APGAR & McDERMET

A Study of Mutual Inductance in Coils by Transient Effect

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A STUDY OF MUTUAL INDUCTANCE IN COILS BY TRANSIENT EFFECT

BY

LEO MAHLON APGAR
AND
RUDOLPH McDERMET

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

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May 28, 1902

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

LEO MAHLON APGAR AND RUDOLPH MC DERMET

ENTITLED A STUDY OF MUTUAL INDUCTANCE

IN COILS BY TRANSIENT EFFECT

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

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THE STUDY OF MUTUAL INDUCTANCE IN COILS

BY

TRANSIENT EFFECT.

I. INTRODUCTION.

It is customary in the study of mutual inductance in coils to employ alternating currents; it is the purpose of this thesis, however, to investigate the feasibility of studying the same phenomena by the use of direct current. In other words it is proposed to investigate by oscillographic records the transient effect induced in one circuit by a definite non-periodic variation of current in another circuit, the magnetic fields of which are mutuallyinterlinked thru air paths.

This investigation is not concerned with measurements of more precision than can ordinarily be obtained with an oscillograph. Itwill also be facilitated by the employment of coils exactly similar in form and with identical electric constants. Under such conditions it is possible to foretell the transient variation in the current of one circuit under a known variation of the current in the second circuit. It has been proved by experience and is reasonable to expect that the condition most easily and accurately controlledis that of complete and sudden interruptionof a continuous unvarying current in one circuit. The problem,therefore, resolves itself into the comparison of oscillographic records with curves plotted from theoretical considerations and such deductions as may be made therefrom.

II. THEORY.

The electromotive force impressed on any series circuit

may be expressed by an equation of the form:

(1) $$e = r\,i + X\frac{d\,i}{d\,\theta} + x_c\int i\,d\,\theta$$

Where e = e.m.f.

r = Ohmic resistance.

$x = 2\pi fL$ = inductive reactance.

$x_c = \frac{1}{2\pi fC}$ = Condensive reactance.

L = Inductance.

C = Capacity.

f = Frequency.

If instead of the variable "θ" the variable time "t" be introduced and the relation between the variables is defined as:

$$\theta = 2\pi ft.$$

the equation reduces to the form:

(2) $$e = r\,i + L\frac{di}{dt} + C\int i\,dt.$$

In equation (2) both "L" and "C", while defined as the inductance and capacity respectively, are, in reality proportionality factors representing the stored energy in the magnetic and dielectric fields in space. In usual circuits at normal voltages the dielectric energy represented by the constant "C" will be entirely insignificant.

If, however the magnetic flux produced by the current is interlinked not only with its own circuit, but also with another circuit, such that by its change, it generates an e.m.f. in the second circuit, and part of the flux produced by the current accompanying this e.m.f. is interlinked with the first circuit, and by its changes produces reactions in it; then this equation no longer holds and must be increased by another quantity.

(3) $$e_1 = r_1 i_1 + L\frac{di_1}{dt} - M\frac{di_2}{dt} + C\int i_1 dt.$$

As long as air paths alone are involved, current and flux are

exactly related and observe the same rate of variation. The defferentials $\frac{"di"}{dt}$ and $\frac{"d\phi"}{dt}$ (where ϕ = flux) may therefore be used interchangeably with the proper constants.

In equation (3) "M" is defined as the mutual inductance between the circuits: that is, the number of interlinkages of one circuit with the flux produced by the second circuit, "i_1" being the current in one and "i_2" being the current in the other circuit. It is thus seen that the flow of current can never be utterly independent of the currents in adjacent circuits. Equation (3) is therefore perfectly general and applies to all circuits whose physical constants do not vary from instant to instant. If the circuit contains only infinitesmal capacity (3) reduces to the form of (4).

(4) $$e_1 = r_1 i_1 + L\frac{di_1}{dt} - M\frac{di_2}{dt} .$$

In both (3) and (4) the question of algebraic sign is entirely a matter of convention and convenience. The negative sign appearing before "M" is intended to show that the two currents are relativly in opposite directions.

Diagramaticaly it is customary to represent the mutual inductance between the two circuits by two coaxial coils "M M" while the self inductance is shown by a single coil and the resistance by a zig-zag line as in fig. I.

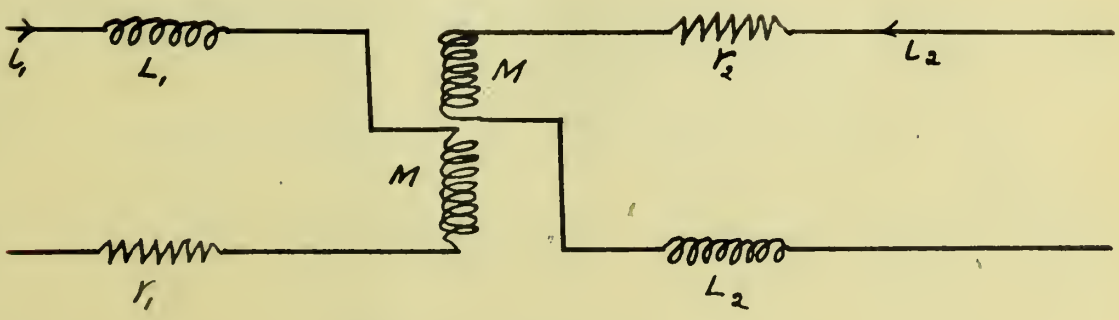


Fig 1

The notation of Fig. (I) will be observed in the equations which follow.

With the aid of equation (4) the circuit conditions of figure (I) may be completely expressed.

$$e_1 = r_1 i_1 + L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \quad . \tag{5}$$

$$e_2 = r_2 i_2 + L_2 \frac{di_2}{dt} - M \frac{di_1}{dt} \quad . \tag{6}$$

By the fundamental operations of algebra and calculus it is the intention to convert equations (5) and (6) into a single simpler form which shall express the relation between the current "i_2" and the time "t".

Differentiating (6) and considering "e_2" as a constant

$$0 = r_2 \frac{di_2}{dt} + L_2 \frac{d^2 i_2}{dt^2} - M \frac{d^2 i_1}{dt^2} \tag{7}$$

Solving (5) for "$\frac{di_2}{dt}$"

$$\frac{di_2}{dt} = \frac{-e_1 - r_1 i_1 - L_1 \frac{di_1}{dt}}{M} \tag{8}$$

Differentiating (8)

$$\frac{d^2 i_2}{dt^2} = \frac{1}{M}\left[r_1 \frac{di_1}{dt} + L_1 \frac{d^2 i_1}{dt^2}\right] \tag{9}$$

Substituting both (8) and (9) in (7)

$$0 = \frac{-r_2}{M}\left[e - r_1 i_1 - L_1 \frac{di_1}{dt}\right] + \frac{L_2}{M}\left[r_1 \frac{di_1}{dt} + L_1 \frac{d^2 i_1}{dt^2}\right] - M \frac{d^2 i_1}{dt^2} \tag{10}$$

Transposing into standard differential form,

$$\left[\frac{L_1 L_2 - M^2}{M}\right] \frac{d^2 i_1}{dt^2} + \left[\frac{L_1 r_2 + L_2 r_1}{M}\right] \frac{di_1}{dt} + \frac{r_1 r_2 i_1}{M} = \frac{r_2 e_1}{M} \tag{11}$$

$$(L_1 L_2 - M^2) \frac{d^2 i_1}{dt^2} + \left[L_1 r_2 + L_2 r_1\right] \frac{di_1}{dt} + r_1 r_2 i_1 = r_2 e_1 . \tag{12}$$

$$\frac{d^2 i_1}{dt^2} + \left[\frac{L_1 r_2 + L_2 r_1}{L_1 L_2 - M^2}\right] \frac{di_1}{dt} + \frac{r_1 r_2 i_1}{L_1 L_2 - M^2} = \frac{r_2 e_1}{L_1 L_2 - M^2} \tag{13}$$

Equation (13) is a standard integration form. It involves complicated constants, however, and the further develcpement

will be facilitated by the substitution of the form:

$$(14)\ \frac{d^2y}{dt^2} + 2C\frac{dy}{dx} + ay + b = 0$$

$$C = \frac{L_1 r_2 + L_2 r_1}{2(L_1 L_2 - M^2)}$$

$$a = \frac{r_1 r_2}{L_1 L_2 - M^2}$$

$$b = \frac{-r_2 e_1}{L_1 L_2 - M^2}$$

Equation (14) may most easily be integrated by the substitution:

$$z = \frac{b}{a} + y$$

From the relation above,

$$\frac{dz}{dx} = \frac{dy}{dx}$$

$$\frac{d^2z}{dx^2} = \frac{d^2y}{dx^2}$$

By these substitutions (14) is converted into (15).

$$(15)\qquad \frac{d^2z}{dx^2} + 2C\frac{dz}{dx} + az = 0$$

Equation (15) is integrated by the equation:

$$z = A\varepsilon^{-kx}$$

A = Integration Constant.

k = Constant.

