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CLASS 1

ARC EXTINCTION PHENOMENA IN VACUUM
I. Modes of Arc Extinction

by

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SUMMARY Experiments have been performed to study the manner in which an arc between copper electrodes in vacuum extinguishes. In an a-c circuit where current is limited to less than 1000 amp peak resistively, the extinctions are often prolonged over a period of many microseconds by successive re-ignitions of the arc caused by circuit recovery voltage. These re-ignitions tend to be suppressed by capacitance paralleling the discharge, thus raising the current at which the arc is extinguished. In a similar circuit, where the current is limited by inductance, the extinction most often occurs at a minimum in high-frequency oscillations of discharge current superimposed upon the 60-cycle arc current near the end of the half-cycle period. These oscillations occur at a frequency determined by the capacitance in parallel with the gap and the inductance of the wires used to connect the capacitors to the gap. For the inductive circuit with low values of capacitance, the oscillations are not apparent and extinction times of 10^{-7} to 10^{-8} seconds are observed.

KEY WORDS

vacuum arcs, current chopping

INFORMATION PREPARED FOR ____________________

ARC EXTINCTION PHENOMENA IN VACUUM
I. Modes of Arc Extinction

G.A. Farrall

INTRODUCTION

When a low-current d-c arc is struck in vacuum it will burn for a finite length of time, then abruptly extinguish. (See, for example, Ref. 1.) If a vacuum arc is drawn in an a-c system where the peak current can be thousands of amperes, the discharge will generally be stable until the sinusoidal current approaches zero at the end of the half-cycle period. At that time, when the current is low, the arc becomes unstable and very suddenly extinguishes, or "chops." This instability is characteristic of all so-called cathode arcs.

At the moment of extinction, the time required for the cessation of cathode emission is said to be 10^{-7} to 10^{-8} seconds for mercury.[2-5] The work by Smith[2] and Mantrov[3] is based upon a determination of the length of time that the arc current must be suppressed in order that the source of emission, that is, the arc cathode spots, cease to function. The technique was first employed by Mierdel[5] in 1936. The experiments of Kesaev[4] consisted of measuring the duration of anode voltage pulses during transient re-ignition of the discharge. These pulses reflected periods of "below-normal" emission. Another approach was used by Masnari[6] who measured the length of time required for emission to drop to zero as the arc extinguished spontaneously. His results suggest that for a triggered vacuum gap arrangement with copper electrodes, the decay of current can occur over an interval considerably longer than this. The present report is a study of the arc current decay times for arcs drawn between copper electrodes in vacuum. Extinction is spontaneous. Unlike the Masnari study, the a-c arcs of the present work are stable up to a point in time close to the end of the half-cycle of current.

EXPERIMENT

The copper electrodes used were 2 inches in diameter and separated by a gap of 1/4 inch when fully apart. The device in which the arcs were drawn has been fully described elsewhere.[7] Ambient pressure within the tube was typically in the 10^{-7} torr range after each arc.

Initial experiments were conducted using a d-c 125 volt source limited resistively to 10 amp. The self-capacitance of the tube was 54 pF. Arcs were drawn using a spring-driven, solenoid-release mechanism which provided full contact separation in less than 4 msec. The extinctions were studied by triggering a Tektronix 581 oscilloscope with the transient voltage developed in the circuit as a result of the extinction. The signal from a coaxial current shunt was delayed (by cable) 1/2 μsec. The shunt-delay cable system had a rise time of about 20 nsec. The decays of current were found in this system to range in time from 0.2 μsec to greater than 0.8 μsec in a collection of 50 trials. Typical of these trials are the three shown in Fig. 1. In the first case the decay time exceeds the line delay time so that only a part of the extinction is shown. In the second case the decay occurs in two distinct steps, and in the last case the decay is fairly continuous. It thus appears that under some conditions, the extinction times can be relatively long and the decays discontinuous.

