MEASUREMENT OF ARC VOLTAGE ACROSS OPENING SWITCH CONTACTS

THESIS

by

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In Partial Fulfillment of the Requirements for the
Degree of
DOCTOR OF PHILOSOPHY

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California Institute of Technology
Pasadena, California

1928

SUMMARY OF RESULTS

The circuit developed provides an excellent means for measuring transient low voltage phenomena on a high voltage circuit with an accuracy comparable with that of a commercial meter. In this work it provides a device with which the relatively low arc voltage, existant when opening contacts carrying current on a high voltage circuit, with all its variations, was made easily discernible even though a voltage 1000 times greater immediately followed.

The results obtained on a vacuum switch by this measuring circuit establish two facts. The arc voltage is generally low and of the order of 10 to 25 volts. The arc voltage is independent of the current in the arc for the higher values (100 amps.) but increases greatly for the lower values (0 to 5 amps.). The theory based on the existence of a cathode spot, brought into being when the contacts open, and maintained by the action of the arc, explains the action of the switch in a satisfactory way and seemingly is in accord with all the observed phenomena.

The results obtained on the oil switch showthat the arc voltage and energy are very much higher than for the vacuum switch and agree in magnitude with those expected from work of Charpentier and Rudenburg.

Introduction

The circuit breaker or switch is a piece of apparatus of prime importance in electrical engineering practice. Its value is evident at once on reflection that in the last analysis the control of electric power is primarily dependent on this part of the electrical system. The modern circuit breaker has taken the form of two or more separable contacts immersed in an insulating fluid, usually oil. However, in the past few years the separation of contacts and the interruption of currents in vacuum has been successfully demonstrated and possesses distinct advantages[1].

In connection with switching problems a difference between opening alternating current circuits and direct current circuits is encountered in that in the former case the current passes thru a zero value twice each cycle. Since the alternating case is the more important in modern practice (because alternating currents and voltages are employed on all large power and distribution systems) this case only will be discussed in this work.

It would seem that the ideal method for electrical circuit interruption would be to separate the switch contacts very rapidly at the instant the current passes thru a zero value for at this time the energy stored in the magnetic fields linked with the circuit would be nil. If at this instant the voltage were also zero and if the contacts were opened with sufficient speed, an arcless switching operation would result. This is true only for the unity power factor case, however, and furthermore the contacts would have to be separated a reasonable distance in a time interval of the order of 0.0001 second[2]. The sensitive timing necessary for the realization of this ideal in a practical switch is as yet out of the question because of mechanical difficulties.

In general the most severe duty imposed on a circuit breaker is that when it is called upon to interrupt short circuit currents. It is well known that one of the characteristics of these currents is their low lagging power factor. The condition is encountered that when the current is passing a zero value the voltage is near its maximum. If the current were interrupted at its zero value a high voltage would be impressed across the switch immediately and tend to strike an arc. If the contacts were separated at a time when the current value was not zero the voltage of induction would act to maintain the flow of current and an arc would necessarily result. Two examples will illustrate these points: Assume an inductive circuit which draws a 50-cycle current of 100 amperes at 0.3 power factor lag from a 10,000 volt source. If the contacts are opened at the time of zero current the voltage immediately impressed across the switch would be

$$10{,}000 \times \sqrt{2} \times \sin(\cos^{-1}0.3) = 13{,}500 \text{ volts}$$

Assume the contacts to be separated 0.001 inch. The stress on the material interposed would be at least

$$13{,}500/0.001 = 1{,}350{,}000 \text{ volts per inch.}$$

It is evident that such stress in the case of an oil circuit breaker would cause a break down of the oil barrier and a formation of an arc. On the other hand if the contacts were opened at zero voltage a condition represented by the following calculation would result. From the above date - Inductance = 0.303 henry. Assuming the electric strength of 0.001 inch of oil to be 2500 volts, the permissible decay of the current would be 8200 amperes per second. For a condition of arcless switching the current should drop instantly to zero and this is of course inconsistent with the permissible decay of 8200 amperes per second. Many oscillograms of switching operation taken on various types of switches confirm the above and furthermore establish the fact that the arc once initiated continues until the current passes a zero value on some succeeding half cycle. It may be concluded that switching alternating currents is normally accompanied by an arc across the switch contacts with the possible exception of interrupting a unity power factor circuit when the current passes a zero value.

In view of the fact that this phenomenon does enter into the switching problem it was considered pertinent to investigate the characteristics and especially to measure the voltages identified with it. The arc voltage is of considerable theoretical importance in the vacuum switch investigation and has never been accurately determined. It was also of interest to compare the arc characteristics of the oil switch with those of the vacuum switch and with those reported for oil switches by other investigators. This work has been undertaken with the purpose in mind of developing a method for accurate arc voltage measurement on a high voltage breaker and applying it to a vacuum switch and an oil switch.

APPARATUS

Referring to Figure 1 which schematically represents the circuit involved, L representing the load; S the switch contacts; V the arc voltage measuring apparatus; it is evident that the measuring device should satisfy several requirements:

a. To be capable of measuring a few volts (10 - 20) accurately on a high voltage circuit (15,000v)

b. To be capable of measuring this low voltage when impressed for a short interval of time (0.001 sec.)

c. To be capable of withstanding full line potential (15,000v) when the circuit is opened by the switch under test.

A method which immediately suggests itself is one using a potential transformer and an oscillograph as shown in Figure 2. This arrangement however fails to meet condition (a) in that the transformation of a line voltage across the switch reduces the already small arc voltage to a lower value and the latter being insignificant in comparison with the former is consequently lost on the oscillogram. Furthermore, it is extremely doubtful if the secondary will faithfully follow a distorted voltage impulse impressed on the primary for so

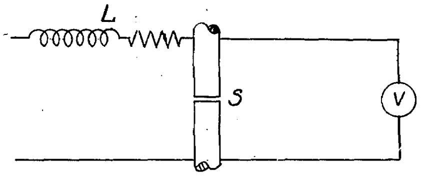

FIG. 1

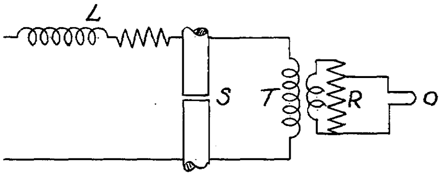

FIG. 2

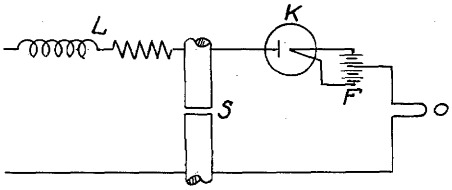

FIG. 4

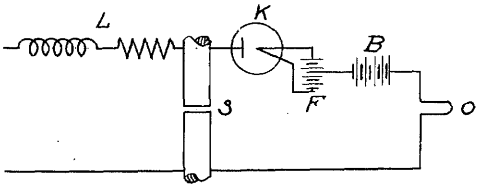

FIG. 7

Fig. 1
Fig. 2
Fig. 4
Fig. 7

short a time as 0.01 seconds or less. The potential transformer and oscillograph method satisfies condition (c) only. Figure 3.

In order to meet the three requirements a method employing the two element vacuum tube characteristics was devised. This method was suggested by Dr. S.S. Mackeown. Since an oscillograph is used a fourth requirement is imposed, namely that the current in the measuring circuit flowing thru the oscillograph shall not exceed a definite maximum value. With the instrument used this value was 150 milliamperes approximately. This condition is also satisfied as is shown in the following. Figure 4 shows the essential parts of the measuring circuit, L being the load, S the switch contacts, K a two element vacuum tube, F the filament battery and O the oscillograph element. As is well known the plate current rises with increasing plate voltage from zero to a saturation value the magnitude of which depends on the filament temperature which is held constant. When this saturation value is attained further increase in plate voltage alters the plate current only a slight amount. The adaption of this characteristic is illustrated in Figure 5. When opening

