 and adopts the chopper technique for limiting the current. The supplementary switch K_2 is necessary to assure the way for current after the switch K_1 was opened. Usually K_2 is a diode, namely freewheeling diode and K_1 is an IGBT or MOSFET. When K_2 is a transistor, the buck converter is named Synchronous Buck.

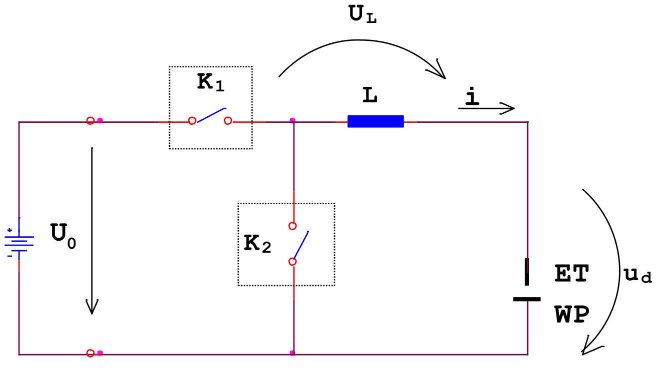

Figure 4. Buck Converter for EDM Pulse Generator with inductive current limiting technique.

Figure 5 shows the two states of Buck Converter in Continuum Conduction Mode (CCM) for current through the coil.

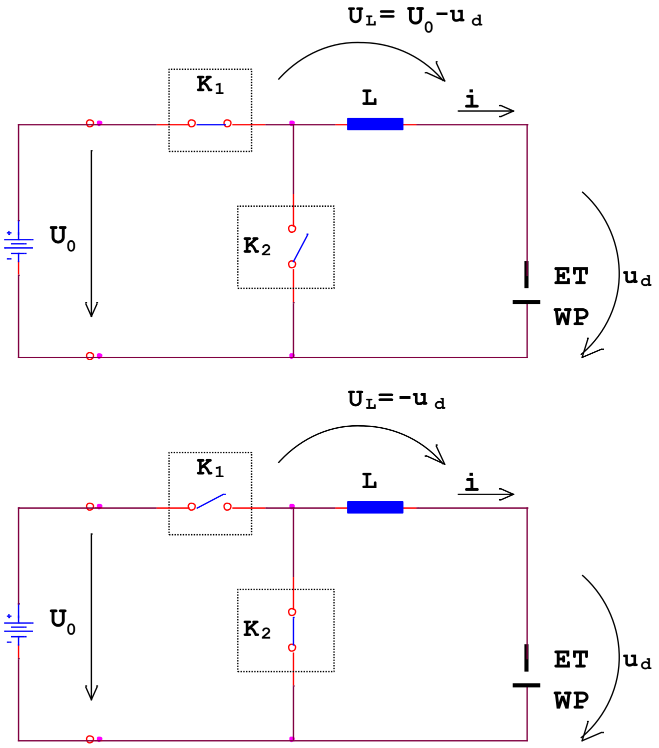

Figure 5. The states of Buck Converter in CCM mode

For the first case, K_1 is "ON", K_2 is "OFF" and, assumes ideal circuit elements, it results:

$$U_L = U_0 - u_d \tag{6}$$

$$U_L = L \cdot \frac{di_L}{dt} \tag{7}$$

$$\frac{di_L}{dt} = \frac{U_0 - u_d}{L} \cong \frac{U_0}{L} \tag{8}$$

The current increases with high slope.
In the second case, when the switch K_1 is "OFF" and K_2 is "ON", results:

$$U_L = -U_D - u_d \tag{9}$$

$$\frac{di_L}{dt} = \frac{-U_D - u_d}{L} \cong -\frac{u_d}{L} \tag{10}$$

The current decreases slowly. The chronograms are showed in figure 6.

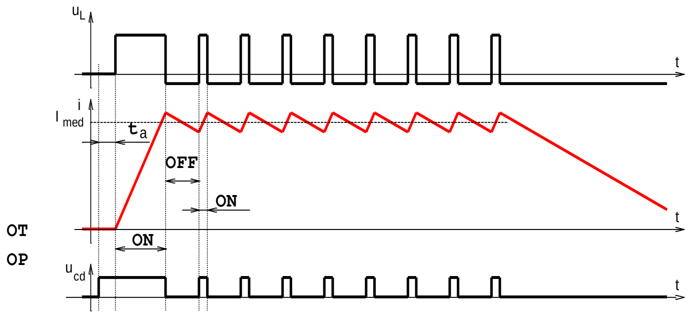

Figure 6. The states of Buck Converter in CCM mode

Because the current decreases too slowly after the EDM pulse is finished, another switch is necessary. This switch is placed in parallel with the gap and assures the rapid decreases for discharge current [5]

3. ELECTRICAL EFFICIENCY OF BUCK CONVERTERS - SIMULATION RESULTS

Apparition on the market, in the last years, of the news MOSFET based on SiC material, gives a new perspective for power electronics circuits. For comparison, polymorphic crystalline structures e.g. 4H-SiC, hexagonal crystal structure, have energy gap E_G=3.26 eV, breakdown field E_B=3x10^6 V/cm, thermal conductivity 4.9 W/cm°C and silicon, diamond crystal structure, have energy gap E_G=1.12 eV, breakdown field E_B=0.3x10^6 V/cm, thermal conductivity 1.5 W/cm°C. SiC devices can be made to have much thinner drift layer and/or higher doping concentration, i.e., they have very high breakdown voltage (600V and up) and yet with very low resistance relative to silicon devices [1, 7].