The oscillogram shown in Fig. 2 was obtained for the same arcing conditions as before but using a lumped 3 μsec delay line having a rise time of 0.1 μsec. In this case the oscilloscope was triggered many times during the lifetime of the arc from transient voltage pulses which normally appear across the discharge. The variations in current for several successive sweeps of the oscilloscope appear as background on this oscillogram. A point of interest in this oscillogram is the repetitive minimum in current magnitude which occurs 3 μsec after the beginning of the sweep. Because of the 3 μsec delay line this reduction in current occurs, in real time, at the same instant the oscilloscope is triggered. Thus the transient voltage peak corresponds to a minimum of current. This concurs with the view[1,4] that the voltage transient is the means by which a faltering arc is restored to continued burning. On the last sweep of the oscilloscope the rate of rise of the

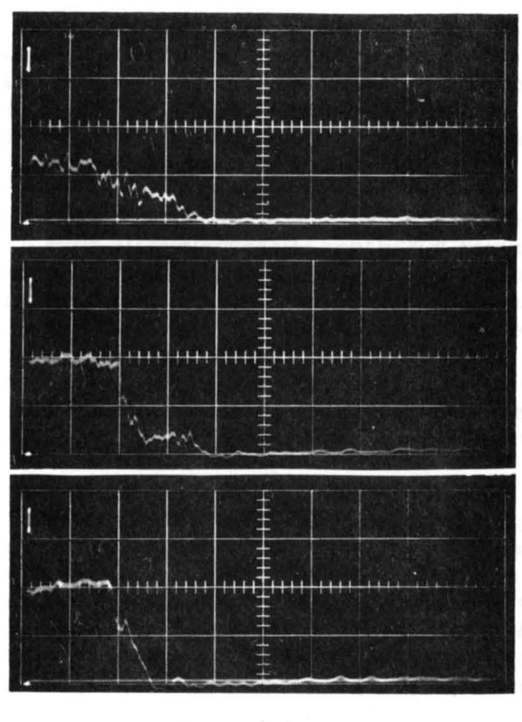

Fig. 1 Arc current. 3.3 amp/cm, 0.2 μsec/cm.

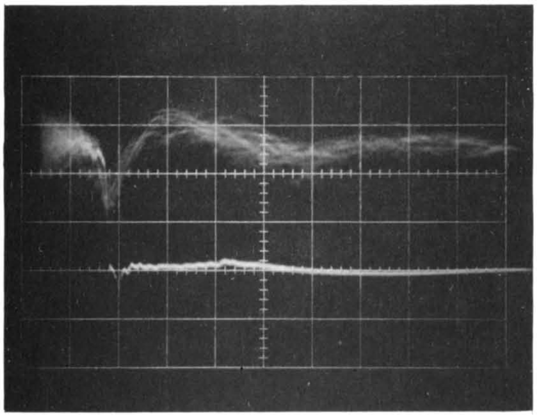

Fig. 2 Arc current. 3.3 amp/cm, 2 μsec/cm.

restoring voltage was apparently not sufficient to maintain the arc so that the extinction process initiated by the momentary dip in current was complete. It seems clear, however, that the extinction of the arc could have occurred at any one of the momentary reductions in current which coincide at 3 μsec on Fig. 2. This is a good illustration of the temporal randomness associated with the extinction of cold cathode arcs.

The remaining experiments to be described were performed on a-c half-cycles of arc current supplied from a 350 volt (peak) transformer bank. Two types of circuits were considered. In the first case current was limited by a series grid resistor which was located physically close to the transformers. The power leads to the arc tube were 14 feet in length and bound together to reduce line inductance. The line-to-line capacitance of the cables was 832 pF. In the second case the current was limited by an inductance located close to the arc tube. Thus the significant capacitances were those of the tube and the inductor.

In both cases capacitors of various sizes were connected in parallel with the gap using lead wires having an inductance of approximately 3 μH. Current through the vacuum gap was monitored by a coaxial shunt. Currents passing through the added capacitors were not monitored by the shunt. Arcs were initiated by separating closed contacts 1 msec from the beginning of a positive a-c half-cycle. Current and discharge voltage were displayed on a Tektronix 555 dual beam oscilloscope.