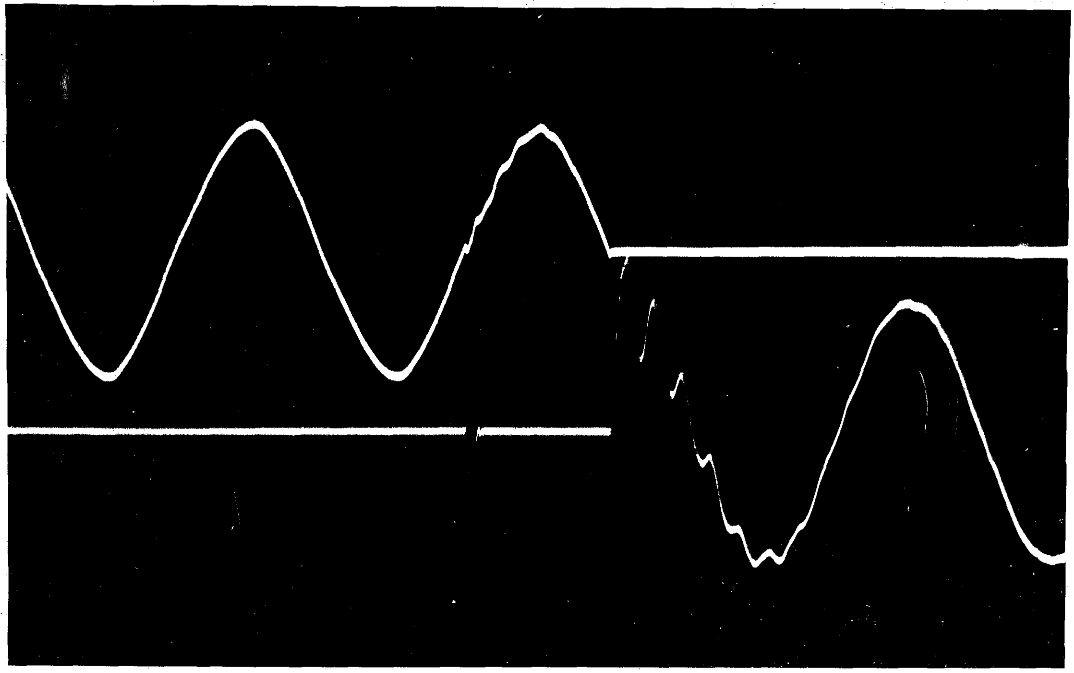

Fig. 3
Oscillogram taken on circuit of Fig. 3

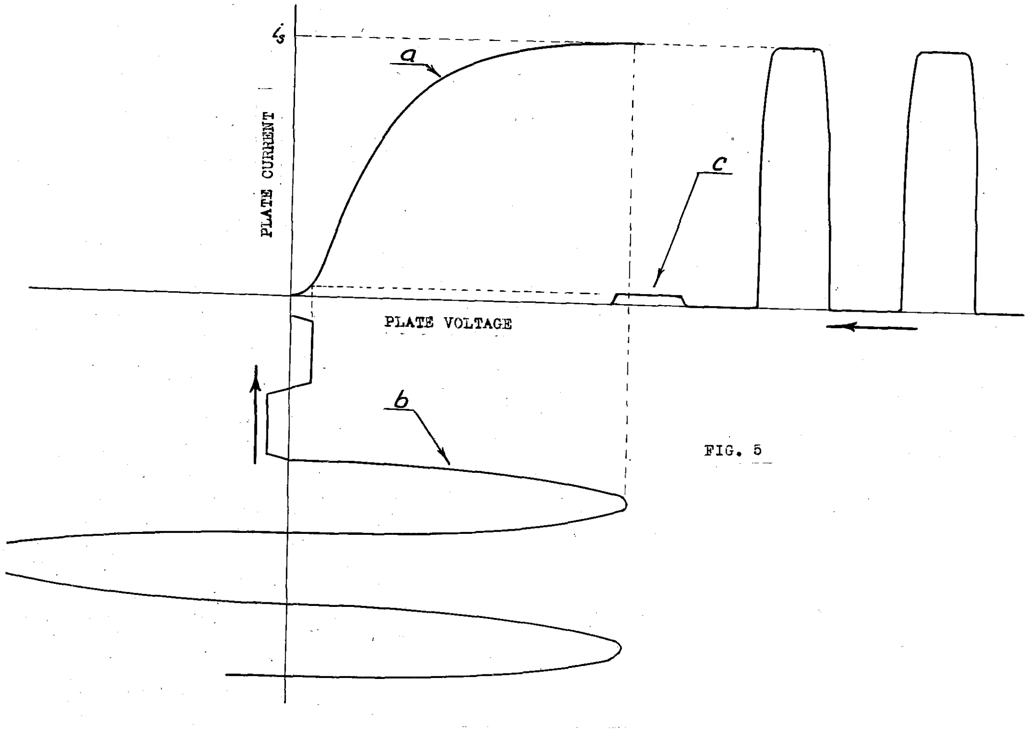

Fig. 5

the switch the voltage variation may be represented by wave "b" which consists of a cycle of arc voltage followed by the normal line voltage alternations when the circuit is finally interrupted. This wave is impressed on a tube having a characteristic curve "a" for a particular constant filament current. A current variation "c" results in the measuring circuit and hence in the oscillograph. The wave "c" consists of a zero voltage line corresponding to the closed switch, followed by one half cycle of arc voltage when the contacts first open, another zero voltage line corresponding to the blocked half cycle and then a succession of half cycles and zero lines corresponding to the application of full line potential across the open switch. It is to be noted that any voltage greater than that corresponding to saturation is consumed in tube drop. With a proper filament current then the permissible oscillograph current is never exceeded presumably no matter how high the voltage across the switch may be. The use of the tube in series with the oscillograph enables the measurement of 10 or 20 volts on a high voltage circuit, 15,000 volts perhaps, without any deleterious effect on the oscillograph element whatsoever.

The tube used in these experiments was a G.E. K-1000-100 Kenotron tube. It would insulate 100 kv. and

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Calibration Curve
Kenotron No. 2.

D.C. EXCITATION
I_f = 27.5 amperes.

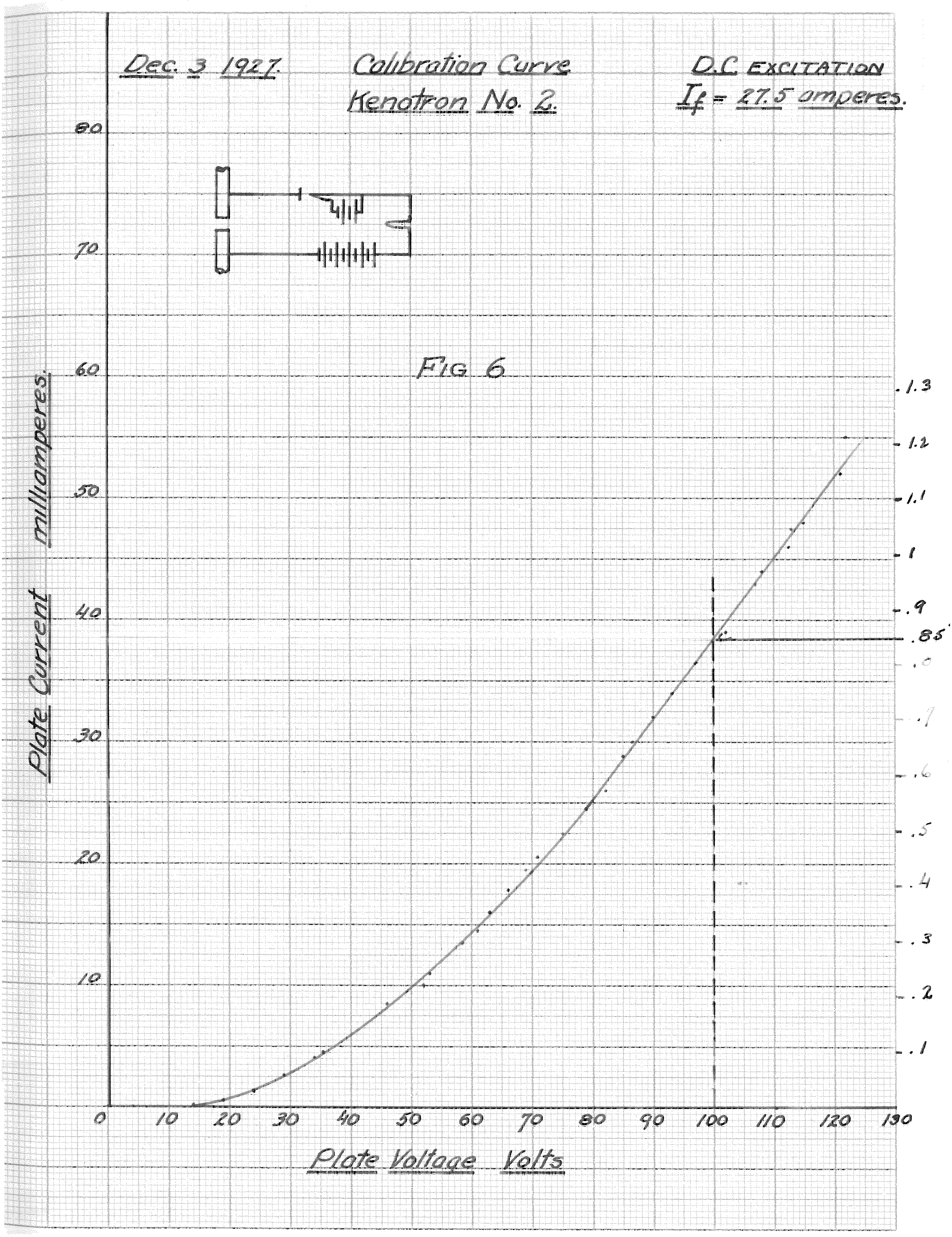


FIG 6

had a plate current rating of 1 ampere for a short time or 0.25 ampere continuous. The tube would heat when dissipating 150 watts and hence high voltage directly across the measuring circuit would quickly destroy the tube as the above value would be greatly exceeded. It was necessary therefore to utilize a secondary switch to remove the potential from the test circuit immediately after the test switch had opened.

Figure 6 shows the actual kenotron characteristic for a certain saturation value. It is readily seen that a voltage of 10 or 20 volts operates the tube on the lower flat portion of its characteristic. It is more desirable to operate on the steep straight part of the curve. This is effected by the use of a direct current bias of 100 volts or so in series with the measurement circuit. Figure 7 shows the circuit with the bias battery "B" introduced. Figure 8 demonstrates the operation. The voltage wave "b" whose axis lies "B" volts from the origin is impressed on the tube of characteristic "a". The wave "c" represents the resulting current thru the oscillograph. It is evident that the introduction of the bias voltage effects two useful improvements. It allows the reproduction of both positive and negative half cycles of arc voltage

