ABRUPT CHANGE OF LOAD
ON A
SYNCHRONOUS MACHINE

By

Harold E. Edgerton

B. Sc. University of Nebraska 1925

Submitted in Partial Fulfillment of the
Requirement for the Degree of

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING

from the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
1927

Signature of author
Signature redacted

Certification by the
Department of Electrical
Engineering.
Signature redacted

The author wishes to express his appreciation to Prof. W. V. Lyon for his supervision of this thesis.

He is also indebted to Dr. Bush and Prof. Dahl for their interest during the course of the investigation, and to the Research Department, especially Mr. Frank Kear who was in charge of the integraph.

CONTENTS

INTRODUCTION

With transmission lines reaching out so that their stable operating limit is approached by their economic limit and with the present practice of interconnecting large power stations through current limiting reactors, there is an insistant demand by the electrical industry for the predetermination of the operating characteristics of a system. Before a large outlay of capital is interested in a project it must be shown without a doubt that the system will do what it is expected to do.

Under steady state conditions methods of attack have advanced and been perfected to a remarkable degree in the last few years. Any system no matter how complicated can eventually be solved for its steady state operating characteristics.

Even the simplest system under transient conditions is not susceptible to direct treatment. Solutions such as shown by Bush and Booth[1] become exceedingly laborious and are point by point solutions at that. The equivalent circuit method of studying a power system with an oscillograph as shown by Nickel[2] gives a method of solving complicated problems but does not take into account any non-linear variations of the coefficients in the differential equations, such as exist in the power-angle characteristic of the

1 Journal A.I.E.E. Vol XLIV p 229 March 1925
Discussion ditto p 766 July 1925

2 Journal A.I.E.E. Vol XLIV p 1277 Dec. 1925
Discussion ditto p 1341 Dec. 1925

~~of the~~ synchronous machine. Mr. Fortesque's[1] method of using the power angle diagram disregards the damping effect which may be one of the most important factors.

One of the most important links in a power system is the synchronous apparatus which tie it together. Here also under steady state conditions the phenomena of breakdown or pullout is fairly well understood while the transient treatment resorts to broad assumptions.

The need for more information of a fundamental nature regarding the synchronous machine during transient conditions furnished the object of this thesis. The ultimate aim was to add a contribution towards clearing up the vagueness which surrounds at present the complicated problem of transient stability in power systems.

1 Journal A.I.E.E. Vol XLIV p 955 Sept. 1925

THEORY

The synchronous motor or generator offers a problem which is inherently difficult to solve for any transient conditions. In this thesis every simplification that presented its self was utilized. This was done on the theory that if a check could be made in the simple case, it would be but a step to add refinements to care for special cases.

A machine for test was selected with these ideas in view and the one used made it possible to utilize the following conditions.

1. Non-salient pole construction
2. Distributed field winding to give sine wave flux
3. Identical field winding in the quadrature axis short circuited at all times.
4. Infinite bus at terminals
5. Instantaneously applied torque on shaft
6. Inflexible shaft between motor and load.

This machine which was used for testing, was a 5 kw sine wave generator and was on the same shaft as two other machines. For a complete description see pages 26 and 27.

It was late in the investigation that a special test showed that the short circuited field in the quadrature axis existed on the machine under test. This made it possible to apply polyphase theory and this simplified considerably the equations.

Prof. Lyon worked out the case of the single phase rotor and his solution will be mentioned later.

A line drawing of a two pole synchronous machine is shown in fig. 1. The differential equation of torques on the shaft becomes,

$$J\frac{d^2\theta}{dt^2} \quad + \quad P \quad = \quad T \qquad\qquad 1$$

where

J = moment of inertia

P = torque due to motor

T = load torque on the shaft

θ = angular displacement of the rotor

This equation holds for any rotating machine. Analysing P (torque due to electromagnetic action) we find that it is a function of the angle and a function of the rate of change of angle with time ($\frac{d\theta}{dt}$ or slip) in the synchronous machine. This makes equation 1 become of the form,

$$J\frac{d^2\theta}{dt^2} + T_d\frac{d\theta}{dt} + T_m \sin\theta = T \qquad\qquad 2$$

(See pages 21 to 25)

where

T_d = damping coefficient (induction motor effect)

T_m = pullout torque as a synchronous motor with gradually applied load.

For a synchronous machine without the shorted field in quadrature, T_d becomes a function of the angle as well as the slip.

This equation is difficult to solve, especially since solutions must traverse a considerable portion of the term involving $\sin\theta$. It is interesting to note that for a small load change, $\sin\theta = k\theta$ and the equation becomes,

$$J\frac{d^2\theta}{dt^2} + T_d\frac{d\theta}{dt} + T_m k\theta = T \qquad 3$$

This is recognized immediately as the same equation as that of charge in a series circuit containing lumped resistance, inductance and capacity.

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = E \qquad 4$$

The solution for this equation when a direct voltage is suddenly applied is of the well known damped sinusoid form,

$$q = A\left[1 - B\epsilon^{-\alpha t}\sin(\omega t+\phi)\right] \qquad 5$$

Similiarity gives a clue to the general form on the curves of angular displacement against time for an abrupt shaft load. It is an experimentally known fact that a synchronous machine is never damped enough so that it will not oscillate upon the application of load.

The general shape of the curve of angle against time following an abrupt shaft load is shown in fig. 2. Also the shape of the load curve and the speed curve are shown in fig. 3. The difference in speed from synchronism (slip) corresponds to current in an LRC series circuit as can be seen in fig. 3.

Return now to the fundamental torque equation which is,

$$J\frac{d^2\theta}{dt^2} + T_d\frac{d\theta}{dt} + T_m\sin\theta = T \qquad 2$$

This is a differential equation with a variable parameter. The form of the equation is identical to that of a damped pendulum

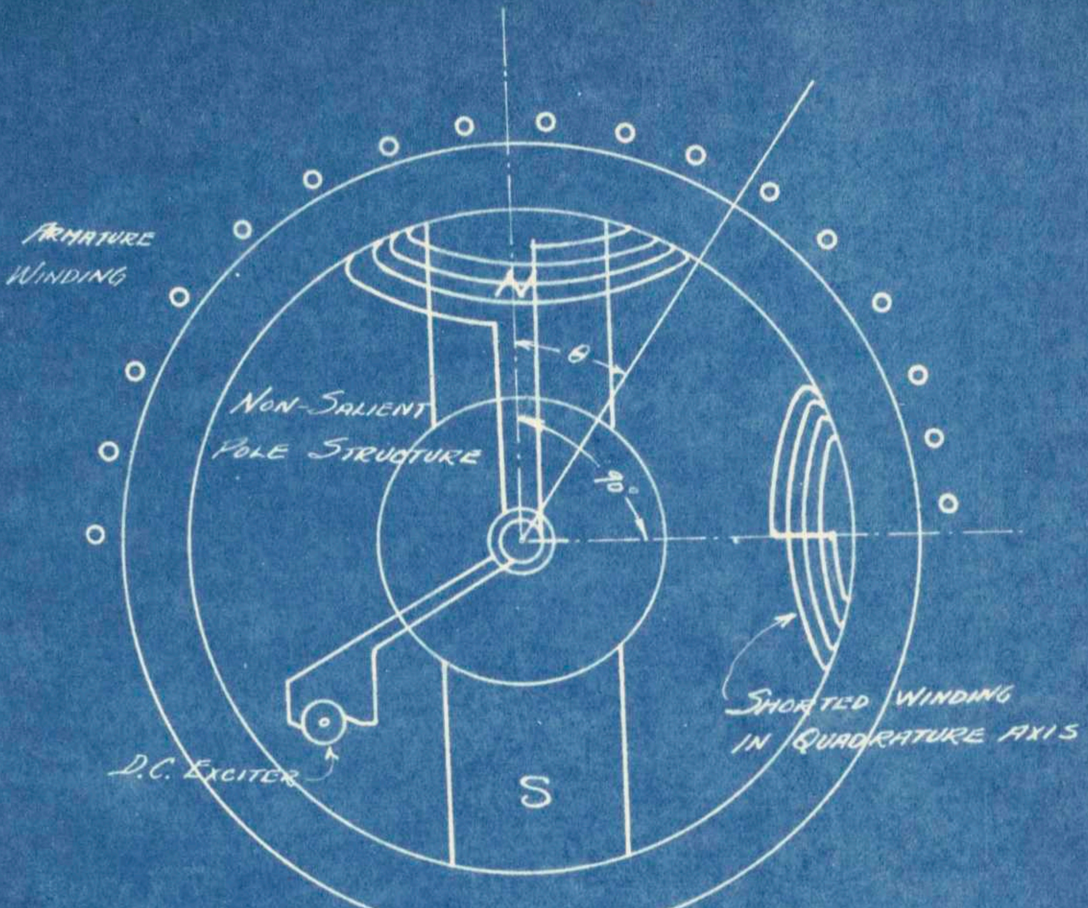


FIG. 1.

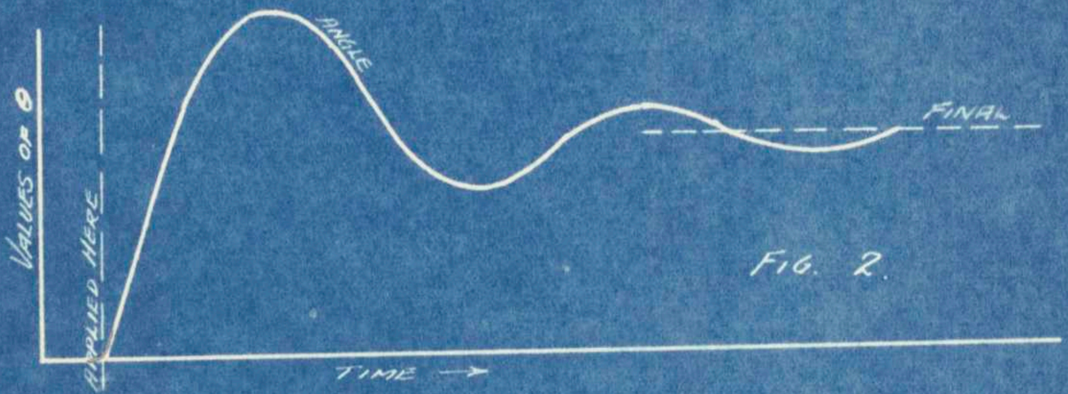


FIG. 2.

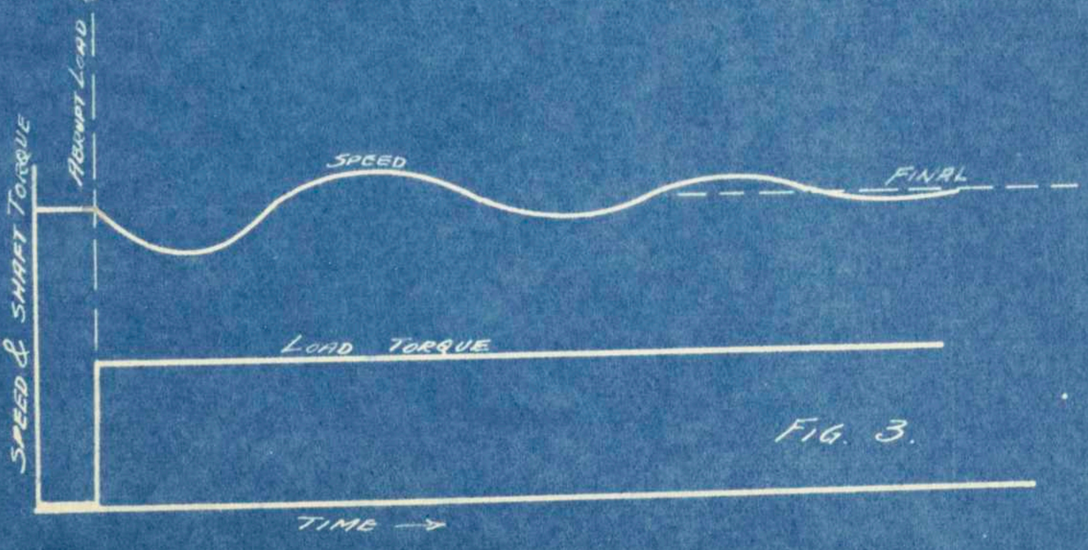


FIG. 3.

EDGERTON

which swings over a considerable arc. A solution probably can be obtained with elliptic functions but a quicker and easier method was available by solving the equation directly on the integraph in the Electrical Engineering Research Department.

For solution on the integraph, equation No. 2 is divided by J and integrated twice, which gives,

$$\theta = \iint \left[\frac{T}{J} - \frac{T_m}{J} \sin\theta\right] dt\,dt - \int \frac{T_d}{J}\theta\, dt$$

The constants can now be put in and a numerical solution mechanically integrated by the integraph.

DETERMINATION OF MACHINE CONSTANTS

Since the torques are acting at a nearly constant speed (about 3.5 % variation by test), they can be converted to power and expressed in synchronous kilowatts. In determining the constants care must be used to have the units the same in all expressions. For this problem it was convenient to express the various terms in the units indicated.

θ in electrical degrees

$\frac{d\theta}{dt}$ in electrical degrees per second

$\frac{d^2\theta}{dt^2}$ in electrical degrees per second per second

J in kilowatts (per elect. deg. per second per second)

T_d in kilowatts (per elect. deg. per second)

T_m in kilowatts (pullout power of synchronous motor)

T in kilowatts (load on the shaft)

The reason for selecting electrical degrees, seconds, and kilowatts was so that the answer would be in the quantities desired.

Three constants need to be determined for the equation in order to get a numerical answer involving angle and time. These are,

- J Power due to an acceleration of one electrical degree per second per second.
- T_d Power due to a slip of one electrical degree per second.
- T_m Pullout power for slowly applied load, field current constant. This occurs about 90° for the non-salient pole machine.

Each will be described in detail and the method of determination shown.

The power due to an acceleration of one electrical degree per second per second was found by the method shown on page 84 which describes fully the retardation method. It shows that the power in kilowatts can be written for this machine in the following manner,

$$KW = .0041 \frac{d^2\theta}{dt^2}$$

This of course assumes that the speed only changes slightly.

There are two definite methods of attack for the determination of the other two constants, T_d and T_m, and they are simply different interpretations of the variation of field current.

