A COMPARISON OF ARC CHARACTERISTICS
IN SWITCHING
IN VACUUM AND IN OIL

THESIS

by

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In Partial Fulfillment of the Requirements for the

Degree of

DOCTOR OF PHILOSOPHY

California Institute of Technology

Pasadena, California

1933

Summary

This thesis describes the results of an investigation of the arc and glow discharges occurring between the contacts when an alternating current is interrupted by an oil circuit breaker; and a comparison with similar phenomena in the vacuum circuit breaker is made. This investigation was made by taking cathode-ray oscillograms of the variation of voltage across the contacts, and the current through the discharge, with time, and the variation of the voltage across the contacts with the current through the discharge. Circuit voltages of 15,000 and 2300 were used, and currents up to 45 amperes were interrupted.

The discharges across the separating contacts of an oil circuit breaker are discussed in detail, and an analysis of the variations near the zero of the current wave is made. This investigation shows that for a brief period, of the order of 300 microseconds, at the end of each half cycle of the current wave the current between the contacts is of a very small magnitude, and may be considered essentially zero. During this interval the voltage completes a part of an oscillation, the frequency of which is apparently determined by the constants of the connected circuit, and rises in the reverse direction until a certain maximum is reached. After this value is reached current again flows and the usual glow and arc phenomena are observed.

Introduction

Phenomena connected with the switching of alternating currents have been under investigation at the California Institute for a number of years. The vacuum switch, developed at the Institute, has initiated a number of questions in regard to just what happens when such an alternating current is interrupted.

The interruption of an alternating current is decidedly different from the interruption of a direct current, since the alternating current is always changing and periodically passing through a zero value.

To open the circuit at the exact instant when the current passes through zero appears then to be the best operating condition, but such operation has a number of objections.

In the first place, even with unity power factor, the velocity of moving parts required to separate the contacts far enough so that the voltage will not restrike would be enormous, and is mechanically impracticable.

Should the break actually occur at the instant when the current passed through zero, the rising voltage would be impressed across the widening gap.

The phenomena then resolves itself into a race, the widening gap tending to decrease the stress on the insulating medium, and the increasing voltage tending to increase the stress on the medium. If the stress in this race increases beyond a certain limiting value puncture of the insulating medium results, and the switch fails to open the circuit at the current zero.

If the power factor is not unity, another factor enters. When the current passes through zero the voltage is not zero, and in the case of a lagging power factor may be rapidly increasing. As soon as the contacts part this rising voltage is applied across the gap and an arc is almost sure to form, and again interrupting the arc at the current zero is not accomplished.

The high velocity required for the moving electrode and the impossibility of exact control will thus make questionable better operation obtained by attempting to open the circuit at the precise moment the current passes through zero.

In practice no effort is made to synchronize the opening of the switch with any part of the voltage or current wave, and the time of switch opening relative to the zero of the current wave is then a matter of chance. Thus the phenomena may vary decidedly for switch openings at different points on the current wave.

Dr. C. C. Lash, in his thesis submitted in 1931[1], describes phenomena that take place in a vacuum breaker at the time the current is interrupted. It was thought desirable to investigate, in the same manner, phenomena connected with the opening of the oil breaker, and to compare the phenomena in the two types of breakers.

Apparatus

The cathode-ray oscillograph is the best device for making records in investigating electric arc and glow phenomena because the variations of current and voltage are extremely rapid and this is the only device that will follow them. The limitations on the device are imposed mainly by the sensitivity limits of the photographic emulsion used to record the motion of the beam, as contrasted to limits imposed by the inertia of moving parts for other types of oscillographs.

The oscillograph used for this investigation, manufactured by the General Electric Company, is of the Dufour cold cathode type having the photographic film placed inside the vacuum system so the electron beam impinges directly upon it. This type of oscillograph is very sensitive, but has the disadvantage of losing the vacuum every time a film is changed. In this instrument six exposures can be made on a roll film before reloading is required.

The essential parts of the instrument are shown in Figures 1 and 2. A detailed description of it can be found elsewhere[2].

The excitation of the cathode was originally

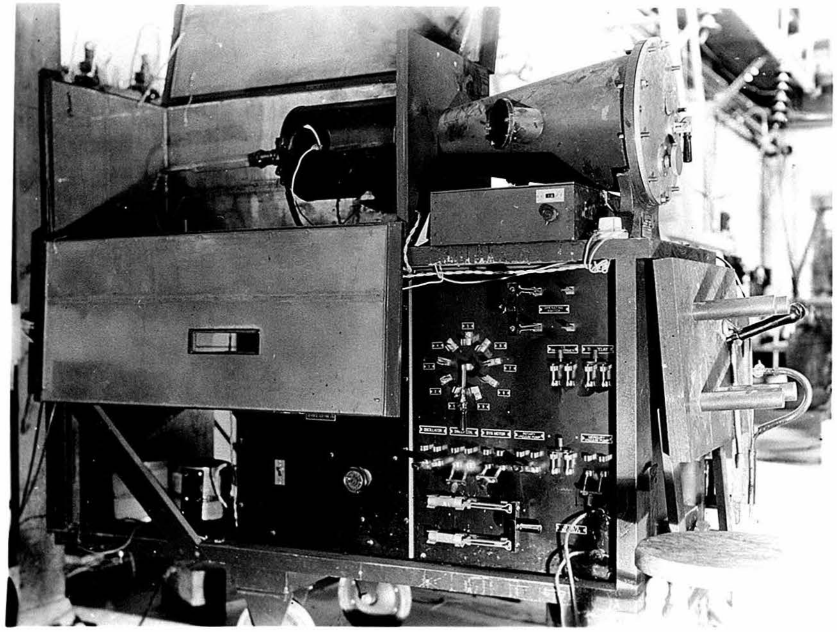


Figure 1

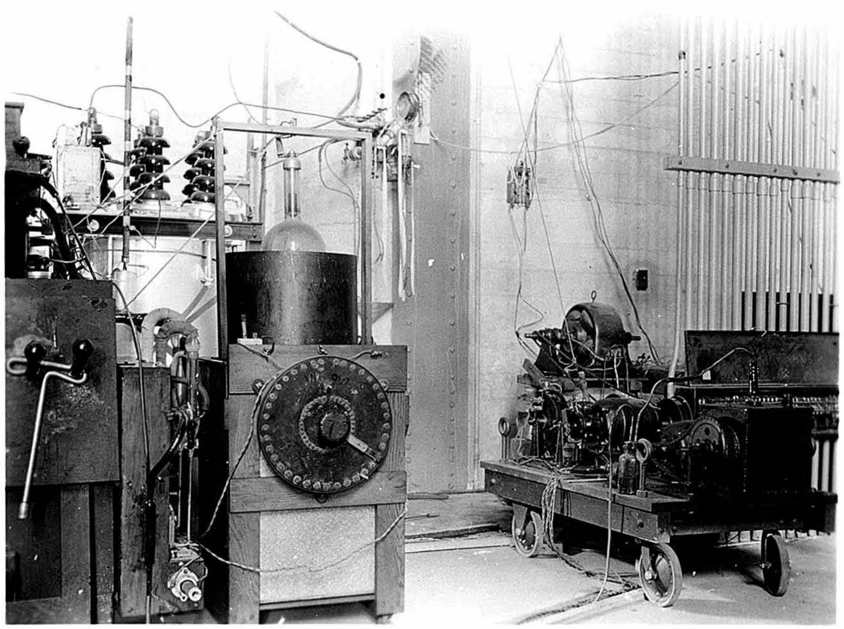
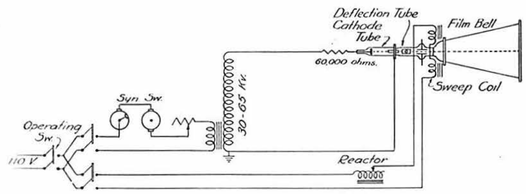