Equivalent electrical schema for MOSFET used as switch is indicated in figure 7, where R_{DS} has a very high value for OFF state and very small for ON

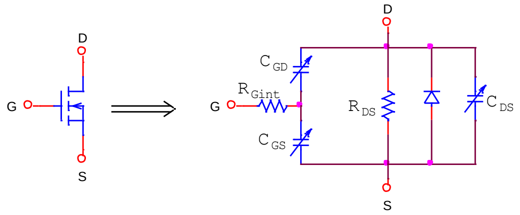

Figure 7. Electrical model for MOSFET used in switching application

In electrical schemas on figures 8 and 9, used in simulation, the silicon MOS transistor is IRFPS43N50, which have R_{DS}(ON)=78 mΩ, C_{GS}(for V_{GS}=0V)=8310 pF, C_{DS}(for V_{DS}=400V)=240 pF, nominal current 47 A and maximum voltage 500 V. The SiC MOS transistor is SCT30N120, which have R_{DS}(ON)=90 mΩ, C_{GS}(for V_{GS}=0V)=1700 pF, C_{DS}(for V_{DS}=400V)=130 pF, nominal current 45 A and maximum voltage 1200 V. The switching parameters, rise time (tr) and fall time (tf), reveal the better properties for SiC MOS SCT30N120: td(on)=19 ns, tr=20 ns, td(off)= 45 ns, tf=28 ns, in comparison with silicon MOS IRFPS43N50, which have: td(on)=25 ns, tr=140 ns, td(off)= 55 ns, tf=74 ns. The short time of tr gives much lower dissipation power for SiC MOS versus Si MOS at switching.