First Method. The variation of the field current changes the power-angle curve of the synchronous machine to correspond to the existing field current at each instant.

Second Method. The variation of field current is simply induction motor rotor current and is superimposed on the field current. Each is analysed as if the other did not exist.

The first method will be described briefly. It was tried but the results were not very good probably due to the shorted field in the quadrature axis which we did not know existed at the time.

For this method a family of curves of power-angle characteristics are needed for various field currents such as were taken by load tests, see page 93. The damping coefficient, T_d, is found by running the machine as an induction motor with the field open, such as shown on page 96. By doing this all effects not due to the field winding are measured together in one term. In a machine without a damper winding or large core loss this factor might not be enough to run the motor. With salient poles there would be a variation with the angular displacement also.

When solving the problem on the integraph for this first method it was necessary to have a curve of slip against percent increase in field current. Data from oscillograms was plotted in the family of power angle curves and thus a certain definite case was solved. The magnitude and damping checked closely but the shape of the curve did not check near the pullout point. Not much time was spent in analysing the discrepancies between test and theory because the second method looked more reasonable.

SECOND METHOD OF ATTACK

The results of the synchronous motor action and the induction motor effect are obtained independently and then their components added in this method.

The induction motor effect, T_d , was obtained directly by running the machine as an induction motor with the field winding short circuited. The auxilliary short circuited field in the quadrature axis makes the machine a balanced polyphase one on both sides of the gap. Power was read against slip both for motor action and for generator action. The test results are shown on the next page. Power is expressed in kilowatts and slip in electrical degrees per second. The slope of this power-slip curve through the axis and over the range used in this problem was found experimentally to be a straight line which has the following equation,

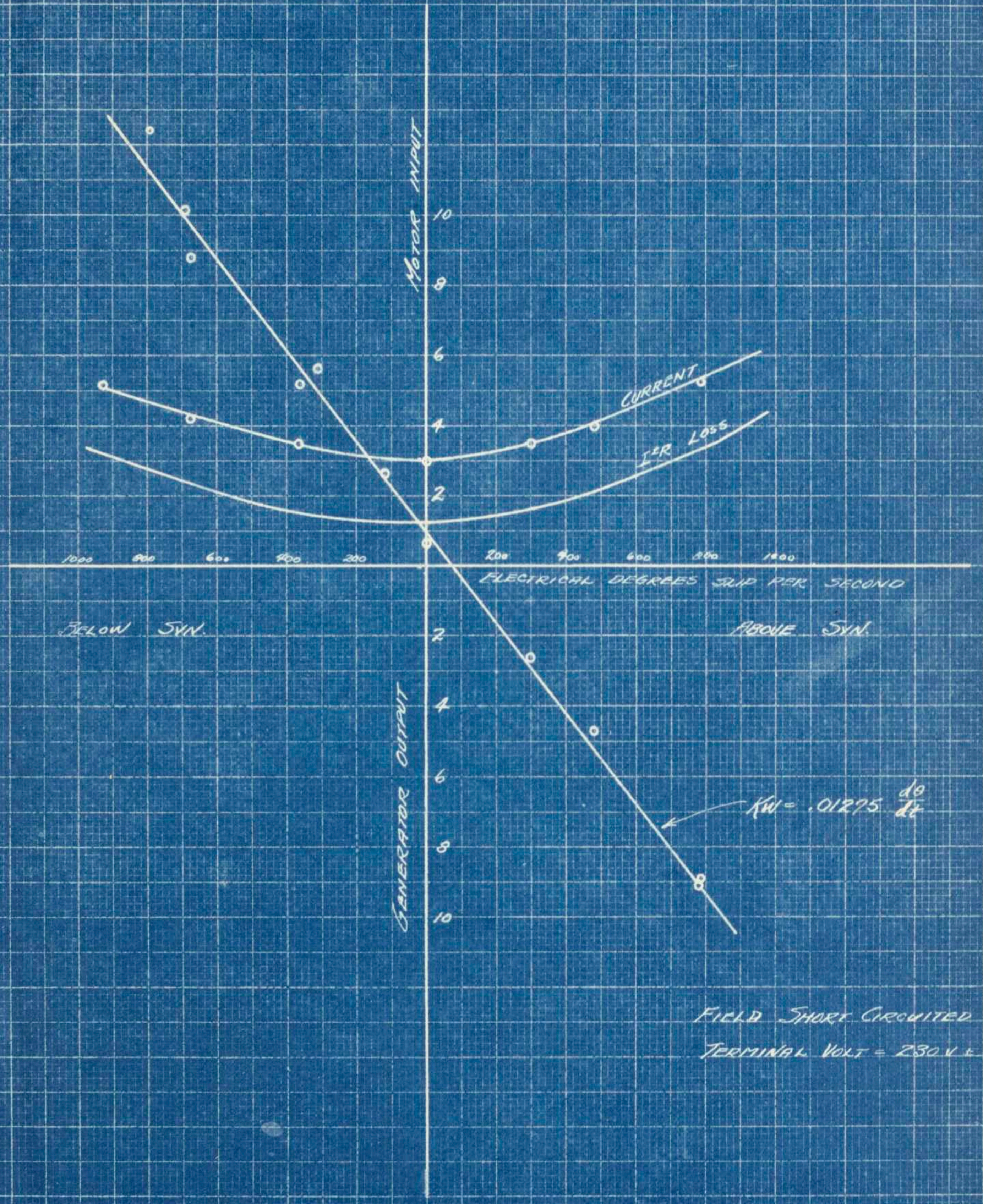
$$KW = .01275 \frac{d\theta}{dt}$$

Two errors are made in obtaining the equation mentioned in the previous paragraph. They are due to,

1. Stator copper loss
2. Large exciting current.

The stator copper loss is read by the wattmeters when input is read. This loss should be subtracted from the input to get the power crossing the air gap. The comparatively large air gap requires a large exciting current. To get the air gap voltage in such a case the stator Iz drop should be subtracted from the terminal voltage. The power for a certain slip varies with the square of the voltage in the air gap.

Both of the above errors are nearly constant over the range determined experimentally because the exciting current is a very appreciable component of the total current. Also the two errors tend to cancel each other. For these reasons the average slope of the test points was taken as correct.


MOTOR INPUT
10
8
6
4
2
CURRENT
I²R LOSS
1000 800 600 400 200
200 400 600 800 1000
ELECTRICAL DEGREES SLIP PER SECOND
BELOW SYN.
ABOVE SYN.
GENERATOR OUTPUT
2
4
6
8
10
KW = .01275 dθ/dt
FIELD SHORT CIRCUITED
TERMINAL VOLT = 230 V

It will be observed that this curve is a portion of the well known slip-torque curve of the induction motor near synchronous speed where it is practically a straight line.

In case there is no balanced quadrature field then the rotor circuit is unbalanced and its torque varies with the instantaneous angular displacement as well as with the slip. Future work will undoubtly attack the single phase rotor problem. As mentioned before, Prof. Lyon has derived the equations of a machine with a single phase rotor running at a constant slip. His equation comes down to the form,

$$P = A\left[\cos(2\theta + \alpha_F) + \cos\alpha_F\right]\frac{d\theta}{dt} + T_m \sin\theta$$

Where A is a constant depending upon the square of the voltage and the machine constants. α_F is the angle of lag of the current in the single phase winding behind the induced voltage and therefore is a function of the slip.

This makes a rather difficult problem but it can be solved on the integraph by taking the proper excursion among a family of straight lines which are the coefficients of the slip term.

There still remains to be determined the effect of the synchronous motor. The well known power-angle curve for a non-salient pole synchronous machine is a sine curve with zero power at zero angle and maximum power at 90 degrees when armature resistance is neglected. The equation for the power angle curve is,

$$\frac{E\,V}{x}\sin\theta = P$$

Where E is the induced voltage due to field current

V is the terminal voltage

x is the synchronous reactance

θ is the rotor displacement angle.

Since the machine under test had appreciable saturation it was thought advisable to get actual operation tests of the power angle relations. The curves are shown on page 93 and are shown for several field currents.

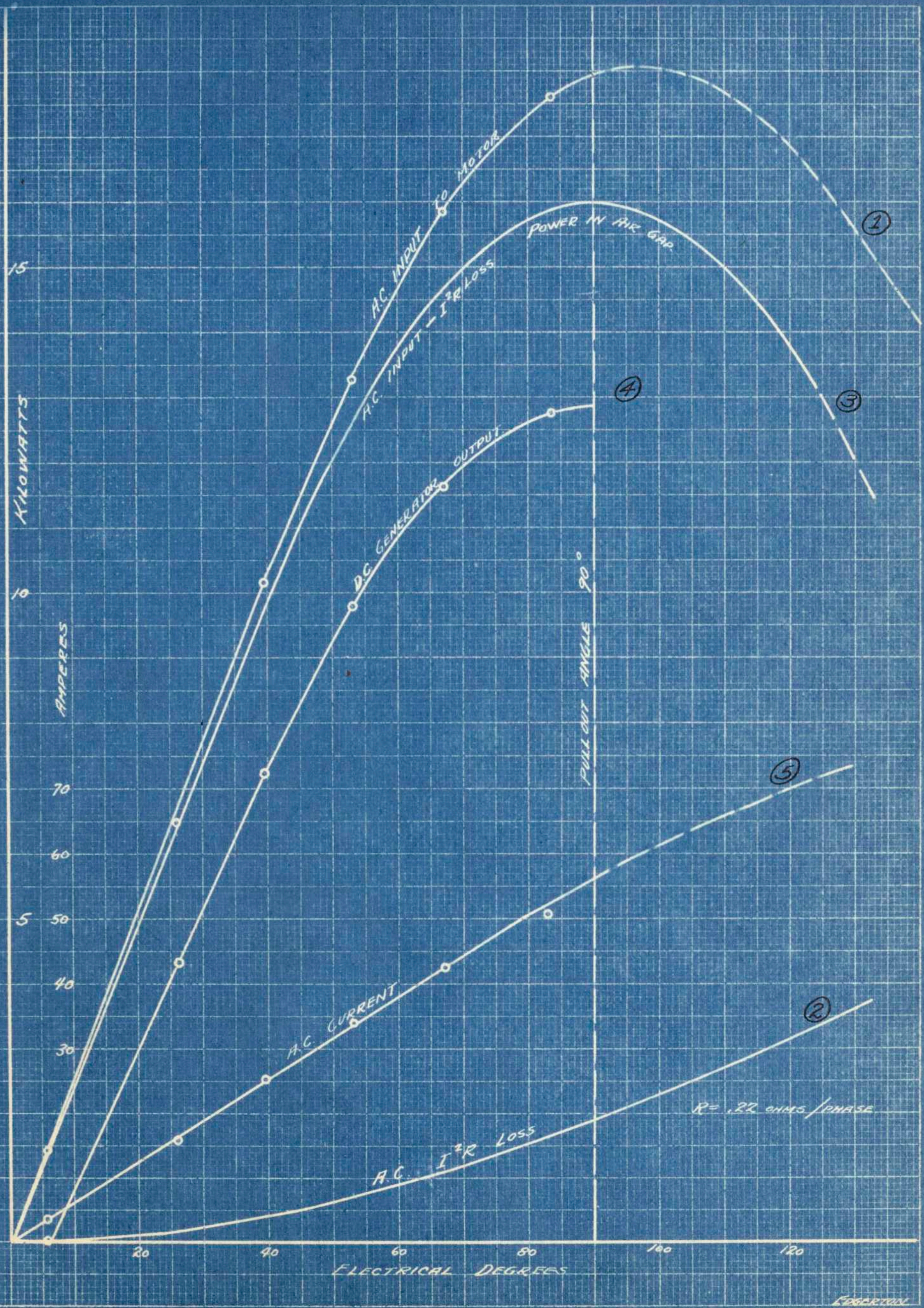
The resistance of the machine under test was appreciable so for this reason the I^2R of the armature needs to be subtracted from the input as measured by the wattmeters. All other losses were considered as shaft load. The curves on the following page show the below listed curves, Normal field

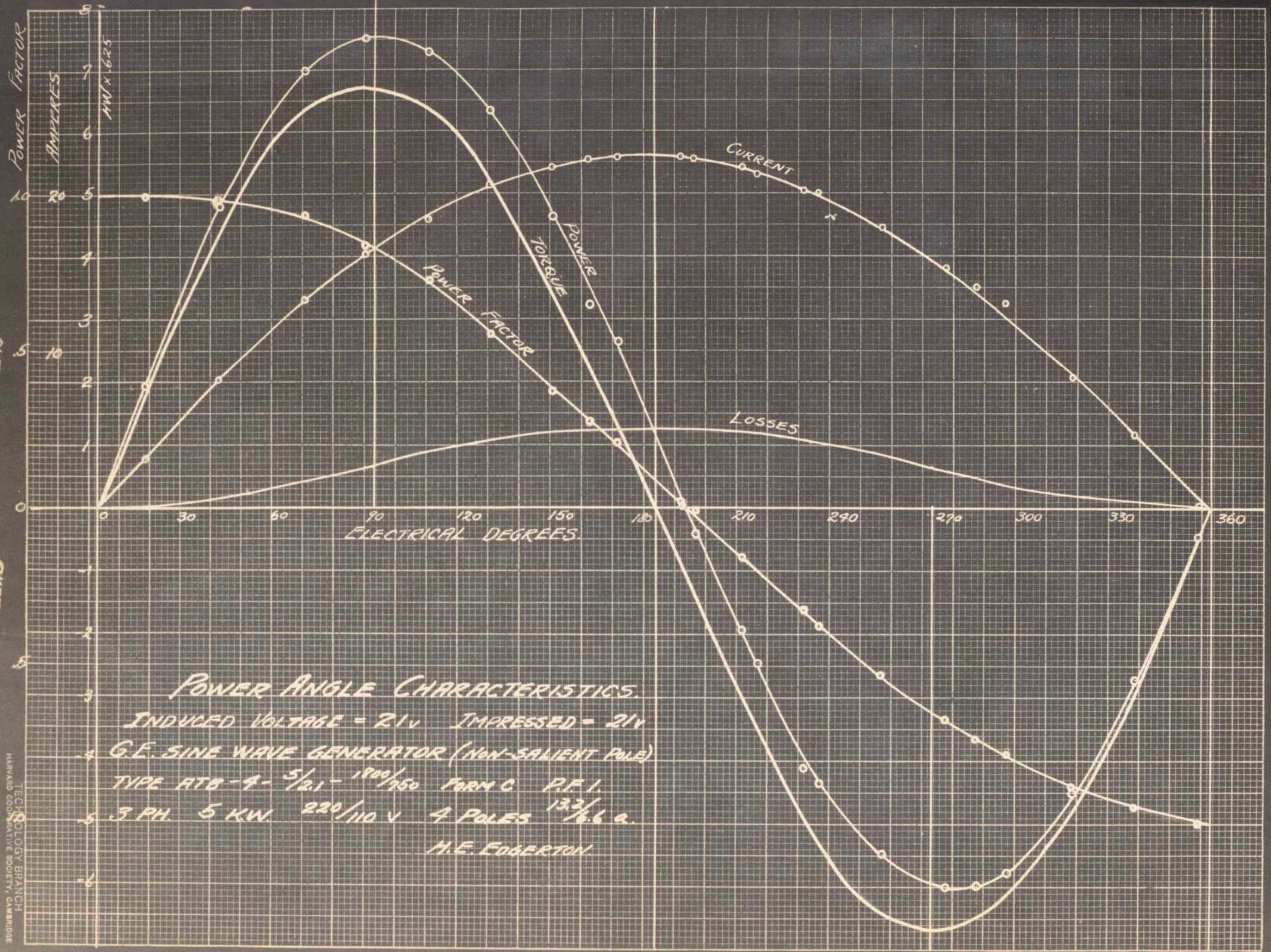
1. Power as read by the wattmeters
2. I^2R of the armature.
3. Curve of 1 minus 2
4. Output of D. C. machine
5. Line current

Curve No. 3 is indicated as the air gap power. This curve is assumed to be symmetrical about the 90° line. The wattmeter input is found to rise to a maximum at 100° by adding the I^2R to the power in the air gap.