Figure 2

produced as shown in Figure 3a, the excitation being provided by an X-ray transformer, the voltage of which can be varied from 30 kilovolts to 65 kilovolts by means of the rheostat shown in the primary. The excitation is applied when the synchronous switch shown is in the appropriate position, which occurs for one half cycle once in every twenty cycles. The operating switch, which is manually operated, is closed while the synchronous switch makes contact once, and is then opened before the succeeding contact is made. In use the synchronous switch is adjusted to excite the cathode by a negative half cycle.

In the regular operation of the oscillograph the sweep coil shown provides a horizontal sweep across the film by having the cathode beam in a varying magnetic field. The excitation for this sweep circuit is from the same source as that which supplies the cathode excitation. The sweep circuit is so designed as to be practically a pure reactive circuit, so that the current in it, and the field of the sweep coil, lags the voltage by almost ninety degrees, hence the current in the sweep coil is near zero while the voltage is a maximum. For the short interval used the voltage is almost constant, and the current in the sweep circuit and the magnetic field that it



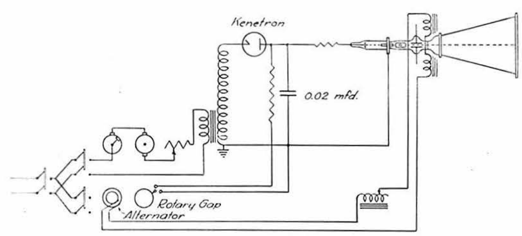


Figure 3a

Figure 3b

Oscillograph Circuits

produces are varying almost linearly with respect to time, the curvature of the sine wave near zero being very small. In using the instrument the transient under observation is studied at this phase of the sweep coil wave.

For an investigation of the nature of arc characteristics a timing system of this sort was found valueless because it allows an investigation only of phenomena whose total time of duration is a very small part of a half cycle. Since it was desired to observe phenomena over a whole cycle, and sometimes over several cycles, some other scheme was necessary.

A second objection to the original system is that in this system the cathode was excited only a small portion of a cycle, and this portion was definitely fixed at the negative maximum of the voltage wave.

This second difficulty was overcome in our investigations by exciting the cathode from a high voltage direct current source. The circuit used is shown in Figure 3b. The output of the excitation transformer is rectified by means of a kenotron, the condenser shown being used to smooth out the rectified wave. The synchronous switch is adjusted to excite the transformer at the appropriate instant, and maintain the voltage on the cathode for the desired length of time. The cathode beam is extinguished at the desired time by having a sphere attached to the rotating synchronous switch arranged to pass between the spheres of a spark gap connected across the condenser, thus firing the gap and discharging the condenser to such an extent as to extinguish the beam. A variation of the time interval during which the cathode is excited is readily made by varying the position of the contacts on the synchronous switch. The building up rate and the extinction of the beam may be controlled closely enough to eliminate the necessity for any sort of a shutter device.

In order to get a uniform time sweep over a longer period than that at first provided a number of circuits were tried. Circuits depending on the discharge of condensers were tried and rejected due to the difficulty of synchronizing the initiating of the discharge with the transient being observed, and the problem of insulating for the voltages required. The building up current in a magnetic circuit, as used by Dr. C. D. Hayward(4), was found unreliable due to vibration of the switch mechanism.

The circuit finally used was excited by an alternator driven synchronously by the synchronous switch and run at frequencies lower than 50 cycles. The straight portion of the current-time curve of this machine could then be made to correspond to a whole cycle, or more, of the 50 cycle circuit being studied. The exact position of the zero could also be shifted by means of a coupling on the shaft of the alternator which allowed its armature to be shifted relative to the synchronous drive.

This system gave excellent results and the adjustments necessary to give the various speeds desired were easily made by varying the field excitation and the armature position. Tracings of a 50 cycle wave showed the timing so nearly linear that no distortion in as many as three cycles could be detected in the oscillograms.

Three kinds of oscillograms were taken; voltage-time, current-time, and current-voltage. In each case the voltage representing the current or voltage being measured was impressed on the electrostatic deflection plates of the oscillograph, the magnetic field being used exclusively for the production of the time sweep.

A magnetic oscillograph was frequently used as an adjunct to the cathode-ray oscillograph, which by its nature is a one-element instrument and cannot be used to record simultaneously both voltage and current variation with time. To determine how the current and voltage are related in time magnetic oscillograms were taken. The instrument used was a General Electric Company oscillograph of standard design. Oscillograms were taken simultaneously on the two oscillographs. Quite obviously, the detail shown in the trace of the cathode-ray oscillograph was lacking in that of the magnetic oscillograph.

Resistance shunts were used for the measurement of current, and a resistance voltage divider was used for the measurement of voltage by this instrument. A vacuum tube amplifier was used to provide the current necessary to record on the instrument. This refinement was necessary as the current required to operate the magnetic oscillograph was too large to take from the voltage divider. The characteristics of the amplifier were fairly good and it was not considered important that its amplification be exactly linear over the whole range.

The oil switch used was a Kelman, type F-2 oil circuit breaker of standard design for 15,000 volt circuits. The oil used was that customarily supplied with this breaker.

Oscillograms were taken at voltages of 15,000 and 2300. The 15,000 volt circuit was provided by a 10 kva., 15,000/115-230 volt distributing transformer, the 15,000 volt side of which was short-circuited by the switch. The current was limited by means of a water barrel rheostat in the low voltage side.

The 2300 volt circuit was similar to the 15,000 volt one, a 25 kva. transformer being used as a power source.

The currents interrupted varied from one ampere to 13 amperes at 15,000 volts, and up to 45 amperes at 2300 volts. The limitations of the transformers prevented the use of greater currents. Furthermore, since a comparison with the work done by C. C. Lash on the vacuum breaker(1) was desired, it was considered best to operate under the conditions used by him in his work.

The switch used was of such a size that the currents used were far less than the rated switch current, but this point was not considered important as it was desired to study the arc characteristics, and the most interesting portion of an arc is that near the current zero. It is interesting to note that the interruption of small currents, of this magnitude, is known to cause the arc to persist longer, and produce worse voltage surges, than currents of larger values.

