# Novel Power Supply Topology for Large Working Gap Dry EDM

A. Looser, L. Linares, C. Zwyssig, and J.W. Kolar
Power Electronic Systems Laboratory
ETH Zurich
CH-8092 Zurich, Switzerland
looser@lem.ee.ethz.ch

*Abstract* — **For material removal in rotor balancing machines, dry Electrical Discharge Machining (EDM) with large working gap is an advantageous alternative to the common mechanical drilling, grinding or laser drilling. This paper presents a novel topology of a power supply required for such an application. It has an increased ignition voltage capability of up to 10 kV compared to standard power supplies with only 300 V, which allows for an increase in working gap distance to millimeters. The control of the current pulse amplitude and length are described. Voltage and current measurements verify the design considerations prove the feasibility of the proposed power supply.**

## I. Introduction

Balancing of rotating shafts requires the addition or removal of small and exact amounts of material, ideally without applying excessive forces on the shaft itself. Therefore, some automated balancing machines employ lasers [1] or standard EDM [2] instead of the commonly used mechanical material removal such as drilling and grinding. However, initial costs of lasers are high and liquid dielectrics in standard EDM complicate the balancing setup. Alternatively, dry EDM has the same advantages as lasers, such as non-contact and precise material removal, however with much lower initial cost, and without a complex setup to handle liquid dielectrics like hydrocarbon oils or deionized water as used in standard EDM. A possible setup of a balancing machine based on material removal with dry EDM is shown in Fig. 1. The two wolfram electrodes allow for a fully non-contact operation. The point of imbalance (POI) is measured by the force sensor, and the imbalance detector triggers the material removal at the right spot via the EDM power supply while the rotor is spinning.

According to EDM theory [3],[4] material is removed by an electrical spark after dielectric breakdown in the interelectrode gap. These electrical discharges melt and vaporize parts of the workpiece material which are ejected by mechanical shock when the plasma collapses and flushed away by the circulation of the liquid dielectric.

Dry EDM is a modification of the standard wet EDM process in which the liquid dielectric is replaced by a gaseous medium [5],[6]. In dry EDM rotating tools are used through which high velocity gas is supplied into the discharge gap to remove the debris and prevent excessive heating. Commonly stated advantages of the dry EDM process are low tool wear, lower discharge gap, lower residual stresses, and smaller heat affected zone [5]. Furthermore, air as a non-toxic dielectric is abundant and no dielectric tank or dielectric waste disposal is required.

In both dry and standard EDM, a power converter, usually called EDM power supply, is required to ignite the spark between tool and workpiece and to melt or vaporize the material. It has to supply a voltage high enough to cause dielectric breakdown and a current high enough to generate heat in the workpiece to melt or vaporize it. Ideally, the power supply provides additional control options: The ignition instant can be triggered, the open circuit voltage can be set in order to control the gap between tool and workpiece and the current pulse can be varied in amplitude and length in order to control the form of material removal.

First, an overview of state of the art EDM power supplies is given. Then, the adaptation of the dry EDM process to a balancing machine is derived and the resulting changes in the requirements on the power supply are highlighted. A novel power supply topology, shown in Fig. 2, is presented fulfilling these requirements and finally, the topology is experimentally verified.

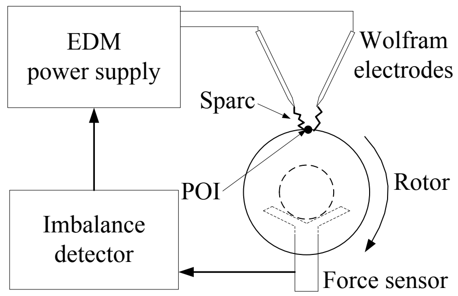


Fig. 1. Balancing machine based on material removal with dry EDM.