ε = Base Naperian Logarithms.

$$\frac{dz}{dx} = -kA\varepsilon^{-kx}$$

$$\frac{d^2z}{dx^2} = k^2 A\varepsilon^{-kx}$$

Equation (15) in the integrated form is, therefore:

$$(16)\qquad A\varepsilon^{-kx}(k^2 - 2ck + a) = 0$$

Equation (16) can be true only on the condition that the quantity within the parenthesis shall be equal to zero.

$$(16a)\qquad k^2 - 2ck + a = 0.$$

Equation (16a) is a pure quadratic having two real roots.

$$k_1 = c + \sqrt{c^2 - a}$$

$$k_2 = c - \sqrt{c^2 - a}$$

Equation (15) in the integrated form is then:

(17) $$z = A_1\epsilon^{-k_1x} + A_2\epsilon^{-k_2x}$$

(18) $$y = A_1\epsilon^{-k_1x} + A_2\epsilon^{-k_2x} - \frac{b}{a}$$

(19) $$i_1 = \frac{e_1}{r_1} + A_1\epsilon^{-k_1t} + A_2\epsilon^{-k_2t}$$

By a precisely similar cycle of operations beginning with equation (5) an expression for "i_2" may be developed.

(20) $$i_2 = \frac{e_2}{r_2} + B_1\epsilon^{-k_1t} + B_2\epsilon^{-k_2t}$$

Both equations (19) and (20) involve integration constants "A_1, A_2, B_1, B_2" which must be determined. Obviously the terms "$\frac{e_1}{r_1}$" and "$\frac{e_2}{r_2}$" represent stationary conditions of current intensity and must not be confounded with the transient effect.

In the determination of the integration constants in (19) and (20) it is necessary to direct attention at the conditions in the circuits which exist at any arbitrary chosen instant. One of these instants may conveniently be that from which time was counted. The following relations are then apparent if the transient in the second circuit is to appear at "make".

$$t = 0 \qquad i_1 = 0 \qquad i_2 = 0$$

This is in accordance with the assumption made regarding the measurement of time. Solving equations (19) and (20) with these substitutions:

$$A_2 = -(A_1 + I_1) \qquad I_1 = \frac{e_1}{r_1}$$

$$B_2 = -(B_1 + I_2) \qquad I_2 = \frac{e_2}{r_2}$$

(21) $$i_1 = I_1 + A_1\epsilon^{-k_1t} - (A_1 + I_1)\epsilon^{-k_2t}$$

(22) $$i_2 = I_2 + B_1\epsilon^{-k_1t} - (B_1 + I_2)\epsilon^{-k_2t}$$

Multiplying equation (5) by "L_2" and (6) by "M"

(23) $$L_2 e_1 = L_2 r_1 i_1 + L_1 L_2 \frac{di_1}{dt} - L_2 M \frac{di_2}{dt}$$

(24) $$M e_2 = M r_2 i_2 + M L_2 \frac{di_2}{dt} - M^2 \frac{di_1}{dt}$$

Adding (23) and(24) and solving for "i_2"

(25) $$i_2 = \frac{L_2 e_1 + M e_2 - r_1 L_2 i_1 - (L_1 L_2 - M^2) \frac{di_1}{dt}}{M r_2}$$

Differentiating equation (21) and substituting in (25)

(26) $$\frac{di_1}{dt} = -k_1 A_1 \epsilon^{-k_1 t} + k_2 (A_1 + I_1) \epsilon^{-k_2 t}$$

(27) $$i_2 = \frac{1}{M r_2} \left[L_2 e_1 + M e_2 - r_1 L_1 i_1 - (L_1 L_2 - M^2) \left(k_1 A_1 \epsilon^{-k_1 t} - k_2 (A_1 + I_1) \epsilon^{-k_2 t} \right) \right]$$

Here,as before,at the instant from which time was counted:

$t = 0$ $\qquad i_1 = 0$ $\qquad i_2 = 0$

Solving from (27)

(28) $$A_1 = \frac{L_2 e_1 + M e_2 - k_2 i_1 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

$$A_2 = -(A_1 + I_1)$$

(29) $$A_2 = \frac{L_2 e_1 + M e_2 - k_1 I_1 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

By an method of solution precisely similar , exactly symetrical expressions may be derived for "B_1" and "B_2".

(30) $$B_1 = \frac{L_1 e_1 + M e_1 - k_2 I_2 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

(31) $$B_2 = \frac{L_1 e_2 + M e_1 - k_1 I_2 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

The equations have now been reduced to a form free from differential notation without affecting their generality in the least. It is desirable in this thesis, however, to apply them only to the specific case in which one of the coils shall

be short circuited.

On short circuit it is obvious that the following relations exist.

$$e_2 = 0 \qquad I_2 = 0.$$

$$(32) \qquad A_1 = \frac{L_2 e_1 - k_2 I_1 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

$$(33) \qquad A_2 = \frac{L_2 e_1 - k_1 I_1 (L_1 L_2 - M^2)}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

From the solution of (22)

$$B_2 = -B_1.$$

$$(34) \qquad B_2 = \frac{Me_1}{(k_1 - k_2)(L_1 L_2 - M^2)}$$

Equation (22) under the short circuit condition, therefore, reduces to the simpler form:

$$(35) \qquad i_2 = \frac{-M e_1}{(k_1 - k_2)(L_1 L_2 - M^2)} \left(\varepsilon^{-k_1 t} - \varepsilon^{-k_2 t}\right)$$

If, however, the transient current is to appear in the second circuit at the "break" a different set of conditions applies at the instant the current is interrupted

$$i_1 = \frac{e_1}{r_1} \qquad i_2 = 0 \qquad t = 0.$$

Substituting and solving equations (19) and (20) with these conditions.

$$A_2 = -A_1$$

$$B_2 = -(I_2 + B_1)$$

$$(21a) \qquad i_1 = I_1 + A_1 \varepsilon^{-k_1 t} - A_1 \varepsilon^{-k_2 t}$$

$$(22a) \qquad i_2 = I_2 + B_1 \varepsilon^{-k_1 t} - (B_1 + I_2) \varepsilon^{-k_2 t}$$

Differentiating equation (21a) and substituting in (25)

$$(26a) \qquad \frac{di_1}{dt} = A_1 (-k_1 \varepsilon^{-k_1 t} + k_2 \varepsilon^{-k_2 t})$$

(27a) $$i_2 = \frac{1}{Mr_2}\left[L_2e_1 + Me_2 + r_1L_1i_1 + (L_1L_2 - M^2)\,A_1(k_1\varepsilon^{-k_1t} - k_2\varepsilon^{-k_2t})\right]$$

Here at the instant from which time was counted, "break":

$$t = 0 \qquad i_1 = \frac{e_1}{r_1} \qquad i_2 = 0$$

Solving from (27a)

(28a) $$A_1 = \frac{L_2e_1 + Me_2 + L_1e_1}{(L_1L_2 - M^2)\,(k_1 - k_2)}$$

The equations for "B_1" and "B_2" in this case are identical with those of (30) and (31).

If the circuits had been previously constructed so that they should be perfectly similar, then;

$$r_1 = r_2 = R.$$

$$L_1 = L_2 = L.$$

With this provision the constants "k_1" and "k_2" introduced in equation (17) are readily determinate. From the defining equations given in connection with (14).

$$e = \frac{L}{L^2 - M^2}\,R$$

$$a = \frac{R^2}{L^2 - M^2}$$

$$b = \frac{-Re_2}{(L^2 - M^2)}$$

$$k_1 = \frac{R}{L - M}$$

$$k_2 = \frac{R}{L + M}$$

$$k_1 - k_2 = \frac{2MR}{L^2 - M^2}$$

Substituting these values in (35):

(36) $$i_2 = \frac{e_1}{2R}\left[\varepsilon^{\frac{-Rt}{L-M}} - \varepsilon^{\frac{-Rt}{L-M}}\right]$$

Equation (36) is the most general form for short circuited secondary circuit and similar coils.

In the previous developement no assumption has been made regarding the flux interlinkages between the two circuits. It should be perfectly possible, if not probable, that all magnetic lines from one circuit should be interlinked with the other circuit. In that case the mutual inductance would be said to be perfect, and from the manner of definition the mathematical condition is evidently:

$$L_1 L_2 = M^2.$$

If in equation (11) substitutions are made on the supposition of perfect mutual inductance;

$$(37) \qquad \frac{di_1}{dt} + \frac{r_1 r_2}{L_1 r_2 + L_2 r_1} i_1 = \frac{r_2 e_1}{L_1 r_2 + L_2 r_1}$$

Similairly for the second circuit;

$$(38) \qquad \frac{di_2}{dt} + \frac{r_1 r_2}{L_1 r_2 + L_2 r_1} = \frac{r_2 e_1}{L_1 r_2 + L_2 r_1}$$

For the short circuit condition;

$$(39) \qquad \frac{di_2}{dt} + \frac{r_1 r_2}{L_1 r_2 + L_2 r_1} = 0$$

Equations (37), (38) and (39) are differentials of the first order and may be immediatly integrated.

$$(40) \qquad i_1 = \frac{e_1}{r_1}\left[1 - \frac{L_1 r_2 - M r_1}{L_1 r_2 + L_2 r_1} \epsilon^{\frac{-r_1 r_2 t}{L_1 r_2 + L_2 r_1}}\right]$$

$$(41) \qquad i_2 = \frac{e_2}{r_2}\left[1 - \frac{L_2 r_1 - M r_2}{L_1 r_2 + L_2 r_1} \epsilon^{\frac{-r_1 r_2 t}{L_1 r_2 + L_2 r_1}}\right]$$

$$(42) \qquad i_2 = \frac{M e_1}{L_1 r_2 + L_2 r_1} \epsilon^{\frac{-r_1 r_2 t}{L_1 r_2 + L_2 r_1}}$$

Equation (36) was the primary form desired and applies only to short circuited secondary and identical coils. Equation (42) is to be considered the limiting condition for (36).