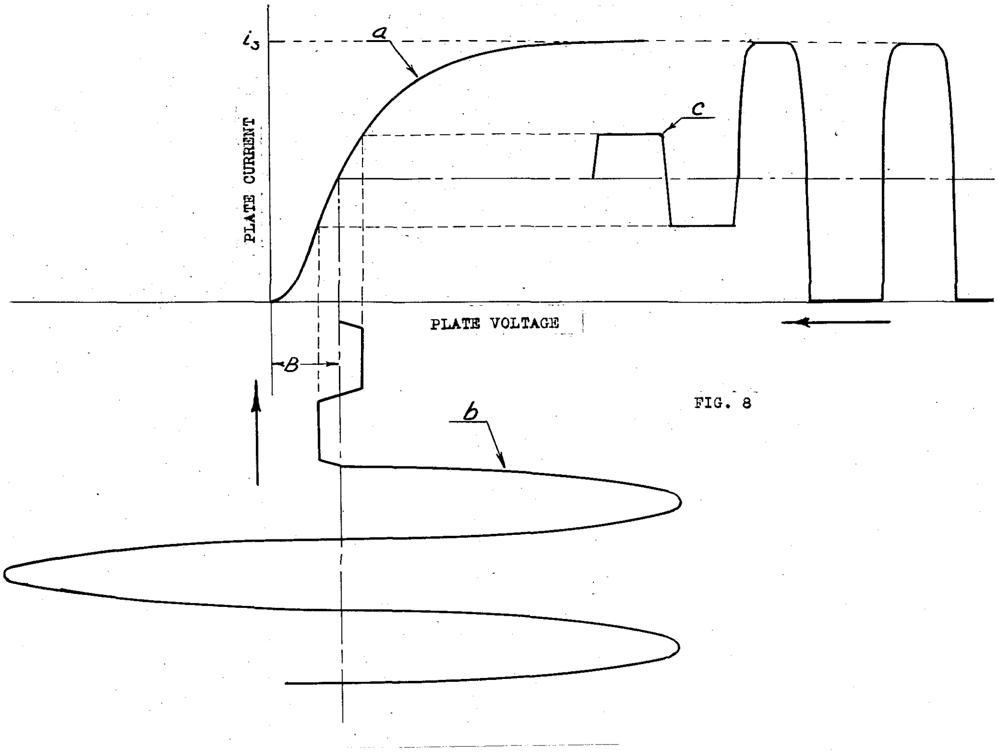


Fig. 8

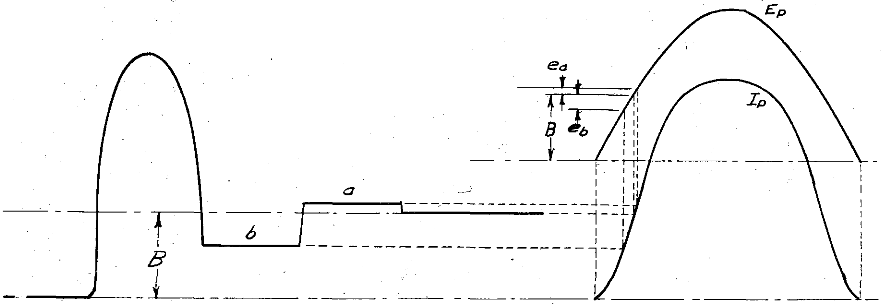


Fig. 9

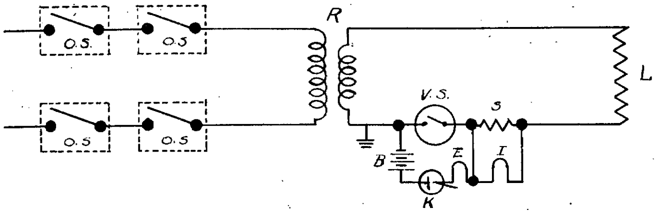
and also amplifies their magnitudes.

An accurate determination of arc voltage necessitates a rather careful calibration of the measurement circuit. This calibration however was very easily determined. The oscillograph vibrator was adjusted to a tension such that 100 milliamperes gave a deflection of the light beam on the film of 1.25 inches. This value was kept constant and frequently checked thruout all the tests with the exception of those made with tungsten contacts in the vacuum switch. A known voltage was impressed on the circuit of Figure 4 and an oscillogram taken. The filament current, constant for a particular film, was varied for other films so that a calibration curve was available for all filament current values used thruout the tests. The determination of the values of arc voltage was then made as follows: The record film and a calibration film with the same filament currents were placed one over the other so that their zero axes coincided. The measurement was then made as shown in Figure 9 in which Ep is the applied calibration voltage, Ip is the resulting plate current, B represents the bias voltage and e_a, e_b represent the positive and negative arc voltages respectively.

Current measurement was effected by two methods.

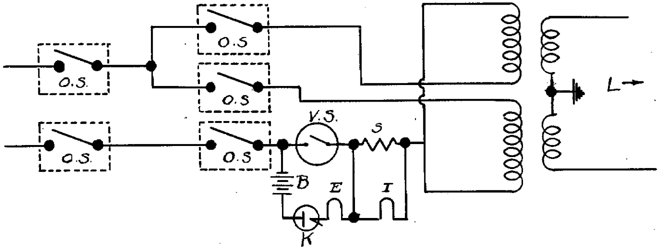
Readings were taken on an ammeter in series with the test circuit. Also one oscillograph vibrator was connected as shown in Figures 10,11,12, the shunt S having a known resistance. Knowing the vibrator deflection per milliampere and the resistance of the vibrator circuit the current thru the switch could easily be measured on the oscillogram. These two methods afforded a mutual check.

The accuracy of voltage measurement depends primarily on the accuracy of the oscillograph. The main source of error in this regard was the deflection of the vibrator per milliampere. This however was frequently checked and no variation was observed. The magnetic field of the oscillograph was normally near saturation and hence any minor variation of field current had negligible effect on the displacement. Resistance in the measurement circuit was negligible in comparison with the kenotron resistance, that is for the kenotron it was at least 100/.06 = 1670 ohms and for the remainder of the circuit 1 ohm. The film calibration brought in the greatest uncertainties. In order to obtain a clear record of all the arc phenomena fairly broad exposures were used, the width of the arc voltage lines being about 5 volts. However in the measurements of the displacements of the arc voltage lines from the bias voltage lines the centers

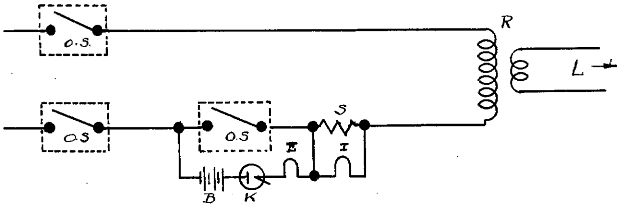


LOW VOLTAGE TEST CIRCUIT

OS F 33 Westinghouse Oil Circuit Breaker; R Voltage Regulators; B Bias Battery; VS Vacuum Switch; K Kenotron; E Oscillograph voltage element; I Oscillograph current element; S Calibrated shunt; L Load.



15000 VOLT TEST CIRCUIT



15000 VOLT TEST CIRCUIT

Fig. 10
Fig. 11
Fig. 12

of the exposures were used and no serious error resulted. The actual measurement indicated in Figure 9 was performed on a tracing table with accurate cross section paper ruled at 1/20 of an inch as a guide. The internal resistance of the bias battery has a known but negligible effect as can be shown by the following:

Voltage drop in battery = 3 volts per 100 ma.

Increase of bias ma.by arc voltage ma.= ± 20

$$\text{Correction in volts} = \frac{20 \times 3}{100} = \pm 0.6 \text{ volts.}$$

This correction was added or subtracted from the measured voltages. The results obtained then are considered accurate within ± 2.5 volts.

One can see from Figures 15 to 23 inclusive that the timing of the oscillograph shutter would have to be rather precise if the arc voltage record whose time duration may be less than .01 second is to appear on the oscillogram. This timing was accomplished by the use of auxilliary magnetic relays, time delay devices and tripping coils, the description of which would be too lengthy to include. Their action however synchronized the shutter and the switch operation.

In some of the tests the measurement circuit had to be insulated from ground and the disturbances introduced by its capacitance to earth had to be eliminated by careful shielding at appropriate points. These disturbances were due to surges that would destroy the oscillograph elements when the test circuit was closed in so that the arc voltage resulting from opening the switch under test would not be recorded. Figures 10,11,12 indicate the electrical set-up.

The vacuum switch used for these measurements was designed by F.C. Lindvall and consisted of a glass container into which two switch contacts were introduced. One of these contacts was rigidly mounted, the other was connected by a flexible metal silphon thus affording an external control of the switch. The switch was opened by the releasing of a stretched spring. The oil switch used was a standard F 33 Westinghouse 15,000 volt 600 ampere circuit breaker. This apparatus is part of the 1000 Kv control equipment.

The method of procedure was extremely simple due to the semi-automatic controls which synchronized the oscillograph and switch mechanisms. For instance, the circuit represented in Figure 10 was closed in by remotely controlled switches O.S. The mechanism for tripping V.S. and the shutter was put in motion. Switches O.S. were then immediately opened. Due to closing in current surges the oscillograph current element switch had to be closed in after switches O.S.

RESULTS

The results obtained are shown in the form of tables and oscillograms. Tables I, II, III, give measurements on the greater part of the films taken of the vacuum switch on the 3000 volt test circuit and 15,000 volt test circuit using copper contacts, and on the 3000 volt test circuit using tungsten contacts respectively. Table IV gives a partial summary of the results on the oil circuit breaker. Figures 13 to 16 inclusive are oscillograms taken on the 3000 volt test circuit using the vacuum switch with copper contacts. Figures 17 to 20 inclusive are those of the same switch on the 15,000 volt circuit. Figure 21 is an oscillogram of the switch with tungsten contacts. Figures 22 and 23 are results on the oil switch using the circuits of Figures 12 and 4.

DISCUSSION

An examination of Tables I, II, III, reveals the fact that the arc voltage existant when opening, in vacuum, outgassed metal contacts carrying current is essentially independent of the effective value of the current thruout the range investigated. However the instantaneous currents varied from 0 to 102 amperes for the copper contacts and from 0 to 177 amperes for tungsten contacts. This is evident from the oscillograms. These values correspond to current densities of 0 to 1340 amperes per square inch and 0 to 2560 amperes per square inch respectively assuming the current distribution to be uniform over the contact surfaces. Moreover the voltage is relatively low, varying from 10 to 25 volts. The latter fact seemingly excludes the explanation of the current conduction by electrons alone and requires positive charges to be present as a simple calculation will show. In this case the space charge equation for parallel plane electrodes[3] should give approximate values , should at least show orders of magnitude.

$$I = 2.33 \times 10^{-6} \frac{V^{3/2}}{X^2}.$$ Assume a typical case: $I = 1000$ amperes per square centimeter

$X = 0.1$ cm.