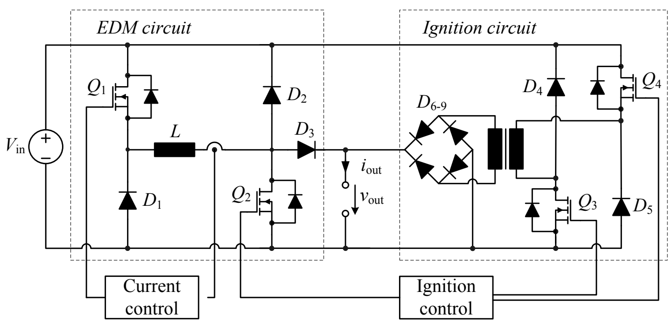


Fig. 2. Novel EDM power supply topology for dry EDM with high ignition voltage capability.

## II. State Of The Art in Power Supplies for EDM

Early power supplies for EDM were either purely passive circuits without control option or circuits including one switch in order to trigger the ignition and to control the length of the pulse [3],[7],[8]. The current pulse amplitude was defined by a series resistor.

Other power supplies employ more power electronics and control, such as a flyback converter [9] or a resonant converter [10] in order to increase efficiency, removal rate or surface quality.

Today's state of the art power supplies employ a buck converter for controlling the current pulse (amplitude and length) and an additional converter for controlling the open-circuit voltage [3],[11],[12]. A typical circuit is shown in Fig. 3. In order to ignite a spark in the working gap, the switch $Q_2$ is opened and the injected inductor current is directed to the output. As long as the spark is not ignited, the current is flowing through $D_2$ and therewith limiting the voltage across the switch $Q_2$ and the working gap to the capacitor voltage (open-circuit voltage).

All the circuits have in common that they require at least one switch that is rated for both the maximum open-circuit voltage and the EDM current amplitude.

Typical specifications of commercial power supplies, e.g. in [13], are pulse widths in the area of 1-10 µs, adjustable open circuit voltages up to 300 V, pulse repetition frequencies up to 200 kHz and maximum currents up to 60 A to 120A. Current research efforts aim for higher cutting speed, higher precision and better surface qualities, and especially towards smaller structures (micro-EDM) [14]. Therefore, the pulse length is reduced down to 0.1 µs, and the repetition frequency is increased up to 10 MHz.

## III. Adaptation of Dry EDM to Balancing

In state of the art EDM, tool electrode tracking is used to keep the working gap small and hence achieve good precision. As a result, the open circuit voltage required to ignite a spark is kept low. Common open circuit voltages range from 60 V to 250 V, which is sufficient to generate sparks in machining gaps of 25 µm to 100 µm with hydrocarbon-oil (kerosene) or deionized water as a dielectric [3].

When changing to dry EDM, e.g. when the media between electrode and workpiece is air, the voltage for the same gap distance could be reduced because the dielectric strength of air is lower than that of kerosene or deionized water (3 MV/m vs. 13-22 MV/m). However for rotor balancing, when removing material at a specific position on a fast rotating, vibrating workpiece to a depth of a few tenths of a millimetre, the gap distance has to be increased significantly, up to 1 mm.

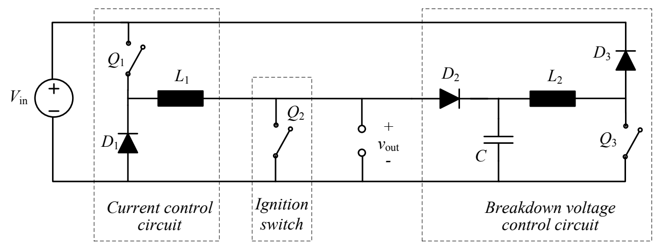


Fig. 3. State of the art EDM power supply topology [11].

Therefore, a power supply with an open circuit voltage of at least 3 kV is required.

From laser fabrication it is well known that decreasing the pulse duration and hence increasing the instantaneous power (keeping the pulse energy constant) yields better surface quality due to the smaller heat affected region resulting from evaporating the material rather than melting it. When using spark erosion for removing material in an automated balancing machine, it would be similarly beneficial that material is mainly vaporized. Moreover, the vapour can easily be evacuated and therefore pollution on the rotor and damage of the sensors are minimized.