This checks very well the photostat on page 13 which shows the complete power angle characteristics from 0 to 360 degrees. To obtain such a curve the two machines must be on the same shaft. Power transfer is varied by rotating one of the stators.

The power-angle curve for the integraph solution was taken as the power in the air gap, which is very nearly a sine wave.


A.C. INPUT TO MOTOR
POWER IN AIR GAP
A.C. INPUT − I²R LOSS
D.C. GENERATOR OUTPUT
A.C. CURRENT
A.C. I²R LOSS
PULL OUT ANGLE 90°
R = .22 OHMS / PHASE
KILOWATTS
AMPERES
ELECTRICAL DEGREES
1
2
3
4
5
15
10
5
70
60
50
40
30
20
40
60
80
100
120


POWER FACTOR
AMPERES
KW x .625
LAG
LEAD
CURRENT
POWER
TORQUE
POWER FACTOR
LOSSES
ELECTRICAL DEGREES
0
30
60
90
120
150
180
210
240
270
300
330
360
POWER ANGLE CHARACTERISTICS.
INDUCED VOLTAGE = 21v IMPRESSED = 21v
G.E. SINE WAVE GENERATOR (NON-SALIENT POLE)
TYPE ATB - 4 - 5/2.1 - 1800/750 FORM C P.F. 1.
3 PH. 5 KW. 220/110 V 4 POLES 13.2/6.6 a.
H.E. EDGERTON

INTEGRAPH SOLUTION

Collecting the various constants just determined and inserting them in equation 2 gives,

$$.0041\frac{d^2\theta}{dt^2} + .01275\frac{d\theta}{dt} + 16 \sin\theta = T$$

Where T is expressed as shaft load and is in synchronous kilowatts.

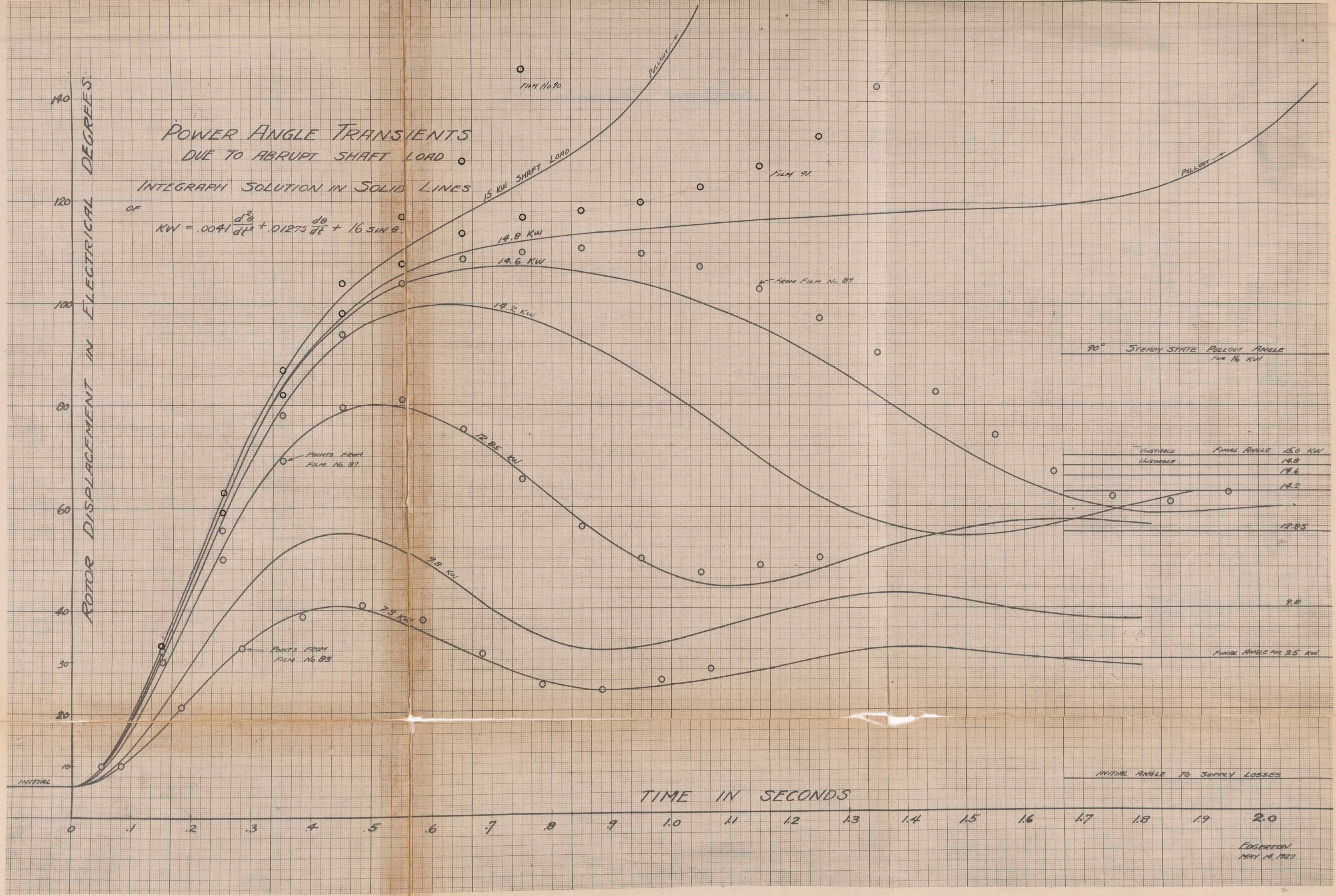
16 $\sin\theta$ is an approximate way of stating the curve marked " Air gap power ", curve No. 3 on page 12.

Tests show that when the set is running light with no load the power-angle is about 6 degrees. This was used as the initial point for the integraph solution also.

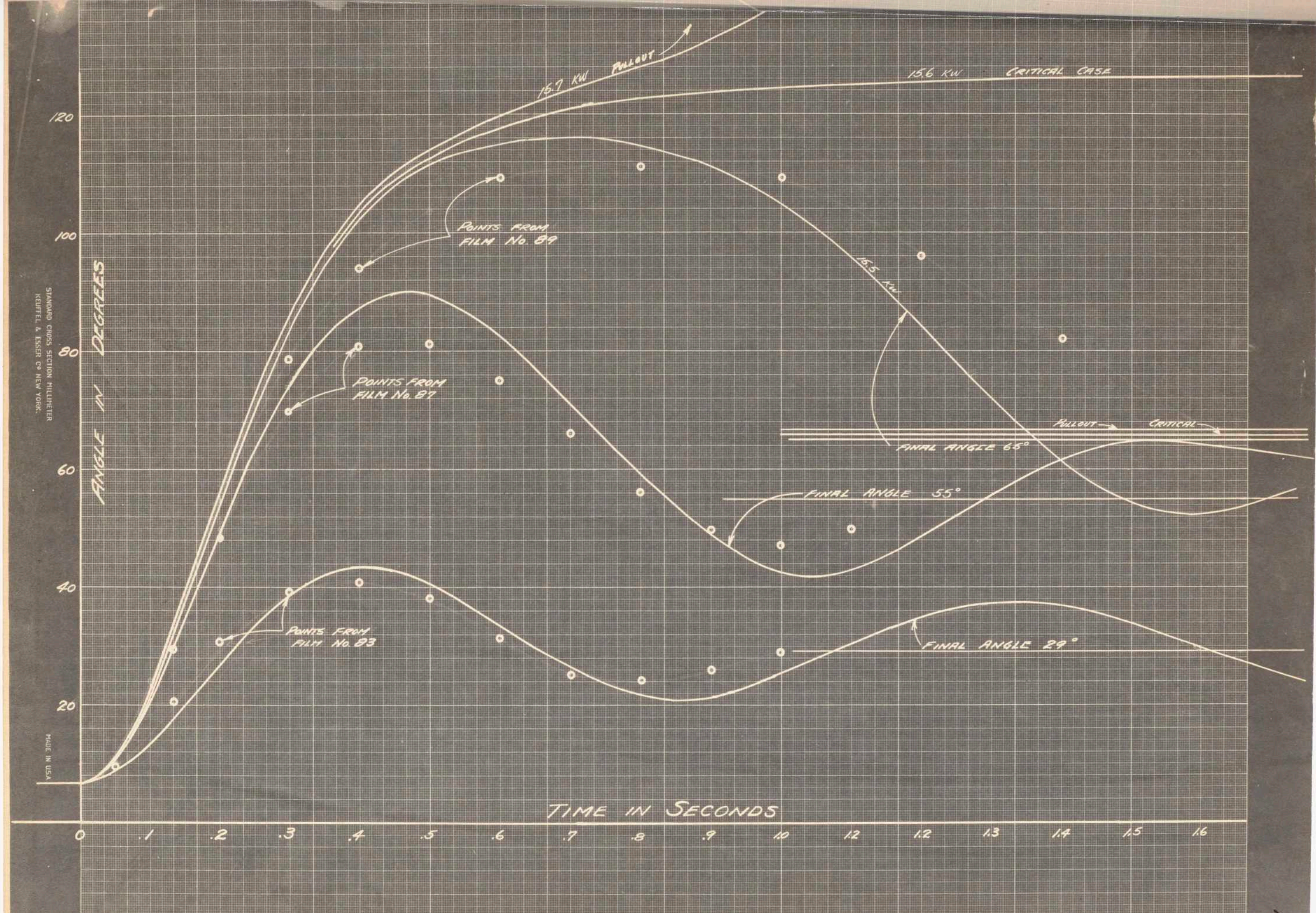
After the integraph was calibrated several loads were applied and the solutions shown on the following page obtained. The tests points superimposed on this page were taken from films Nos. 83, 87, and 89. They can be found on page 67. These three films are from a series of eight which were taken under different loads. Data from the films appears on page 73, and shows clearly the excellent check between theory and test.

When the I^2R losses of the stator are not taken into account the curve numbered 1 on page 12 was used for the integraph solution and the results are shown on page 16.

INTEGRAPH SOLUTIONS



POWER ANGLE TRANSIENTS
DUE TO ABRUPT SHAFT LOAD
INTEGRAPH SOLUTION IN SOLID LINES
OF
$KW = .0041\frac{d^2\theta}{dt^2} + .01275\frac{d\theta}{dt} + 16\sin\theta$
ROTOR DISPLACEMENT IN ELECTRICAL DEGREES.
TIME IN SECONDS
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
10
20
30
40
60
80
100
120
140
INITIAL
15 KW SHAFT LOAD
14.8 KW
14.6 KW
14.2 KW
12.85 KW
9.8 KW
7.5 KW
PULLOUT
FILM No. 90
FILM 91
FROM FILM No. 89
POINTS FROM FILM No. 97
POINTS FROM FILM No. 83
90° STEADY STATE PULLOUT ANGLE FOR 16 KW
UNSTABLE
UNSTABLE
FINAL ANGLE 15.0 KW
14.8
14.6
14.2
12.85
9.8
FINAL ANGLE FOR 7.5 KW.
INITIAL ANGLE TO SUPPLY LOSSES
EDGERTON
MAY 14, 1927



ANGLE IN DEGREES
120
100
80
60
40
20
TIME IN SECONDS
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.2
1.2
1.3
1.4
1.5
1.6
15.7 KW PULLOUT
15.6 KW CRITICAL CASE
15.5 KW
POINTS FROM FILM No. 89
POINTS FROM FILM No. 87
POINTS FROM FILM No. 83
PULLOUT
CRITICAL
FINAL ANGLE 65°
FINAL ANGLE 55°
FINAL ANGLE 29°
STANDARD CROSS SECTION MILLIMETER
KEUFFEL & ESSER CO NEW YORK.
MADE IN USA

POWER-ANGLE DIAGRAMS

Thus far only the angle against time relations have been mentioned. An equally interesting study is the trace of power input on the power angle diagram between two load points when the load is applied abruptly. Mr. Fortescue[1] uses such a scheme for the determination of the transient stability in a system but he does not consider quantitatively the damping or induction motor action.

Keeping in mind the ideal conditions under which we are analysing the machine under test we trace the action following an abrupt change of load. The shaft load previously requiring an angle, θ_1, is increased so that it requires an angle of θ_2 (see diagram on the following page). No more electrical energy can be obtained until the rotor drops back to a new angle. Thus the inertia of the rotor must supply the additional load for the first instant. As soon as the rotor begins to move with respect to the rotating magnetic field two distinct sources of power are available. One gives power proportional to the angular displacement and the other gives power proportional to the slip or speed of the rotor with respect to the rotating magnetic field. This last term's coefficient is only a constant when a balanced polyphase condition exists on the rotor as has been mentioned. The electrical power input is the sum of the two.