The voltages were measured by means of a liquid voltage divider consisting of a half inch hose filled with tap water. Investigation, see Appendix, has shown that this type of divider gives a linear division over the frequency range investigated. For the measurement of currents a liquid resistance shunt was used.

Results.

The results of this investigation consist of a series of about two hundred oscillograms from which illustrative ones were selected for this thesis.

When a circuit is opened by any circuit breaker the current and voltage waves appear somewhat as shown in Figure 4. The current is not broken on the initial separation of the contacts and an arc forms. This arc persists in the oil circuit breaker for a number of cycles, the current continuing to flow and the polarity of the arc changing at each reversal of the current. Finally, the current passes to a zero value, apparently in its regular cyclic variation, and stops. The voltage at this time, after some oscillation, builds up to its full value. The distortion in the voltage wave shown has been amplified in recording this picture. Obviously, the phenomena taking place near the zero values are not shown by such a picture and the following analysis will be made by means of a series of cathode-ray oscillograms.

Figure 5 shows the arc voltage over a half cycle beginning with the reversal of the arc polarity and ending with the beginning of the sine wave of the voltage established across the open contacts.

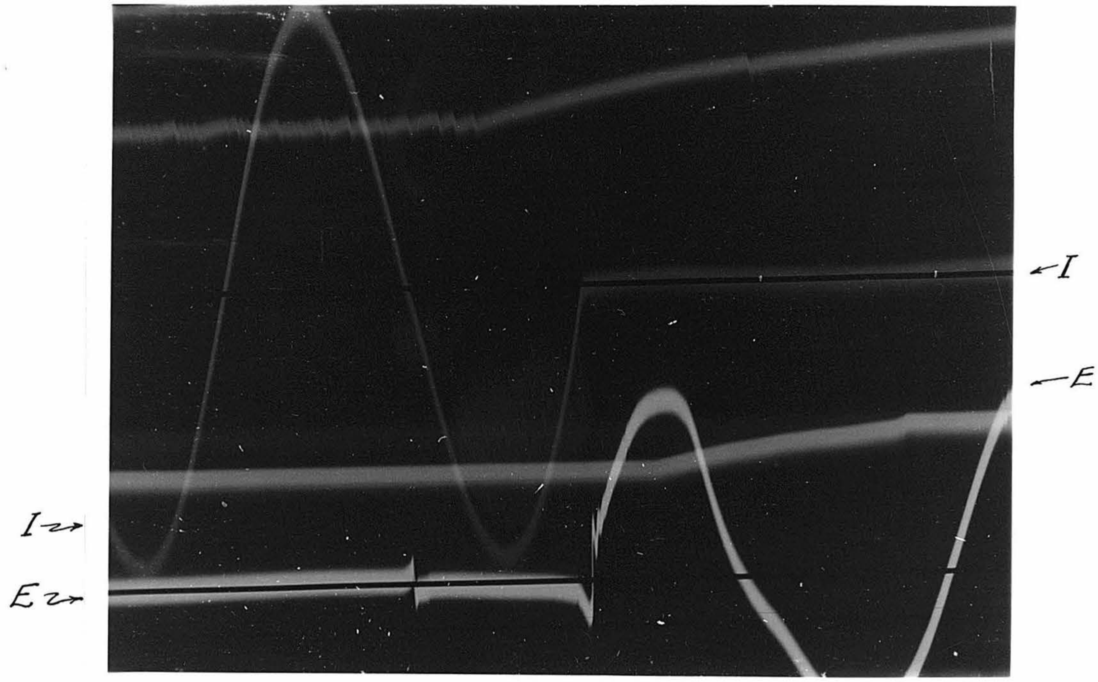


Figure 4

The current and voltage curves are marked.

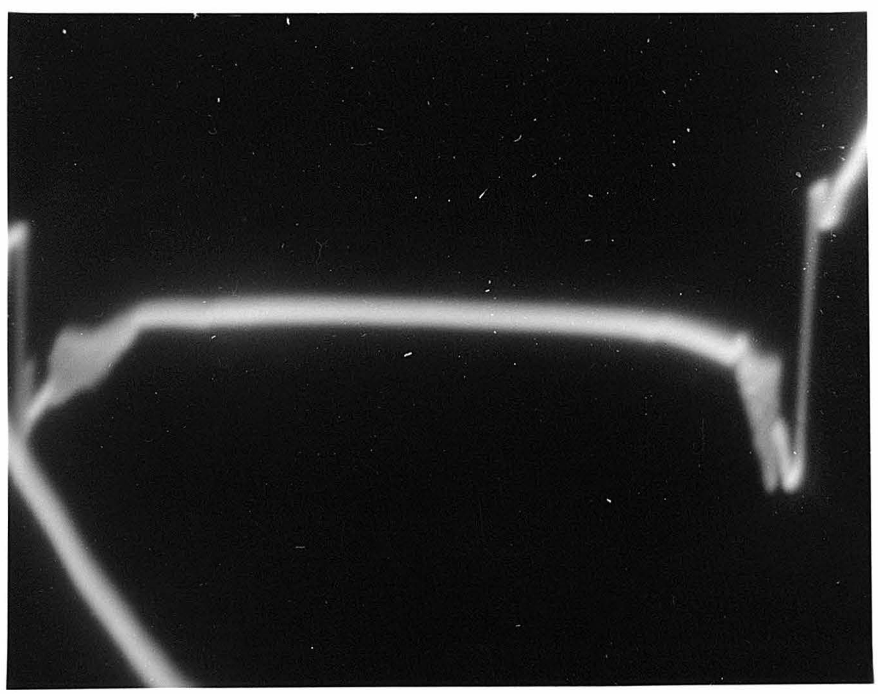


Figure 5.