In summary, the power supply for EDM material removal in a balancing machine requires current amplitudes and pulse control possibilities similar to state of the art EDM power supplies. However, open circuit voltages are ten to thirty times higher than for conventional EDM systems. Therefore, a novel power supply topology is required.

## IV. Novel EDM Power Supply Topology

A state-of-the-art power supply like the one depicted in Fig. 3 for high voltage capability up to 10 kV requires the ignition switch $Q_2$ to be rated for high voltage. This same switch undergoes very high current stresses when the EDM power supply operates at low output duty cycle $d_{out}$ and therefore $Q_2$ must be rated for the continuous injected inductor current of up to 55 A. For these voltage and current ratings no standard switches are available that still satisfy the specifications for short pulses of a few microseconds at a rate of up to 200 kHz.

Changing the working principle slightly and splitting the power supply into two sub-circuits by separating the high current paths from the high voltage nodes allows the use of standard fast switching components. In a first step, the working gap is ionized with a high voltage, low current pulse generated by the ignition circuit. After dielectric breakdown of the working gap the voltage required for arcing is in the range of only 100 V to 150 V and the EDM current is immediately fed from the EDM circuit to the workpiece.

The input supply voltage $V_{in}$ is set to the maximum required arcing voltage of 150 V necessary to feed the EDM current to the workpiece. Hence in the fast switching EDM circuit, low voltage MOSFETS $Q_1$ and $Q_2$ and diodes $D_1$ and $D_2$ can be employed. If necessary, the conduction losses could be further reduced by replacing diodes $D_1$ and $D_2$ with MOSFETs.

Also in the ignition circuit the low input supply voltage $V_{in}$ allows the use of low voltage components for the MOSFETs $Q_3$-$Q_4$ and the diodes $D_4$-$D_5$ on the primary side of the high voltage pulse transformer. On the secondary side, high voltage rectifier diodes are required for $D_6$-$D_9$, however with a very low current rating. The ignition voltage is determined by the turns ratio of the pulse transformer.

The high current EDM circuit and the high voltage ignition circuit are decoupled by the diode $D_3$ which is the only component exposed to both the high voltage and the high EDM current. However considering that the EDM power supply will operate with pulsed output currents of duty cycles in the range of 10% to 20%, relatively small pulse overload rated avalanche diodes can be cascaded to reach the high blocking voltage.

This new topology presents several advantages over the circuit in Fig. 3 designed with semiconductors allowing for a higher open circuit voltage. These advantages include the use of standard switches, the need for only one diode with high current and voltage rating, and the achievable high repetition rates requiring fast switching, which are not possible with the usually slow high-voltage switches. Disadvantages are the larger number of components required and the increased complexity in control.

The power supply has six distinctive states of operation: idle (all switches off), magnetization (current ramp-up in $L$), stand-by (ready for ignition), ignition (application of ignition voltage), discharge (current pulse with controlled amplitude and length) and demagnetization (current ramp-down in $L$). Fig. 4 illustrates each of these states.

### *A. Magnetization*

During magnetization switches $Q_1$ and $Q_2$ are turned on and the inductor current $i_L$ increases to the pulse amplitude current required for the discharge phase. All other switches are turned off.

### *B. Stand-by*

In the stand-by phase, the current in the inductor is controlled to the pulse amplitude current by turning on the switch $Q_1$ for the time $t_{on1} = (i_{ref} - i_L)*L/V_{in}$. During this time switch $Q_2$ is closed and the output voltage is zero.