On the score of many simulation, based on electrical schemas presented in figures 8 and 9, for different frequency of voltage pulse sources V1 and V2, using a Pspice source program like hereinafter, we was obtained the values of electrical efficiency showed in figures 10 and 11.

```
simulare Buck SiC MOS-SiC diode la fsw=200KHz
VI IN  0 300V
V1 CD1 S1 PULSE(0V 12V 0    5N 5N    0.5U   5U)
RG1 CD1 G1   3.3
RG1B 1B G1   5
D1B  1B CD1  MBR140P
L S1 OUT 470U IC=10A
RLOAD OUT 0 2.94
X1 IN G1 S1 SCT30N120_V2
X4 0     S1 SCS220AE
.LIB SCS220AE.LIB
.LIB SCT30N120_V2.LIB
.LIB DIODE.LIB
.TRAN  1N  800U   120U   1N
.OPTIONS   ITL1=150000    ITL2=20000
+ITL4=10000    RELTOL=0.04   ABSTOL=1E-05
+VNTOL=5E-003
.PROBE
.END
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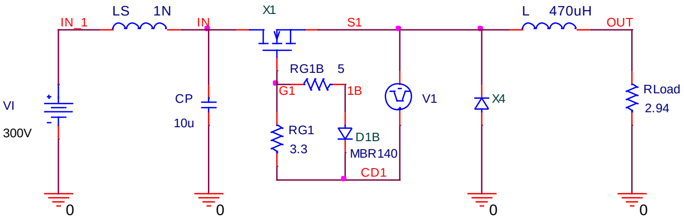

Figure 8. Electrical schema for basic Buck converter used for Pspice simulation.

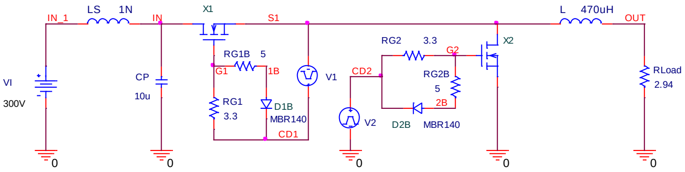

Figure 9. Electrical schema for synchronous Buck converter used for Pspice simulation

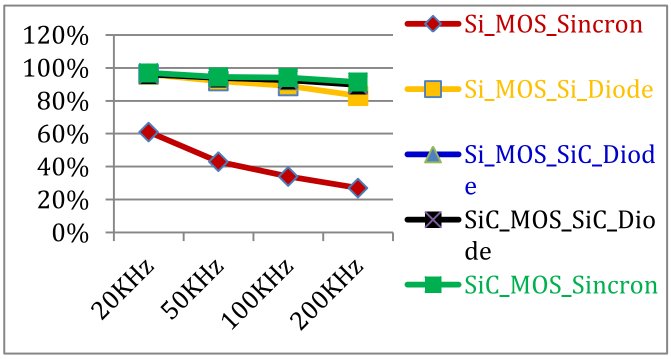

Figure 10. Electrical efficiency of Buck converters versus switching frequency for different types of power devices

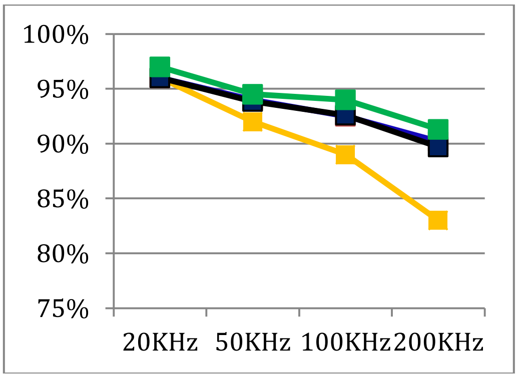

Figure 11. Close-up view for electrical efficiency of Buck converters

Electrical schema presented in figure 12 can assures the inductive limiting of current, but polarity of discharge voltage is only negative. To obtain the both polarities for ignition voltage and for discharge voltage is necessary to use full bridge schema like shown in figure 13. The inductive limiting of current implies to use a coil of desired inductance L. Every leg of bridge together with inductance can be considered a Buck converter. Attended to