SPARK EROSION APPARATUS

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Filed July 16, 1958, Ser. No. 748,903

Claims priority, application France July 19, 1957
7 Claims. (Cl. 219—69)

The invention relates to apparatus for the working of electrically conductive materials by means of spark erosion.

Spark erosion apparatus which operates by the discharge of a device for storing electric energy is often provided with a charging circuit supplied with a rectified alternating current. It is, in fact, necessary to have a current of constant direction available in order to be able to maintain the respective polarities of electrode and work piece so that a minimum of wear in the electrode may be ensured.

The current in use, whether single-phase or poly-phase, is generally mains current at 50 or 60 c./s. In some appliances an alternator-supplied current at a somewhat higher frequency is employed and use is made of special charging circuits designed to limit the arcs. It has become customary to measure the speed of the spark-working operations, the so-called "working speed," by the amount of matter removed per unit of time from a piece worked in this manner. And up to now it has proved impossible, with most of the known and most generally employed methods, to surpass speeds of 100 to 200 mm./minute.

The applicant has found that the working speed is limited by phenomena connected with the intensity of the charge during certain periods of time within the operational cycle of the spark generator, and dependent to a large extent on the particular lay-out of the latter.

To begin with, it is well known that erosion must be effected by the action of sparks, to the exclusion of an arc the action of which is destructive. Now arcs have a tendency to form when, at the close of a discharge from the energy-storing device, the current delivered across the spark by the source which is then momentarily short-circuited is of sufficient strength to prolong the spark.

Also, a too rapid increase of the charge intensity immediately following the extinction of the spark creates a tension at the terminals of the storage device which threatens to lead to premature sparking without useful effect, due to the residual ionization which has not as yet dissipated during the discharge interval and which at any rate tends to favour the formation of an arc.

In most of the existing spark erosion generators attempts were made to obviate these dangers by keeping the strength of the charge current below a certain value, thus preventing the formation of arcs in the spark gap and guarding against too steep a rise of tension at the terminals of the said storage device after each discharge.

To this purpose a charging resistance, possibly augmented by an inductance, is employed to act on the charging circuit. This, the oldest and most generally adopted solution, does not afford working speeds higher than the above-mentioned speeds in the region of 100 to 200 mm.² per minute in industrial application.

Similarly, a limitation of the risks of arc formation was proposed by the inclusion of one or more capacitors, to be arranged in series in the charging circuit. This solution, better than the previous one since it does not limit the charge intensity when the capacitors are discharged, affords outputs of the order of 500 mm.³ per minute.

Apparatus constructed on this latter principle nevertheless requires a very accurate regulating system which it is difficult to put into effect.

It is known that each spark lifts a few particles of the worked material by causing the formation of a crater element. The dimension of such element is the determining factor for the surface condition of the piece after working and is a function of the energy \( \frac{1}{2} CE_0^2 \) which has accumulated in a storage device having a capacity \( C \), at the instant of sparking. With a given disruptive tension \( E_0 \), i.e. an electrode-workpiece distance which must not be excessive, so as not to reduce erosion accuracy, nor too small as it would then be impossible to remove the metallic particles produced by working, it is in practice the capacity which determines erosion accuracy, the latter being the greater, and the surface condition the better, the smaller the capacity \( C \).

For a given capacity \( C \) and disruptive tension \( E_0 \), the working speed then becomes a function of the frequency of spark recurrence and is consequently the higher the greater the charging speed for such capacitance.

The present invention has for its object a spark erosion apparatus in which the charging speed of the energy-storing device is carried to the extreme limits of possibility; the conditions achieved in pursuance of this result lead moreover to the additional and incidental advantage of favouring the regularity of the sparking operation and of preventing the process of discharge between electrode and work piece from assuming the character of an arc discharge.

According to the present invention, apparatus for working electrically conductive materials by spark erosion comprises a charging circuit consisting of a source of alternating current connected to the input terminals of a rectifier network, capacitive storage means connected to the output terminals of said rectifier network, an electrode spaced from the material to be worked and defining therewith a spark gap, and a discharging circuit connecting said spark gap in parallel with said capacitive storage means characterized in that for a predetermined value \( C \) of the capacitance of said capacitive storage means, the total inductance \( L \) of said charging circuit and the pulsation \( \omega \) of said source of alternating current are chosen so as substantially to satisfy the equation

\[
\omega L = \frac{1}{\omega C}
\]

Moreover, when the capacity \( C \) is equal or larger than 2 microfarads, the total self-inductance \( L \) is as small as possible and preferably comprised between 0.1 and 2.5 millihenrys.

