DEVELOPMENT TRENDS OF PROCESS ENERGY SOURCES FOR SPECIAL APPLICATIONS OF THE SPARK EROSION

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ABSTRACT:
The process energy source is the main unit of the electrotechnical system for the spark erosion. The different fields of EDM application have made it necessary to develop different types of energy sources. In this paper, a brief review of the main types of energy sources is presented and the specific uses that are supposed to deal with. The examples are needle pulse energy sources with very short pulse duration (< 500 ns) and series-parallel resonant converters. The short needle pulse source does not produce any thermal-affected zone at the workpiece so that refinishing is not necessary. The series-parallel resonant converter can be forced in the robotics technology, which is of special interest for operations in critical rooms or environment.

KEYWORDS: Process Energy Source, Power Supply, Impulse Generator, Electrical Discharge Machining (EDM), Spark Erosion, Needle Pulse, Resonant Power Conversion

1. MOTIVATION

The development of energy sources for spark erosion has advanced, as in any other circuit, in parallel to the existing technological evolution. This evolution has been characterized by taking into account issues such as the power dissipation reduction and the achievement of specific process parameters. At present, the development of EDM energy sources is determined by the needs of specific EDM applications and there is no solution suitable for all the possible applications. Most of the circuits for the energy sources in the literature use well-known topologies adapted to this process and differences are found in the way they are controlled for EDM applications.

2. CLASSIFICATION OF ENERGY SOURCES FOR EDM

The EDM energy sources can be classified attending to different characteristics such as: the operating principle, their output impedance, the polarity, the modularity, the shape of pulses or the pulse rate [1]. Attending to the operating principle, the relaxation generators and the static impulse generators are considered [2].

The \( RC \) circuit is a relaxation generator that is characterized by its non-controlled discharges. Fig. 1 shows the typical voltage and current waveforms of a \( RC \) circuit. The dc voltage charges the capacitor through the resistor. When the capacitor is charged and the electrode and the workpiece are close enough (or the voltage between the electrode and the workpiece is high enough), a discharge takes place and the capacitor discharges through the gap. The charging time is characterized by \( \tau = RC \), in this way, by changing the value of the resistor or the value of the capacitor, the charge and discharge time, and then the frequency, can be established. The energy storage devices can be capacitors, inductors or a combination of them (type \( RC, RLC, RLCD, \) or \( LC \)). Some auxiliary switching devices can be included (controlled relaxation circuits).

The main advantage of this topology is that is a simple and low cost solution and its main disadvantage is the mutual dependence between process parameters such as the pulse energy, the discharge duration and the pulse interval. The main parameters of the energy source cannot be independently adjusted, thus, for example, a change in the pulse interval produces a change in the period.
Another disadvantage of the relaxation generator is the presence of a negative overshoot during the discharge phase, this effect can be minimized by the use of diodes, but it cannot be suppressed. This non-controlled effect causes a high electrode wear [1] and imposes a limitation on the choice of electrode materials, as they have to deal with both polarities.

At present, this type of energy source is used for applications which require low energy pulses at high frequency, such as anodic polarity micromachining [3] and finishing.

To adjust independently the parameters, static impulse generators appear. This type of generators can be designed as voltage or current sources.

The first static pulse generators were voltage sources with the objective to provide the necessary voltage to achieve the ignition. As shown in Fig. 2, this type of generator consists of a dc voltage supply, a switching device and a limiting resistor. The resistor value defines the discharge current and, under a short-circuit condition, its absence would result in a non-limited increase of the current that could damage the circuit. The current peak value is limited by the resistor according to the required metal removal rate and surface finish for the workpiece. The discharge current is a pulse whose duration is controlled by the switching device and the switching device is driven by a circuit that provides the control signal that defines the pulse duration and the pulse interval. The energy source parameters are the current peak value, the pulse duration and the break duration, which are established according to the specific machining operation. The switching device can be one transistor or several paralleled transistors, depending on the current required by the operation.

In single module solutions, the high power of the dc voltage supply is dissipated by the limiting resistors and not supplied for the machining of the workpiece. Thus, multi-level solutions appear. High and low voltage modules are used to provide an efficient transfer of energy by using voltage sources that closely match the impedance of the de-ionized and ionized gap, respectively, thus they allow to achieve the ignition voltage and the discharge voltage, respectively, and also to generate free shape pulses.

Fig. 3 shows the basic schematic of a multi-level generator [4], [5]. The dc supply V1 (100-300 V) provides the necessary voltage to ionize the dielectric, through transistor T1. If the dielectric breakdown and the resulting discharge is detected, the control unit activates the low voltage module, in which a dc supply V2 (e.g. ~80 V) provides the required voltage across the gap, through transistor T2. In this way, after the ignition delay time, the energy source generates discharges that show the typical burning
Fig. 3 Multi-level static impulse generators and main waveforms

Voltage value around 20-30 V. Diodes D1 and D2 isolate both modules. Once again, by means of the parallel connection of modules, different current values are achieved.

Anyway, current limitation by means of resistors implies low efficiency and it is the main disadvantage of this topology. For the same reason, the energy source requires a high dc voltage supply and high-power resistors which require heat dissipators or even cooling resulting in an increase of the volume of the circuit.