results presented in figures 10 and 11, the schema presented in figure 12 can use Si MOS transistor, but schema showed in figure 13 don't use Si MOS transistor because the electrical efficiency is too poor. But SiC MOS transistors, used in full bridge schema, obtain the best performances on terms of electrical efficiency and switching at high frequency.

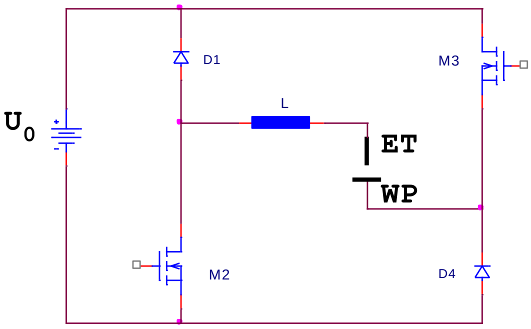

Figure 12. Si MOS transistor EDM Pulse Generator - Power section

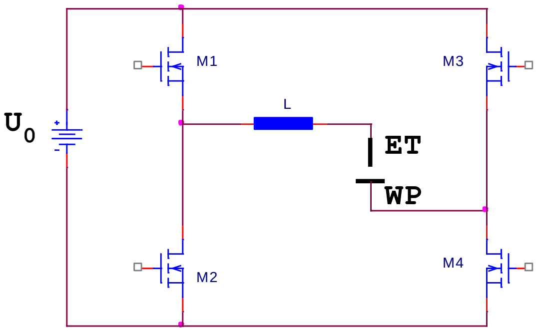

Figure 13. Full Bridge SiC MOS transistor EDM Pulse Generator - Power section

4. GAP EMULATION ON PSPICE SIMULATOR

For simulation the running of entire EDM Pulse Generator is necessary to give an electrical model for gap. The authors were conceived a model showed in figure 14, where the gap is in discharge state. This model, by adequate voltage sources for MOS gate drive, can describe the behaviour of gap in principal states: pre-ignition state for both voltage polarities and discharge state for both voltage polarities and both direction of discharge current. In pre-ignition condition the both transistors are OFF. The gap is equivalent by a capacitor with loses, R_0 in parallel with C_0 [4]. The values for R_0 and C_0 was determined for Diesel oil dielectric, gap =10 µm, and aria A =1 cm^2, at frequency of 180 KHz. The diodes D11 and D12 are necessaries for prevent MOSFET body diode conduction. The independent voltage sources V_EM2 and V_EM3 assure the discharge voltage drop on the gap, V_EM2 for positive polarity and V_EM3 for negative polarity. The current-voltage DC diagram, obtained by simulation, is presented in figure 15.

Another analyse, realised in time domain, confirm the rapid change of gap state at transient.