In this case, the self-inductance of the circuit is only the self-inductance of the alternator feeding the circuit, in which case \( L \) and \( C \) being given, the equation

\[
\omega L = \frac{1}{\omega C}
\]

is satisfied by adjusting the r.p.m. of the alternator, to obtain the adequate value of \( \omega \).

The invention is illustrated in and will be further described in connection with the accompanying drawings which show by way of example, various embodiments of the invention and in which:

Fig. 1 is a schematic diagram of one form of apparatus according to the invention.

Fig. 2 illustrates curves characteristic of the variations, as a function of time, of the current and the voltage.
in the charging circuit of Fig. 1 when the condition $L_{0} = 1/C_{0}$ is accurately fulfilled.

Fig. 3 shows, in the capacity-frequency plane, a section in the range of capacity values which lead to the best conditions for spark working when using the apparatus shown in Fig. 1.

Referring to Fig. 1, a motor M drives, by way of a speed-changing device of any preferred type B, an alternator 1 whose frequency is thus variable. A full wave bridge rectifier network 2 comprising four mercury-vapour rectifier valves 3 and 3' on the one hand, and 4 and 4' on the other hand, rectifies both recurrent alternations supplied by the source 1. The valves are connected to the energy-storing device, i.e., to the spark-working capacitor 5, by means of conductors which may comprise a self-inductance 6 and a resistance 7, and the working electrode 8 acts on the work piece 9 across the dissipative gap 10 which separates the two electrodes 9 and 8.

In the following the total self-inductance of the circuit, i.e., the sum-total of the self-inductance of alternator 1 and of that of the circuit, will be called L, and similarly R will be the total resistance of the circuit. Moreover, the capacitor 5 which constituted the energy-storing device, will be assumed to comprise the total capacitance C of the charging circuit.

Owing to the two rectifier pairs 3–3' and 4–4', the alternating source 1 charges the capacitor 5 in a known manner and in a constant direction as indicated by the fine and bold arrows. This capacitor is cyclically discharged into the circuit comprising the capacitor 5, the electrodes 8 and 9 and the gap 10 which separates the latter.

As mentioned before, experience has shown that if the value of the capacitance C of the storage device 5 has been chosen so as to obtain a definite surface condition, a primary prerequisite for achieving a considerable working output consists in providing the charging circuit with a very low reactance, i.e., lower than or equal to a few ohms, and in satisfying, therefore, at least, approximately, the equation

$$L_{0} = \frac{1}{C_{0}}$$

by influencing these different variables, and more especially the pulsation $\omega$, i.e., the source frequency, by varying the speed of the alternator.

In a circuit of this kind the current is interrupted in one half of the bridge rectifier circuit 2 with each alternation, to pass into the other half; with each alternation thereof, the current establishes itself in a transient mode in the corresponding portion of the circuit to feed the spark-working capacitor.

In these circumstances, if the tension of the source be given by $e = E \cos \omega t$, the damping factor $a = R/2L$ of the charging circuit be assumed very low in relation to $\omega$, and if the initial current and tension be accepted as negligible, the value of the charge intensity is:

$$i = \frac{E}{2} \cos \omega t \left(1 - e^{-at}\right)$$

an expression in which Z is the impedance of the circuit.

The experimental condition just now explained, of a circuit reactance being very small or zero, results in an impedance $Z$ approaching the value of resistance $R$, i.e., in an intensity of utmost strength, a factor which favours the achievement of a considerable speed, or output, in working operations.

On the other hand, an examination of the above-quoted formula which, at the inception of the transient condition (t being small) may be written

$$i = \frac{E}{2L} t \cos \omega t$$

shows that the application of the factor $t$ to the expression $\cos (\omega t)$ leads to a flattening of the sinusoidal characteristic which makes the intensity correspondingly greater the closer $t$ is to the origin; this circumstance causes a slowing down in the rise of the charge intensity following the discharge of the storage capacitor (or spark-working capacitor), and therefore a slowing down in the recharging of such capacitor which will then not tend to discharge prematurely.

Under these conditions (reactance negligible) moreover, the charging current is practically in phase with the source voltage.

Should the charging operation require more than one current pulsation—such being the case of Fig. 1—a charge acquired by the working capacitor during the first alternation—the intensity of the charge during the following alternation or alternations will decrease more and more.