III. APPARATUS.

It would be infered from the method of attack under "Theory" that the problem would be investigated only for identical coils. Such was the case. The first difficulty arose, therefore, in the winding of the coils.

Two lathe turned wood cores of equal dimensions were first made with approximately the size indicated below.

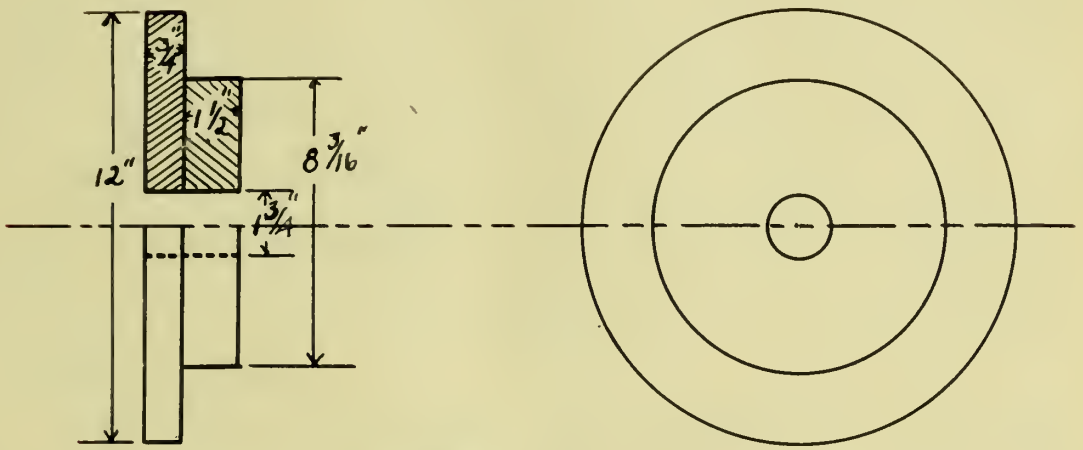


Fig 2

Dimensions were not of importance as long as the cores were precisely alike. Holes were bored in each core while running in the lathe, and a spindle was subsequently turned to size so that the coils might be displaced from each other without shifting their axial position. By this method the distance between coils could be easily and accurately varied.

In winding the coils every precaution was used in obtaining equal reactance and resistance. Similarity in shape was insured by the cores. New double cotton covered number sixteen (16) Brown and Sharpe guage wire was employed, and the winding was done in a lathe at constant speed and tension, care being taken

to manipulate the wire as little as possible. When finished each coil had ninety three (93) turns in three (3) equal layers and the leads were wound together and brought out to eliminate inductive effect. As was subsequently proved the precautions were sufficient for the purpose at hand.

Preliminary Measurements.

The ohmic resistance of the coils was determined by the potential drop method. Storage battery current and precision instruments were used to minimize error, and the final value selected was the mean of many trials extending over several days to eliminate the effect of heating due to currents in the coil. Atmospheric temperature both during the time of making the measurements and the later trials did not vary enough to introduce a consistant error.

The inductive reactance was obtained from the ohmic resistance and impedance drop. Sixty (60) cycle current having a wave shape closely approximating a sine was employed.

The mutual reactance of the coils furnished a more difficult subject. With currents of ordinary frequency the inductive effect between the two circuits was so small that it could not be measured with the instruments available. As a last resort recourse was had to an inverted converter which was capable of yielding a desirable wave shape at two thousand (2000) cycles per second. This permitted the use of instruments of the available range. No correction was made for the inaccuracies of the metering instruments at this high frequency. It is to be expected that the instruments would show considerable deviation from correct readings chargeable principally to their own reactance. The voltmeter exhibited high

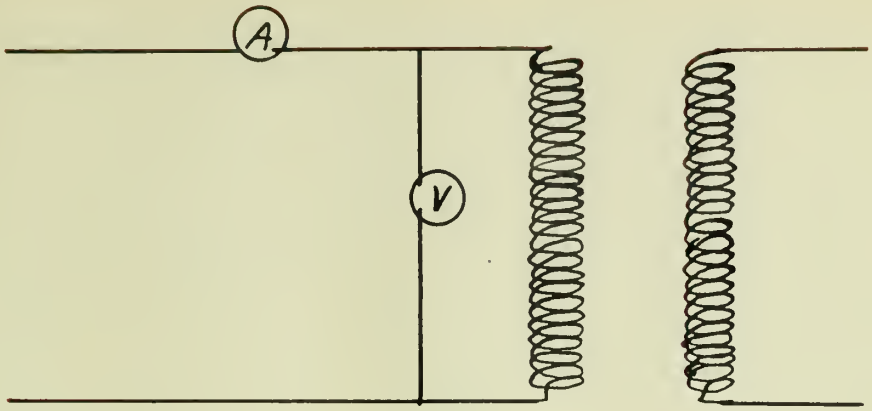


Fig 3

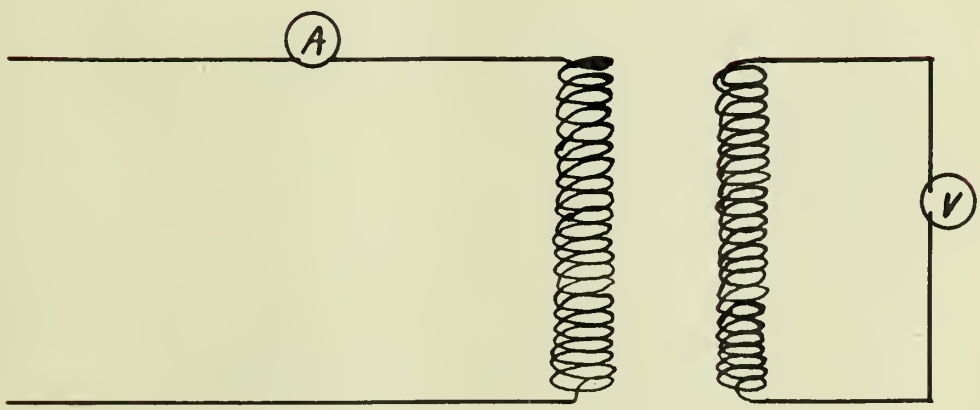


Fig 4

reactance and apparently had a negligible current capacity. At least its effect was not apparent in the current taken by the primary coil. No allowance was made therefore for the voltmeter current in calculating the mutual inductance.

Measurements were made for four (4) distances between coils one of which was zero and the maximum of which was two (2) inches. It was impossible to exceed this distance on account of flux leakage, and inability of the instruments to measure the small currents and voltages. Primary current was limited by the capacity of the converter to about seventy five (75) hundreths amperes.

"Owing to the transformer action between coils that coil upon which the e.m.f. was impressed has been and will be designated in what follows as the primary. The other, of course, will be designated as the secondary."

Methods of connection are illustrated in fig.(3) and (4).

Coil Constants.

As explained under"Preliminary Measurements" the methods of determining the constants of the coils were more or less rough. They were, however, consistant with the purpose of this thesis. The oscillograph, while capable of recording extremely rapid fluctuations of current, is not capable of making records which admit of more than rough measurement. Under a weakened galvanometer field it may require as much as one ampere to operate the element. The accuracy of the data is therefore well within the accuracy of the oscillograph.

Primary.

Impedance	2.123 ohms.
Resistance	1.761 ohms
Reactance	1.357 ohms
Inductance	.003599

Secondary.

Impedance	2.133 ohms
Resistance	1.744 ohms
Reactance	1.232 ohms
Inductance	.003258

Primary and Secondary.

Distance.	Mutual Reactance	Mutual Inductance.
Zero	5.447	.0004330
$\frac{3}{4}$"	4.027	.0003205
$1\frac{1}{4}$"	3.132	.000249
2"	2.221	.0001769

In the tabulations above the maximum variation in percent of the least corresponding value is ten (10) percent and occurs with the inductive reactance.