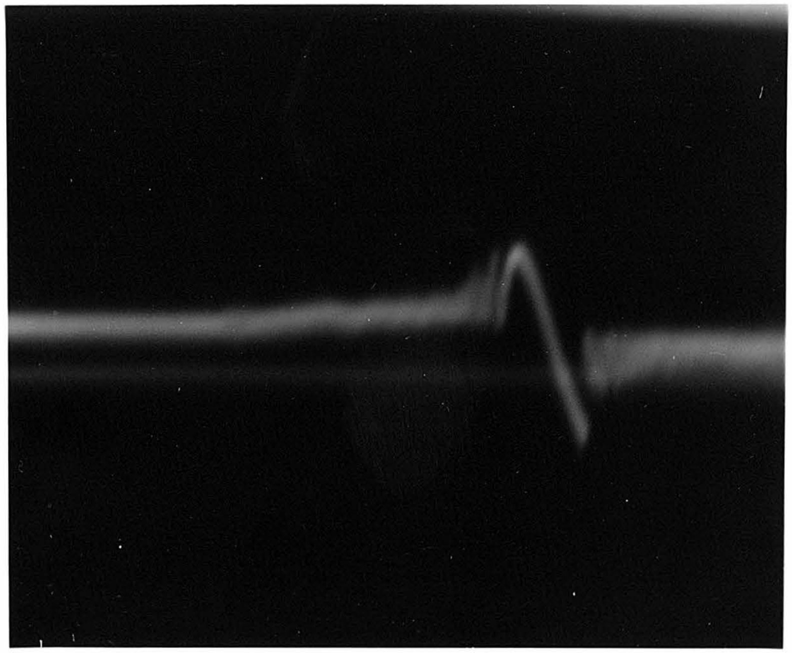


Figure 6

The total length of the figure is about a half cycle

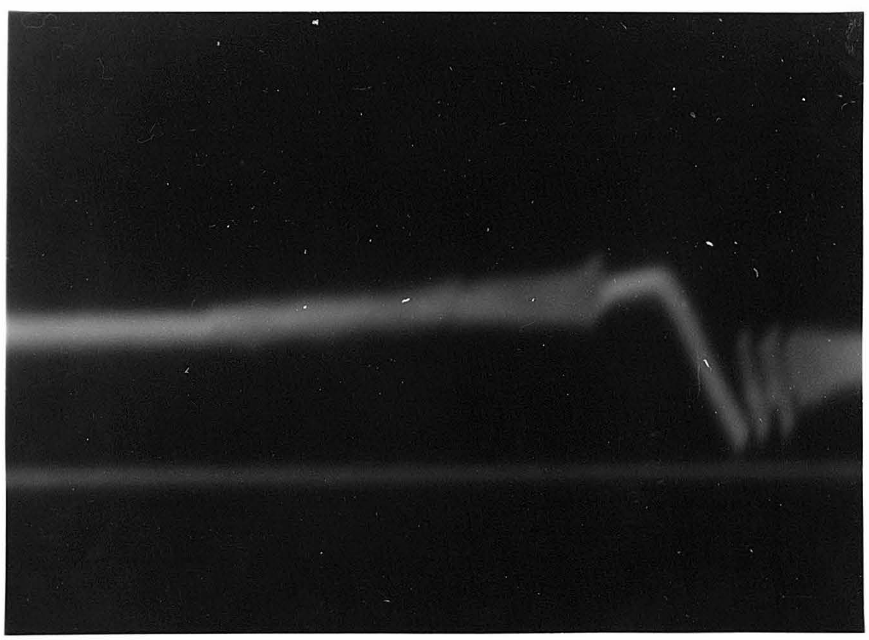


Figure 7

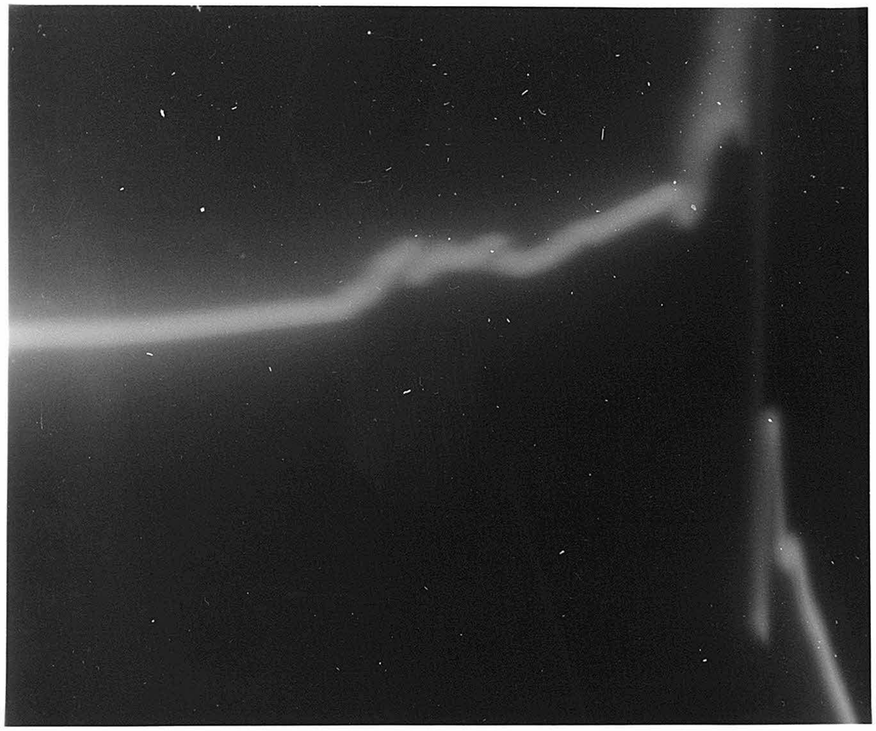


Figure 8

The irregularity of the glow region is quite marked in this picture

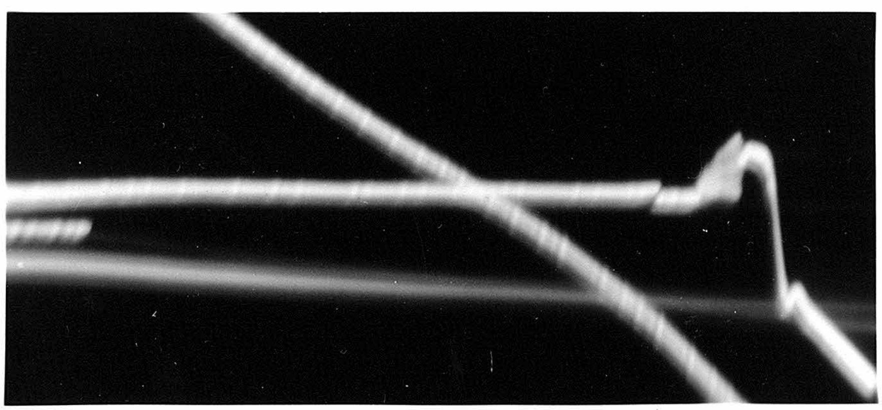


Figure 9

There are several traces on this picture but the interesting one stands out

The reversal of the voltage wave at the time the current changes polarity is interesting. This change is shown in Figures 6 and 7. At this time the arc becomes unstable and goes over into a glow (high voltage, low current phenomena). It then goes through a part of an oscillation and starts to rise in the other direction. When a certain voltage is reached the gap between the contacts breaks down and glows for a while. After a short period the glow becomes an arc (high current, low voltage phenomena) with the opposite polarity from the last arc and remains as an arc throughout most of the half cycle. At the end of the half cycle the above phenomena may be repeated and the arc reestablished. The number of cycles that the arc continues in the oil appears to depend on the current flowing and the point on the current wave at which the contacts start to open. At the end of the second half cycle of arcing the arc may not be reestablished. In my investigation of the oil circuit breaker no arcs were observed, for the circuit used, which went out with less than two half cycles of arcing.