Charging of the said capacitor will be interrupted as soon as the tension at its terminals attains the value of the disruptive tension $E_{d}$ (Fig. 2) at the gap which separates the work piece from the working electrode. At this moment, in fact, a spark flashes between these two electrodes and the capacitance C is discharged within a total time $t_{c}$ which is far shorter than its charging time $t_{c}$.

These results are illustrated in Fig. 2. This figure shows by a dotted line (curve I) the voltage of source 1 rectified by the valves 3–3' and 4–4'; by a solid line (curve II) the charging current for the charging circuit, similarly by a dash-dotted line (curve III) the tension at the terminals of the said capacitor. These three characteristics correspond with the particular case in which the relation $L_{0} = 1/C_{0}$ is exactly fulfilled and in which consequently voltage and current are in phase. This drawing shows clearly that during each source-current alternation the curve II which represents the charge current is non-symmetrical. It admits the axis of the abscissae as a tangent at the origin, then grows gradually to attain its maximum after a certain delay $\tau$ in relation to the maximum of the source voltage, but collapses practically together with the latter. Its leading slope therefore is flattened and prolonged as it grows whereas its trailing slope is straightened and foreshortened as it descends.

The tension acquired by the capacity C (curve III) is also tangential to the time axis at the origin, grows very slowly to begin with, then more quickly, and again more slowly so as to admit again a horizontal tangent, at least approximately, as the charging current collapses (charge $q_{0}$).

In dividing the Figure 2 it was assumed (merely for reasons of simplicity) that the tension at the terminals of capacitor 5 attains the value of the disruptive tension $E_{d}$ in somewhat less than one A.C. cycle of the source. During the second half-wave the branches described by curves II and III repeat themselves except that the respective origins now coincide with the ends of the preceding branches, and that their amplitudes are smaller. At some time near the end of this second alternation the tension at the terminals of capacitor 5 attains at point D the value of the disruptive tension $E_{d}$ and a spark is set up in the discharge circuit.

During discharge the tension $E_{d}$ at the terminals of the capacitor 5 diminishes according to a curve which corresponds with the arc DD.

Within the same time the current diminishes in the charging circuit as shown by the end of the curve II until it reaches a low value. Its curve is directed towards the end of the discharge following a characteristic such as shown by the initial portion of curve II. The next-following spark is accompanied by a similar drop in strength, etc.

It should be noticed that the mutual adjustment of L, C and $\omega$ for obtaining the minimum value of the impedance Z is in no way a tuning of the circuit providing electrical resonance thereof as a matter of fact this circuit cannot oscillate, because the current is always of
the same direction in that part of the circuit comprising the capacitor $S$. Moreover, as previously explained, after each alternation of current, said current is always a transient current.

The creation of a charging circuit according to the invention which has a self-induction of very small value has led to the exclusion of the arcing risk although such circuit, at certain instants, may be traversed by currents of considerable strength.

For instance, a charging circuit has been successfully devised in which resistance was limited to that of its indispensable elements: source, rectifier, etc.; self-induction in the said circuit was of very low value, i.e. the value of that in the said indispensable devices; the sum total of the internal self-inductances, reduced in the course of experience practically to that of the alternator $I$ employed as a source, had a value, according to experiments, of 0.3–0.8 and 1.2 millihenrys.

It was experimentally ascertained that optimum operation was attained in regard to the lowest values of $L$ when the circuit showed its lowest ohmic-resistance values.

This surprising result which is contrary to the teachings of all prior art (according to which additional self-inductive impedances are included in the charging circuit in order to obviate the danger of arcing) may be explained in the following way.

In the circuit according to the invention which has a low self-inductance, the ohmic resistance, and in particular that of the rectifiers, is by no means negligible. Therefore the damping factor

$$\alpha = \frac{R}{2L}$$

of the circuit has a relatively high value. Owing to this fact, the duration of the spark, especially when the employed working capacitors are large, is quite considerable. Now the spark gap short-circuits not only the spark-working capacitor but also the charging circuit so that the energy accumulated in the self-inductance may also discharge into the spark gap provided that the duration of the said discharge is of the same order than the duration of the spark if provided that the self-inductance as previously explained is low.

Thus, when the spark terminates, the source will have to re-commence charging the self-inductance together with the spark-working capacitor which fact stalls the growth of the charging current and most obviously reduce the danger of arcing. This is true particularly in regard to spark-working capacitors equal to, or greater than, 2 microfarads. Given the low self-inductance values employed, the inherent circuit resistance is sufficient, without additional resistances having to be used, for obtaining high values for $\alpha$, and this offers the advantage of reducing to a minimum the losses caused by the Joule effect in the circuit.