Therefore, pulse generators that provide constant current with higher efficiency than voltage sources are proposed. In order to achieve higher efficiency, an inductor is used as storage device; for example, in [6] it is presented a buck converter, Fig. 4, in which the current is controlled to provide the desired value. When T1 is on, current increases until T1 is off and the inductor is discharged through the gap and D1. In this case, current pulses are triangular. With this generator, it is difficult to control precisely pulses duration and to provide high frequency pulses for finishing operations. The break duration depends on the time that the current needs to drop to zero, in addition to the necessary time for the recovery (complete de-ionization) of the gap, so the break duration is long and the machining time with this energy source is also long.

To ensure that the cut-off of the current takes place with the control signal for stopping the current pulse, allowing to obtain current pulses with a steep falling edge in the frequency range from rough to finish machining, pulse generation modules are included. Fig. 5 shows the basic schematic of a current source pulse generator [7], [8] that allows to control the duration or period of each pulse precisely.

This energy source consists of a module in which a certain constant current is generated and another module that generates the pulses. For simplicity, in Fig. 5, control circuits and sensors are not shown. The first module, the current source module, is a buck converter designed to provide the desired mean current by means of its regulation through T1. The second module generates the machining pulses at the required frequency by means of the switching of transistor T2, during the pulse duration T2 is off and during the break duration T2 is on. Diode D2 connects the input and the output to protect the circuit under over-voltage conditions that may take place in open-circuit conditions when T2 is off, so the inductor current circulates through D2 and T1 when T1 is on, or through D2, V1 and D1 when T1 is off.
Fig. 5 Current source energy source and main waveforms [7]

In [7], this energy source and some modifications of it and its control are presented. Another pulse generation module and a multi-level version of the current source module are described. The multi-level version consists of two current sources with different voltages, a low current source for the ignition phase and a high current source for the discharge phase.

In addition to achieving better efficiency, modular topologies allow to supply higher power by means of parallel connection of modules and to perform pulse shaping. Parallel connection of modules provides distributed heat dissipation and the desired output power with smaller-size power components and requirements [9]. Moreover, as the output impedance of a current source module tends to infinite, their parallel connection provides the sum of each module current.

Pulse shaping is of great interest for applications such as the machining of special materials [10] and for fundamental research of discharges.

Other possible classifications of the energy sources refer to polarity and to the pulse rate. Bipolar generators are ac sources and unipolars are dc pulse generators.

Bipolar energy sources are mainly used for wire-EDM with the objective to suppress or minimize the electrolysis effect on the workpiece which produces its oxidation and corrosion. Different proposals for bipolar energy sources can be found e.g. in references [11]-[13].

Iso-energetic pulse generators provide constant energy pulses and, since roughness is proportional to the discharge energy, they produce a regular surface finish. The ignition delay time is of no importance, and the break duration between pulses may be very long with the consequent increase in the machining time.

Iso-frequent pulse generators provide constant frequency pulses achieving greater process stability. If the ignition delay time is long, the discharge energy is low and if the ignition delay time is very short the resulting pulses are of maximum energy and quite constant.

3. SPECIFIC APPLICATIONS

3.1 Needle pulse energy sources

Pulses with approximately a triangular shape and a very high current amplitude to pulse duration ratio are called needle pulses. Needle pulse energy sources for EDM provide pulses with a duration between 100 ns and some µs and with current slopes of more than 1 A/µs.

Due to the short discharge duration and the short current rise time (t_r), anodic polarity for the workpiece is chosen to reduce the electrode wear. Nevertheless, the electrode wear is high compared with long pulse durations and negative polarity of the workpiece. Therefore, needle pulses are used in the applications in which electrode wear is not a consideration. Typical applications are wire-EDM or the production of small through holes, because in these cases the electrode is renewed continuously.

The advantage of needle pulses is the minimization of the thermal affected zone of the machined surface. This is caused by the short time for heat conduction into the workpiece. The thermal energy density is very high for a short duration and most of the heated material is vaporized.

With suitable parameters the achievement of surfaces with a small “white-layer” without a separate finishing process is possible (Fig. 6).
Needle pulse energy sources are mostly voltage sources. An appropriate circuit to generate needle pulses is the well-known topology of the asymmetric half bridge, shown in Fig. 7.

**Fig. 7 Asymmetric half bridge topology**

When T1 and T2 are on, the voltage $U_L$ is connected on the gap. After the dielectric breakdown, the current increases until T1 and T2 are turned off. The stored energy in the inductance of the feed cable is discharged through the diodes D1 and D2 and the gap. A small part of the energy is dissipated in the gap and the other part flows back to the capacitor $C_L$.

The main disadvantage of this topology is the dependency of the ignition voltage on the current slopes. Therefore, in most cases a separate unit is connected in parallel to the asymmetric half bridge, which provides the gap with the necessary voltage for the dielectric breakdown. This unit can be a circuit similar to the high voltage module of the multi-level static impulse generator in Fig. 4 or another appropriate topology.