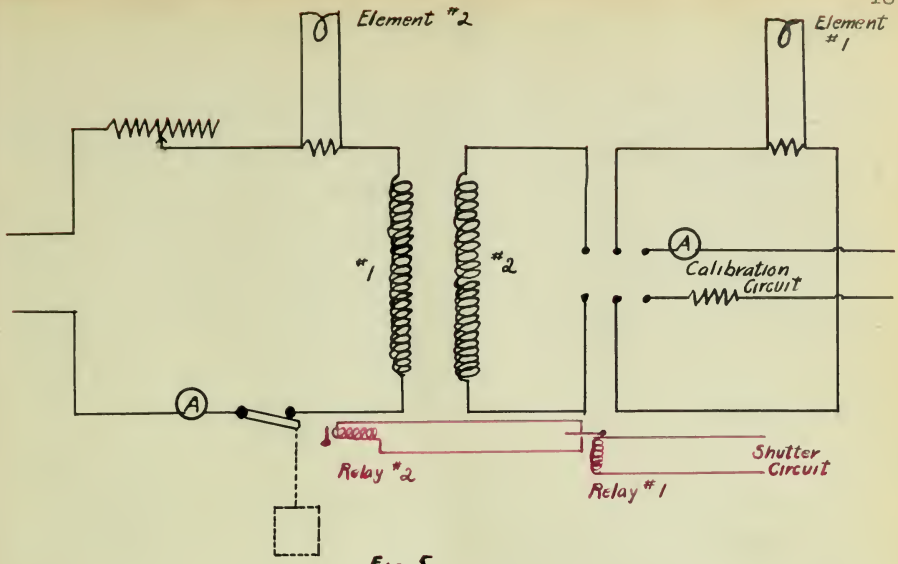

Element #2
Element #1
#1
#2
A
Calibration Circuit
A
Relay #2
Relay #1
Shutter Circuit

Fig 5

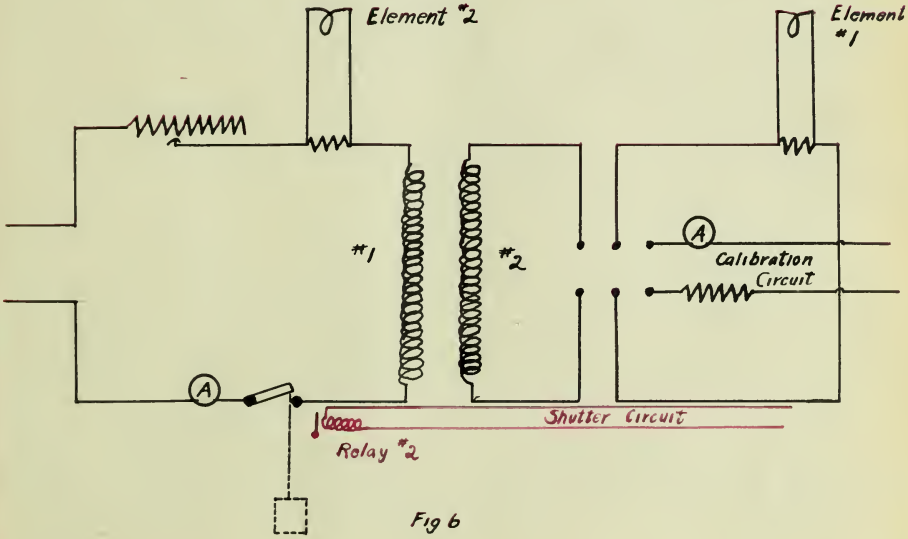

Element #2
Element #1
#1
#2
A
Calibration Circuit
A
Shutter Circuit
Relay #2

Fig 6

OSCILLOGRAPH CONNECTIONS.

The diagram of oscillograph connections is shown in Fig.(5). The following remarks are explanatory of this figure.

The method of operation was briefly as follows: one element of the oscillograph was connected in to photograph the primary circuit; another to photograph the transient current in the secondary circuit, while the third was to record upon the film a sixty (60) cycle timing wave.

It was not preferable to connect the oscillograph element in series with the secondary coil for the reason that the resistances were approximately in the relation of one and seventy five hundreths to one (1.75 to 1). This would introduce a very formidable error in the assumption that the secondary coil was short circuited. Neither was it possible on account of non uniform flux distribution to connect the oscillograph element as a shunt to a portion of the coil. It was therefore necessary to short circuit the secondary thru as small a resistance as possible and regulate the primary circuit so that the transient current thru the parallel paths would be of sufficient magnitude to opperate the element. As a result the permanent primary current was approximately fifteen (15) amperes. With this value of current it was necessary also to shunt the primary element across a calibrating resistance. Both of these resistances were made by winding wire between a row of staggered nails at opposite ends of a short board.

The timing element was shunted around a resistance, the current thru which was controlled by a thirty two candle power incandescent lamp on a one hundred ten volt a.c. lighting circuit.

It was expected that the phenomena under observation could best be observed on breaking the circuit after the current had attained a steady value. Accordingly a double break switch was arranged to open the circuit in air thru the action of a weight released automatically by the oscillograph shutter. The plane of contact of this switch was arranged perpendicular to the direction of motion and the whole was made as frictionless as possible. Its action under the impetus of a twelve pound falling weight was extremely rapid. It was subsequently arranged to break between zinc contacts and under a heavy blast of compressed air.

The oscillograph shutter was electro-magneticaly controlled and in series with the relay controlling the circuit switch. It was found by experiment that the rapidity of the switch action exceeded that of the shutter. A second relay was therefore introduced which should control the current thru the trip switch and introduce enough lag to allow the shutter to fully open.

In the case where the circuit was to be made and the photograph of the transient and primary rise taken, the operation of the triping switch was reversed and the second relay eliminated. Every effort in this case was made to cut the time lag as low as possible.

Oscillograms.

A glance at the oscillograms of Fig.(7) immediately indicates that the transient of the circuit does not follow the theoretical law. The curve of the primary break suggests the reason; arcing at the switch contacts. The records show that the arcing rarely endures for more than one one-hundredth part of a second which, as time goes, is a very small interval. Small as it

is, however, it is very formidable in this connection. Viewed with the eye only the switch action seemed almost instantaneous with practicallyno visible arcing. As recorded by the oscillograph the switch opening was followed first by a very sudden decrease of current, then by an appreciable period of arcing, and finally by another sudden decrease of current as the arc broke. The two sudden decreases of current produce a transient of two nodes, neither of which has the apparent magnitude of the calculated value.

The use of a non-arcing contact such as zinc improves the condition very little. It, however, smooths out the more violent fluctuations in both primary and secondary currents. Breaking the contact in a compressed air blast has a more gratifying effect, in that, arcing is almost entirely suppressed and the transient current approches the theoretical condition.

The attempts at photographing the transient on "make" were uniformly failures; so much so that after securing some bromide prints in which the effect was observed no attempt was made to secure films. The difficulty arose in the matter of getting an instantaneous contact of constant resistance. With the metal surfaces the resistance of the contact varied with the pressure and friction for the first few intervals of time. This effect, superimposed upon the inductance of the external storage battery circuit, practicaly eliminated the transient in the secondary. It appears extremely doubtful whether it would be possible to design any form of contact which would entirely eliminate these objections. Accordingly as was presupposed it seems most feasible to study the phenomena at break.

Index to Oscillograms.

(8a) Oscillograph element in series with coil.....Air break.

(8b) Coils together.... ...Air break.

(8c) Coil distance $\frac{3}{4}$" ... ...Air break.

(8d) Coil distance $1\frac{1}{4}$" ... ...Air break.

(8e) Coil distance 2" ... ...Air break.

(8f) Coil distance $1\frac{1}{4}$"... ..Zinc contact.

(8g) Coils together.. . ...Air blast.

(8h) Coils together... ...Air blast.

Of this series (8a) has no special significance. It is included to show in exaggerated detail the effect of the varying resistance arc on the transient current.

(8i) Bromide print. Coils together. ."Make".

CONCLUSIONS.

Certain inferences may be drawn from the progress of this thesis, part of which concern themselves with the difficulties of manipulation, and part with the significance of the results obtained.

It is obviously not possible to interupt a circuit instantly, for, if it were possible, the instaneous power developed would be infinite. A certain amount of arcing is therefore inevitable at "break", and any arc of varying length is of varying resistance. The primary objection to arcing is, therefore, in the introduction of this fluctuating resistance. Any attempt to eliminate arcing, therefore, can only result in deminishing the interval during which it occurs, and not in entirely supressing it. Short intervals of time ordinarily insignificant are of the greatest importance.

Of the methods employed in suppressing the arc that of a compressed air blast of high velocity is the most uniformly successful. A magnetic blowout of equal shifting effect lacks the cooling action of the blast, and non-arcing alloys require an appreciable time in which to become effective. Breaking in liquids requires even a longer time to overcome the sluggishness of the liquid. There is, in general, no advantage to be observed in suppressing the arc beyond that of eliminating the fluctuations in the resistance of it.

The difficulties at "make" are insurmountable. The completion of the circuit between rigid contacts with suddenly applied pressure produces a variable resistance; between liquid contacts there is sure to be a certain amount of spatting and

inequalities of contact area, which produce the same effect; the application of the current thru the breakdown of a dielectric is very likely to be oscillatory. Superimposed upon these objections is the inductance of the external circuit. The method of "make" is therefore inherently more difficult than that of "break", and neither of them has the convenience or the general desirability of the measurements with alternating current.

Capacity between turns of the coils has been entirely neglected. It is, however, apt to be and seems to be a formidable factor. Its calculation is one of the most tedious in electrical circuits, and with inductive e.m.f's. can be made accurate only with uniform distribution of magnetic flux. There is no logical reason for assuming that flux distribution can be uniform. It was for this reason that the accuracy of the occillograms was impaired by connecting an additional resistance in the secondary circuit instead of including part of the coils for this resistance. Any attempt to include capacity calculations would invariably result in an approximation.