Regarding the size of the damping coefficient $\alpha$, the preceding theoretical exposition cannot be considered as absolutely exact. In particular, the cycle characteristic for the charging circuit does not coincide rigidly with the cycle of the source, and the intensity of the charging current is not rigidly in phase with the rectified voltage of the source. However, the characteristic progress of the intensity curves and particularly their delayed growth at the origin of each current pulsation, remains true. Moreover, to given values of $L$ and $C$ there corresponds, rather than a single optimum value of the source frequency, a whole range of values on both sides of such optimum value which corresponds to the minimum reactance

$$L \omega = \frac{1}{\omega C}$$

irrespective of the damping factor $\alpha$.

Finally, the numerical relations based on experience can now be indicated below; they connect in a general way, according to the invention, the capacitance $C$ in this circuit with the self-inductance $L$ and the pulsation $\omega$ of the source $I$ and express the conditions of a good operational mode for spark-working.

These relations are:

$$\frac{3.6}{2\sqrt{LC}} < \frac{\omega}{0.5\sqrt{C}}$$

C being expressed in farads and

$$0.1 < \frac{\omega}{2\sqrt{LC}} < 0.25$$

or, by introducing the frequency $f$ of the A.C. source:

$$\frac{5.5}{2\sqrt{LC}} < f < \frac{5.5}{0.5\sqrt{C}}$$

and

$$0.1 < \frac{f}{2\sqrt{LC}} < 0.25$$

These conditions in their entirety are especially applicable to circuits in which the capacitance of the energy-storing device is greater than 2 micro-farads. When this capacitance lies below that figure the condition which aims at an approximation to minimum impedance may be regarded as satisfactory and is then written

$$\frac{1}{2\sqrt{LC}} < \frac{\omega}{0.5\sqrt{C}}$$

the limitation of the self-induction value being of lesser importance in practice.

The conditions set out above and defined for the case of a simple circuit comprising a supply of rectified alternating current, or an equivalent supply, and a charging circuit having in series: self-inductance, resistance and capacitance, are sufficient in that any more complex circuit comprising several self-inductances, resistances or capacitances in series or in parallel will allow to ensure a spark-working operation with the same underlying efficiency characteristics, provided that it fulfills equivalent conditions as stated in detail below: (a) approximation, within identical limits of proximity, of the charging-current resistance in regard to $S$; (b) limitation of the self-inductance $L$ of the charging circuit to values which take into account inequalities 2 and 2.5.

The table below shows the results just set out, for capacitance values of capacitor $S$ between 5000 micro-farads (coarse erosion effect) and 0.01 micro-farads (very fine erosion effect).

<table>
<thead>
<tr>
<th>Capacitance in micro-farads</th>
<th>Self-inductance in milli-henrys</th>
<th>Range of admissible source frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,000</td>
<td>0.1 to 2.5</td>
<td>40–160</td>
</tr>
<tr>
<td>2,000</td>
<td>0.1 to 2.5</td>
<td>20–100</td>
</tr>
<tr>
<td>1,000</td>
<td>0.1 to 2.5</td>
<td>50–200</td>
</tr>
<tr>
<td>500</td>
<td>0.1 to 2.5</td>
<td>100–400</td>
</tr>
<tr>
<td>200</td>
<td>0.1 to 2.5</td>
<td>150–600</td>
</tr>
<tr>
<td>100</td>
<td>0.1 to 2.5</td>
<td>750–1,080</td>
</tr>
<tr>
<td>50</td>
<td>0.1 to 2.5</td>
<td>350–540</td>
</tr>
<tr>
<td>30</td>
<td>0.1 to 2.5</td>
<td>250–360</td>
</tr>
<tr>
<td>20</td>
<td>0.1 to 2.5</td>
<td>160–250</td>
</tr>
<tr>
<td>15</td>
<td>0.1 to 2.5</td>
<td>100–190</td>
</tr>
<tr>
<td>10</td>
<td>0.1 to 2.5</td>
<td>70–120</td>
</tr>
<tr>
<td>5</td>
<td>0.1 to 2.5</td>
<td>30–55</td>
</tr>
<tr>
<td>2</td>
<td>0.1 to 2.5</td>
<td>20–35</td>
</tr>
</tbody>
</table>

The results of this table are condensed in Fig. 3.
For the values of C entered in the co-ordinate system, those frequencies which give the best results are comprised in the shaded zone between the two curves a and b; this zone which occupies only a small part of the plane CΩ, confines narrowly the frequencies which give an interesting result, from among all the possible frequencies.