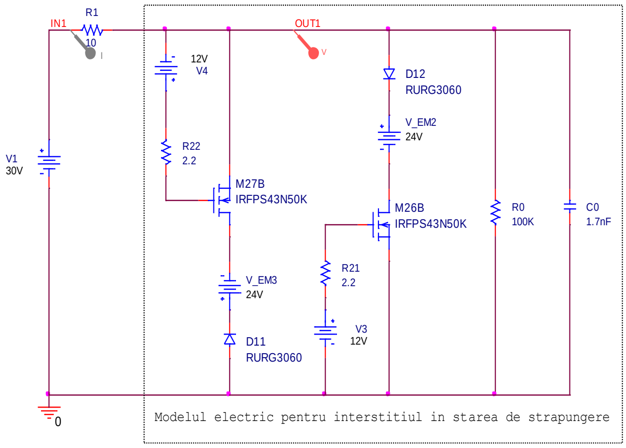

Figure 14. The gap model for discharge state

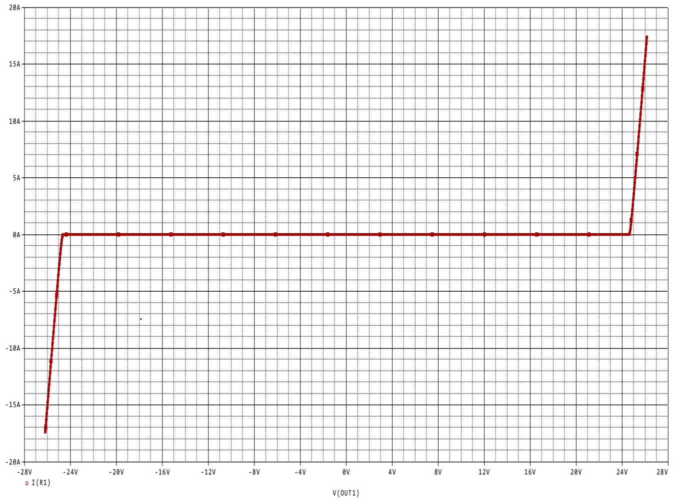

Figure 15. The current-voltage DC diagram for gap model

5. ELECTRICAL SIMULATION OF FULL BRIDGE SIC MOSFET EDM PULSE GENERATOR

The authors was conceived the electrical schematic, revealed in figure 16, for Pspice simulation. The worked piece is at the net alias named OUT and the electrode tool is grounded. The power supply DC voltage source, VA, is floating. To achieve a high speed of rising slope, indicated for short EDM pulses, the coil has a low value of inductance. For symmetry we use two coils, L1 and L4 of 10 µH. The Full Bridge SiC MOS transistors is realised with SCT30N120 transistors. The diodes D1...D4 are the freewheeling diodes. The coaxial cable between printed circuit board (PCB) and ET-WP EDM process gap, was modelled by RS1, L2, C2 and RS2, L3, C4 circuits. The gate drivers for SiC MOSFET were emulated by controlled voltage sources E1...E7. The discharge current is limited by peak current limiting technique, using Rsense current sensor, differential amplifier realised with three precision operational amplifier, OPA365, fast analog comparator TLV3501, RS flip-flop 74HC74, and PWM signal formatting circuits (trigger Schmidt inverters 74HC14, AND gates 74HC21, 74HC08 and NAND gate 74HC00.).

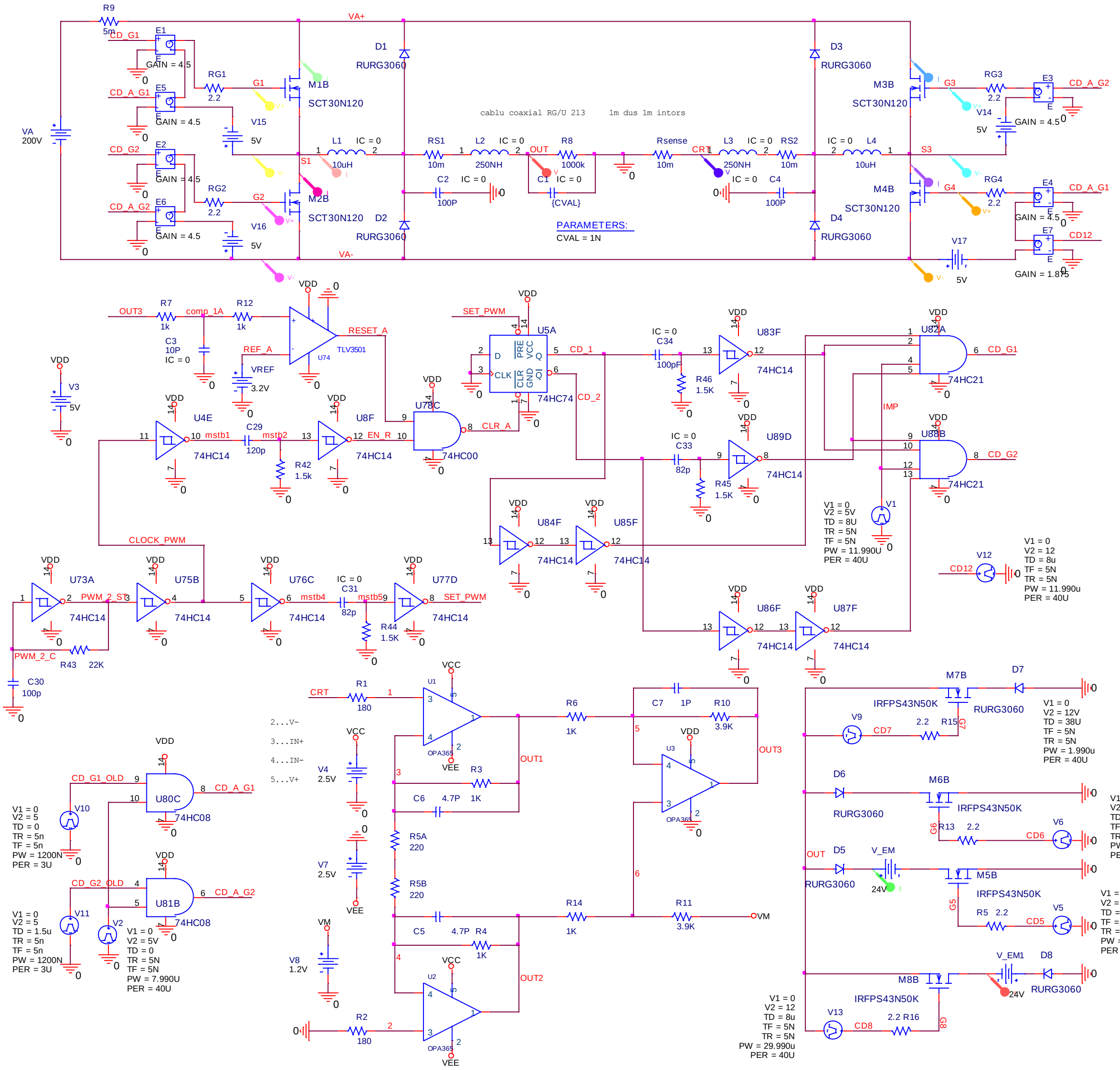

Figure 16. Full Bridge EDM Pulse Generator electrical schematics used in Pspice simulation

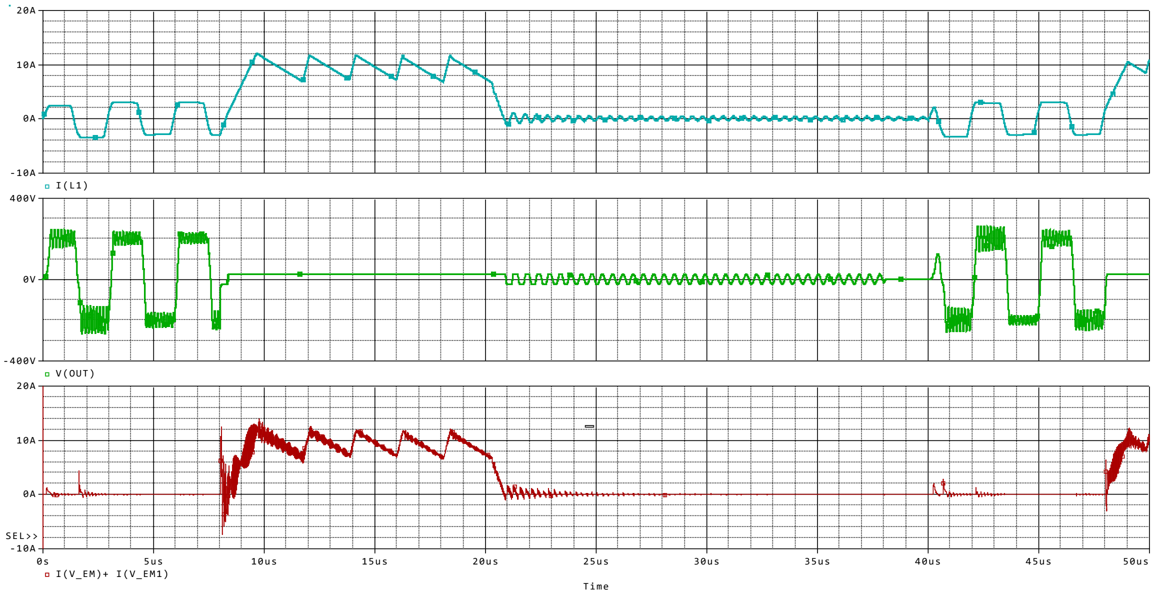

Figure 17. Voltage and Current chronograms for Full Bridge EDM Pulse Generator