In the transient current the effect of capacity is to prolong and diminish the peak and in some cases to produce oscillations. Such oscillations actually appear in the record with the element directly short circuiting the secondary. They may be due, however, to the inertia of the element, in the damping fluid. The latter explanation is the most probable. It is interesting to note that, due to the phase difference between charging and magnetizing current, the results obtained with alternating current are surely of less accuracy than those obtained with direct current, and transient effect. Of the curves shown in the series of Fig. (7) the calculated values

are arbitrarily selected as the criterion. Due to the effect of capacity which can not be eliminated or calculated with precision the oscillograph records are the more accurate and most truly represent the effect of mutual inductance; that is, with capacity the effect of mutual inductance can not be measured as accurately with alternating current as with direct currents. This is the only gratifying result of the investigation.

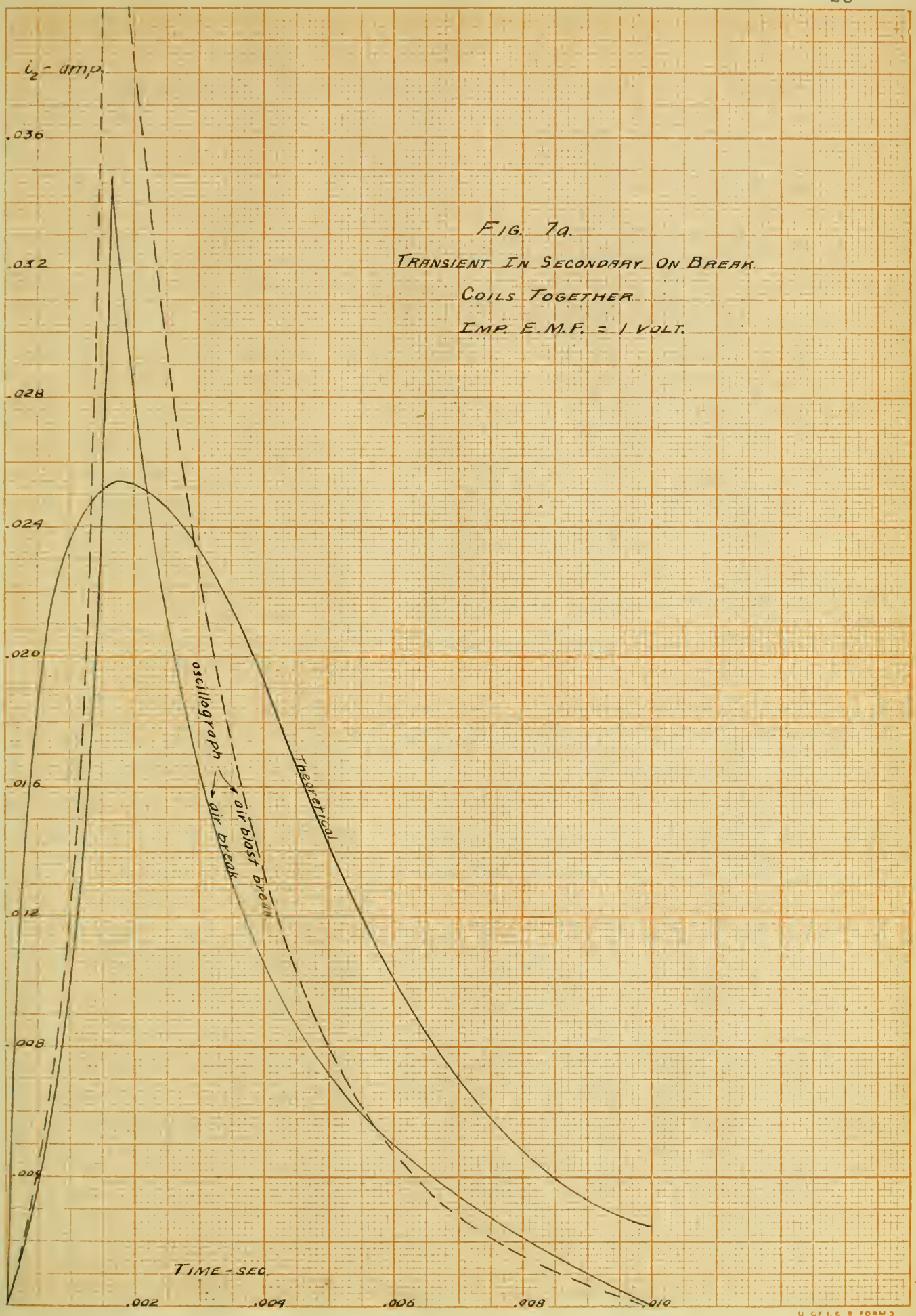


FIG. 7a.

TRANSIENT IN SECONDARY ON BREAK.

COILS TOGETHER

IMP. E.M.F. = 1 VOLT.

U. OF I. E. S. FORM 3

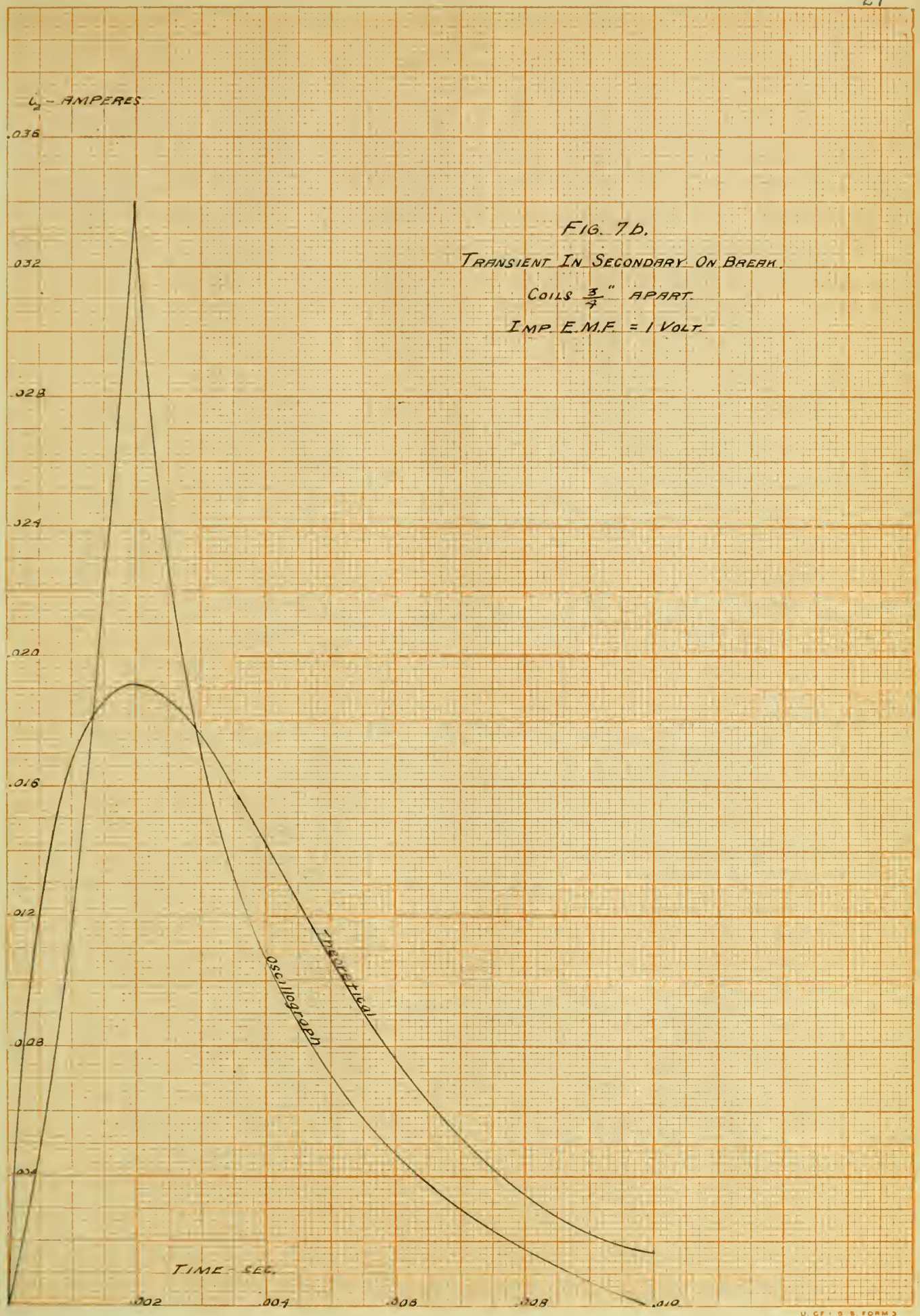


FIG. 7b.

TRANSIENT IN SECONDARY ON BREAK.

COILS $\frac{3}{4}$" APART.

IMP. E.M.F. = 1 VOLT.

U. CF I S S. FORM 3

FIG. 7C

TRANSIENT IN SECONDARY ON BREAK.

COILS 1¼" APART.