The oscillograms of Fig. 3 were taken at 20 μsec/cm and show current at the upper trace and voltage across the arc on the lower at a time close to the end of the half-cycle of arcing. The beam displaying current has been displaced to the right to avoid confusion of the two signals at extinction. Illustrated is the effect of added parallel capacitance upon the general mode of extinction at the end of a half-cycle of arcing. The peak a-c current was 145 amp.

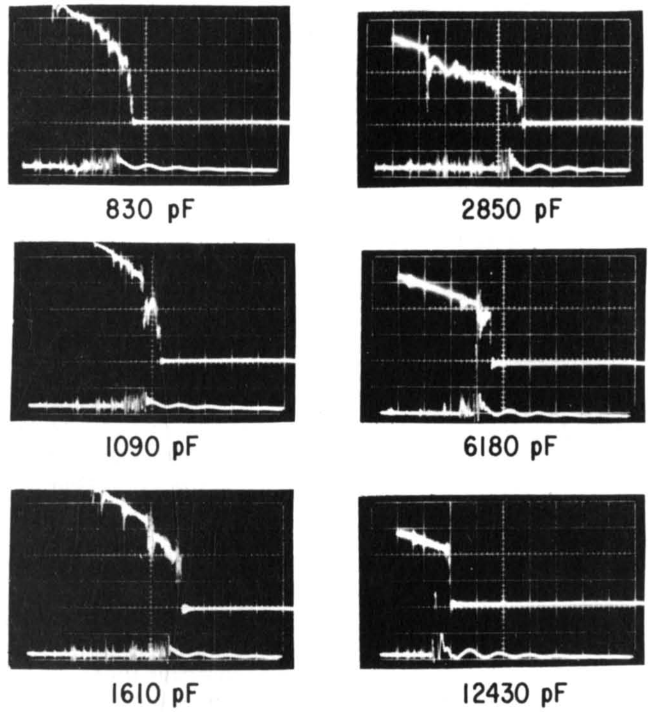

Fig. 3 Arc current and voltage--resistive circuit. 355 V/cm, 20 μsec/cm. Current sensitivity: left, 3.9 amp/cm; right, 7.8 amp/cm.

With only the line capacitance and that of the arc tube (total 830 pF) the decay of current deviates strongly from a normal sinusoid. It is seen that at several points in the wave the decline in current is stepwise rather than continuous and suggestive of the d-c decay in Fig. 1. Although the sweep rate of the oscilloscope is relatively slow, it is clear that the deviations of the current wave from the expected sinusoid are accompanied by increasingly larger voltage transients across the discharge. Recalling our earlier comments regarding Fig. 2, it appears that these transients are associated with a partial extinction of the arc with subsequent re-ignition by the transient voltage. Due to the instabilities introduced by the decreasing magnitudes of both current and voltage, the extinction, re-ignition process occurs more frequently as the current continues to decline with the arc requiring higher and higher voltage for re-ignition. Finally, the voltage or perhaps more properly the rise rate of voltage required for re-ignition exceeds that produced by the partial extinction and full extinction results.

As more capacitance is added, the current at which the arc finally extinguishes becomes higher and better defined. (Note that the current sensitivities for the three oscillograms on the left are 3.9 amp/cm and for the three on the right, 7.8 amp/cm.) With a total capacitance of 12, 430 pF the extinction occurs directly from an essentially undistorted sinusoidal current wave. Generally, on all oscillograms of this kind it is possible to find a point on the decaying waveform at which the current begins to be seriously distorted from the sinusoid. This point varies from arc to arc but seems to occur on the average at about 20 amp for the 145 amp peak regardless of the capacitance added to the gap up to about 0.01 µF. It would thus seem that the increase in extinction current with added capacitance is due to an impaired ability of the arc to be re-ignited from the voltage transient appearing across the arc. That is, the added capacitance does not act to introduce a greater number of instabilities into the arc but rather exploits those which are already present possibly by reducing the rate of rise of the re-igniting voltage.