The two power inputs mentioned are termed respectively the synchronous motor power and the induction motor effect.

1 Journal AIEE Sept. 1925 page 951

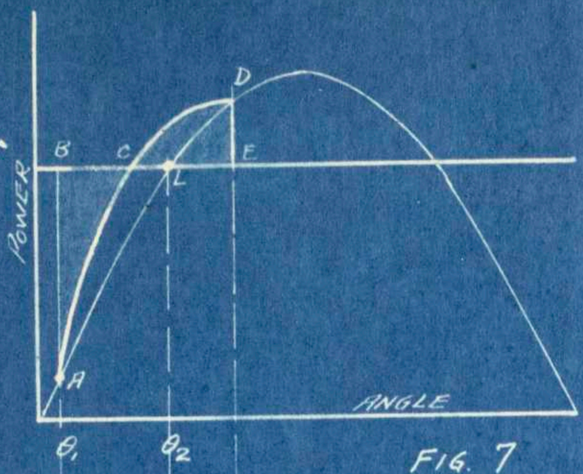


FIG. 7

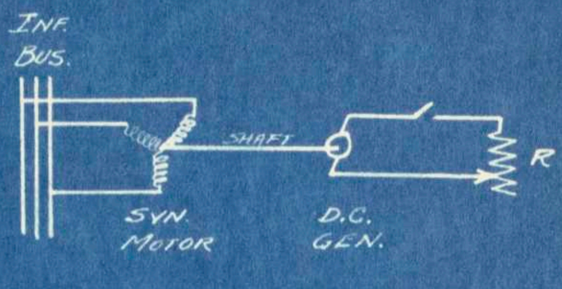


FIG. 9

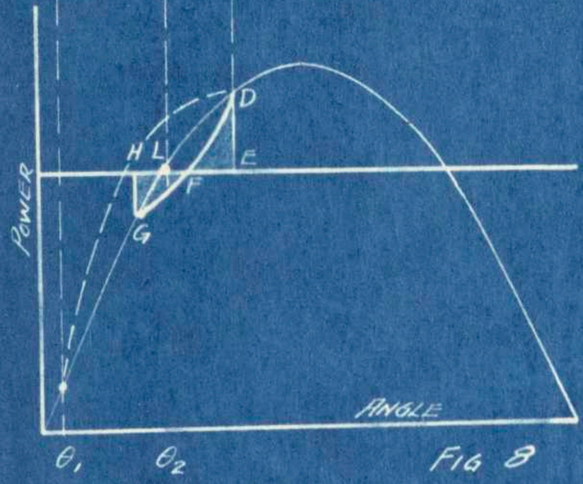


FIG 8

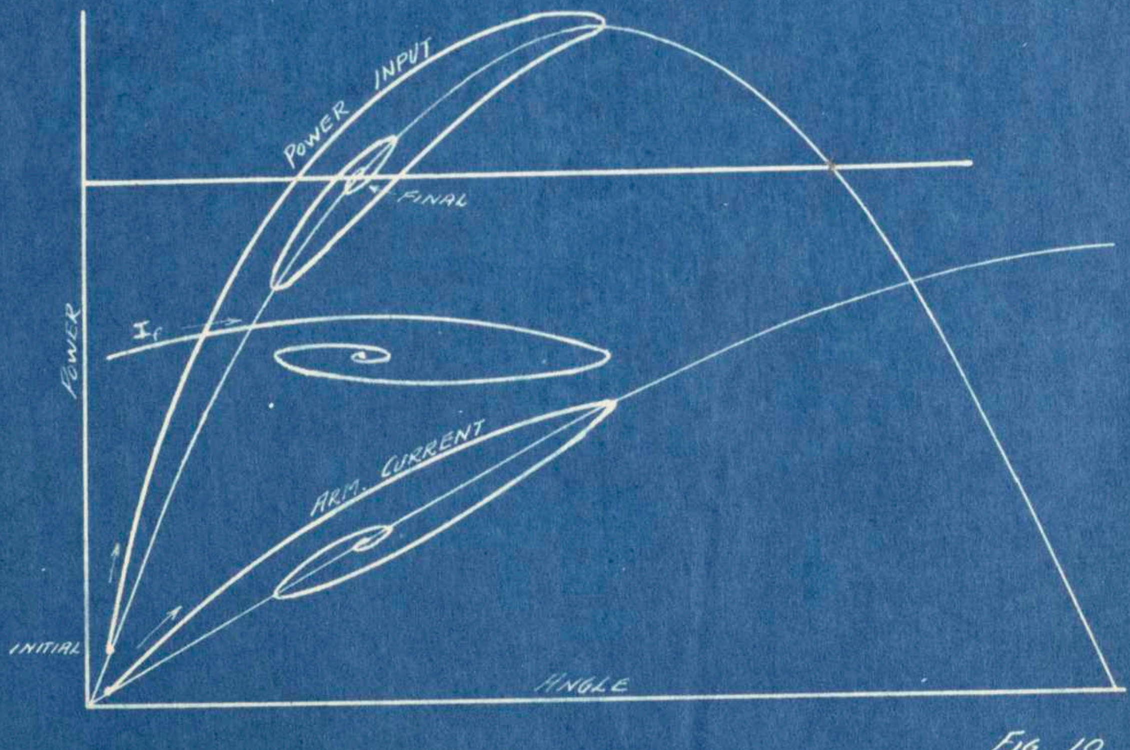


FIG. 10

EDGERTON

The slip increases until it reaches a maximum where the load equals the power input, point C, fig. 7. The ~~power~~ energy supplying the load due to the inertia is proportional to the area ABC. The inertia now causes the rotor to overshoot and the slip will now return to zero at a point where the area CDE is equal to the area ABC, that is the energy taken from the rotating parts has been returned.

The effect of the induction motor effect up to the point C is to speed up the rotor. If this effect were absent the inertia would be called upon to supply the area ABL instead of ABC. Above point C the induction motor action is furnishing energy to the rotor still but it is storing it in the rotating parts by speeding them up.

Now point D is the position of the rotor and the power input is more than the load on the shaft. This causes a speeding up of the rotor or a negative slip. The induction motor effect is now like a generator and puts energy back into the line. The slip increases until point F is reached where it begins to decrease (fig. 8) until point G at which it becomes zero. This point is so situated that the area DEF is equal to FGH.

The phenomena is repeated again and again with decreasing amplitudes for each swing until finally the point L is reached for the new steady state.

So if we trace the power input between two points on a power angle diagram we find that it is a spirial which starts at the initial point of load and ends on the final as shown in figure 10.

The method of measuring angle during transient conditions made it possible to trace such a power curve over a considerable portion of its swing. No effort was spent in calculating such a spirial although it should not be difficult with the aid of the integraph.

A trace of armature current is also a spirial beginning at the initial point and ending on its new position. Such a curve is sketched in fig. 10. Field current likewise increases, decreases and finally ends at the same value it held at first. Its trace is shown in fig. 10 also.

Experimentally determined spirials are shown throughout Section III following each group of films.

SYNCHRONOUS MACHINE THEORY

The synchronous machine is a coupled circuit which has relative motion between the two windings. One winding is a polyphase balanced one and the other is usually a single phase with sometimes modifications such as damper windings.

The machine under test had a shortcircuited field winding in the quadrature field so under transient condition the machine had a balanced polyphase winding on each side of the gap. This makes the attack quite simple.

For analysis each effect is considered by itself with the rest of the machine shortcircuited. Then the various components are totaled up. Of course such a method depends upon the circuit constants remaining constant and this calls for negligible saturation.

STEADY STATE

Let the rotor be driven from an outside force at synchronous speed. Three phase voltage applied on the balanced polyphase winding produces no effect in the rotor but causes a current in quadrature to flow in the armature. The current will have a magnitude of V/Z where V is the voltage and Z the synchronous impedance. Power only to supply losses in the stator are required and this is usually very small. Fig. 11 shows the vector diagram for this case.

Next short circuit the stator and excite the field winding. If the stator was opencircuited a voltage, E, would be induced. This is shorted through the impedance of the

STATOR ROTOR

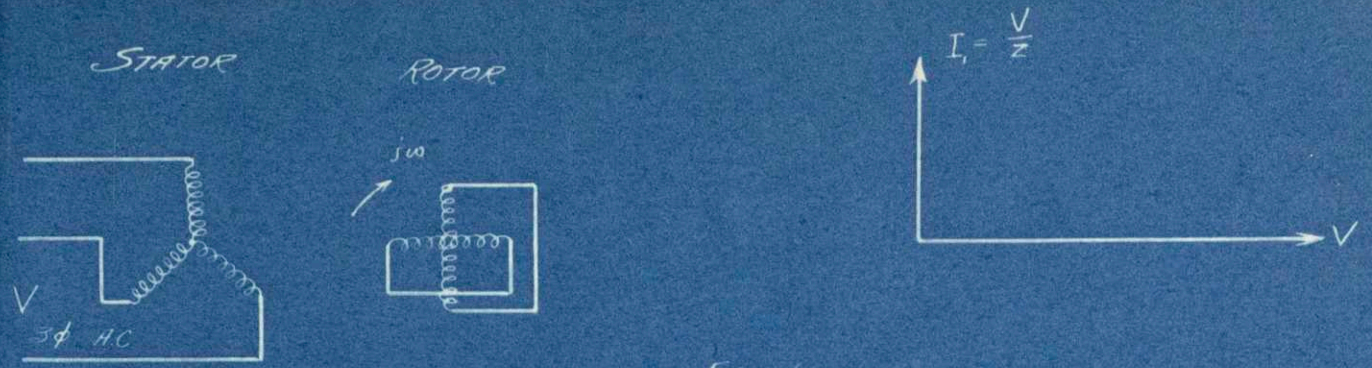


FIG. 11

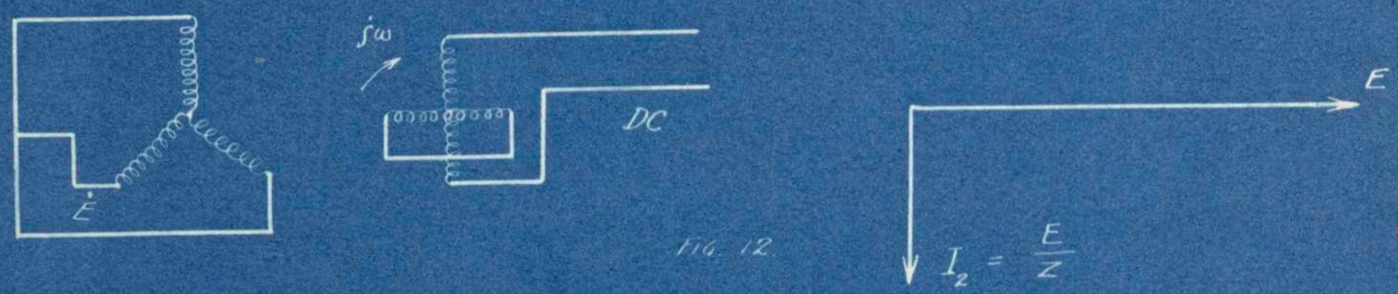


FIG. 12

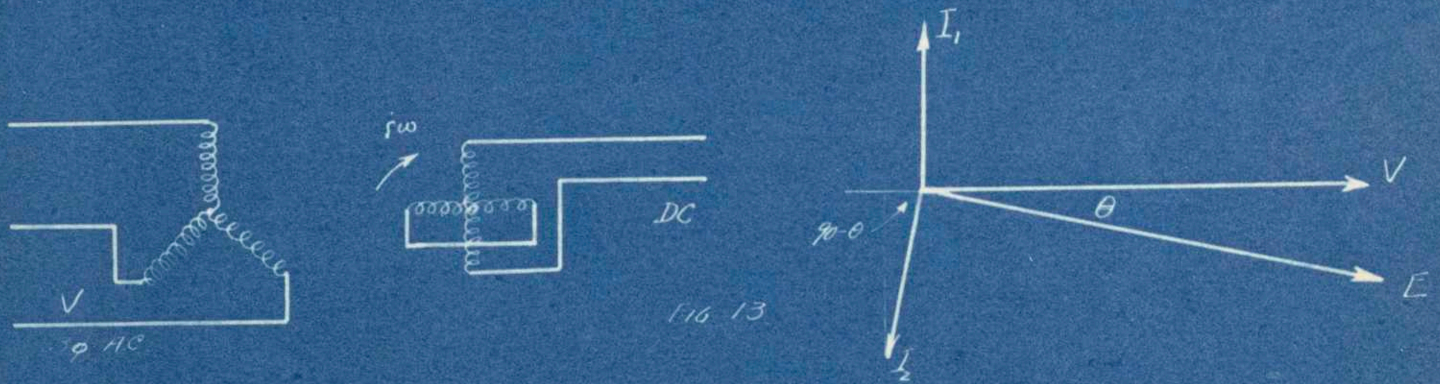


FIG. 13

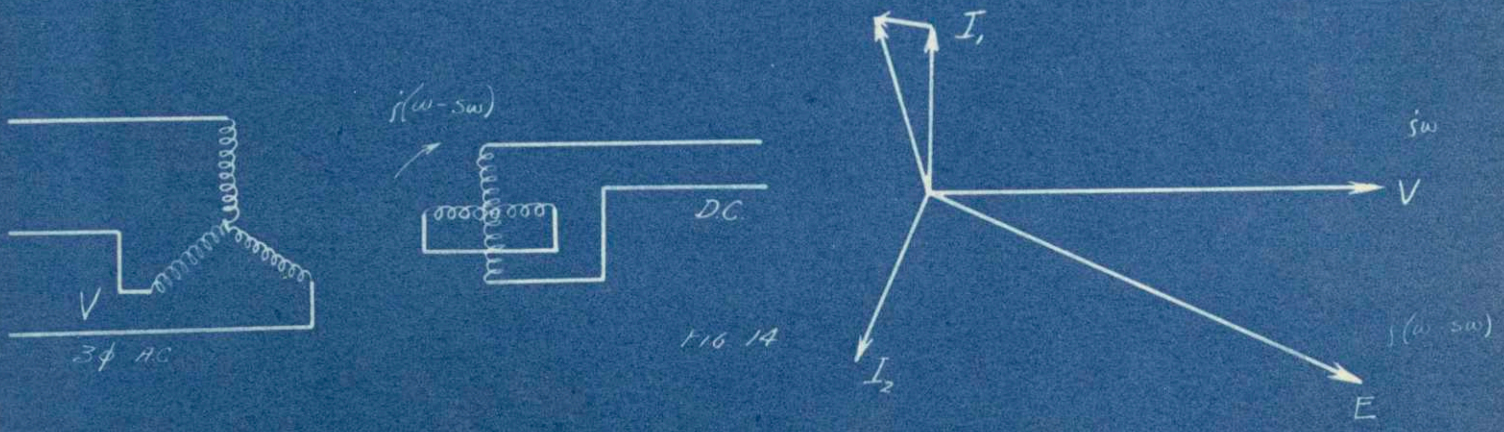


FIG. 14

stator winding (Z) also, so the current has a magnitude of E/Z amperes. Vector representation of this appears in fig. 12.