It has already been mentioned that charging the energy-storing device may terminate during the first half-wave of the charging current which follows a discharge, or during one of the subsequent half-waves. All things being equal otherwise, the growth of the charging current is the more rapid, during the first half-wave, the longer such half-wave lasts and it is preferable, in order to re-charge the said storage device rapidly, to employ a source at a frequency as low as possible yet corresponding to the spark-working capacitance in accordance with the indicated formulae. In practice, therefore, storage devices of successively decreasing capacity will be put into operation and this procedure, according to the invention, will lead to the employment of current sources at increasing frequency. As a matter of fact, the given equation

\[ L_{\Omega} = \frac{1}{C\Omega} \]

may be written

\[ L_{\Omega}^2 = \frac{1}{C} \]

L being constant, if the value of C decreases the pulsation ω should be increased for continuously satisfying the equation condition.

These variations, on the one hand of spark-working capacitances which go on diminishing and, on the other hand, of source frequencies which go on increasing, constitute an essential feature of the present invention which provides means for causing the said variations. These means consist for example of an alternator capable of being driven at different speeds which may vary in a continuous manner or by successive steps of different value, either by means of several alternators of different speed or by means of frequency changers directly supplied with mains current, etc.

Thus, for example, when proceeding with the spark erosion of a work-piece at a tension of approximately 200 v. with capacitors of 21.5 and 8 micro-farads in succession, frequencies of 975 and 1490 c./s., were employed respectively, the output obtained being 950 mm.3/minute in the first case and 640 mm.3/minute in the second case. The capacity of the energy-storing device 5 whose value is determined, as explained before, by the particular characteristics of the spark erosion to be carried out may assume successive values to which different source frequency values will correspond. The said capacitance may comprise several separate capacitors capable of being connected in series, in parallel, or in series-parallel by means of known switching devices whose operation may be linked to that of the devices for altering the speed of the alternator used as source.

I claim:

1. Spark erosion apparatus for working a conductive material, comprising a source of alternating current, a full-wave rectifier network the input of which is connected to said source, capacitive storage means having a given definite capacity C in farads and two terminals connected to the output of said rectifier network, an electrode connected to one of said terminals spaced from the said material to be worked and defining therewith a spark-gap, and a connection between the other of said terminals and said material; the pulsation ω of said alternating current source and the total inductance (L) in henries of the circuit constituted by said source, said rectifier network, said capacitive storage means and the connections therebetween being such as to substantially satisfy the equation

\[ \omega L = \frac{1}{\omega C} \]

2. Spark erosion apparatus according to claim 1 wherein the value of said total inductance (L) is greater than 0.1 milli-henry and smaller than 2.5 milli-henries.

3. Spark erosion apparatus for working a conductive material, comprising a single-phase alternator having an inner self-inductance (L) in henries, a full-wave rectifier network the input of which is connected to the output of said alternator through conducting members having negligible impedances, capacitive storage means having a capacity C in farads and two terminals connected to the output of said rectifier network through conducting members having negligible impedances, an electrode connected to one of said terminals and spaced from the material to be worked to define therewith a spark-gap, a connection between the other of said terminals and said material, and means for operating said alternator at a speed corresponding to a pulsation (ω) of the single-phase current so as to substantially satisfy the equation

\[ \omega L = \frac{1}{\omega C} \]

4. Spark erosion apparatus according to claim 3 wherein the said inner self-inductance (L) of the alternator is greater than 0.1 milli-henry and smaller than 2.5 milli-henries.

5. Spark erosion apparatus according to claim 3 wherein in the means for operating the alternator comprises a motor and a speed-changing device for adjusting the value of the pulsation (ω) to the value of the capacity C of the capacitive storage means whereby to satisfy the equation

\[ \omega L = \frac{1}{\omega C} \]

6. Spark erosion apparatus according to claim 1 wherein the value of ω is comprised between

\[ \frac{1}{2\sqrt{LC}} \]

and

\[ \frac{1}{0.5\sqrt{LC}} \]

so as to satisfy approximately the equation condition

\[ \omega L = \frac{1}{\omega C} \]

7. Spark erosion apparatus according to claim 1 wherein the terminals of said capacitive storage means are limited to said two terminals and the connection of said capacitive storage means is limited to a parallel connection in relation both to said rectifier network and to said spark-gap.

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