The arc voltage will be then 2.5×10^4 volts which is 1000 times the actual voltage measured. Consequently some other explanation is necessary.

Dr. K.T. Compton[4] proposes a definition of an arc which is as follows: "An arc is a discharge of electricity between electrodes in a gas or vapor which has a zero or negative volt ampere characteristic and a voltage drop at the cathode of the order of the minimum ionizing or exciting potential of the gas or vapor." All lines of evidence indicate that the essential feature of an arc of this type is the emission of electrons from the cathode which produces sufficient ionization to give a positive space charge immediately outside the cathode, thus facilitating a large electron emission at a low value of cathode drop. Compton gives evidence to show that Langmuirs'[5] theory of current at the cathode gives the most probable explanation of the arc phenomena. Prince and Vogies[6] give the application of the theory to mercury arc characteristics. In brief it is as follows:

The arc is initiated by the separation of a metal anode from the mercury cathode resulting in a characteristic cathode spot which serves as a source of a copious supply of electrons and mercury vapor. The electrons travel outward under the influence of the high electric field ionizing the vapor by collision at a short distance from the cathode. The positive ions so formed are accelerated to the cathode. Due to the differential of the velocities of the electrons and positive ions, the former being about 600 times the latter there results a positive ion space charge at a distance of the order of 10^{-4} millimeters from the cathode. Its presence is accompanied by an extremely high electric field strength, estimated as 10^6 volts per centimeter, which together with the high temperature of the spot enables the emission of an abundance of electrons at a relatively low value of cathode drop. The current then is conducted by positive ions and electrons, their action being such as to make the arc self-sustaining. The high temperature of the spot is accounted for by the losses in the spot due to the positive ion bombardment. The current density at the spot in mercury arcs is about 4000 amperes per square cm. and the cathode drop has a value of 9 volts[7].

It is interesting to apply the above theory to the vacuum switch. In this case the arc has the same characteristics as those in Compton's definition. The arc voltage measured is of the same order as the minimum exciting potential of the copper vapor which is 7.7 volts from spectroscopic data. The arc has approximately a zero volt ampere characteristic. The cathode spot is formed by the separation of the contacts appearing on the contact that happens to be the cathode at the instant of opening. Its presence is to be expected, and has indeed been observed, since the last point of contact is extremely hot and hence a source of electrons, ions and neutral metal vapor. The electrons in accordance with the above theory travel outward and ionize the vapor forming a positive space charge sheath at a very short distance from the cathode spot. When the current passes thru its zero value the cathode spot vanishes and cannot appear on the opposite electrode for the succeeding half cycle unless some mechanism is present to introduce it. The metal vapor, present during the arc in the form of electrons, positive and negative ions and neutral molecules possessing high kinetic energy, is immediately neutralized and condensed on the walls of the tube when the current reaches its zero value. In general therefore the vacuum switch in good condition, (that is, having properly outgassed contacts and very little residual gas present), affords no such mechanism.

The oscillograms taken on the vacuum switch, Figures 13 to 21 inclusive, indicate that the cathode spot is brought into existance without any high transient voltages. The arc voltage in all cases rises immediately to a steady value of 10 to 20 volts and remains until the current has nearly reached a zero value. In all cases except two shown, Figures 19 and 20, the arc has disappeared at the first zero current value, an occurrance which is to be expected from previous experience with the switch and is in accord with the considerations pointed out above. The exceptions may be explained as due to the presence of relatively large gas pockets in the metal electrodes which when tapped during the process of switching furnish the medium for a gas discharge and a mechanism for the re-establishment of the cathode spot. If this occurs it would be expected that the voltage across the gas discharge would be high for the current values at the time in question, i.e. current densities at the cathode of the order of amperes per square cm.[8]

Figures 19 and 20 give evidence as to the correctness of the above explanation. The current values after the extinction of the cathode spot and before its reappearance on the other contact are relatively low. The voltage across the switch contacts is seen to be relatively high. On the formation of the cathode spot for the second half cycle the arc voltage drops to a value of 25 volts and the current endeavors to build up to its normal value. The increase of the arc voltage for the second half cycle over that of the first may be due to the greater separation of the contacts and accordingly a greater positive column drop.[9]

An effect which is noticed on a close examination of Figures 13 to 21 inclusive is that the current wave in approaching its final zero value exhibits a disturbance and decays rapidly from its normal form.

This is accompanied by a sharp increase in the arc voltage. The cathode spot theory may account for this behavior. When the current approaches a zero value the cooling action of the metal surrounding the cathode spot overcomes the heating action of the arc causing a rapid disappearance of the cathode spot and a consequent rapid decrease in the current. The voltage impulse is then due to the reversion of the arc to a glow[10] discharge condition or some other condition having a characteristic high voltage.[8] This phenomenon suggests that the vacuum switch does not exhibit the same characteristics on low currents as on high currents. In some of the first attempts to measure arc voltage small currents were used, currents of the order of 3 or 4 amperes effective. Switching these currents was accompanied by high voltage surges which invariably damaged the oscillograph elements. As yet no attempt to obtain records of vacuum switch operation has been successful for low current values.

Another feature of the oscillograms taken on the 15,000 volt low power factor circuit which may cause question is the fact that when the current is finally interrupted the voltage across the switch does not immediately reach its normal line voltage value but exhibits a time lag of .0001 sec. or so. In a purely self-inductive circuit where the applied voltage is balanced at every instant by the voltage of self-induction the lag would not be expected. However in the actual case the load consisted of the 1000 KV.cascade connected transformer set and was consequently not a simple inductance. The out of phase currents in the transformers develop back voltages thru mutual induction which explains the presence of the time lag of the voltage across the switch.

DISCUSSION OF OIL SWITCH RESULTS

The operation of an oil circuit breaker is characterized by the same major phenomena that have been discussed in connection with the vacuum switch. Secondary effects are however more important in an oil switch such as the extremely high local pressures developed when the arc energy vaporizes the oil. The theory of oil switch operation is very completely presented in Rudenburg's Elektrische Schaltvorgänge. The criterion for successful switch operation is given as follows: If after the first arcing period the restriking value of voltage exceeds at all times the voltage applied across the switch the circuit willbe successfully interrupted. In general the restriking value does not exceed the impressed voltage for several cycles after the contacts have separated. It depends moreover on the condition of the oil and the thermal constants of the metal electrodes and therefore in general on the arc energy.

In contrast with the vacuum switch characteristics the oil switch exhibits very much higher values ofarc voltages as Figures 22 and 23 and Table IV show. In making oil switch records the use of the bias voltage in the measuring circuit was not convenient and hence

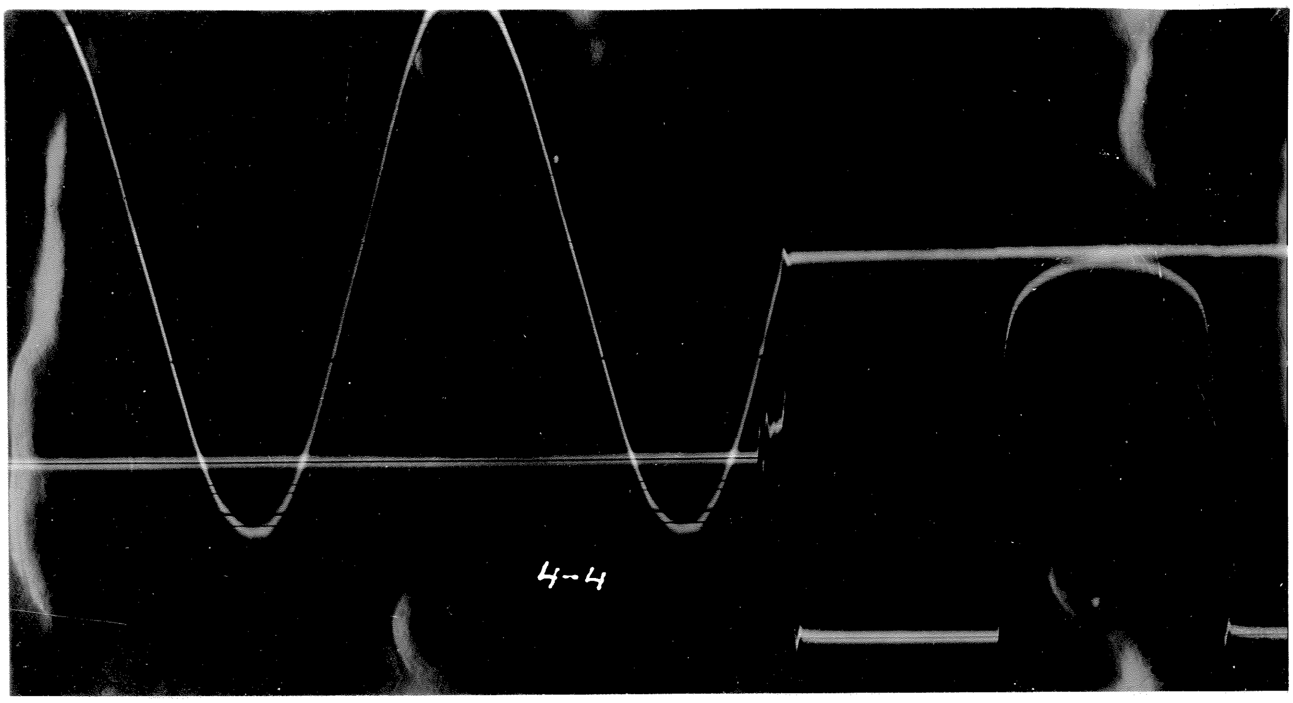


Fig. 13 Table I (4)