The two effects are now combined to give the power due to angular position of the rotor. Angular position is the angle between V and E. Also it can be considered the angle between the rotating magnetic field and the center line of the field pole. Power is the product of the terminal voltage by its in phase component of current. As is evident in fig. 13 the power is

$$P = V \cdot I_z \cos(90-\theta) = \frac{V\,E}{Z} \sin\theta$$

An interesting point to note here is that when V and E are 90° apart the power is a maximum. The in-phase current is E/Z. This is recognized immediately as the current from the short circuit characteristic curve corresponding to the field current to induce E volts at open circuit. So to find the pullout power of a synchronous machine for slowly applied load simply take the short circuit current corresponding to the existing field current and multiply it by the terminal voltage and the square root of three. This will be slightly high if saturation is present in the machine.

So for steady state operation the power is proportional to the induced voltage and the sine of the displacement angle.

ROTOR NOT AT SYNCHRONOUS SPEED

Changing from one steady load angle to another requires a motion of one winding with respect to the other different from synchronous speed. This analysis is carried through as though the difference in speed was constant, that is, a constant slip. The effect of acceleration is disregarded.

Let the rotor rotate at a constant slip. The effect of each winding is found by itself and then the two components are combined.

First short the field winding and apply a three phase voltage, V, to the stator. Now we have an ordinary induction motor. Power[1] transferred across the gap is given by the expression,

$$P = \frac{E_2^2 (1-s) s r_2}{r_2^2 + (x_2 s)^2}$$

For the usual values of r and x a straight line can represent the relation between power and slip when within a few percent of synchronism. If slip is small the power across the gap is approximately,

$$P = \frac{E_2^2 s}{r_2}$$

The slope of this curve can be obtained in three methods which are,

1. Circle diagram
2. Design data
3. Direct load test

The load test was used to determine the slope for this machine and this has been discussed fully on page 8.

1 Lawrence Alt. Current Mach. page 461

Next shortcircuit the armature and apply a direct current in the field winding. The induced voltage will be smaller in proportion to the slip but the current remains the same as before if the resistance is small compared to the reactance. This shows that the power due to angular position does not vary when the rotor is not running at synchronism.

Summing up the various components to find the total power gives,

$$P = \frac{VE}{Z} \sin\theta + \frac{E_z^2 s}{r_z}$$

or

$$P = T_m \sin\theta + T_d \frac{d\theta}{dt}$$

since

$$s = \frac{d\theta}{dt}$$

SECTION NO. III.

TRANSIENT TESTS

The following tests were made to determine experimentally the transients following an abrupt load on the shaft of a synchronous machine. This section gives first a description of the machine tested and the other apparatus used. Then the test procedure is described. The tests next follow with notations of any special features.

DESCRIPTION OF SYNCHRONOUS MACHINE TESTED

The synchronous machine used in these tests was a sine wave generator made by the General Electric Co. and was rated 5 kw 3 phase wye connected 220volts 13.2 amperes 1800 rpm 4 pole 60 cycles. Its serial number was 1775497. This type of machine was specially designed so that it would give a good wave form for testing watt-meters and samples of iron. The rotor was smooth and had a distributed winding.

A few clippings from G. E. Bulletin No. 42567 appear on the next page and these describe very well the three unit set used for these tests.

THE SINE WAVE GENERATOR

After careful study and investigation, a special generator has been developed which gives an exceptionally good wave form. This generator is of the revolving field type, wound three-phase, four-pole, and is small and compact.

Practically a true sine wave is obtained by the use of a cylindrical rotor and by a large number of distributed stator and rotor coils.

Meter Testing

For meter testing a special three-unit motor-generator set has been developed. Fig. 7 shows this motor-generator set which consists of a direct-current driving motor coupled to two 5-kv-a. alternating-current sine wave generators.

The driving motor is capable of driving the generators at any frequency from 25 to 60 cycles. If only alternating current is available, a synchronous motor may be substituted for the direct-current driving motor. In this case, variation of frequency can not be obtained.

The base is rigid and self-supporting so that the assembled set may be moved or lifted without affecting its alignment.

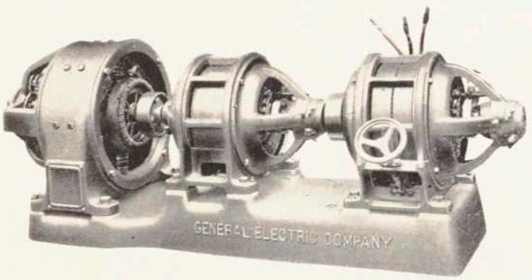


Fig. 7. TWO SINE WAVE GENERATORS (ONE HAVING AN ADJUSTABLE FRAME) DIRECT CONNECTED TO A D-C. MOTOR

This three-unit motor-generator set is equipped with a special device for shifting the stator of one generator relative to the other so that a phase displacement between the voltage of the two generators can be obtained. This phase shifting device consists of a handwheel, worm, and worm segment, which is of sufficient length for rotating the frame 60 mechanical degrees or 120 electrical degrees in either direction from the neutral position. The desired power-factor setting is obtained by mechanically shifting the stator of the adjustable frame generator. This generator is furnished with a special bearing which is properly lubricated without spilling oil when the stator frame and end shields are rotated.

In wattmeter testing the potential generator is usually furnished with a 220-110-volt winding which is used to excite the potential coils of the wattmeter. The current generator is furnished with an 18-volt winding which is used to excite the current coils of the wattmeter. If the motor-generator set is to be located some distance from the Testing Laboratory, it is recommended that both generators be furnished with the higher voltage winding and transformers be used to step down the voltage of the current generator at the testing table. In this case, the motor-generator set should be furnished with a motor-operated phase shifting mechanism.

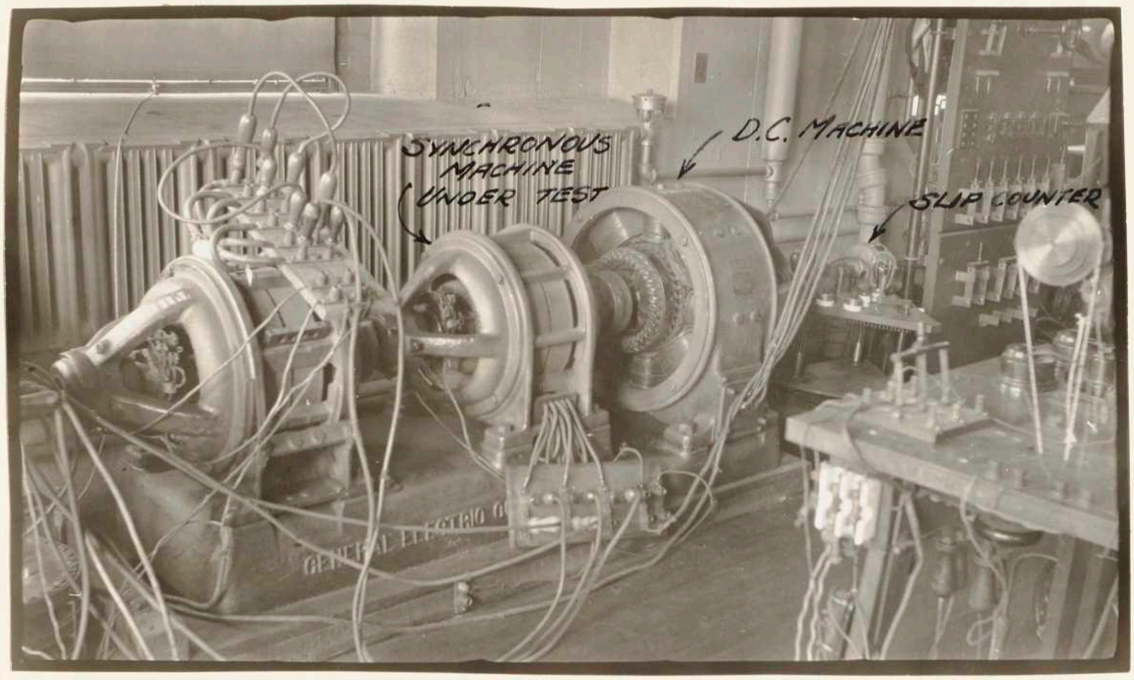
AUXILLIARY APPARATUS

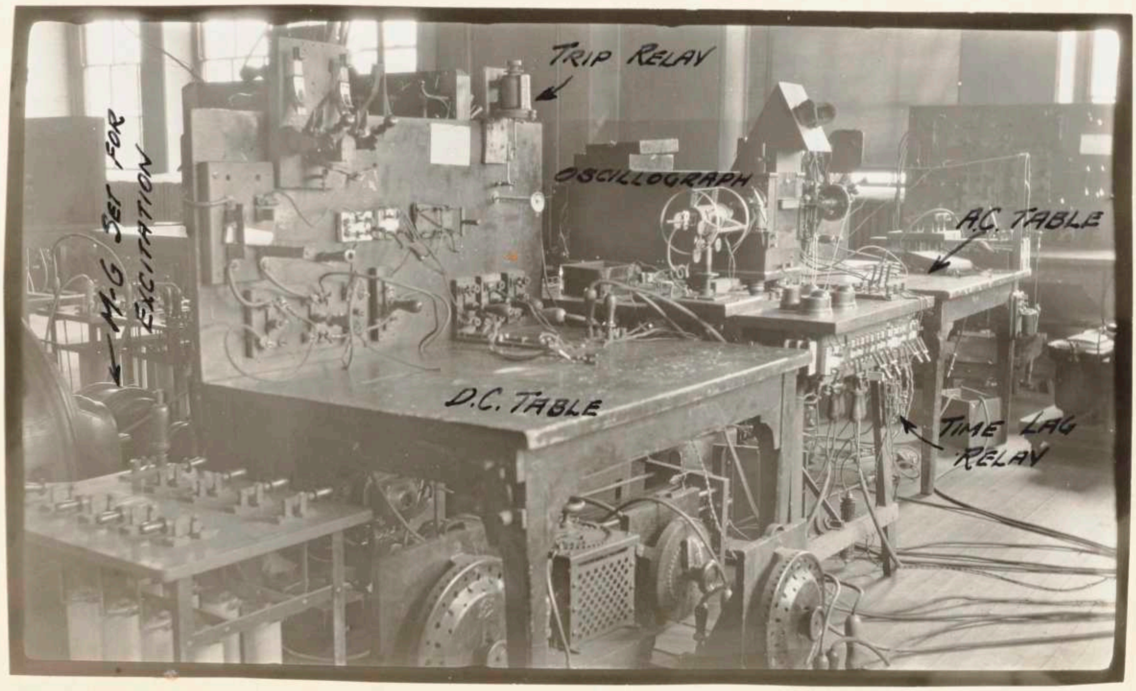
The transients were taken with an abrupt shaft load applied to the set. This was procured by suddenly loading the direct current machine by closing its armature circuit across a resistance load. The time for load to build up on the shaft depended upon the time constant of the circuit. Oscillogram No. 2 page 30 shows that the time constant is negligible when compared to the rest of the transient which lasts some two seconds. Thus the direct current machine applies an abrupt shaft load which is zero before the switch closes and a constant value afterwards.

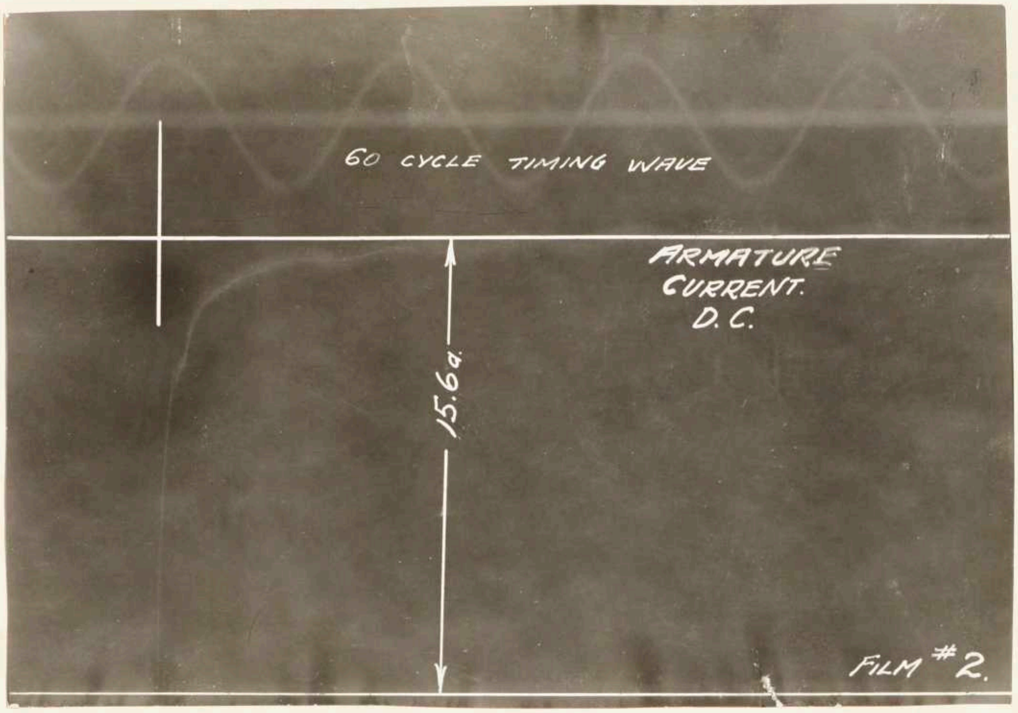
On page 29 , appear two photographs of the setup in the laboratory. The upper one shows the machines and the lower one the control tables, relays, and the oscillograph.