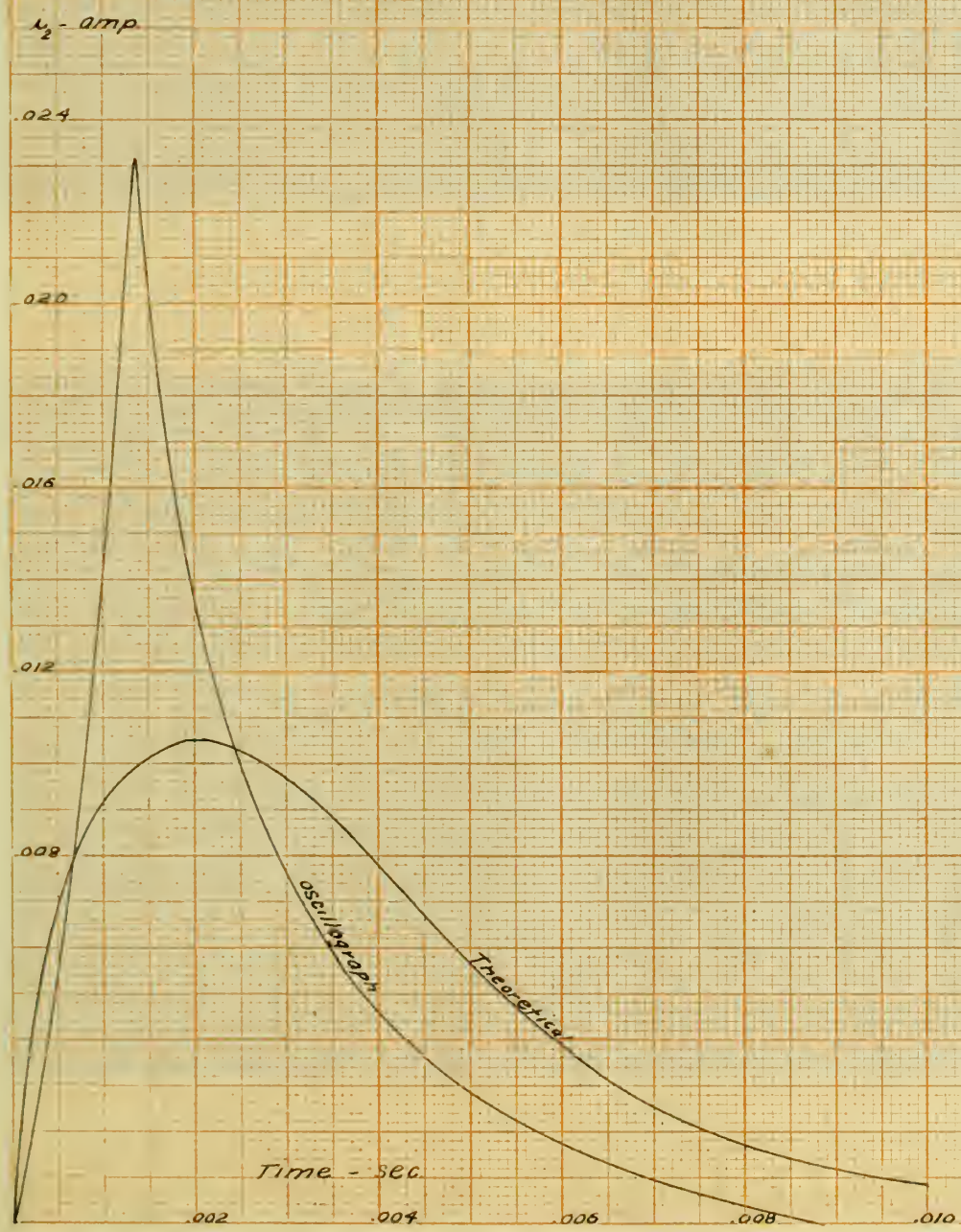
IMP. E.M.F. = 1 VOLT.

FIG. 7d.

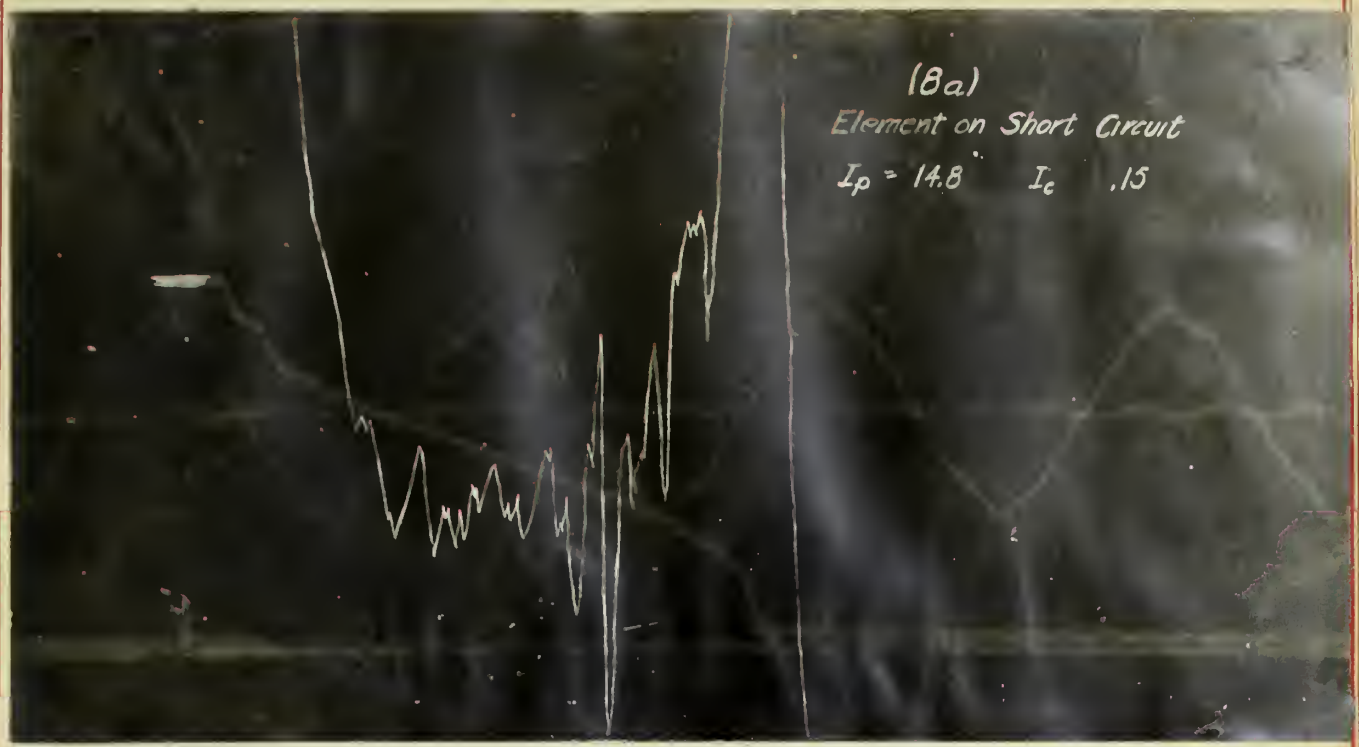
TRANSIENT IN SECONDARY ON BREAK.

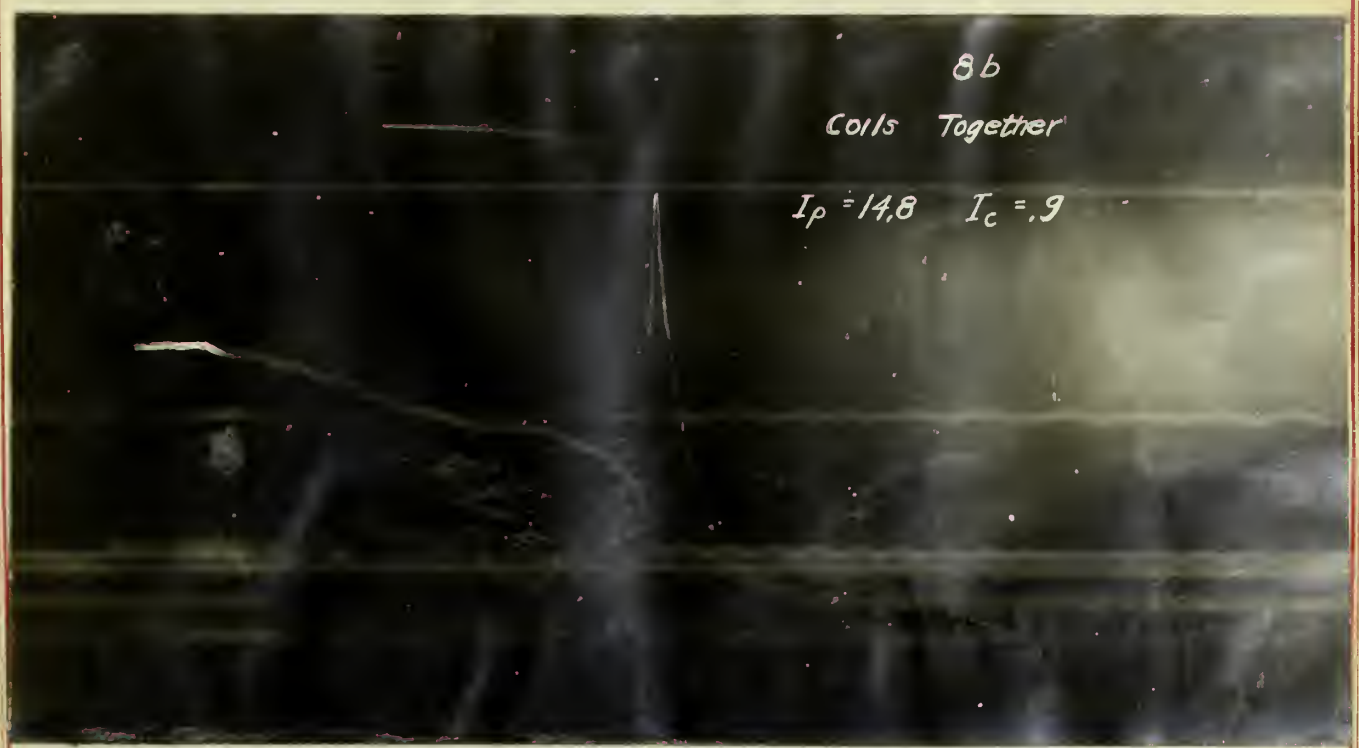
COILS 2" APART.