### *C. Ignition*

To trigger the ignition a high voltage pulse is applied by closing the switches $Q_3$ and $Q_4$. Immediately after closing switches $Q_3$ and $Q_4$, switch $Q_2$ is opened. The EDM current flows through diode $D_2$ as long as the output voltage $v_{out}$ is higher than the input supply voltage $V_{in}$. After the working gap is ionized the output voltage drops and when it becomes lower than the input supply voltage $V_{in}$ the current in $L$ starts flowing through $D_3$ to the working gap.

The switches $Q_3$ and $Q_4$ remain closed for a fixed time. When the working gap is ionized, the secondary side of the transformer is shorted and the transformer current is only limited by the stray inductance.

In the case of an ignition failure the ignition voltage $V_{IGN}$ is applied again when opening the switches $Q_3$ and $Q_4$ until the magnetization current in the transformer flowing through the diodes $D_4$ and $D_5$ has decreased to zero.

### *D. Discharge*

The discharge phase is initiated by the ignition. The inductor current $i_L$ is fed to the workpiece as long as $Q_2$ remains open. The discharge phase ends by closing the switch $Q_2$ and the system enters the stand-by state.

### *E. Demagnetization*

During demagnetization, switches $Q_1$ and $Q_2$ are turned off and the inductor current $i_L$ flowing through the diodes $D_1$ and $D_2$ finally decreases to zero. After the inductor is fully demagnetized, the EDM power supply holds in the idle state.

### *F. Intermittent operation*

For higher EDM working currents intermittent operation is required in order to keep the average conduction losses of the MOSFETs and the inductor in a tolerable range by periodically forcing the power supply to the idle state.

When using the EDM power supply for automated rotor balancing, periodically pausing EDM for a few milliseconds will be necessary while waiting for the location where excess material on the rotor spinning between the electrodes has to be removed. Thus the balancing process inherently allows for intermittent operation and hence higher instantaneous EDM currents.

## V. EXPERIMENTAL RESULTS

### *A. Hardware*

Tests on a first experimental setup have shown that depending on the arrangement of the electrodes remarkably higher voltages than 3 kV are required in order to guarantee the ignition of an electrical spark. For this reason, the power supply hardware is designed for a maximal ignition voltage of 10 kV. The EDM circuit is designed to deliver a maximal EDM current of 55 A for constant EDM which is to be increased up to 200 A in the case of intermittent operation when pulsing for a window of 70 µs and then pausing for 1.2 ms. The minimum pulse width is specified to 1 µs at a repetition rate of 200 kHz.
The experimental setup of the EDM circuit is realized with paralleled 250 V MOSFETs of type IRFS4229. Twelve paralleled MOSFETs are used for $Q_1$ and sixteen MOSFETs for $Q_2$. Twelve paralleled MOSFETs are also used instead of the diode $D_1$ and another eight for the diode $D_2$ in order to reduce the conduction losses further. The diode $D_3$ is realized by a cascade of ten 1.2 kV avalanche rated silicon diodes of type DSEC60-12A. For $L$, an amorphous C-core inductor is used. The ignition circuit is realized by a transformer with a ferrite core and a turns ratio of 48. The full bridge on the