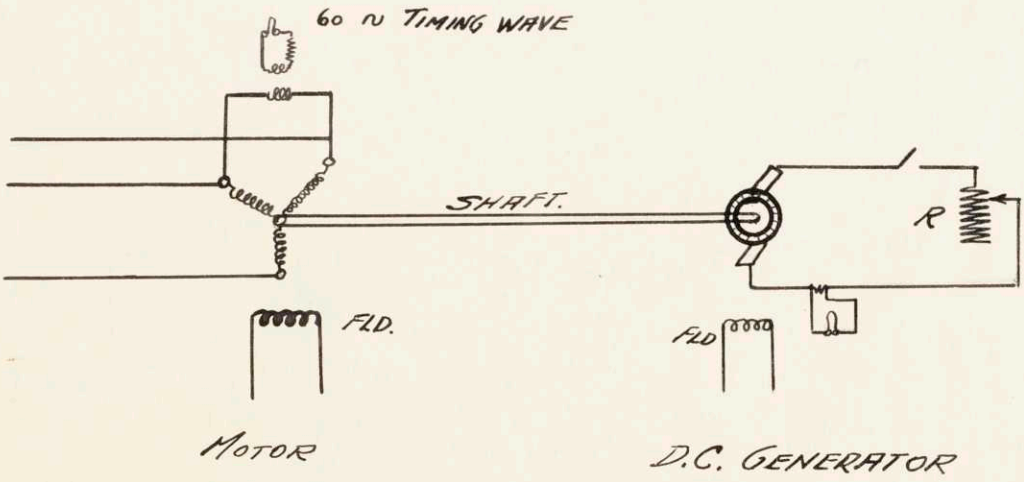
To record the transients a General Electric three element oscillograph was used. Since the duration of the phenomena was several seconds it was necessary to either use a longer film or slow up the drum. Both schemes were resorted to for tests. The drum was slowed up by using a special small pulley on the film driving motor.

A wiring diagram is shown on page 31 and since it applies to both these tests and those of Mr. Boyle it looks rather complicated. A more comprehensible diagram is that below film No. 2 on page 30 .


SYNCHRONOUS MACHINE UNDER TEST
D.C. MACHINE
SLIP COUNTER
GENERAL ELECTRIC


TRIP RELAY
OSCILLOGRAPH
A.C. TABLE
M-G SET FOR EXCITATION
D.C. TABLE
TIME LAG RELAY


60 CYCLE TIMING WAVE
ARMATURE
CURRENT.
D.C.
15.6 a.
FILM #2.


60 ~ TIMING WAVE
SHAFT.
R
FLD.
FLD
MOTOR
D.C. GENERATOR

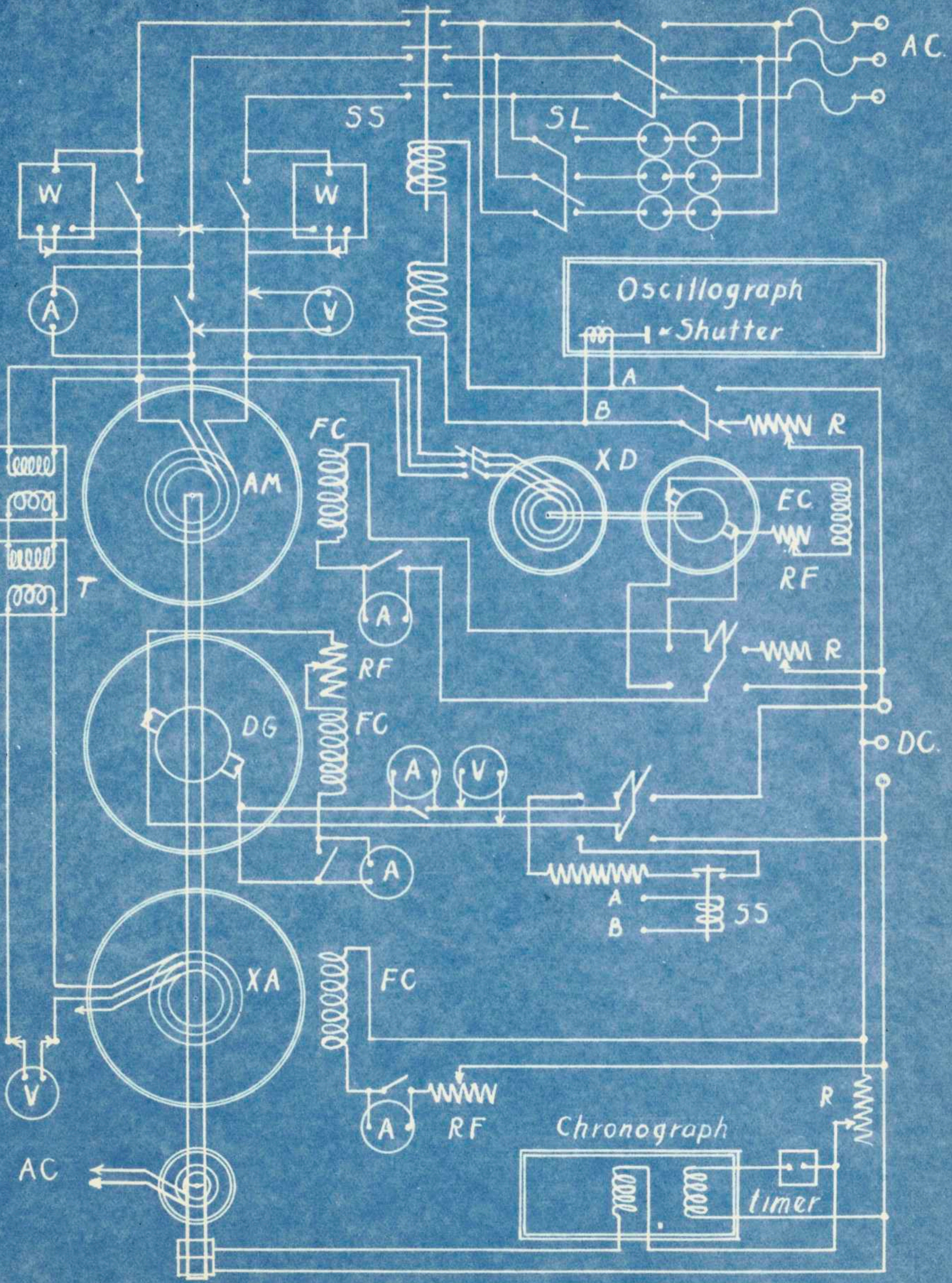


Fig. 1.

Edgerton & Boyle
March '27

Automatic relaying was necessary to get the correct time delay between the oscillograph shutter and the transient trip switch. Sometimes inductance in the trip circuit will slow it down although for these experiments it would require too many reactors to get the necessary time lag. A line drawing of the time relay used is shown on page 33. The relay arm must displace a mass before closing the trip circuit. The time interval is easily changed by adjusting the current in the relay coils.

On the same page mentioned in the previous paragraph is also a drawing of the trip switch. When the coil is energized it raises the trip catch and the compressed springs close the transient switch. Both this switch and the time relay gave excellent operating results.

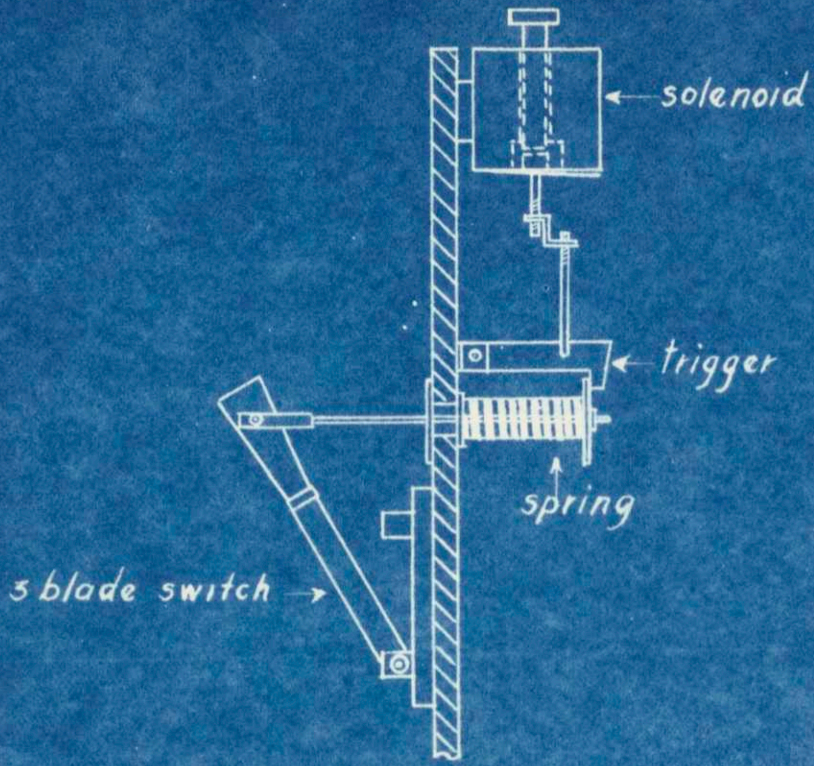


Fig 2.

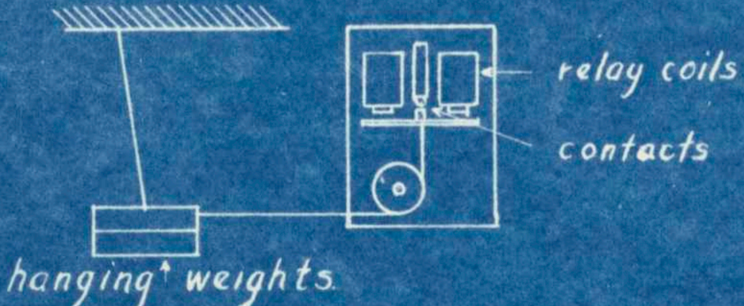


Fig 3.

Boyle & Edgerton
April 1927

TEST PROCEDURE

The synchronous machine was run as a motor from the 230 volt, three-phase, 60 cycle laboratory circuit. Load was abruptly applied to the shaft by loading the direct current machine . The oscillograph elements read,

No. 1 armature current in synchronous motor

No. 2 field current of synchronous motor

No. 3 angle voltage.

For a description of angle voltage and its relation to the angle between terminal voltage and the centerline of the field poles see the tests under Section IV, page 89. Meters were placed in the various circuits and were read before and after each transient.

When power was wanted during the transient it was necessary to slow up the drum and use a long film so that the angle between current and voltage could be read. For such tests the oscillograph read,

No. 1 armature current in synchronous motor, phase No. 1

No. 2 voltage to neutral, phase No. 1

No. 3 angle voltage.

By this means power could be followed fairly accurately over a time interval of about one second.

CALIBRATION OF OSCILLOGRAPH

Peak values measured in millimeters from the zero line multiplied by the calibration factor give the rms values or the AC meter readings which correspond.

For each set of films one was run through the oscillograph with known values on it to supply the calibration information.

The machine under test, the procedure, and other details of test have been described. These apply to all the tests which are now described. Any special features will be described when necessary.

A number was assigned to each oscillogram at the time of its exposure and this number was marked on the film as soon as it reached the dark room. The consecutive number system includes both oscillograms for this thesis and for Mr. Boyle's.

The same set of meters was used throughout the tests. The calibration errors were well within experimental error and so were disregarded.

Meters used.

Wattmeter		No. 545557	150-300 volt	30-60 amp.
Wattmeter		558460	150-300; volt	30-60 amp.
Voltmeter	AC	24869	150-300; volt	
Ammeter	AC	498129		30-60 amp.
Voltmeter	AC	2374	20 volt	
Voltmeter	DC	21921	150-300 volt	
Ammeter	DC	25951		20 amp.
Ammeter	DC	655		100 amp.

FILMS NO. 4 AND NO. 5

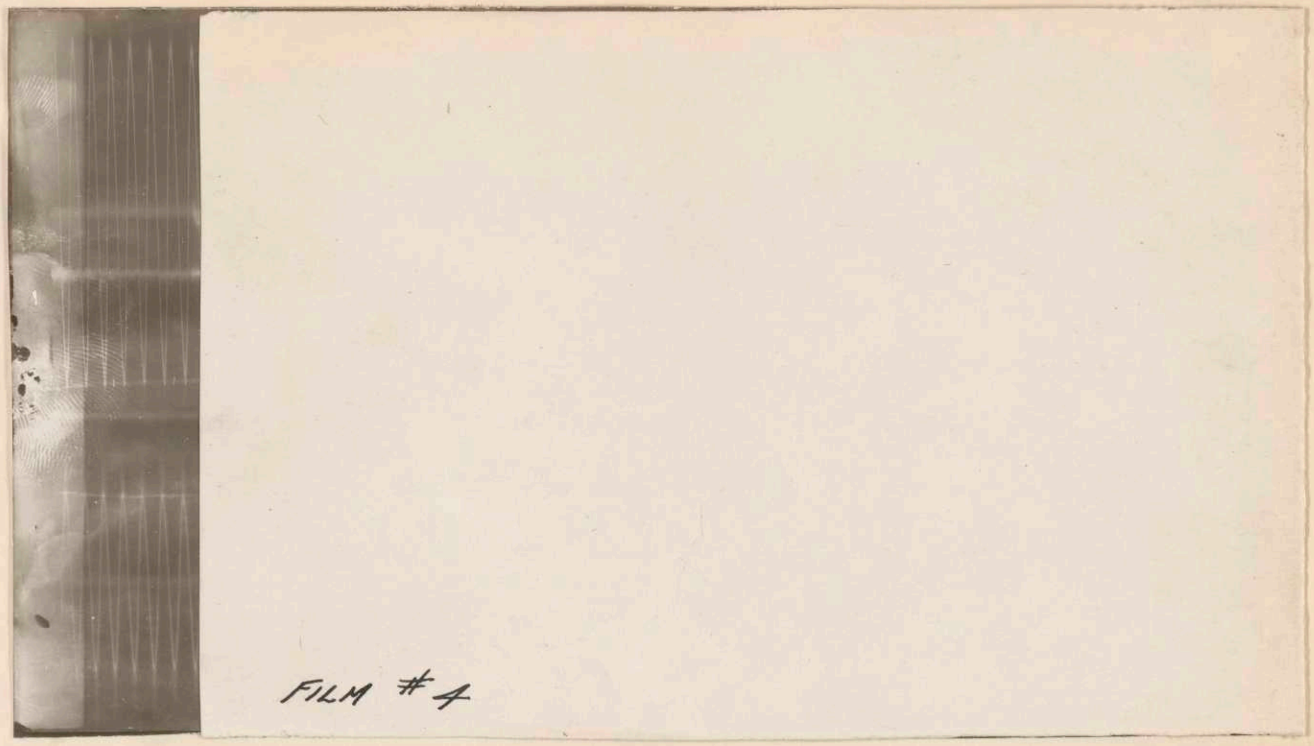
The synchronous motor exciting current was taken from the 115 volt circuit in the laboratory . Of this 60 volts drop occured across the field and the rest across the field rheostat. The stator of the machine to measure angle was set on the 32 cm mark for this test. (See curve on page 92.) Film No. 5 was taken for calibration.