Independent sources V5 and V13 make MOS transistors M5B and M8B in ON state during the discharge interval and OFF as for the rest. The sources V6 and V9 command the transistor M6B and M7B in ON state during the pause interval between two EDM pulses and assure short-circuit condition for ET-WP gap in this time interval to restore the dielectric state.

The chronograms for EDM voltage and current pulses, resulted after Pspice simulation are showed in figure 17. For actual settings of control signal sources, like figure 16, the first ignition voltage bipolar pulse appear in the time interval 0 to 7 µs. Breakdown of the ET-WP gap appear at the moment of 7 µs. The discharge current pulse runs for a time 7 µs to 21 µs. In the simulation presented in figures 16 and 17, the command of MOS transistors M6B and M7B is active only in interval 38 - 40 µs, but normally must be active between 21 µs and 40 µs. That permits to observe the behaviour of ET-WP gap without short-circuit condition. Another setting of command signal sources gives otherwise profile of EDM voltage and current pulses, the current can be positive or negative, the ignition voltage can be positive, negative or bipolar.

6. EDM PULSES GENERATOR BASED ON INTERLEAVED BUCK CONVERTERS

A small value of inductance gives a high speed of rising slope, but ripple of discharge current can be important. For roughing EDM machining, the polarity of current is positive and value can be high, at several tens of amperes or more. This implies to use of high current MOS transistors that means high values of MOSFET parasitic capacitors. At result the switching on high frequency have poor efficiency.