The voltage wave as the arc goes out is

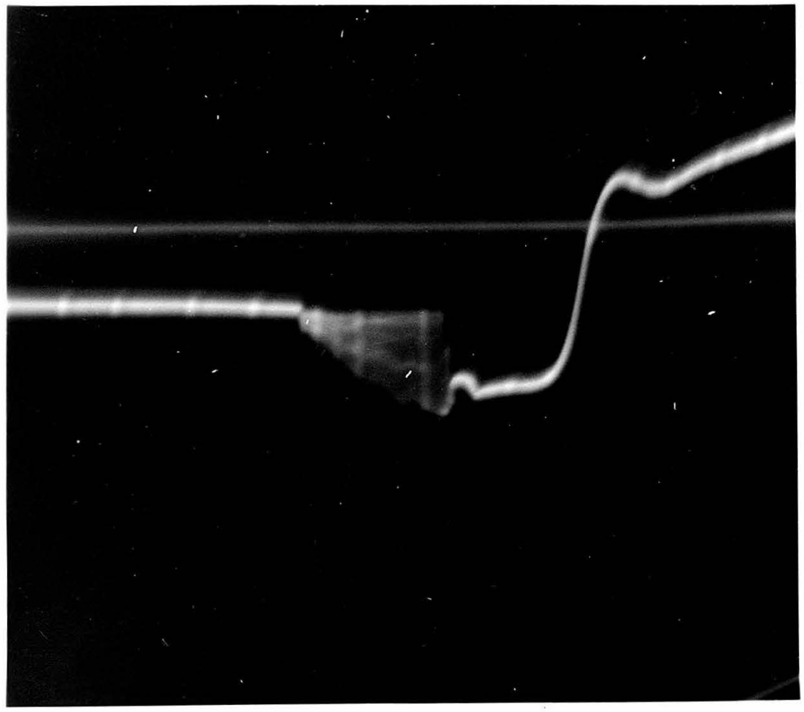


Figure 10

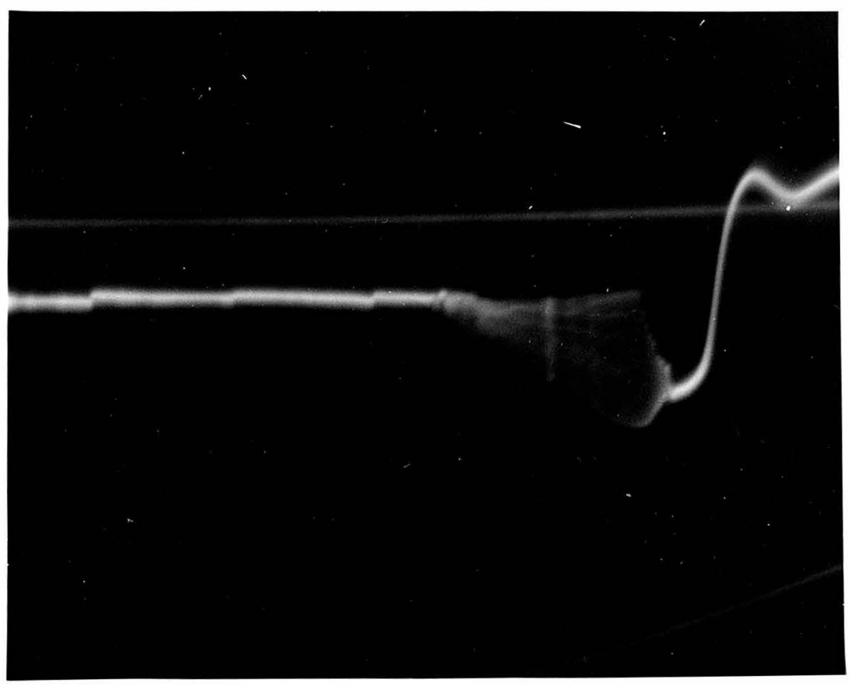


Figure 11

The upper figure shows an arc with very few irregularities, the lower one having a series of breaks. The final glow phenomena in the two are the same.

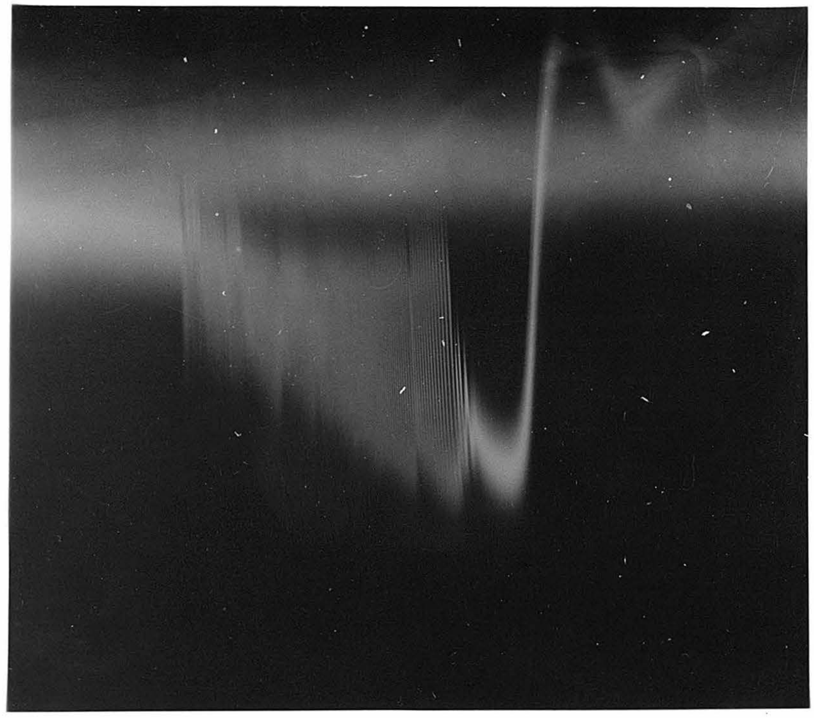


Figure 12

This picture indicates the oscillations present during the glow phenomena

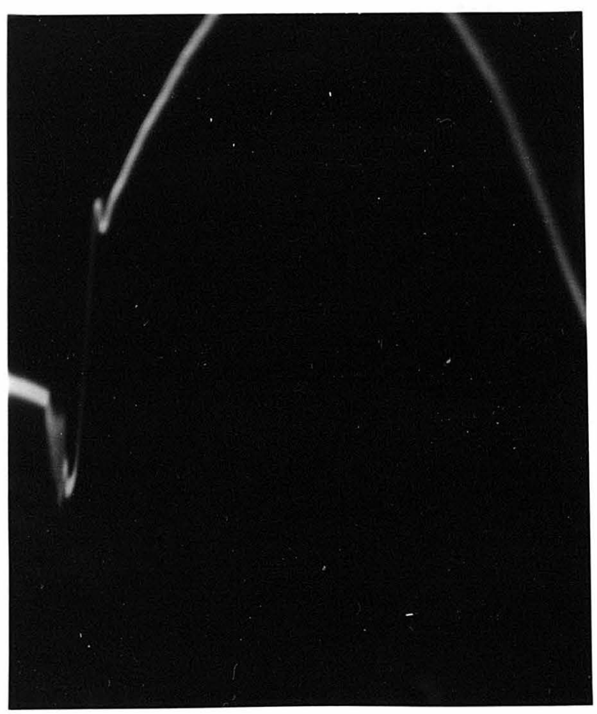


Figure 13.

shown in Figures 8 to 13. These oscillograms show the arc as it changes into a glow, reverses in polarity, goes through some oscillations, then follows a sine wave form. The unstable region just before the reversal is quite noticeable. This unstable region is shown in more detail in Figures 10, 11, and 12. It is evident that the change from an arc to a glow is quite sudden, and that during this glow discharge there is an oscillation having a frequency of several million cycles.