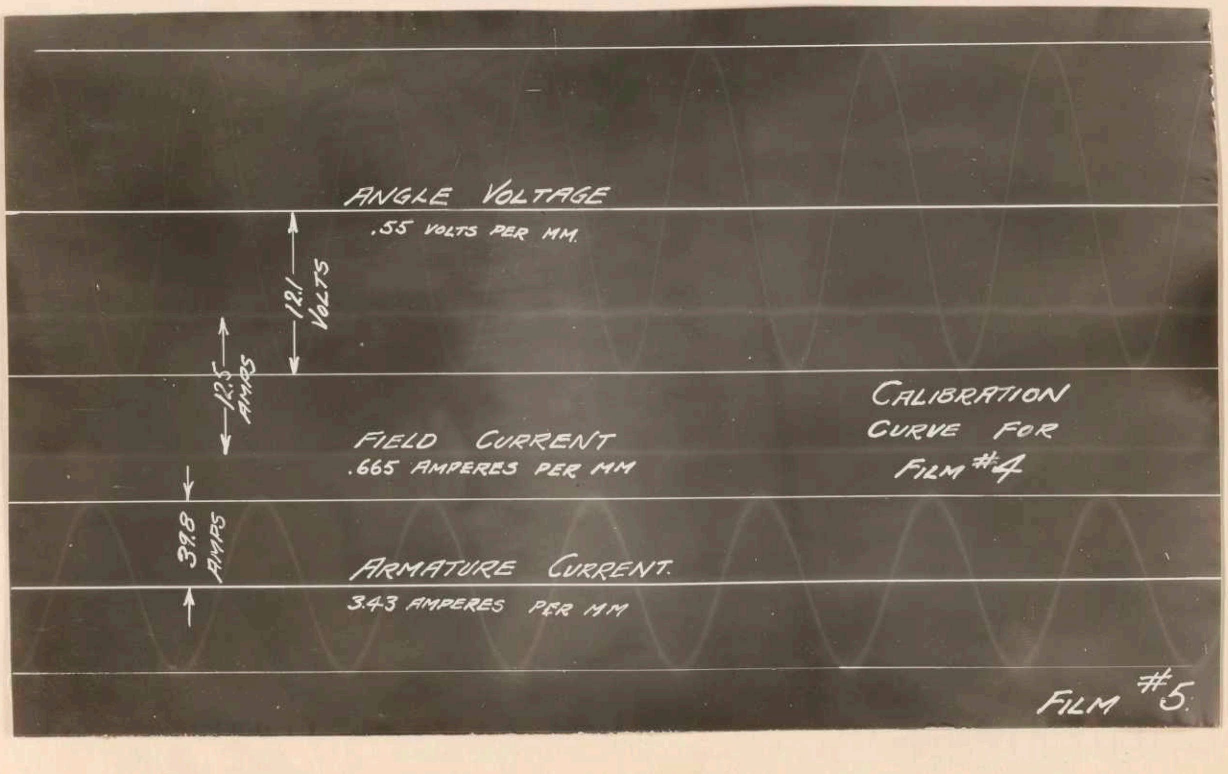
Meter readings.

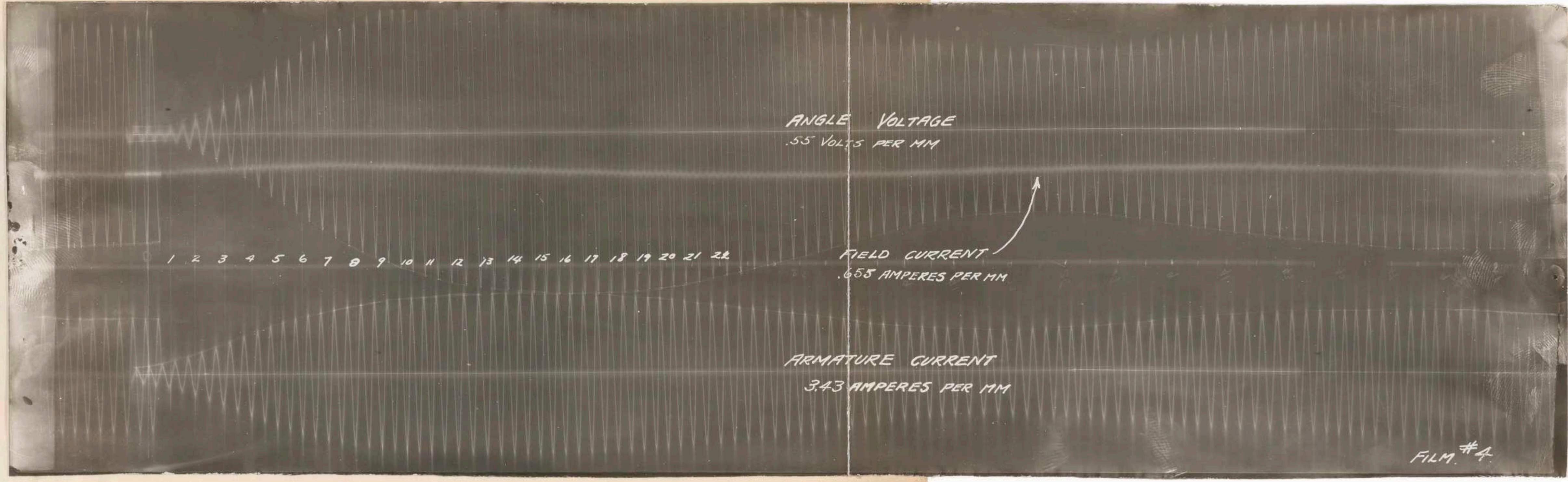
	Before	After	Film No. 5 Calibration
V	228	224	
I	4.4	42	39.8
KW	1.6	14.7	
I_f	12.6	13	12.44
# E^o	1 (6^o)	12.08 (59^o)	12.09
E_{dc}	190	184	
I_{dc}	0	59.3	

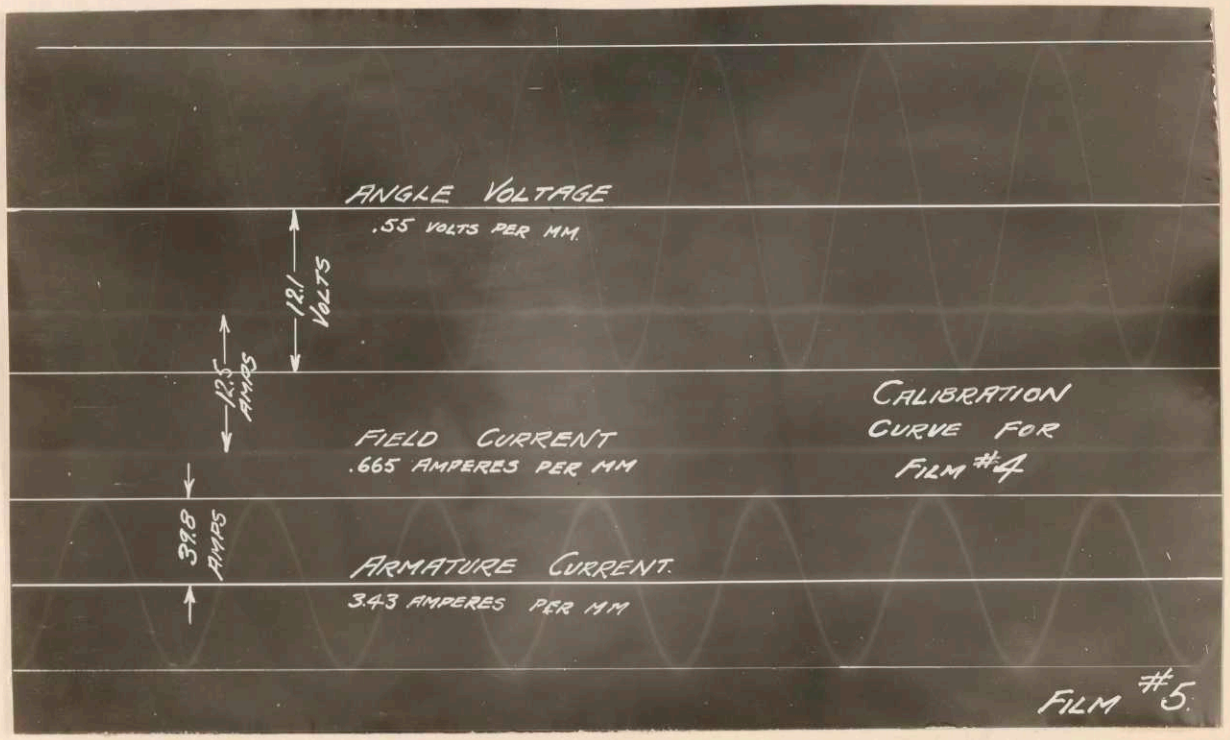
Note that E^o means angle voltage, see Section IV, page 89.

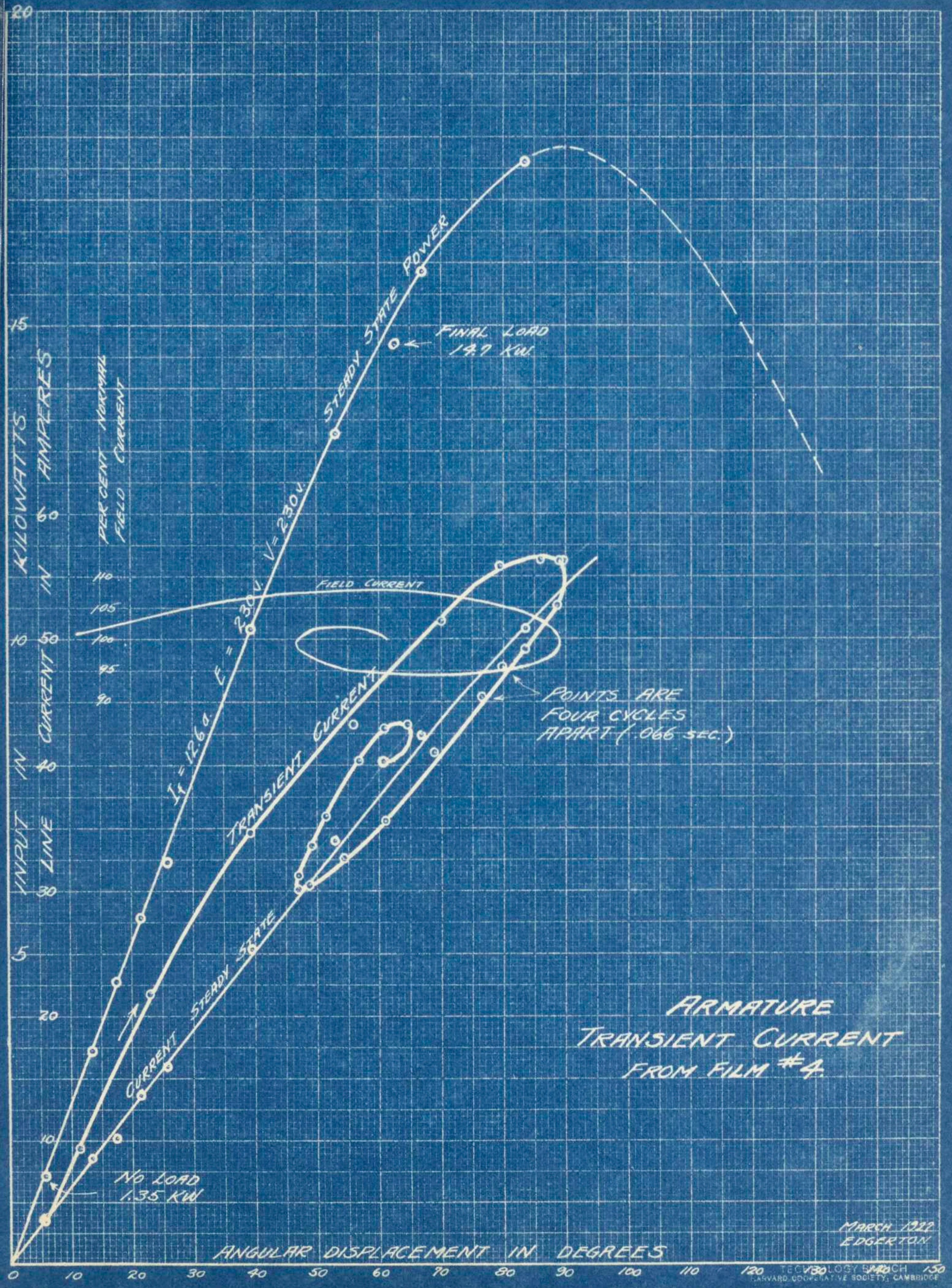
A plot of armature current against angular displacement is shown on page 38, following the oscillograms. The curves are superimposed on the steady state values.