If this view is correct, one should anticipate that when sufficient capacitance has been added to the gap to raise the extinction current to greater than 20 amp the effect of adding further capacitance should be small. This supposition is supported by the data of Fig. 4 (145 amp data). Here is shown the average extinction current for approximately 100 arcs as a function of total capacitance across the gap. In two decades of capacitance between 0.001 and 0.1 µF the extinction current <u>increased</u> by about 14 amp, whereas in the next two decades the <u>increase</u> is 4 amp or less. Further, the rate of increase of extinction current appears to undergo a change at about 20 amp. Similar remarks can be made for the 650 amp data in Fig. 4.

The oscillograms of Fig. 5 were obtained with the current limited by a 3.4 mH inductance giving a peak arc current of 250 amp. In the four oscillograms at left the top trace is arc current; the lower is voltage across the discharge. Sweep speeds are either 20 or 50 µsec/cm (see caption). In each of the oscillograms at the left the trace showing the voltage has been shifted to the right to avoid confusion with the current trace. The voltage records show the voltage oscillation that results from the sudden change in current through the 3.4 mH inductor at arc extinction. The frequency of this oscillation is determined by the inductance and the capacitance paralleling the gap. Thus as the capacitance across the gap is increased, the ringing frequency decreases. We

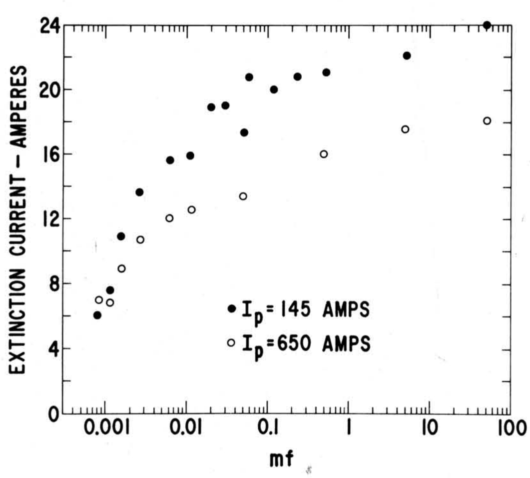

Fig. 4 Change in extinction current with shunt capacitance.

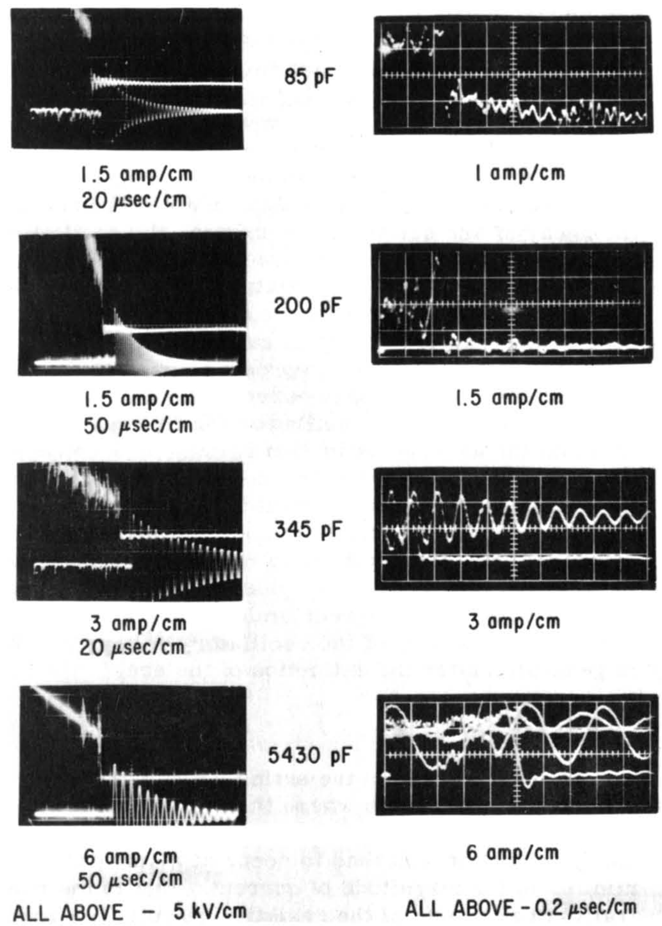

Fig. 5 Arc current and voltage--inductive circuit.

also note that, as in the resistive case, added capacitance acts to increase the average extinction current (see caption for current sensitivities). Unlike the resistive case, however, the wave shape of the current near zero, although noisy, lies averaged about the expected sinusoidal waveform.