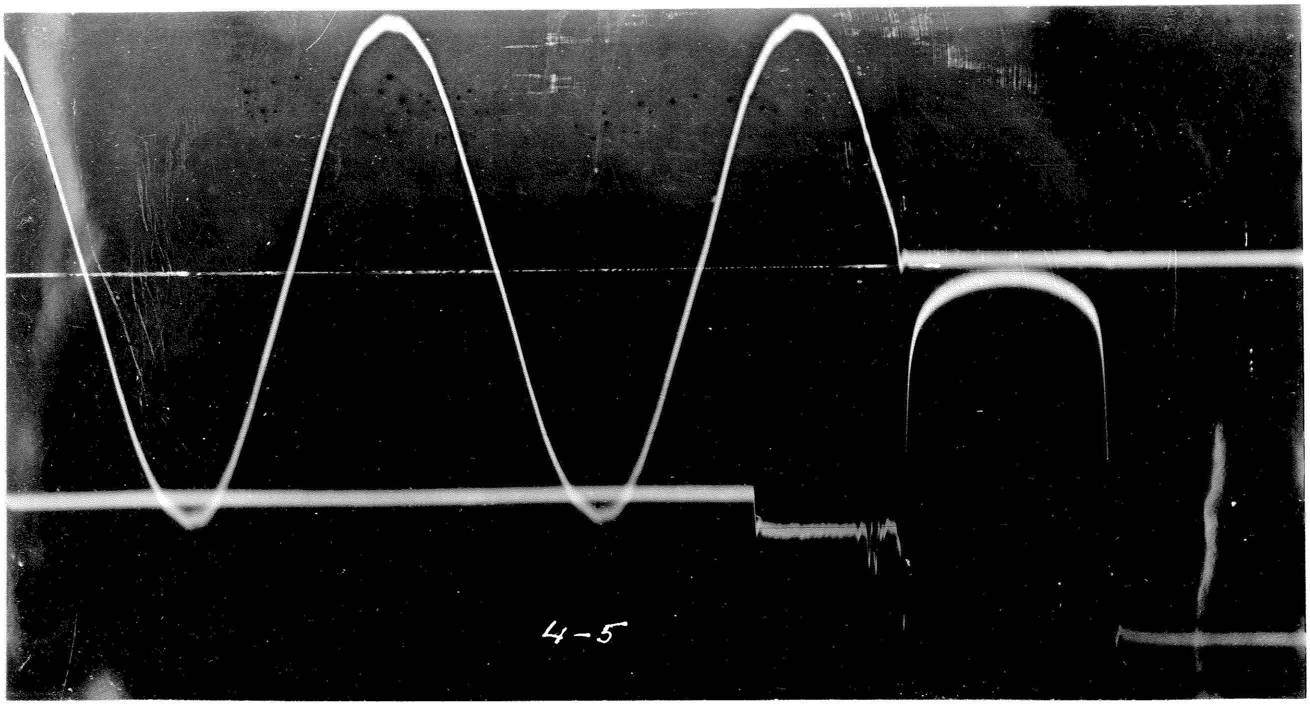


Fig. 14 Table I (5)

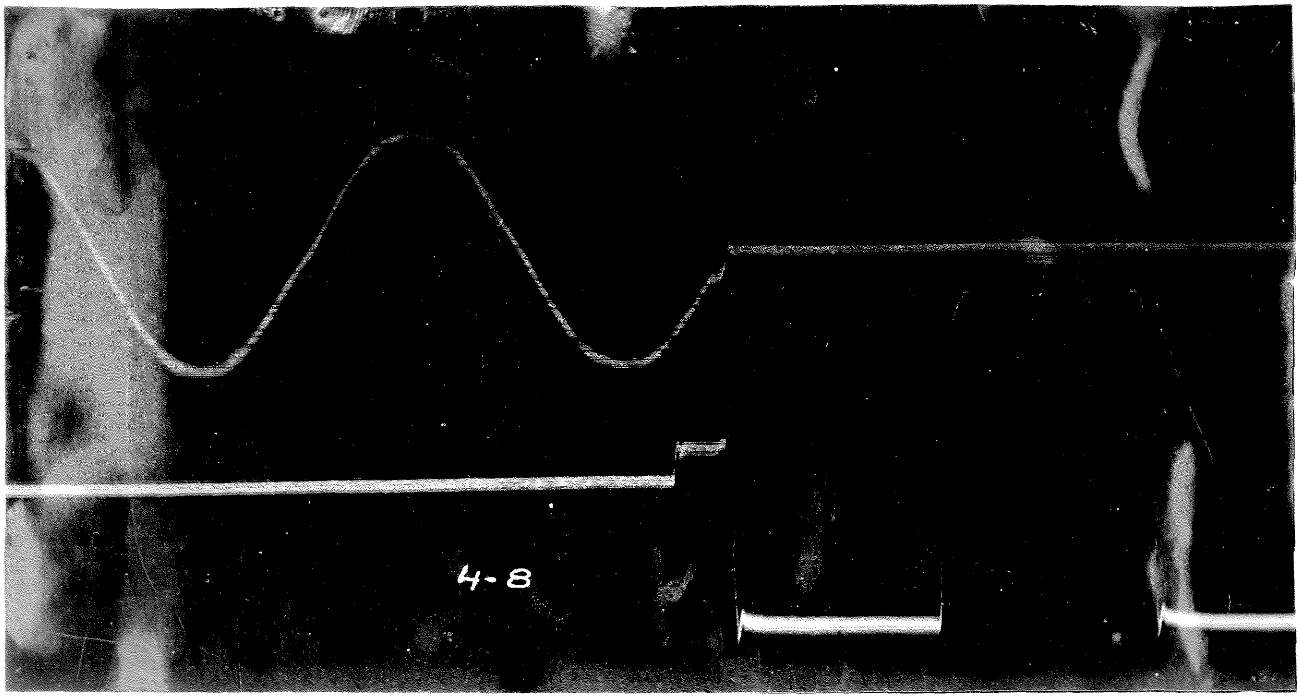


Fig. 15 Table I (8)

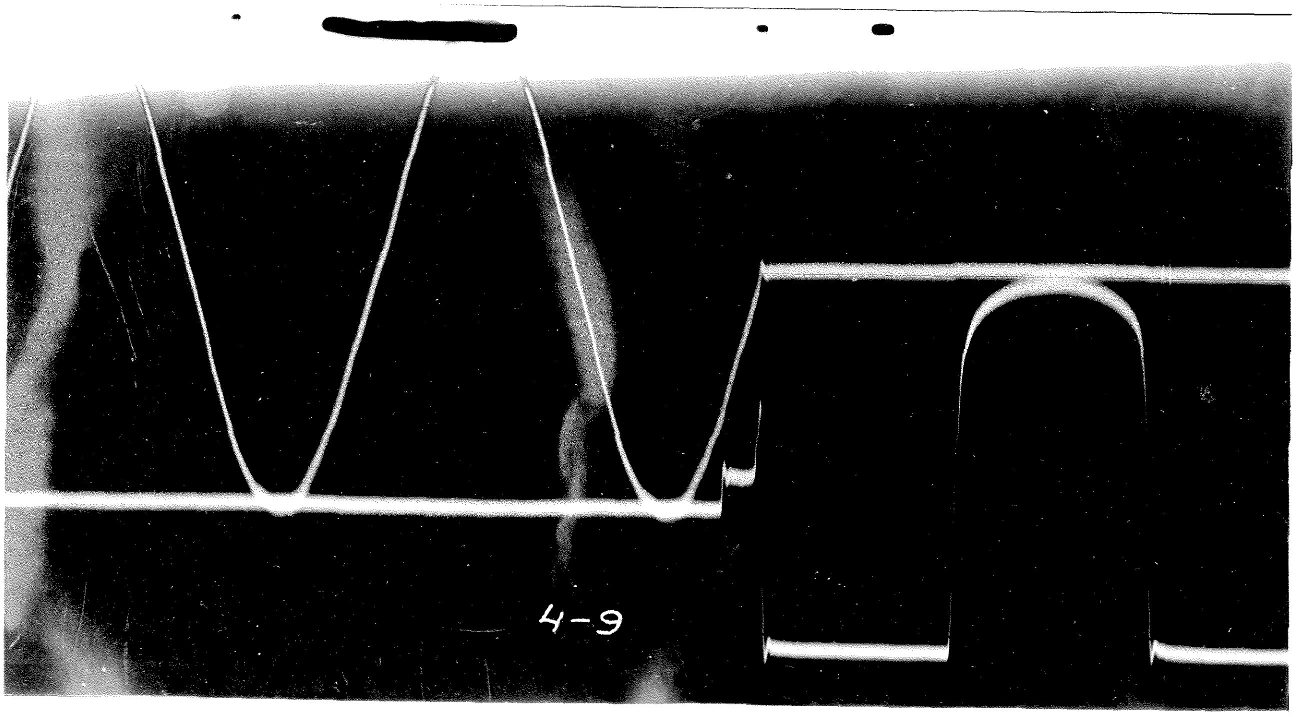


Fig. 16 Table I (9)