When this oscillation stops the voltage passes through part of a "cycle of an oscillation" of a much lower frequency, reverses in polarity, rises in this reverse direction to a certain value, passes through another oscillation, then follows the sine wave of the applied voltage. This last is clearly shown in Figure 13.

It is interesting to see just what is happening to the current when these oscillations are taking place. Let us consider first the variation in current when the arc is merely reversed in polarity without being extinguished.

Such a case is shown in Figure 14. Here the current is decreasing toward its cyclic zero. When

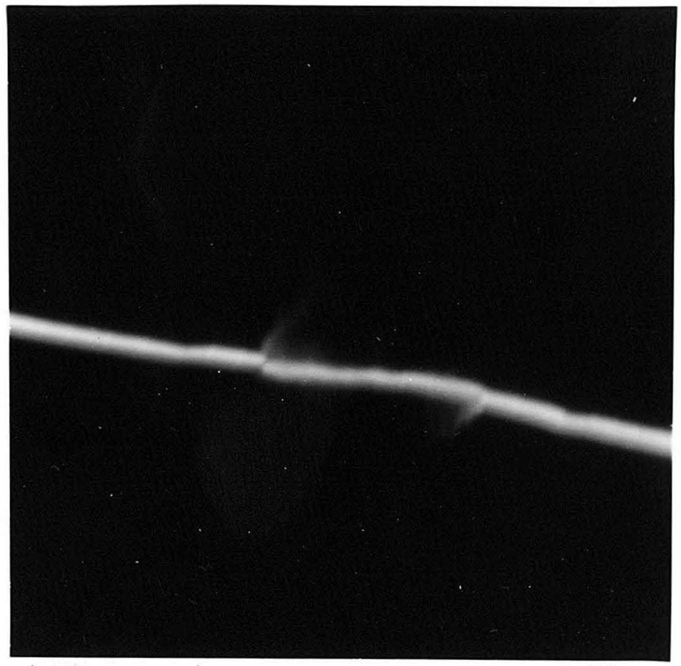


Figure 14

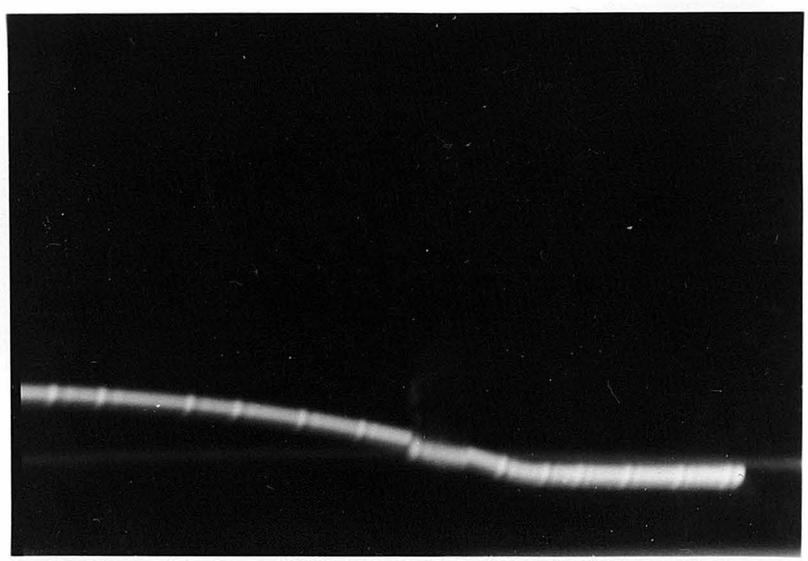


Figure 15

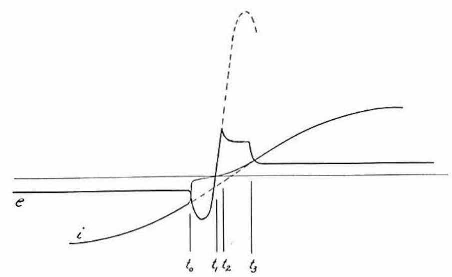
it has almost reached zero, it makes an abrupt drop, very nearly to zero, the time of fall being certainly less than a microsecond, although no time is indicated, and then decreases at an appreciably slower rate. Irregularities in the trace at the point where the current suddenly drops indicate that some phenomena are occurring at this point, but nothing has been recorded to indicate what happens to the trace at this point. Pictures taken at very much higher speeds do not give any additional data in regard to the trace at this point in the curve.

The trace then passes through zero, rising in the reverse direction slowly. Suddenly, at a certain value, the current jumps to a larger value, and continues along a curve very close to an extension of the original sine wave of current. Repeated observations have been made of this variation and the same shape of trace is always obtained. In many oscillograms the apparent continuation along about the same sine curve as before the zero is reached is quite striking.

In the case where actual extinction of the arc is obtained the trace of the current is somewhat different, as shown by the oscillogram of Figure 15. Here, again, the current decreases along a sine wave toward its cyclic zero. It also jumps suddenly just before the zero is reached, and then continues to drop at a slower rate. Again there is the suggestion of special phenomena at the time of the sudden drop, but no detail has ever been observed, even in oscillograms taken at a much higher speed than those shown. After a second variation in slope, which does not appear on all oscillograms of this type, the current falls to zero and remains at zero as indicated by the horizontal trace.

In order to correlate the current and voltage phenomena, cyclegrams of voltage against current were taken.

From these curves the voltage-time and current-time curves have been reconstructed on the same time axis. The reconstructed curves are shown in Figure 16. Figure 16a shows the variation as the arc is reversed in polarity and restrikes with the opposite polarity. The arc voltage is just about constant and the current varying along a sine wave toward a cyclic zero. When it is almost to zero, of the order of 0.1 ampere, the current drops to a very low value, as shown at t_0 in the diagram. The voltage then appears to go through an oscillation of a higher frequency as shown by the voltage curve from t_0 to t_1. Reference back to Figures 6 and 7 will show this portion of the curve quite clearly. No oscillogram of the type shown has ever



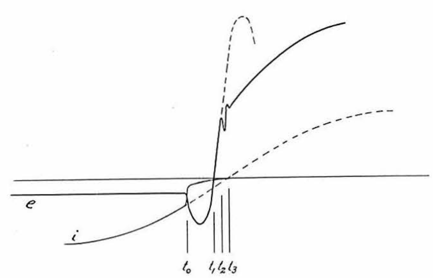


Figure 16a

Figure 16b

Reconstructed voltage-time curves and current-time curves plotted on the same axis.

been observed which did not have this curve. The explanation of its shape is probably that the current flowing in the circuit connected to the breaker will always be flowing through the inductance that this circuit must have. This current through the inductance can not drop instantaneously to zero but surges into the distributed capacitance of the circuit. This capacitance may be small in many circuits, but it is by no means negligible. The curve of voltage rise is then a portion of the curve of voltage oscillation in this circuit. If the constants of the circuit were known, the shape of the curve could be calculated if one assumes that the current has dropped to zero. This is substantially true as the current has dropped to a very low value.