The current slopes depend on the voltage of the intermediate link $U_L$, the inductance of the feed cable, the load conditions and the ohmic losses.

If these parameters are fixed, then the maximum current depends only on the on-time of the transistors. On a first approximation, the ohmic losses are considered very small and negligible, in this way, the maximum current results

$$I_{\text{max}} = \frac{U_L - U_{\text{sum}}}{L} \cdot t_{\text{on}}$$

Conventional needle pulse energy sources work with a fixed slope and the maximum current and the discharge energy depend on the rise time as shown in Fig. 8 (a). Thus, short rise times to achieve a small thermal affected zone imply a low maximum current value, low energy and low removal rate.

**Fig. 8 Maximum current, rise time and slope correlation [14]**

New needle pulse energy sources are designed to provide different current slopes, Fig. 8 (b). In this way, high energy pulses with short discharge time can be generated for relative high removal with small thermal affected zone or high energy pulses with long discharge time for roughing applications.

**Fig. 9 Current pulses of the novel needle pulse energy source**
Low power needle pulse energy sources are used for micromachining applications and for small surfaces finishing. The machining frequencies are in the MHz range and these energy sources are designed for special applications and machines due to their high sensitivity with respect to the operating frequency and pulse energy.

Fig. 10 shows the gap current and voltage of a high-frequency energy source. Roughness values below 0.3 µm $R_a$ are achieved with a maximum current of 15 A and a pulse duration of 100 ns.

3.2 Series-parallel resonant converter

Special applications such as machining operations in areas of difficult access, under space restrictions or critical environments (underwater, radiation) require small and light energy sources for portable on-site machining.

As EDM is a non-contact cutting technique, the strength and weight requirements of the mechanical system are reduced and this facilitates remote operation. The increase of operation frequency to reduce the size of magnetic components leads to higher switching losses. High-frequency resonant converters present reduced switching losses [16].

Series-parallel $(LC_sC_p)$ resonant inverters are able to achieve the required voltage for the dielectric breakdown and, working above the resonant frequency current lags voltage so this topology achieves zero voltage switching, resulting in minimum switching losses.

The resonant inverter is designed as a current source to supply a constant current independent of the load and, therefore, the system is inherently protected against short circuit conditions. An over-voltage protection circuit limits the voltage during an open circuit fault condition.

Figure 11 shows the designed EDM energy source, a full-bridge $LC_sC_p$ resonant converter operating at a switching frequency of 200 kHz [17].

The utility voltage is rectified and filtered to generate the inverter input voltage. The full-bridge inverter produces a high frequency square wave voltage, $V_{AB}$. The switches are low-cost MOSFET transistors. The resonant circuit filters the output voltage of the inverter, $V_{AB}$, to obtain sinusoidal voltage and current waveforms at the load. The resonant circuit is designed to provide the necessary steady-state load voltage and current with minimum resonant current to reduce switching losses. The high-frequency transformer reduces the input voltage to supply the gap with the required voltage.

The output stage is a full-wave rectifier, no output filter is used to minimize cost and weight, although it could be used to reduce the ripple.

**Fig. 10 Current and voltage waveforms of the needle pulse energy source presented in [15]**

**Fig. 11 EDM energy source using a full-bridge LCsCp resonant converter**
Fig. 12 (a) voltage gain and (b) normalized output current of the LCsCp circuit as a function of frequency for different loads

Fig. 12 (a) and (b) show the modulus of the inverter voltage gain and output current as a function of the normalized switching frequency for different values of parallel quality factor that represent the different load conditions in the gap. As depicted in Fig. 12 (b) the current has no dependence on the load at the unloaded natural resonant frequency of the LCsCp circuit, therefore, this frequency is chosen as the fixed switching frequency. At this frequency, the voltage gain, shown in Fig. 2 (a), depends on the load and on the value of the parallel and series capacitor ratio. In this way, the inverter is designed to provide the necessary voltage gain first to achieve the ignition and then to maintain the discharge. Figure 13 shows the eroding pulses generated by the energy source based on the series-parallel resonant converter.

Fig. 13 Voltage (Ch1) and current (Ch2) waveforms of the LCsCp resonant converter

The spark erosion energy source has been validated to perform operations in a nuclear power plant application. A comparative analysis with other alternative technologies (traditional machining by means of an abrasive wheel and metal disintegration machining) demonstrates that the proposed EDM system achieves higher controllability and tighter tolerance in a practical cutting process [18]. Current source operation allows the increase of the output power as needed by connecting the necessary power modules in parallel as well as the reduction of the output ripple by interleaving the control of the modules [9].

4. CONCLUSION

The process energy sources are the main part of the EDM machines. Nowadays, the development of EDM energy sources is determined by the needs of specific applications. A trend for wire-EDM energy supplies is to minimize the thermal affected zone. A solution is to reduce the pulse duration and to increase the current slopes without a decrease the maximum current. Other trends are the development of energy sources for special applications such as micromachining and on-site machining. High frequency and low energy per pulse are the demands for micromachining. Machining operations in areas of difficult access require small, light and high efficiency energy sources. High-frequency resonant power converters fulfill these requirements.

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