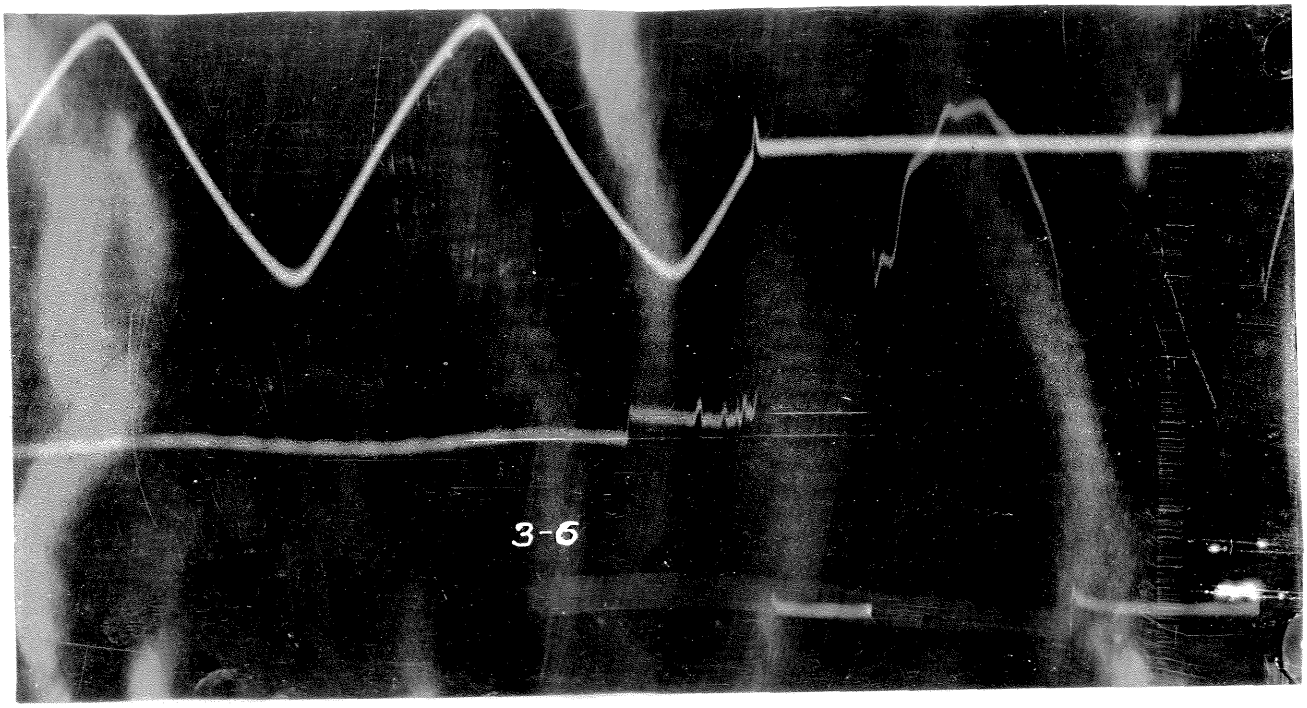


Fig. 17 Table II (2)

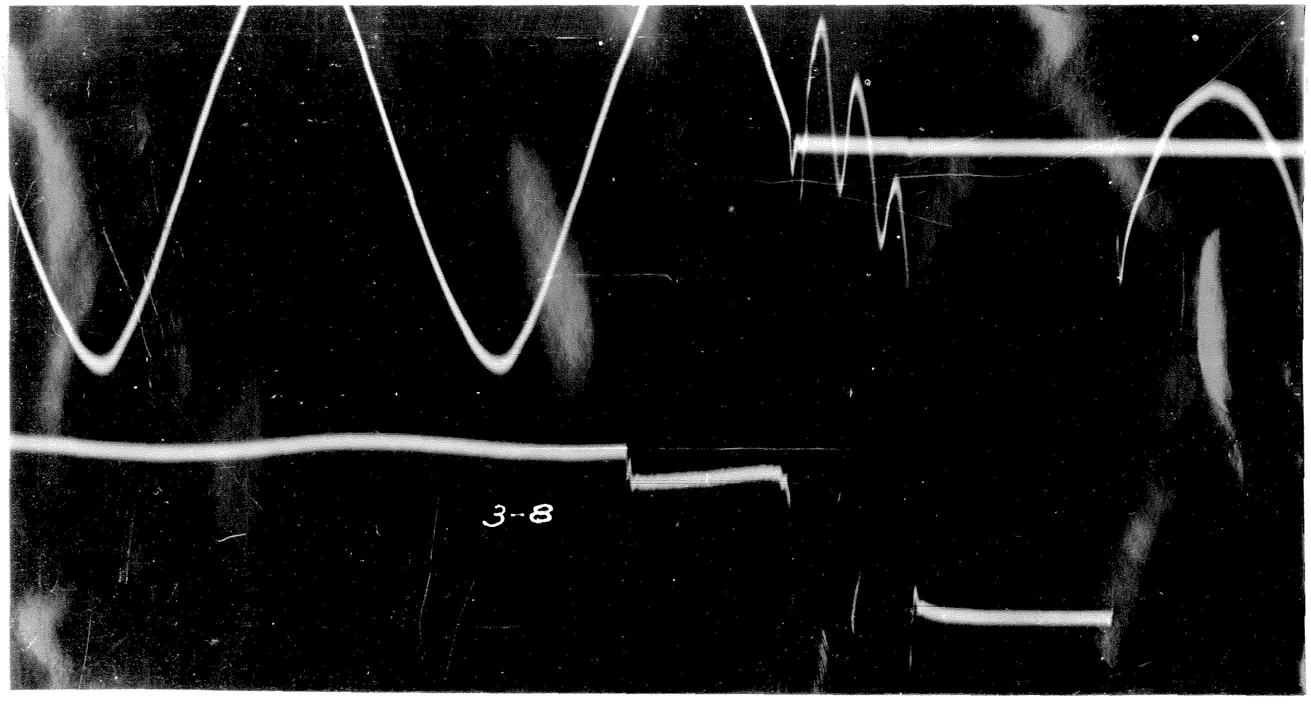


Fig. 18 Table II (3)

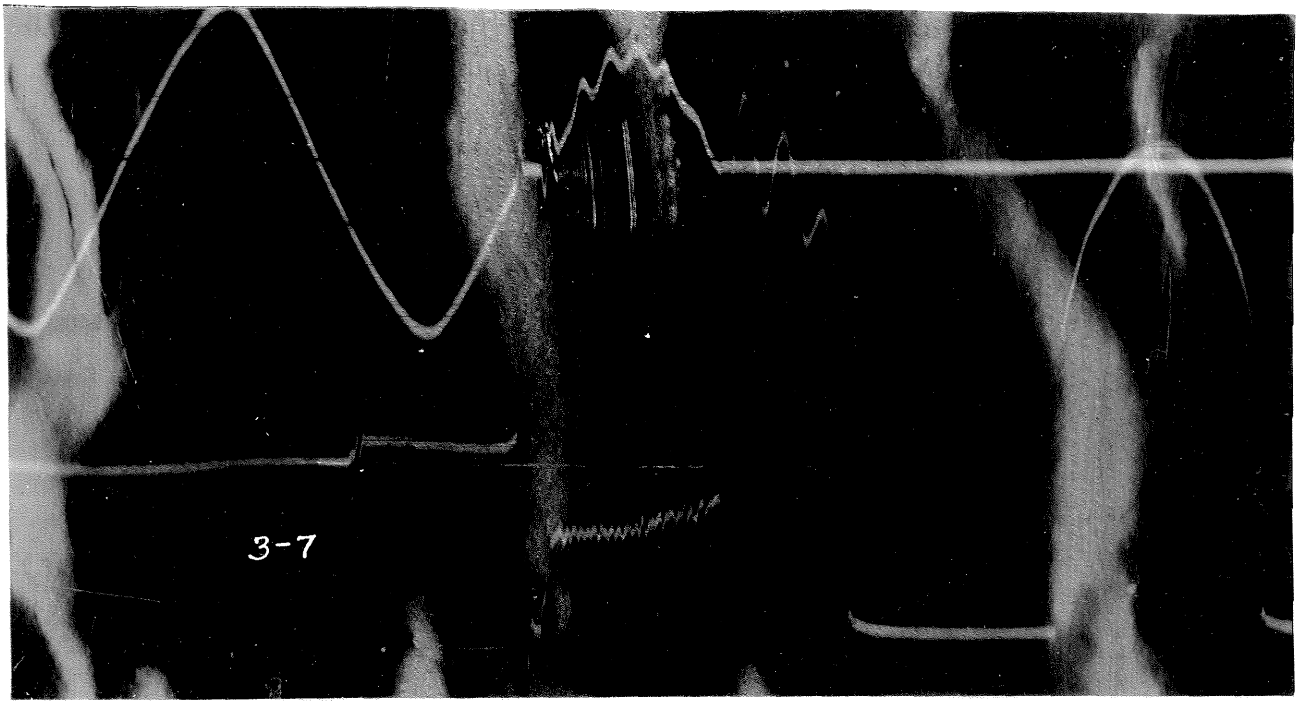


Fig. 19 Table II (4)