The current continues to drop to zero, the voltage rising with the opposite polarity. When a certain value is reached, as shown at t_2, the voltage breaks off and a glow is formed. The current now starts to rise. The voltage curve during this period is quite irregular as can be seen from Figures 6 and 7. The current rises steadily until at t_3 an arc proper is formed and the voltage drops to its lower arc value. In many pictures the voltage curve from t_2 to t_3 is not nearly so regular as in the diagram, and the sharp break shown at t_3 is absent. In such a case the whole curve from t_2 to t_3 is irregular with a general trend downward until the arc is formed at t_3.

The arc voltage as measured from oscillograms was found to lie between 75 and 200 volts. Considerable variation was found, and a systematic increase as the time from the moment of the opening of the switch increased seemed to indicate a variation with the length of the arc.

The period of current zero at the time of reversal was of the order of 300 microseconds, but considerable variation was observed.

The voltage rises always to a certain value, of the order of 400 volts, before it drops into a glow. Apparently, the voltage must rise to this minimum value before current can flow in the new direction.

Figure 16b shows the variation of current and voltage when the arc goes out. There is no difference from the previous case except that the glow and arc are not reestablished at t_2. When a certain voltage is reached there is some oscillation, then the voltage assumes its sine character.

Reference back to Figures 8 to 13 will show oscillations illustrating this phenomena.

The frequency of the oscillation at t_3 is probably determined by the constants of the circuit.

The phenomena encountered here are essentially the same as those encountered with the vacuum breaker. However, with the vacuum breaker the arc does not hold over into the second half cycle except when the opening of the contacts comes late in the half cycle.

C. C. Lash[1] distinguishes a "first" and a "second transient" in his study of the vacuum breaker. The phenomena that he calls the first transient is apparently the glow that accompanies the formation of the arc.

In the vacuum breaker, if the separation of the contacts occurs just after the cyclic zero of the wave of the impressed voltage, it appears that a glow discharge (low current, high voltage phenomena) always precedes the arc. The study of a number of oscillograms seems to verify this effect. The discharge then drops into an arc, and the voltage accordingly falls to that corresponding to the arc value, of the order of 25 volts. The value of the glow voltage is considerably higher.

The reversal of arc voltage observed in the oil circuit breaker occurs very seldom in the vacuum breaker, since the arc in the vacuum breaker does not hold for more than a single half cycle, or very seldom, a small fraction of a half cycle and a half cycle. All of the reversals noticed occurred due to this latter cause; the switch was opened so late in the half cycle that the contacts had not separated far enough by the first current zero after opening to withstand the voltage impressed across them.

When these reversals of arc voltage do occur the oscillograms are of exactly the same form as those obtained in this investigation and indicate the same mechanism.

In making similar studies of the vacuum breaker there are numerous examples of the breaker opening without any arc at all. In this case the glow preceding the arc, or the glow that results immediately after the reversal of the arc voltage leads directly into the glow preceding the establishing of the sinusoidal voltage across the gap. This glow may be as long as a whole half cycle. Investigations of its frequency indicate that it is of the same order of magnitude as in the corresponding conditions in the oil circuit breaker.

The fact that the arc fails to form sometimes in the vacuum breaker, but has never been observed not to form in the oil circuit breaker, might be explained by the relatively large number of conducting ions in the vaporized oil compared to the scarcity of such particles in the vacuum circuit breaker. Such a lack of ions in the vacuum breaker would tend to prevent the formation of an arc.

The "second transient" is the oscillation that takes place when the voltage wave changes over into its sinusoidal form. This transient appears to be of much greater magnitude and longer duration in the vacuum breaker than in the oil breaker, but such a phenomena could be entirely accounted for by a difference in the circuits connected to the breakers. I am of the opinion that this is not the real cause and that the transient is of greater size in the vacuum switch.

The variations of current in the vacuum breaker are of the same form as in the oil breaker with the exception that the initial current drop, from the small value previously mentioned, seems to be abruptly to zero. Apparently this final deionization of the gap is much quicker in the vacuum breaker than in the oil breaker. Again, this is what one would expect from the nature of the medium.

Conclusions

A comparison of the tests we have made on these two types of breakers leads to the following conclusions. The arc does not hold on as many half cycles in the vacuum breaker as in the oil breaker, and for the vacuum breaker the arc voltage is not so high as for the oil breaker. A comparison of the glow voltages can not be accurately made, but they seem to be of the same order of magnitude in the two types of breakers. The same phenomena occur in both types of breakers, but some portions of the series of voltage variations are often lacking in the vacuum breaker, due probably to the quicker and more thorough deionization of the insulating medium. The glow effect is of relatively longer duration in the vacuum breaker, and the arc persists, in general, for a smaller part of the half cycle. The voltage oscillations when the current flow ceases appear to be of greater magnitude and longer duration in the vacuum breaker, but this may be due entirely to a difference in circuit conditions in the tests made on the two types of breakers.

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Acknowledgements

The author wants to especially thank the Kelman Electric and Manufacturing Company of Los Angeles for the loan of a suitable oil circuit breaker, with its auxiliary equipment, for use in these tests.

Some suggestions for future research

The arc problem in switching is too complicated to be readily analysed successfully in a broad way. For this reason an investigation of the type made by the author can yield only qualitative results.

It appears to me that a fruitful series of investigations of the different phases of the arc phenomena can be continued, both in oil and in vacua, with the hope that the variables present may be eliminated one by one until a better understanding of the arc is provided.

As an example, both arc and glow phenomena should be investigated for a series of fixed spacings of the electrodes and with various values of current flowing through the arc. This should be done both in oil and in vacuum.

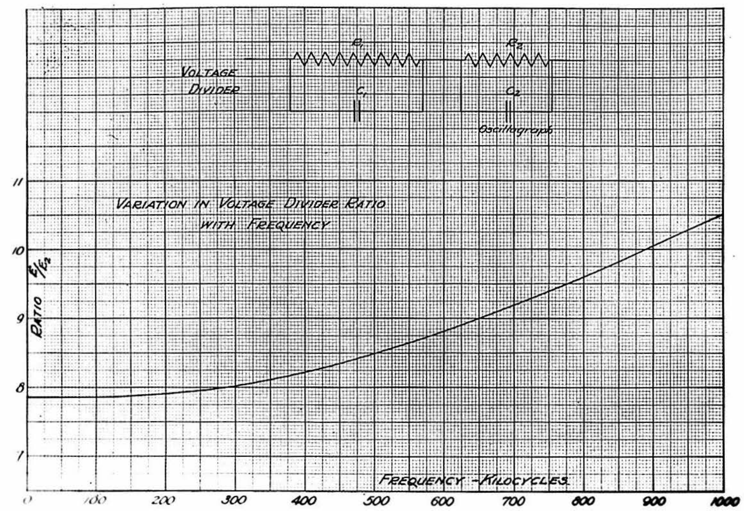
The large number of variables present in an opening breaker mask many effects that could be found by investigating its phases separately.