Interleaved technique permits to preserve the advantages of moderate current MOS transistors, like high switching frequency and permits to use coil with low value of inductance to achieve a high speed of current rising slope. The commands for K1 switch of Buck converters are shifted in time like in figure 18. As a result, the value of current increases proportional to number of interleaved Buck converters and the ripple of current decreases. The apparent switching frequency increased too [6, 7].

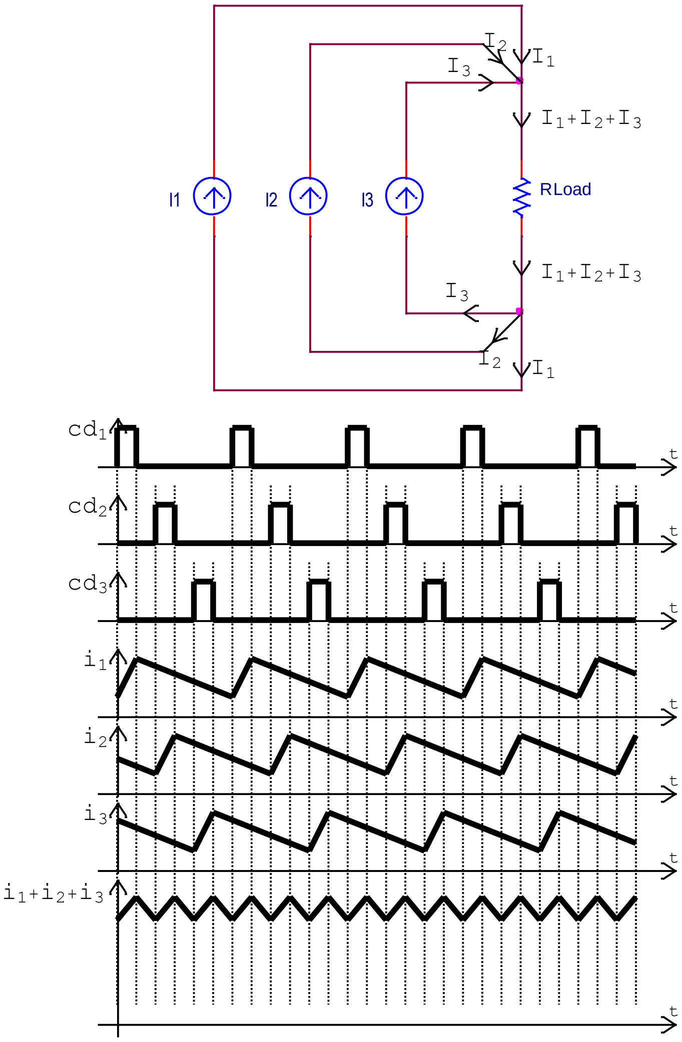

Figure 18. Interleaved Buck Converter: principle and chronograms

A power supply for EDM Pulse Generator and Z axis electrode tool displacement was conceived, like

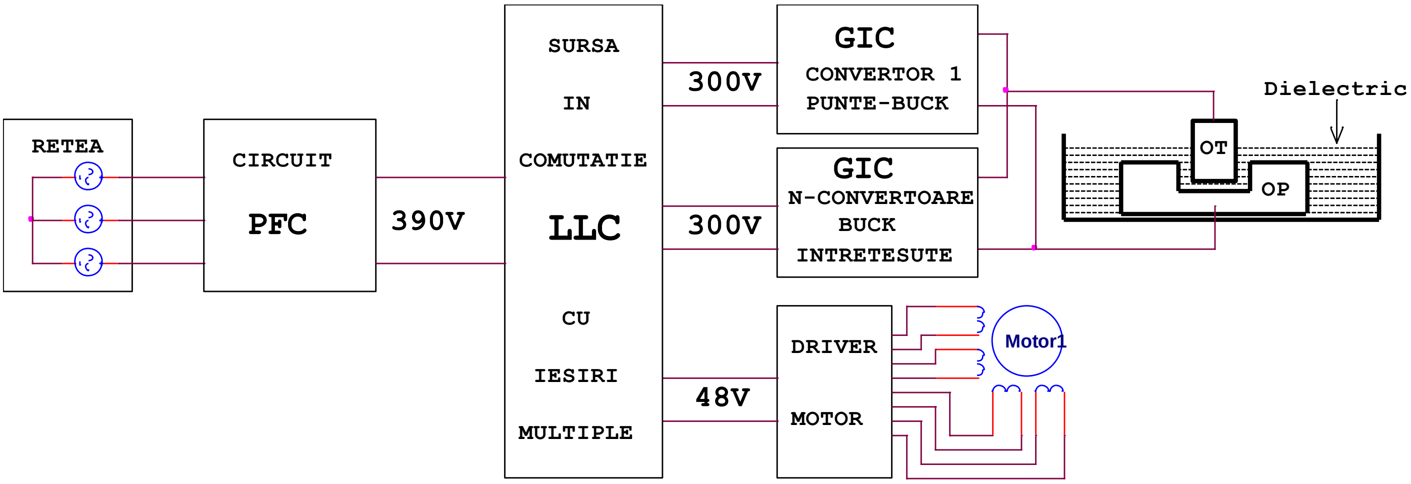

Figure 19. Bloc diagram of Power Supply for EDM Pulse Generator and Z axis electrode tool displacement

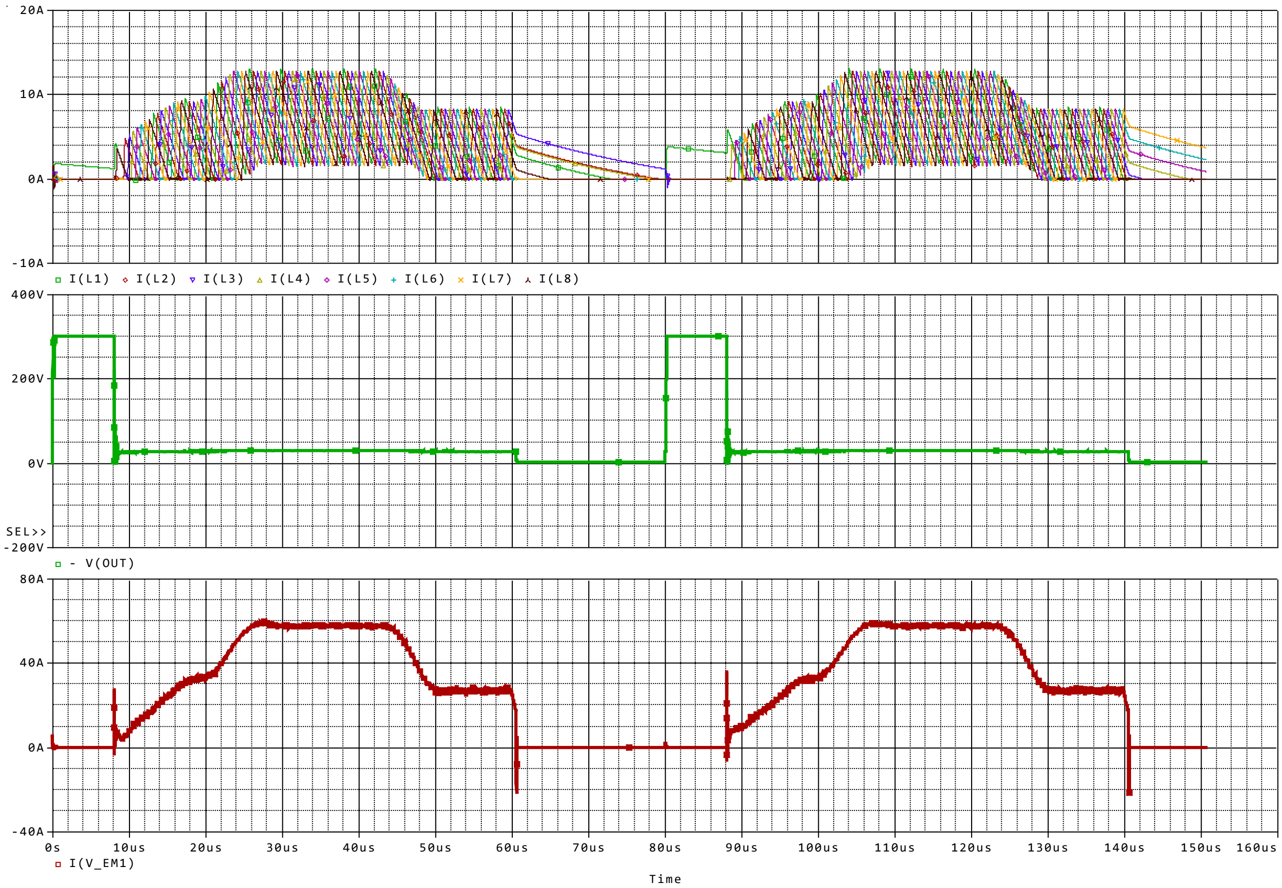

Figure 20. EDM voltage pulses, V(OUT), EDM current pulses, I(V_EM) and current through every Buck coil

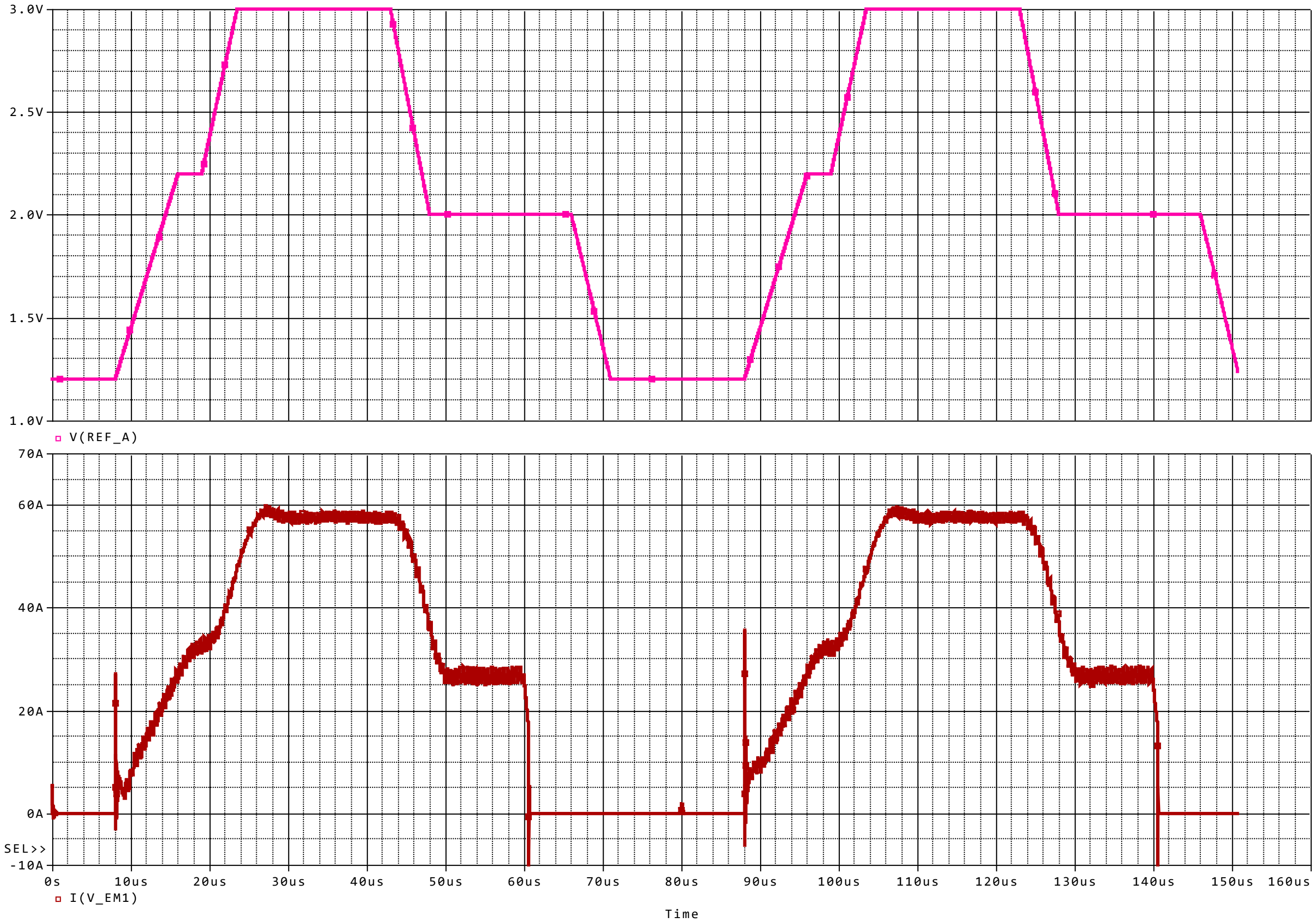

Figure 21. Dynamic performances of peak current control for interleaved Buck converters V(REF_A) represent the reference for EDM current profile and I(V_EM) represent the current obtained through the EDM ET-WP gap

is showed in figure 19. For reducing the harmonics of current absorbed from mains we use a Power Factor Correction (PFC) electronic circuit which obtain a power factor near the unit. PFC circuits have a comprehensive treatment in scientific literature, and the control can be realised with dedicated integrated circuits or with digital signal controller (DSC) [9, 10].

The voltage source which supplies EDM Pulse Generator is based on DC to DC LLC resonant converter. This type of converter has a natural behaviour of voltage source, and has a high electrical efficiency, the bridge power transistor are switched at zero voltage (ZVS) [10]. For fixed output voltage, like in figure 19, the same source can have another output for supply the stepper motor driver. For adjustable ignition voltage it must to use two voltage power supply, one for Pulse Generator and one for stepper motor driver