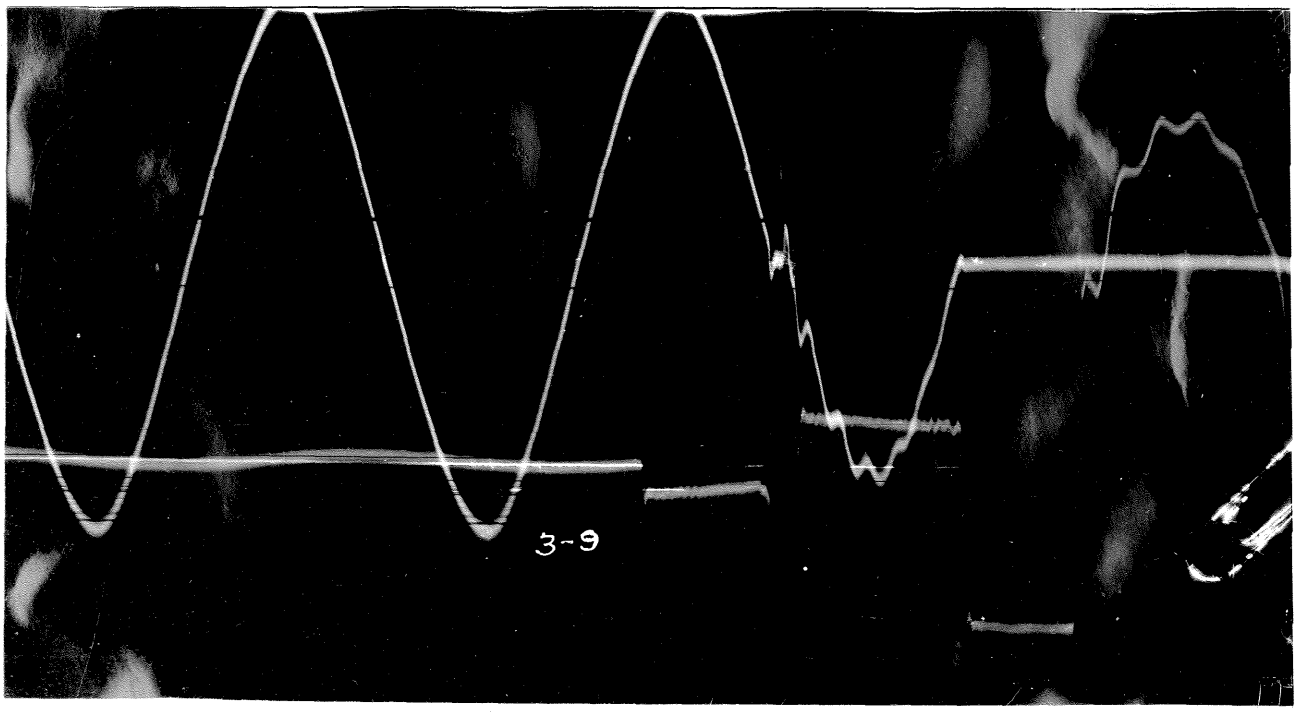


Fig. 20 Table II (5)

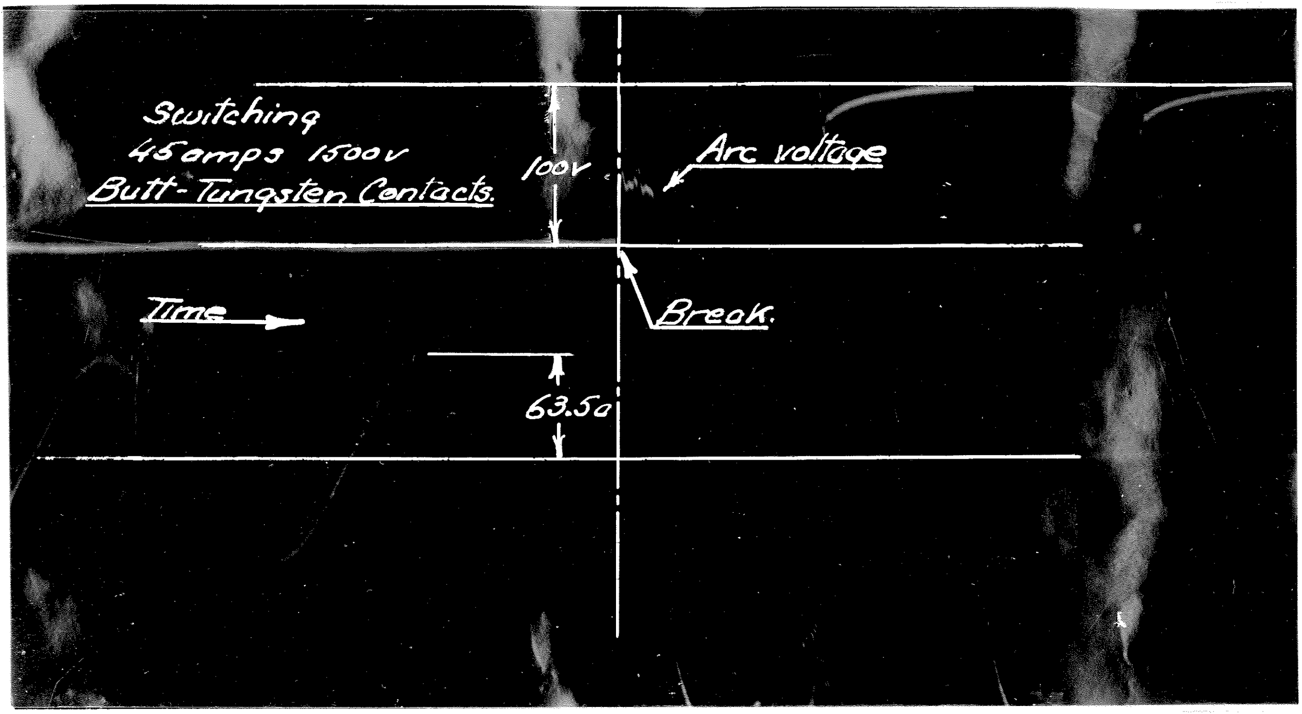

Switching
45 amps 1500v
Butt-Tungsten Contacts.
100v
Arc voltage
Break.
Time
63.5a

Fig. 21

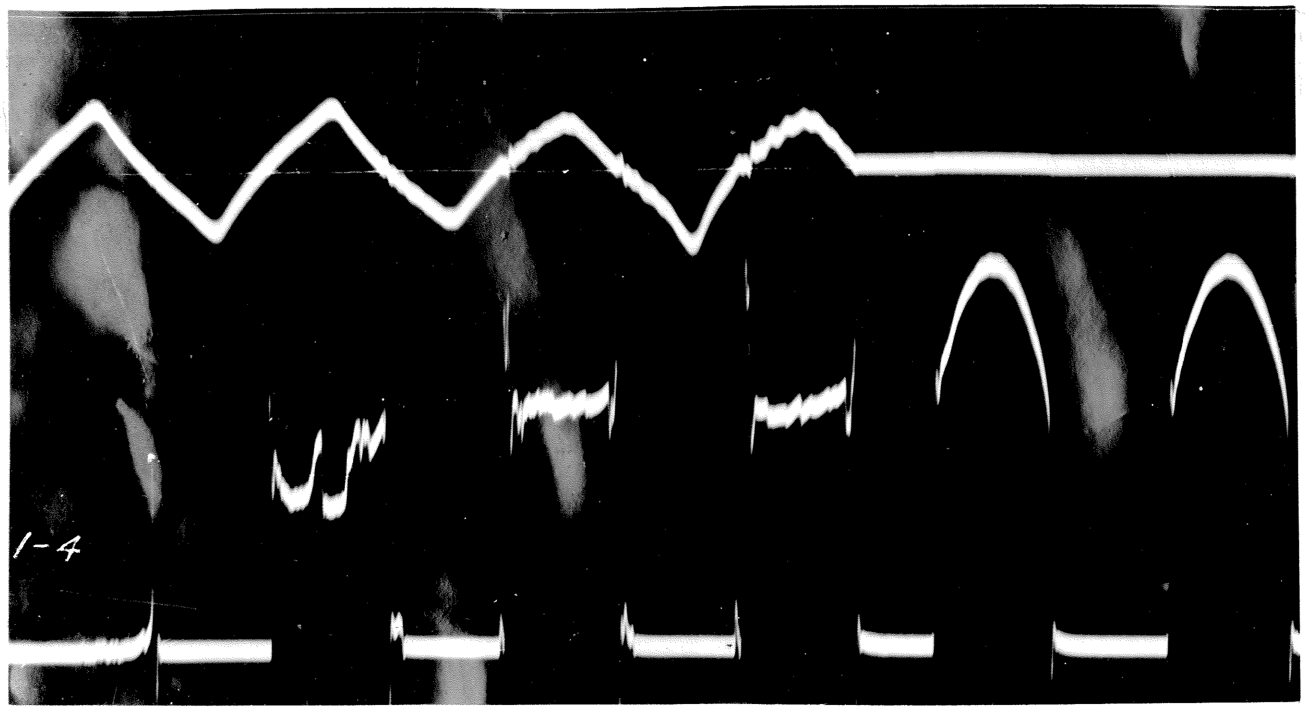


Fig. 22 Table IV (1)

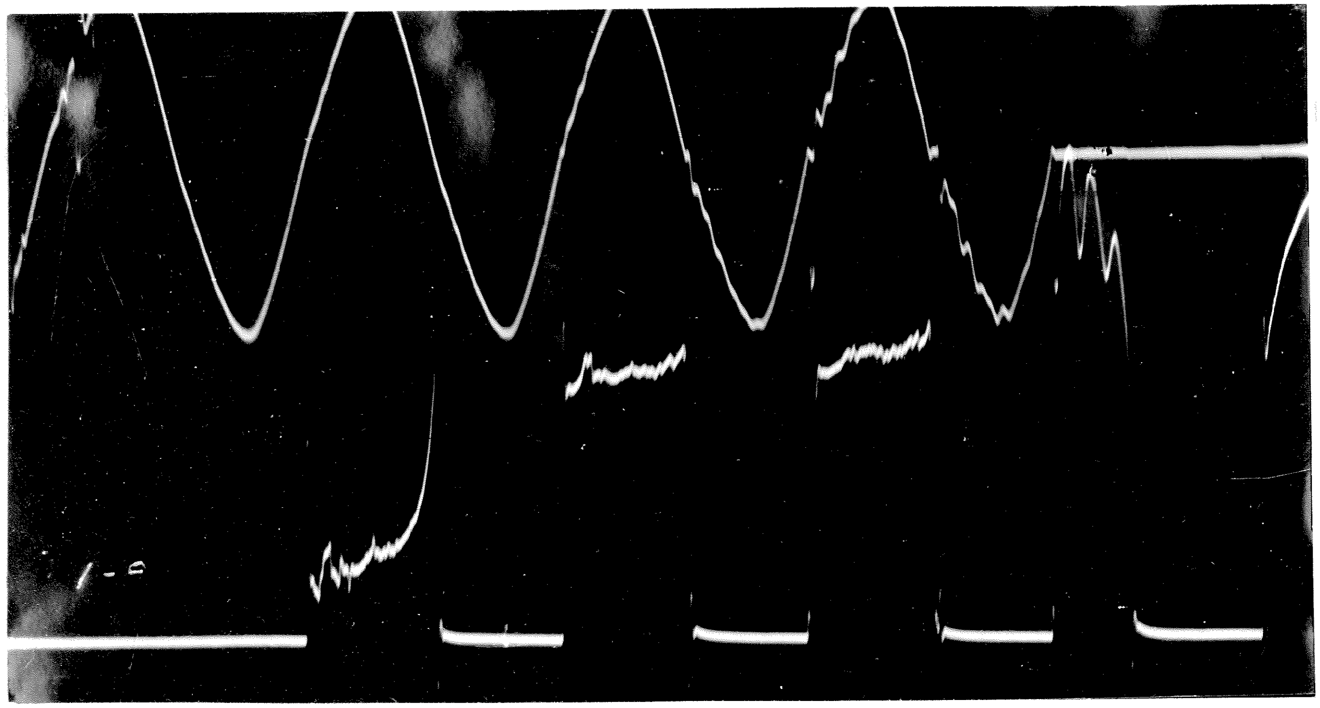


Fig. 23 Table IV (2)