Appendix

The arrangement of the voltage divider is shown in Figure 17. If a low frequency is impressed across the divider, the impedance of the deflection plates is so high that no current is shunted through them, and the ratio of the voltage to be measured to that on the deflection plates of the instrument is practically independent of frequency. Any phase difference present will be very small.

In the following it will be shown that in order to keep the ratio of the divider constant the resistance would need to be decreased as the frequency increased, and the resultant current required for the divider at high frequencies might seriously change the characteristics of the voltage being measured.

If one considers inductance, capacitance, and resistance of the parts of the voltage divider, as well as a distributed capacitance to ground, the calculation becomes very involved. For this reason, the inductance of the divider and the capacitance to ground will be neglected. This will be quite justified in the present case, as in the experimental arrangement these quantities were very small.



VOLTAGE DIVIDER
R_1
C_1
R_2
C_2
Oscillograph
VARIATION IN VOLTAGE DIVIDER RATIO WITH FREQUENCY
RATIO E_1/E_2
11
10
9
8
7
FREQUENCY - KILOCYCLES
0
100
200
300
400
500
600
700
800
900
1000

Figure 17.

Let us designate the resistances and capacitances of the two parts of the voltage divider as shown in Figure 17. In general, the value of C_1 will be very small, but C_2 will be larger because the deflection plates of the oscillograph will be in shunt with the second part of the voltage divider.

The impedance of each part of the circuit can then be written as:

$$\frac{1}{Z_1} = \frac{1}{R_1} + j\omega C_1 \qquad \frac{1}{Z_2} = \frac{1}{R_2} + j\omega C_2 \tag{1.}$$

or

$$Z_1 = \frac{R_1}{1 + j\omega C_1 R_1} \qquad Z_2 = \frac{R_2}{1 + j\omega C_2 R_2} \tag{2.}$$

where ω is 2π times the frequency of the circuit, and j is the imaginary operator $\sqrt{-1}$. The total impedance is the sum of the two, or:

$$Z = \frac{R_1}{1 + j\omega C_1 R_1} + \frac{R_2}{1 + j\omega C_2 R_2} \tag{3.}$$

The voltage will divide in the ratio of the impedances, or:

$$\frac{E}{E_2} = \frac{\dfrac{R_1}{1 + j\omega C_1 R_1} + \dfrac{R_2}{1 + j\omega C_2 R_2}}{\dfrac{R_2}{1 + j\omega C_2 R_2}} \tag{4.}$$

If $C_1 R_1$ is equal to $C_2 R_2$ it is evident from the above equation that the denominators of all of the fractions will cancel leaving

$$\frac{E}{E_2} = \frac{R_1 + R_2}{R_2} \tag{5.}$$

This would be a voltage divider that would be independent of the frequency of the applied voltage.

If however, going back to equation (4), we consider the case where C_1 is equal to zero, we have

$$\frac{E}{E_2} = \frac{R_1 + \frac{R_2}{1 + j\omega C_2 R_2}}{\frac{R_2}{1 + j\omega C_2 R_2}} = \frac{R_1}{R_2}\left(1 + j\omega C_2 R_1\right) + 1$$

or

$$\frac{E}{E_2} = \sqrt{\left(\frac{R_1}{R_2} + 1\right)^2 + \left(\omega C_2 R_2\right)^2}$$

Putting R_1 = 382,400 ohms, R_2 = 55,600 ohms, and C_2 = 20 micro-microfarads, and plotting the ratio of E/E_2 as ordinates against the frequency in kilocycles as abscissae, the curve shown in Figure 17 is obtained. These values are approximately the ones used in the voltage divider. The resistances were measured and the capacitance calculated from the physical dimensions of the parts.

The actual voltage division is somewhat better than that indicated by the curve, as the value of C_2, 20 micro-microfarads, is probably high. Also, any capacitance in C_1 will tend to improve the characteristics of the divider. A variation in the values of the resistances for various frequencies is not a very practical solution.

As a check it was considered advisable to take oscillograms showing the actual voltages in the voltage divider. The oscillator provided with the oscillograph was connected directly to the vertical deflection plates, and also across the voltage divider. The horizontal deflection plates were then connected to the points on the voltage divider that were used in measuring voltages. Frequencies up to a million cycles were then supplied to the divider by the oscillator. Any change in the reduction ratio and phase of the applied voltage by the voltage divider would cause the figure drawn by the oscillograph to become a loop rather than a straight line. Figures 18, 19, and 20 show this phenomena for 100, 300, 500, and 1000 kilocycles. For frequencies up to 300 kilocycles the variation from a straight line is not appreciable, but for higher frequencies there is a decided variation. The figure for a million cycles is somewhat smaller as a higher voltage was not available at that frequency.

It is obvious from the above that the resistance voltage divider will give a satisfactory indication if the frequency of the phenomena under investigation is not too high. In the present investigation of the arcs accompanying switching this will not introduce appreciable error, but in many investigations the error introduced may be quite large.

Figure 18.

Taken at 100 kilocycles

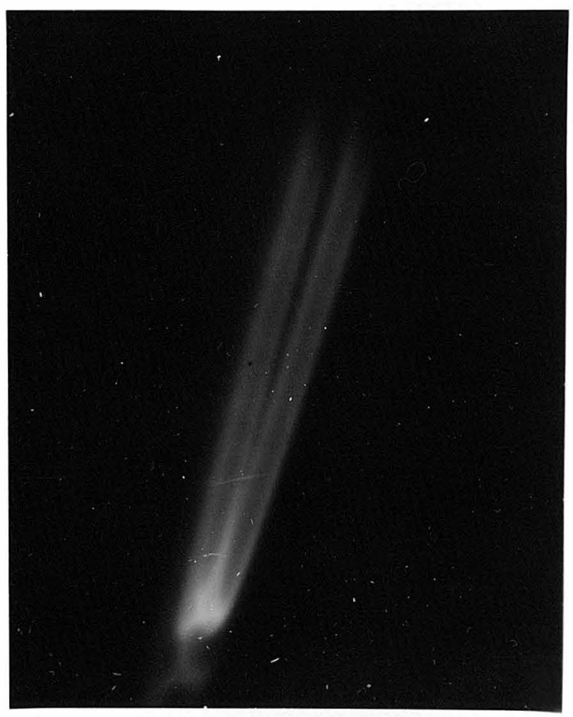


Figure 19.

Taken at 300 kilocycles

Figure 20.

The loops for both 500 kilocycles and 1000 kilocycles are shown in this picture. The loop for 500 kilocycles is the larger one. The contacts were so set that the beam went out before the loop at 500 kilocycles was completed, but the shape is quite evident.