IMP. E.M.F. = 1 VOLT.

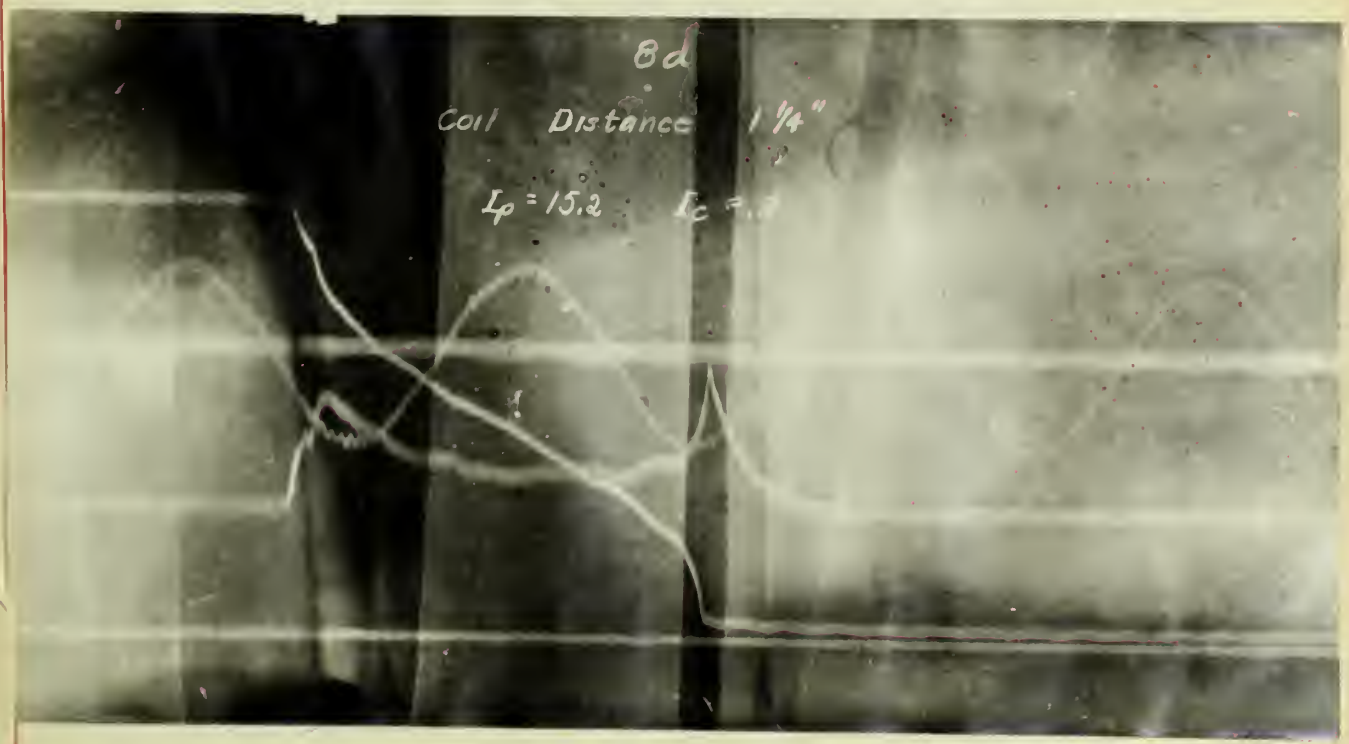


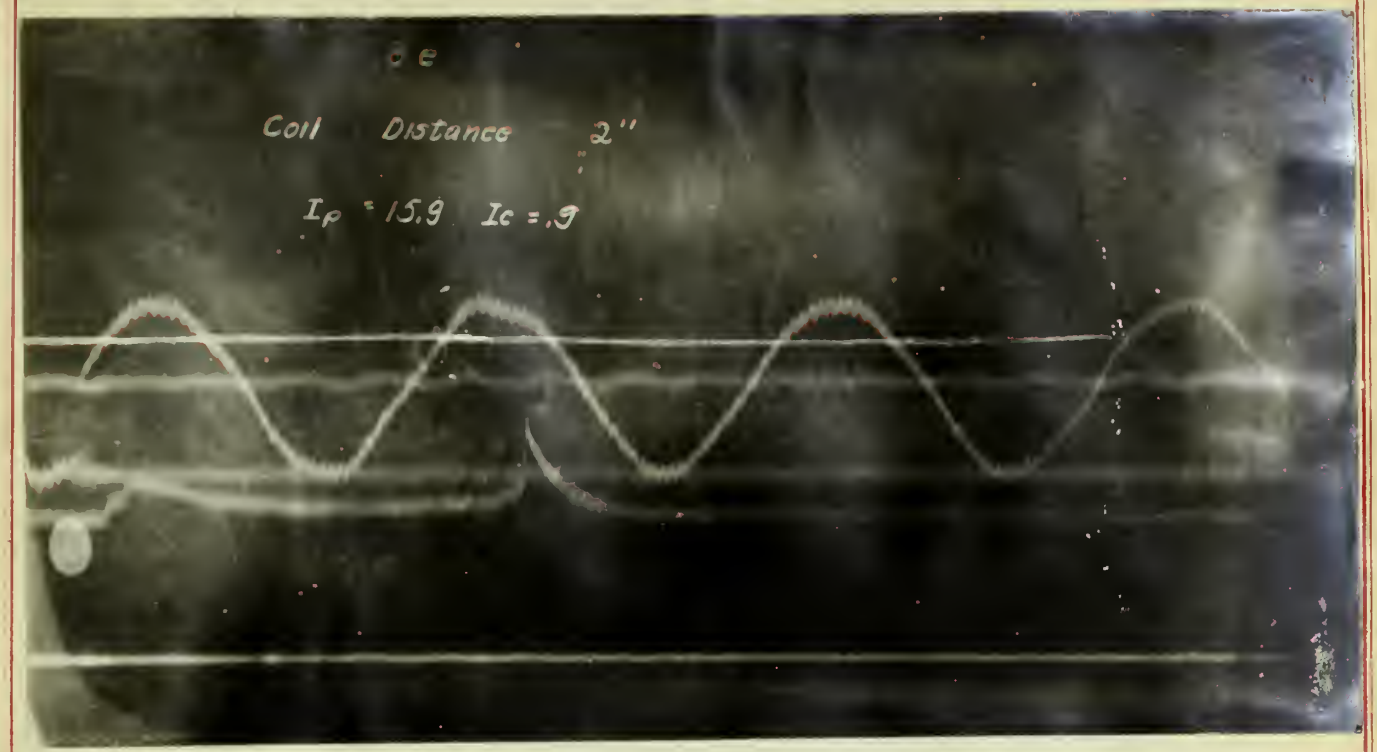
U. OF I. E. S. FORM 3

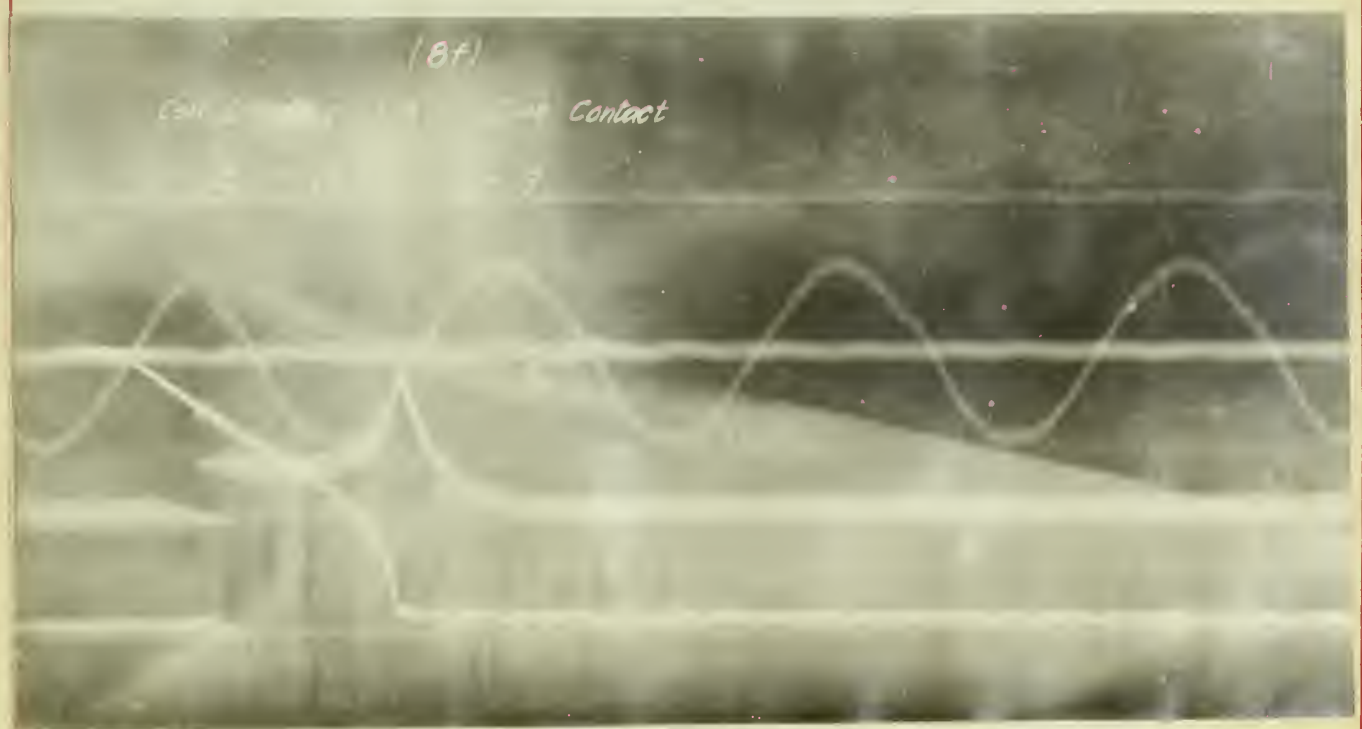

(8a)
Element on Short Circuit
I_p = 14.8 I_c .15

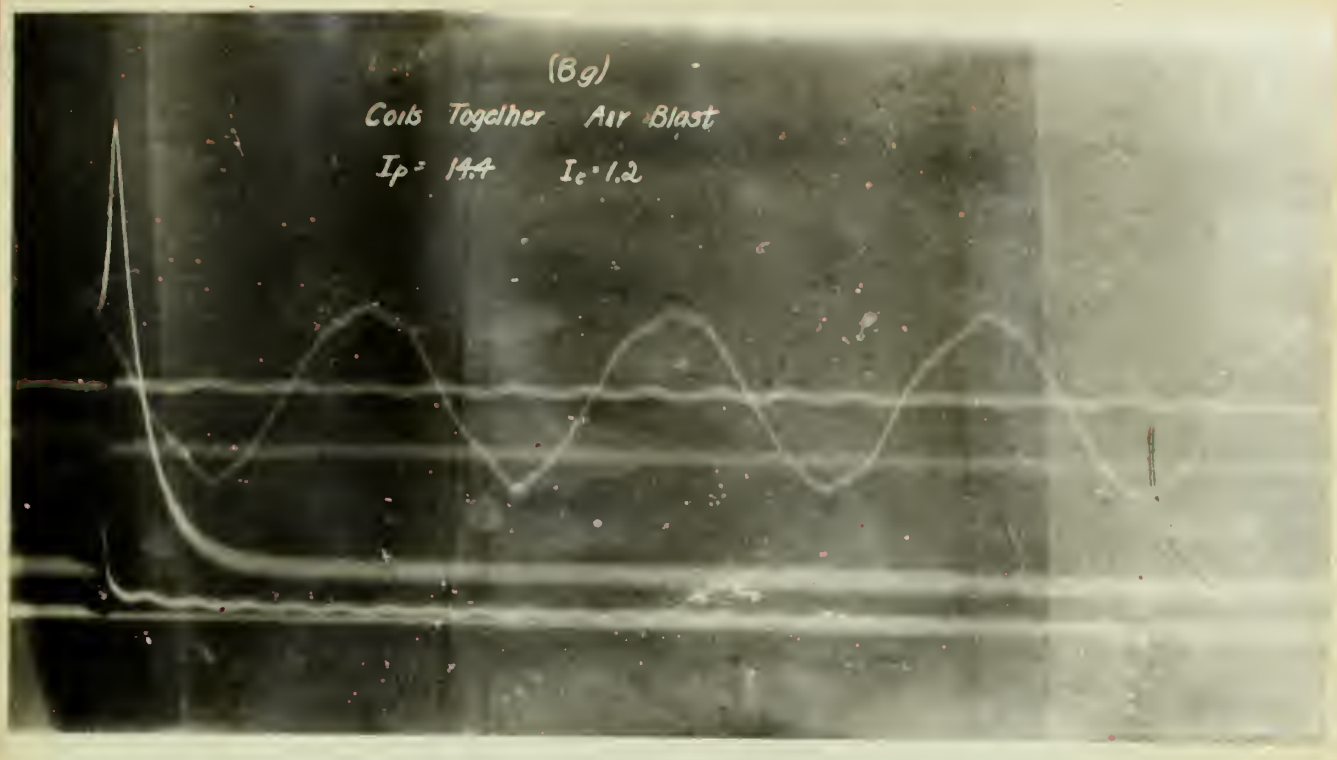

8b
Coils Together
I_p = 14.8 I_c = .9

8c
Coil Distance 3/4