the circuit of Figure 4 rather than Figure 7 was employed. The oil switch records give data on alternate half cycles. A preliminary examination of the oil switch oscillograms brings to light two facts. First: the arc is not extinguished on the first zero current value. Second: the arc voltage is more or less independent of the arc current. The first conclusion is evident; the second however needs supporting data. In view of this necessity the switch travel as a function of time was determined. Noting the data in Table IV(2) the arc voltage increased from 190 to 215 volts; the contact separation from 0.9 inches to 1.25 inches. The former is an increase of 10%, the latter 39%. During this time the current varied from 0 to 79 amperes. It seems evident therefore that the increase in arc voltage is due rather to increased arc length than change in current strength. This is to be expected however in view of the fact that the current density in the arc tends to remain constant[2] and varying current is accompanied by varying arc cross section. The arc voltage depends on current density and not on total current.

There are available for oil switches two equations for calculating arc energy. The first is an empirical equation by Charpentier

$$A = f\ E\ I\ t.$$

in which A = energy, f = const., E = effective voltage across switch after opening; I = effective current before opening and t is the duration of arc. Charpentier gives for f a value of .03 to .07. The value of f is calculated from measurements of film and are shown in Table IV. It is noted that the values of f in the table are lower than those given by Charpentier but approach them when higher currents are broken.

Rudenburg has derived an equation similar to Charpentier's employing certain assumptions. It is:

$$A = \frac{1}{\pi} \frac{e_b}{e_z} E\ I\ t$$

in which A = energy; e_b = arc voltage assumed a linear function of contact separation; e_z = restriking voltage also assumed a linear function of contact separation; E = maximum voltage after arc extinction; I = maximum current before extinction; t = duration of arc. In Table IV the value of e_z has been calculated from the records and in all cases has a reasonable value.

CONCLUSIONS

The circuit developed provides an excellent means of measuring transient low voltage phenomena on a high voltage circuit with an accuracy comparable with that of a commercial meter. In this work it provided a device with which the relatively low arc voltage with all its variations was made easily discernible even though a voltage 1000 times greater followed immediately.

The results obtained on the vacuum switch establish two facts. The arc voltage proper is low and of the order of 10 to 25 volts. The arc voltage is independent of the current for the higher values but increases greatly for low currents. The theory based on the existance of a cathode spot explains the action of the switch in a reasonable way and seemingly is in accord with all the observed phenomena.

It is interesting to compare the relative energies involved in the operation of the oil and vacuum circuit breaker for the same value of voltage and current. Comparing a typical value in Table IV(2) with a corresponding one in Table II(3),

	Vacuum Switch	Oil Switch
I_{rms}	58.1 amp.	56 amp.
E_{line}	16.2 Kv.	16.2 Kv.
Time	0.008 sec.	0.05 sec.
Energy	7.2	552

$$\text{Ratio of energies} = \frac{552}{7.2} = \quad 77 \text{ to } 1$$

REFERENCES

1. R.W. Sorenson and H.E.Mendenhall, Journal A.I.E.E., December, 1926
2. R. Rudenburg, Elektrische Schaltvorgänge; Springer
3. I. Langmuir, Phys. Rev. N.S. Vol.2, Dec. 1913
4. K.T.Compton, Journal A.I.E.E., Nov. 1927
5. I. Langmuir, G.E. Review, 1923
6. Prince & Vogies, Mercury Arc Rectifiers & Circuits
7. Gunther-Schultz, Engineering Progress, Aug. 1925
8. Seeliger, Phys.Zeit. 27 1926
9. Karl Darrow, Contemporary Physics, Van Nostrand
10. Hull & Berger, Bulletin of American Phys. Soc. Apr.7, 1928

J. Slepian Journal A.I.E.E., Dec. 1926

TABLE I

Test of Vacuum Switch on 3000 Volt Circuit. Fig. 10
Copper butt contacts. Area -------- 0.03 sq.ins.

No.		1	2	3	4	5
Line Current	rms.	50	40	30	65	60
	av.	45	35	27	60	55
	peak	70.7	56.5	42.5	92	85
Line Voltage	rms.	1300	1100	1000	1050	1100
Power Factor		1	1	1	1	1
Arc Voltage	av.	15	0	20	18	20
Arc Duration	secs.	.003	0	.01	.0013	.0075
Arc Energy	watt secs.	2.02	0	5.4	1.4	8.25

No.		6	7	8	9	10
Line Current	rms.	32.5	30	30	60	60
	av.	30	27	27	55	55
	peak	46	42.5	42.5	85	85
Line Voltage	rms.	1300	800	1000	1100	1100
Power Factor		1	1	1	1	1
Arc Voltage	av.	17	15	15	15	20
Arc Duration	secs.	.0038	.005	.0024	.0016	.0075
Arc Energy	watt secs.	1.9	2.02	1.00	1.32	8.25

TABLE II

Test of Vacuum Switch on 15000 Volt Circuit. Fig. 11
Copper butt contacts. Area -------- 0.03 sq. ins.

No.		1	2	3	4		5	
					a	b	a	b
Line Current	rms.	3	31	58	45	31	72	56.8
	av.	2.5	43	53	41	28	65	51
	peak	5	49	82	64	44	102	80.3
Line Voltage	kv. rms.	16	16	16	16	16	16	16
Power Factor		low	.04	.29	.32		.19	
Arc Voltage	av.	14	10	17	10	25	17	25
Arc Duration	secs.	.0011	.006	.008	.008	.008	.0063	.0084
Arc Energy	watt secs.	.0039	2.6	7.16	3.28	5.6	6.93	10.8

TABLE III

Test of Vacuum Switch on 3000 Volt Circuit. Fig. 10
Tungsten butt contacts. Area --------- 0.011 sq. ins.

No.		1	2	3	4	5	6	7
Line Current	rms.	45	45	75	125	125	72	72
Line Voltage	rms.	1500	1500	1800	1800	1800	1800	1800
Arc Voltage	av.	21	22	0	22	22	0	0

TABLE IV

Test of Oil Circuit Breaker on 15000 Volt Circuit. Fig. 12

No.		3				
Half cycle		1	3	5	7	
Current	rms.	27	27	26	17	Power Factor 0.24
	max.	46	46	44	27	
Arc Voltage	av.	20	120	150	165	
	Io	0	135	150	150	
	Imax.	---	125	160	155	Total Energy 100 watt secs.x 2
	Io	70	145	160	170	
Reignition	calc.	12000	12000	11000	10000	
Voltage	obs.	---	170	2000	2000	
Energy Coefficient (f)			.007	.009	.007	
Contact Separation ins.		0-.175	.65-1.0	1.35-1.65	1.95-2.17	

No.		4			
Half cycle		1	3	5	
Current	rms rms.	45.5	45.5	40.5	Power Factor 0.37
	max.	66	66	58	
Arc Voltage	av.	---	172	190	
	Io	---	160	185	
	Imax.	---	170	190	
	Io	---	185	200	Total Energy 155 watt secs.x 2
Reignition	calc.	---	9400	9250	
Voltage	obs.	---	2000	2000	
Energy Coefficient (f)		---	.011	.013	
Contact Separation	ins.	0-.5	.9-1.25	1.6-1.9	

TABLE IV

Test of Oil Circuit Breaker on 15000 Volt Circuit. Fig. 12

No.				1 Fig. 22		
Half cycle		1	3	5	7	
Current	rms.	18	17	14	13	Power Factor .34
	max.	28	27	24	22	
	av.	50	135	170	170	
Arc	Io	0	175	>500	>500	
Voltage	Imax.		110	165	170	Total Energy 70 watt secs.x 2
	Io	135	160	210	250	
Reignition	calc.		7500	11000	11000	
Voltage	obs.		>200	>2000	>2000	
Energy Coefficient	(f)		.0085	.0088	.0082	
Contact Separation	ins.	0-.3	.7 - 1.1	1.4-1.7	2-2.2	

No.				2 Fig 23		
Half cycle		1	3	5	7	
Current	rms.	56	55	54		Power Factor .28
	max.	79.5	79	78		
	av.	100	195	210		
Arc	Io	175	190	195		
Voltage	Imax.	70	190	205		Total Energy 276 watt secs.x 2
	Io	200	215	235		
Reignition	calc.	6500	9000	9200		
Voltage	obs.	>200	>2000	>2000		
Energy Coefficient	(f)	.0066	.0128	.0133		
Contact Separation	ins.	0-.5	.9-1.25	1.6-1.9		