In the electrical schema whose simulation results are presented in figures 20 and 21, we have use one Full Bridge SiC MOS transistors Pulse Generator, and seven simple Buck converters with silicon transistor - silicon diode.

For EDM finishing process is active only SiC MOS - Full Bridge Generator to achieve short duration pulses and negative polarity.

For EDM roughening process SiC MOS - Full Bridge Generator and all the simple Buck converters are active. In the pre-ignition time interval, only Full Bridge are active and can gives alternant bipolar voltage to reduce pre-ignition time [2]. After the ignition is started, only positive polarity of voltage is accepted and at this moment the other Buck converters are activated.

The current pulse shape obtained in figures 20 and 21 gives the possibility of current control. The adjustable rising slope of current pulse permits to reduce the electrode wear [3, 4].

7. CONCLUSIONS

SiC MOS transistors have switching time smaller than silicon MOS transistors and permit to realize synchronous Buck converters working at high voltage and high switching frequency.

That permits to obtain Full Bridge EDM Pulse Generator with good electrical efficiency, which gives pulses with parameters adjustable in the large range.

Combining SiC MOSFET Full Bridge EDM Pulse Generator with Interleaved Buck Converters the authors was obtained a versatile EDM Pulse Generator with parameters adjustable in the large range and having a good dynamic behaviour.

8. REFERENCES

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