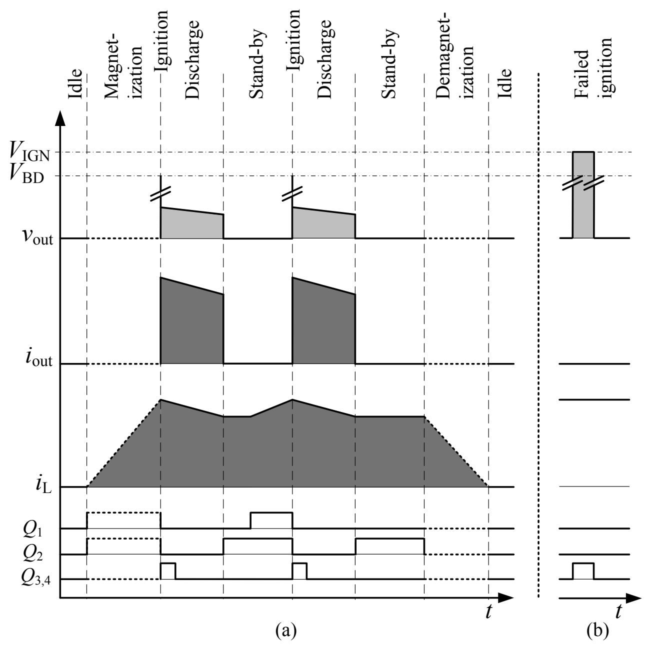


Fig. 4. States of operation of the novel power supply, gate signals for the switches $Q_1$-$Q_4$ and theoretical waveforms for the output voltage $v_{out}$, output current $i_{out}$ and inductor current $i_L$ for standard operation (a) and the case of ignition failure (b).

primary side consists of two IRFS4229 for the MOSFETs and two DPG60IM300PC for the diodes, and the high voltage rectifier on the secondary side is built from 15 kV diodes of type NTE517. All the switches are controlled by a TMS320F2808 DSP. The electrodes are made from wolfram. A photograph of the experimental setup without the inductor can be seen in Fig. 5.

### B. *Ignition Circuit*

In a first step, the ignition circuit has been tested independently. The working gap was set to 1 mm. The input voltage $V_{in}$ was then increased resulting in random sparks starting at 40 V (leading to an output voltage $V_{IGN}$ of 2 kV) and a guaranteed spark at every switching instant around 100 V (leading to an output voltage $V_{IGN}$ of 4.7 kV). In Fig. 6 the output voltage and the gate-source voltage of $Q_3$ is shown. Fig. 7 depicts one single ignition. The voltage rise is limited by the stray inductances and the parasitic capacitance of the working gap and high-voltage rectifier diodes. In contrary, at breakdown, the voltage slope is as high as 500 V/ns, which causes distortions in the entire circuit, as can be seen from the gate-source voltage.

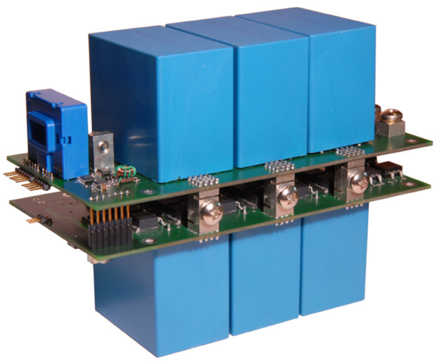

Fig. 5. Photo of the experimental setup.

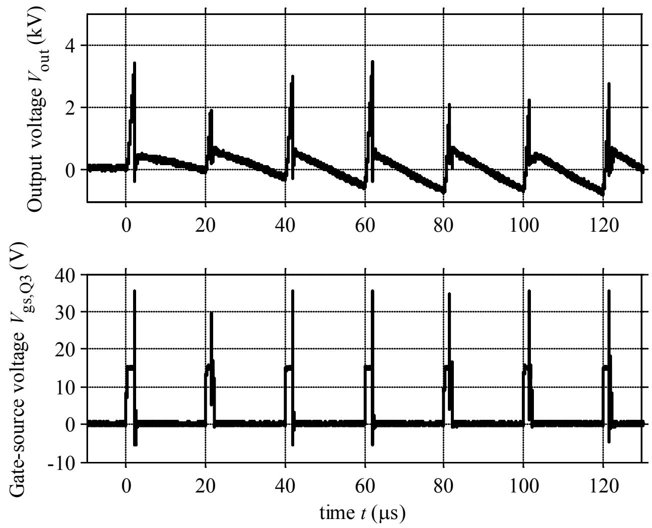


Fig. 6. Output voltage and gate-source voltage of $Q_3$ for seven consecutive successful ignitions.