The four oscillograms at the right display current near arc extinction at a sweep speed of 0.2 µsec/cm. Each horizontal pair of oscillograms is recorded from the <u>same</u> arc. When the capacitance across the gap is small, the decay rate of current is most rapid, typically ranging from 50 to 80 amp/µsec. This gives decay <u>times</u> of 10^{-7} to 10^{-8} second range. As larger capacitances are used the total time for the current to come to zero increases in a very particular way.

It will be noted that in the first of the high-speed oscillograms, there are what appear to be two cycles of sinusoidal oscillations of current superimposed upon the instantaneous 60-cycle current. These oscillations have become more apparent as more capacitance is added. In the high-speed oscillogram with a capacitance of 345 pF there is a sweep of the oscilloscope prior to the one containing the actual arc extinction. This shows a regular oscillation superimposed upon the instantaneous 60-cycle level of current and is, in fact, the time expansion of one of the many noise bursts on the slow-speed oscillogram at the left. This oscillation during arcing occurs at a resonant frequency determined by the capacitance in parallel with the gap and the inductance of the lead wires used to connect this capacitance to the gap. While the lowest values of capacitance appear not to influence the decay of arc current at extinction, the oscillations become large for the other three values of capacitance shown in Fig. 5. These oscillations tend to dominate the arc such that extinction occurs at the negative peak. Thus the decay rate of current in these instances is, to very fair approximation, determined by the ratio of the average current at extinction divided by a quarter period of oscillation. Experimentally we find that the average extinction current is dependent upon the 1/2 power or less of the capacitance. Thus the actual decay rate of current with an increase in capacitance will tend to decrease. We perhaps should emphasize that the oscillations under discussion are those of current which occur during the arc and up to its extinction. The current limiting inductor determines the frequency of the oscillatory voltage which is generated after the extinction of the arc.

SUMMARY

We have examined the extinction of a copper vacuum arc in circuits where the arc current was limited resistively and inductively. In the resistive case, extinction will tend to occur at momentary minima in the magnitude of current. Due to the rapid transient response of the resistive circuit, re-ignition of the arc may occur from voltages which appear across the arc as a result of the momentary current reduction. At the end of a half-cycle of arcing a long succession of such re-ignitions tends to produce a step-wise reduction of current similar to that seen for the low-current d-c arc in Fig. 1, and also tends to produce distortion of the current waveform from the expected sinusoid. With added parallel capacitance the likelihood of a re-ignition tends to diminish so that the discharge extinguishes, on the average, at higher currents.

In the inductive case, the succession of re-ignitions and the distortion of the current wave at the end of the half-cycle seen for the resistive case do not appear. During the arc just prior to arc extinction, oscillations are seen superimposed upon the 60-cycle component of current. The arc tends to extinguish at the negative peak of one of those oscillations much in the same manner as was seen for the low-current d-c arc of Fig. 2. Thus the decay time of the extinction is largely determined by the external circuit. In circuits where the shunt capacitance is small, however, the decay is not so influenced and decay times of the order of 10^{-8} seconds are observed.

CONCLUSION

Under fast circuit conditions it appears that the current decay times determined for copper are similar to the emission loss times measured for mercury; that is, times in the 10^{-7} to 10^{-8} second range. We note, however, that much slower decays can occur especially in resistive circuits. The artificial extinction method employed by Mierdel (who imposed an oscillatory current from an auxiliary source to extinguish the arc) was functionally similar to the spontaneous extinctions reported here. Both arise from momentary reductions in current. It does not seem to matter that these reductions might be due to fluctuations in the discharge itself, to oscillatory behavior arising from interactions of the arc and the external circuit, or to a disturbance totally imposed by the external circuit.

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