Ip = 15.2 Ic = .9


8d
Coil Distance 1 1/4"
Ip = 15.2


(8e)
Coil Distance 2"
I_p = 15.9 Ic = .9


(8f)
Contact


(8g)
Coils Together Air Blast
I_p = 14.4 I_c = 1.2

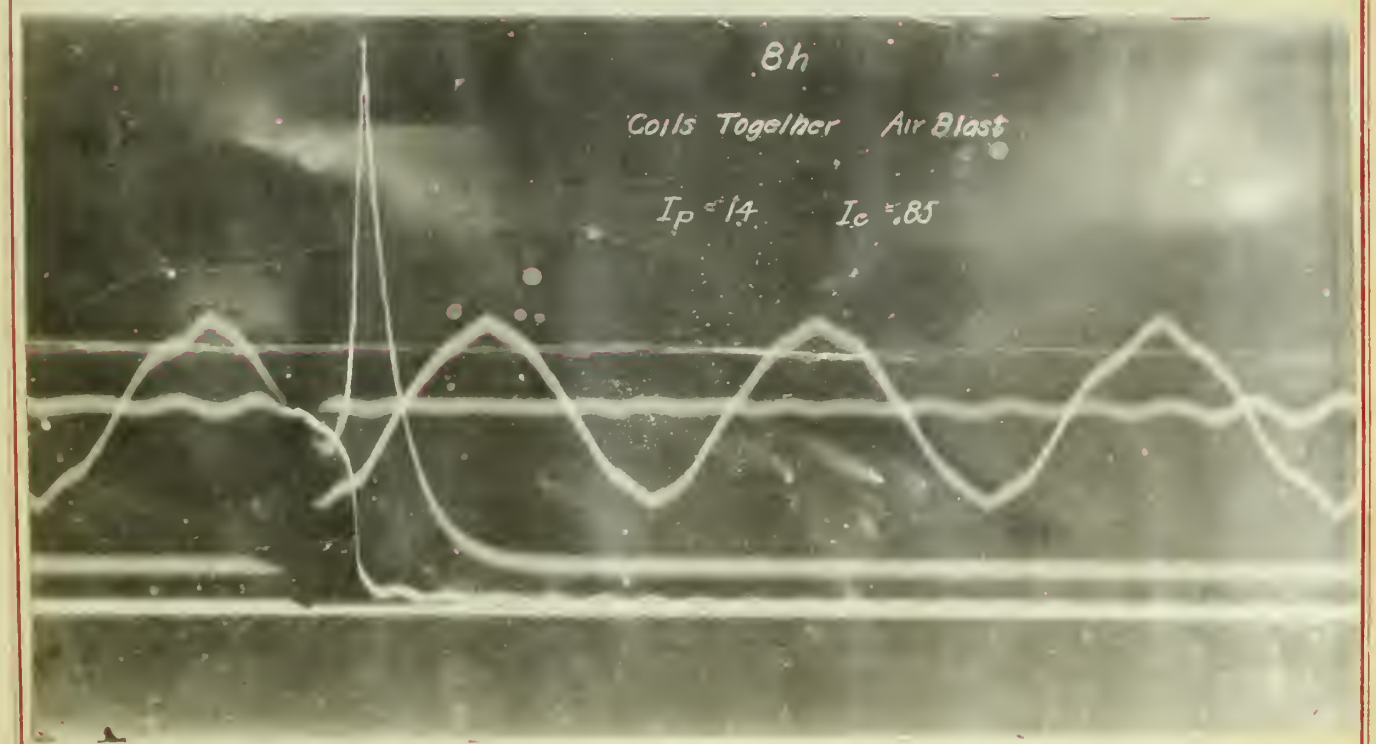

8h
Coils Together Air Blast
I_p = 14 I_c = .85

Fig 31
Coils Together Made.

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