### C. *EDM Circuit*

In a second step, the EDM circuit has been started up independently, with connecting the output to a load resistor of 6 Ohms. In Fig. 8 the according currents and gate signals are depicted. The current is increased with a magnetization interval to 5 A, and then switch $Q_2$ is opened and closed with a

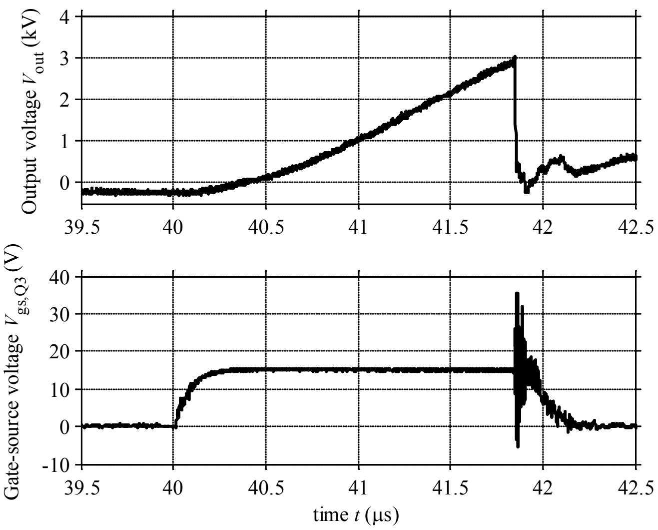


Fig. 7. Output voltage and gate-source voltage of $Q_3$ for one successful ignitions. The voltage slope is 500 V/ns at ignition of the spark.

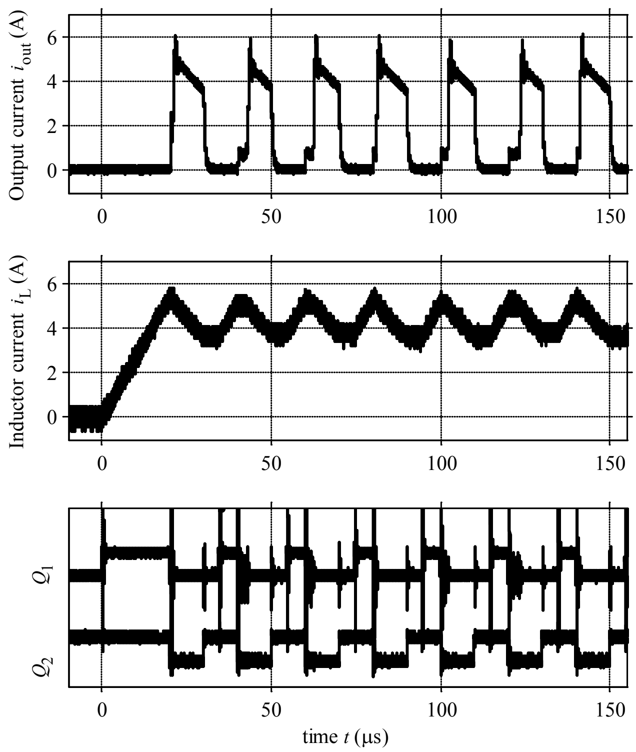


Fig. 8. Output current, inductor current and gate signals in the EDM circuit.

frequency of 50 kHz and a pulse width of 10 µs. During the on interval of $Q_2$ the current in the inductor is increased again by closing $Q_1$.

## VI. Conclusion

Dry EDM seems an advantageous material removal method for rotor balancing machines. The large air gaps in the area of millimeters result in a breakdown voltage requirement of at least 3 kV which is ten times higher compared to standard EDM. Therefore, a novel power supply topology capable of producing a 10 kV breakdown voltage is presented, while still being able to apply high discharge currents up to 200 A peak in intermittent operation and control its amplitude and pulse length.

The biggest challenge in the realization is the EMI due to extremely high voltage slopes at dielectric breakdown in the area of 500 V/ns. Initial individual measurements of the ignition and EDM circuit including current and voltage waveforms prove the feasibility of the power supply. The next steps include an increase of the output current and material removal tests.

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