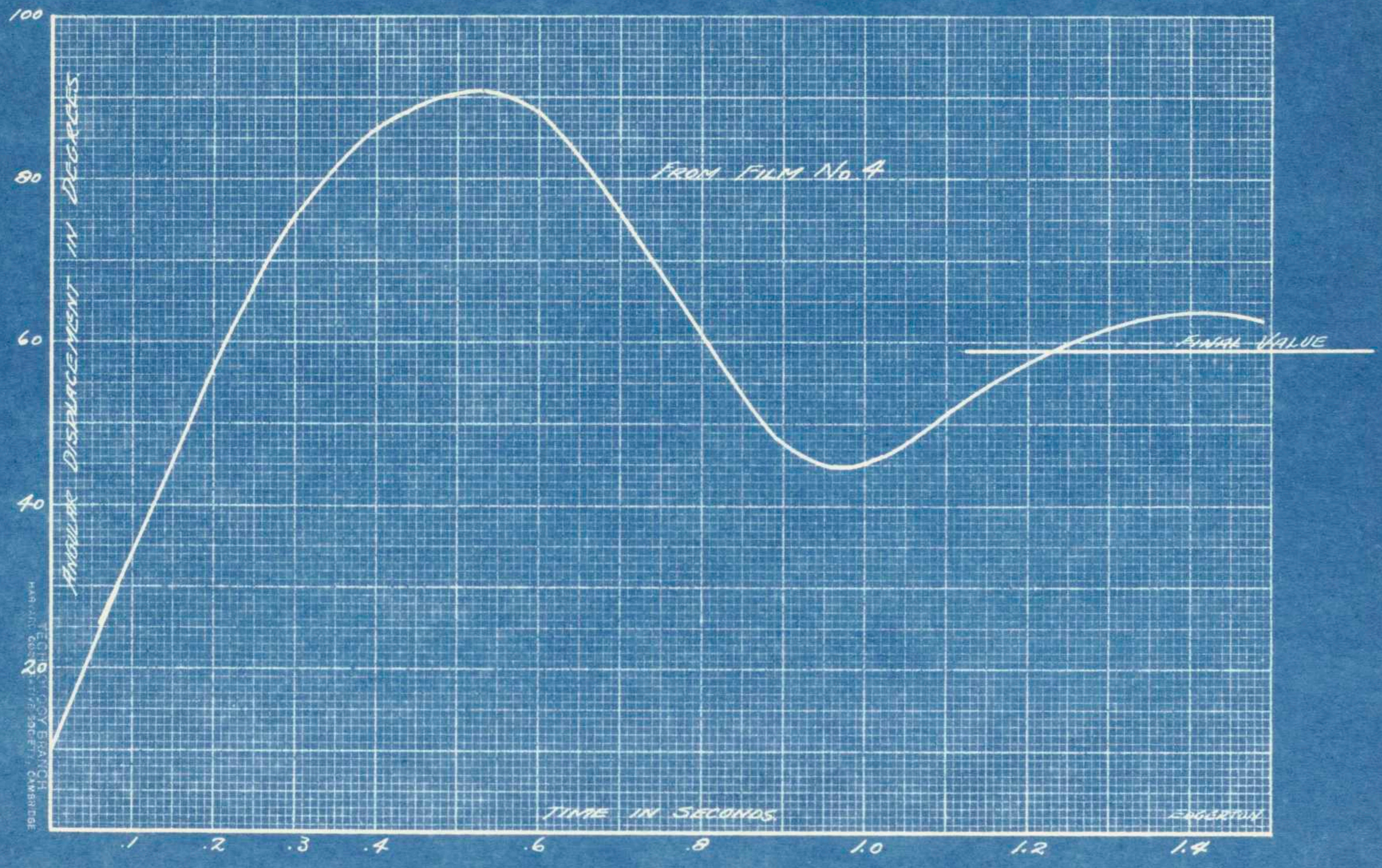

FILM #4


ANGLE VOLTAGE
.55 VOLTS PER MM.
12.1 VOLTS
12.5 AMPS
FIELD CURRENT
.665 AMPERES PER MM
39.8 AMPS
ARMATURE CURRENT.
3.43 AMPERES PER MM
CALIBRATION
CURVE FOR
FILM #4
FILM #5.


ANGLE VOLTAGE
.55 VOLTS PER MM
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
FIELD CURRENT
.655 AMPERES PER MM
ARMATURE CURRENT
3.43 AMPERES PER MM
FILM #4


ANGLE VOLTAGE
.55 VOLTS PER MM.
12.1 VOLTS
12.5 AMPS
CALIBRATION
CURVE FOR
FILM #4
FIELD CURRENT
.665 AMPERES PER MM
39.8 AMPS
ARMATURE CURRENT.
3.43 AMPERES PER MM
FILM #5


ARMATURE
TRANSIENT CURRENT
FROM FILM #4
INPUT IN KILOWATTS
LINE CURRENT IN AMPERES
PERCENT NORMAL FIELD CURRENT
ANGULAR DISPLACEMENT IN DEGREES
STEADY STATE POWER
$I_f = 12.6a$ $E = 230V$ $V = 230V$
FINAL LOAD 14.7 KW.
FIELD CURRENT
TRANSIENT CURRENT
CURRENT STEADY STATE
POINTS ARE FOUR CYCLES APART (.066 SEC.)
NO LOAD 1.35 KW
MARCH 1922
EDGERTON
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
5 10 15 20
10 20 30 40 50 60
90 95 100 105 110
TECHNOLOGY BRANCH HARVARD COOPERATIVE SOCIETY, CAMBRIDGE


100
80
60
40
20
ANGULAR DISPLACEMENT IN DEGREES
FROM FILM No 4
FINAL VALUE
TIME IN SECONDS
.1
.2
.3
.4
.6
.8
1.0
1.2
1.4

FILMS NOS. 6, 7. 8. & 9.

Excitation for these was obtained from the 115 volt dc mains in the same manner as for film No. 4.

Film No. 6 supplied calibration data.

Film No. 7 was a four foot film. The film driving motor on the oscillograph did not have sufficient power to pull it all the way through. Also the armature current did not record. Still it records the angle voltage over about one second. The load on the shaft was enough to pull the motor out of step.

Film No. 8 records the breakdown of the synchronous motor. The curve on page46 gives the variation of current with angle for this film.

Meter readings

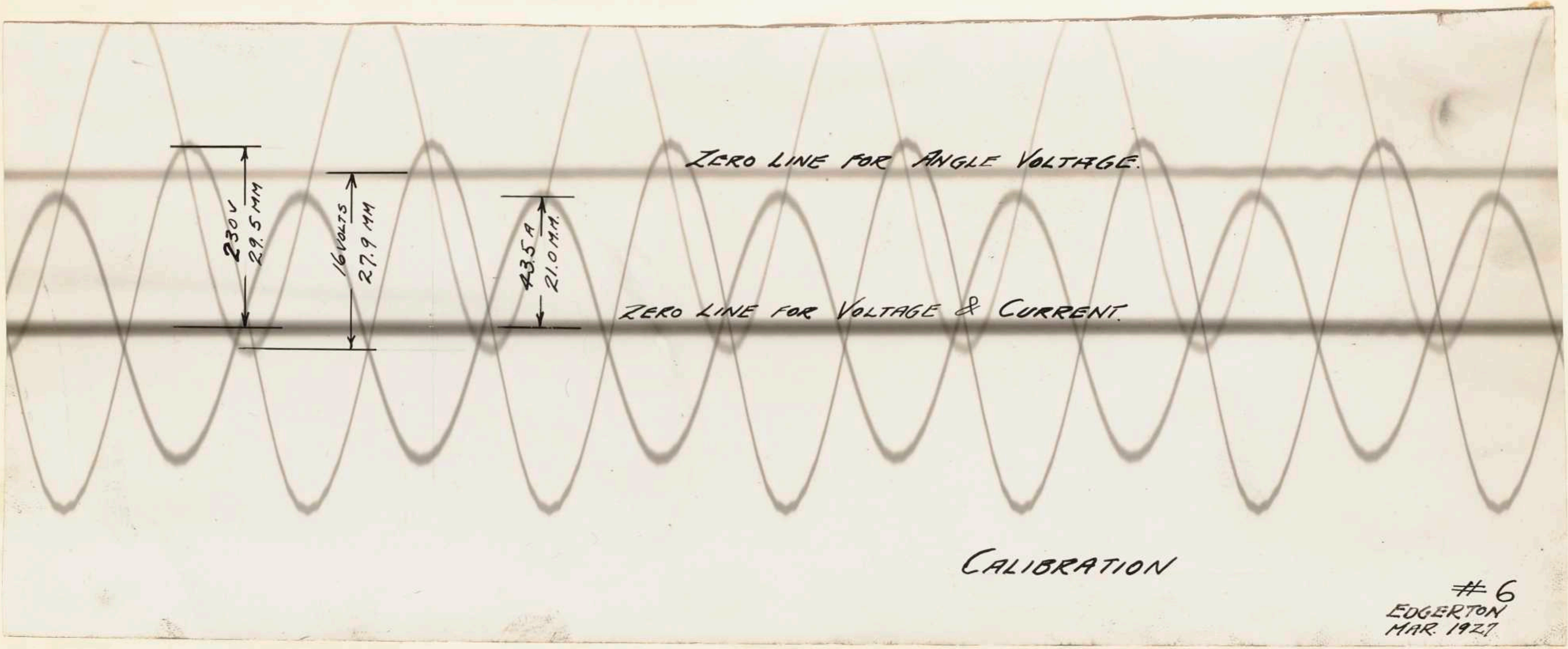
	Before	After	
V	226	224	volts
I	4.4	Pulled out	amperes
KW	1.68		kilowatts
I_f	12.6		amperes
E^o	1		volts
E_{dc}	185	180	volts
I_{dc}	0	61	amperes

Film No. 9. Abrupt load was applied for this film and then removed after steady conditions had been reached. The oscillogram shows that the rotor when the

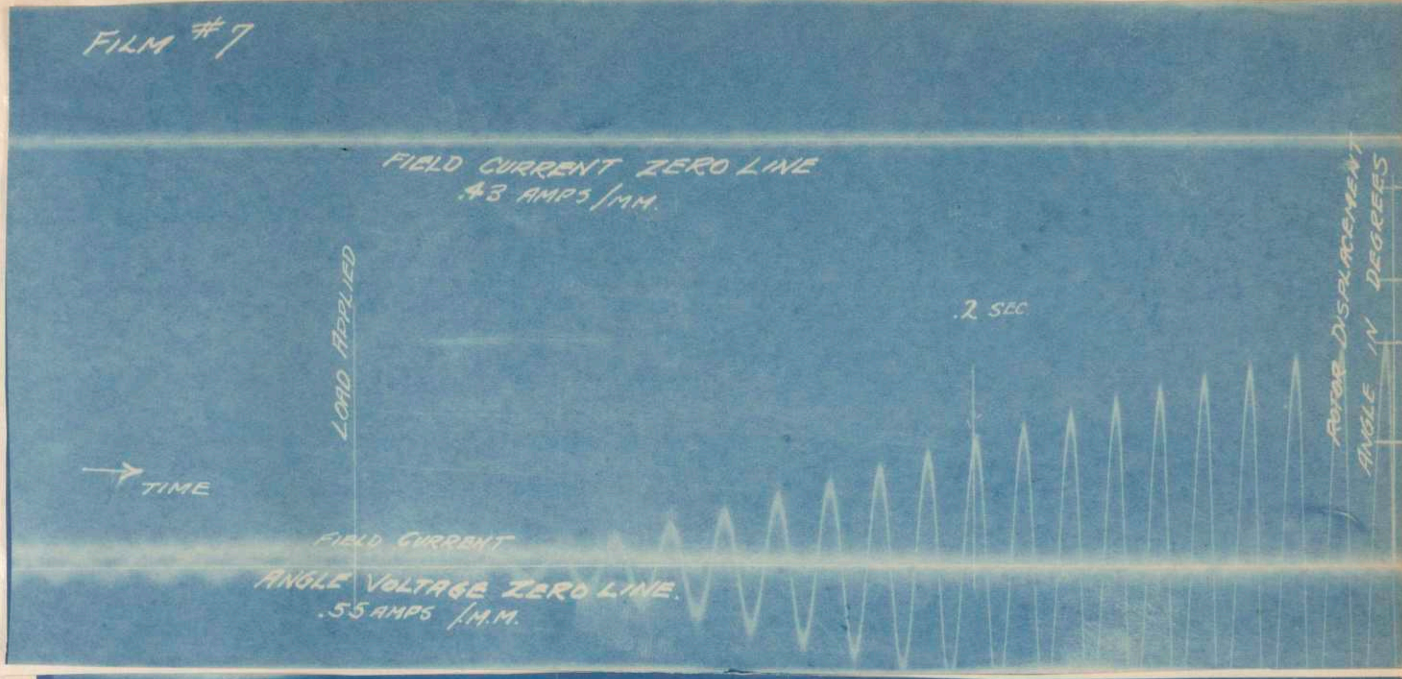
the load was removed actually swung past the zero angle position. This means that the machine was acting as a generator for a short time.

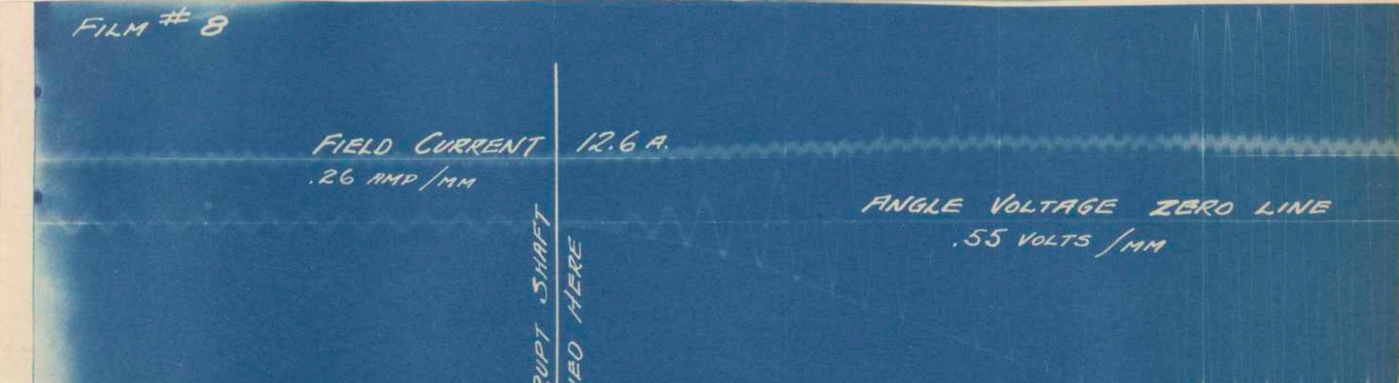
Meter readings

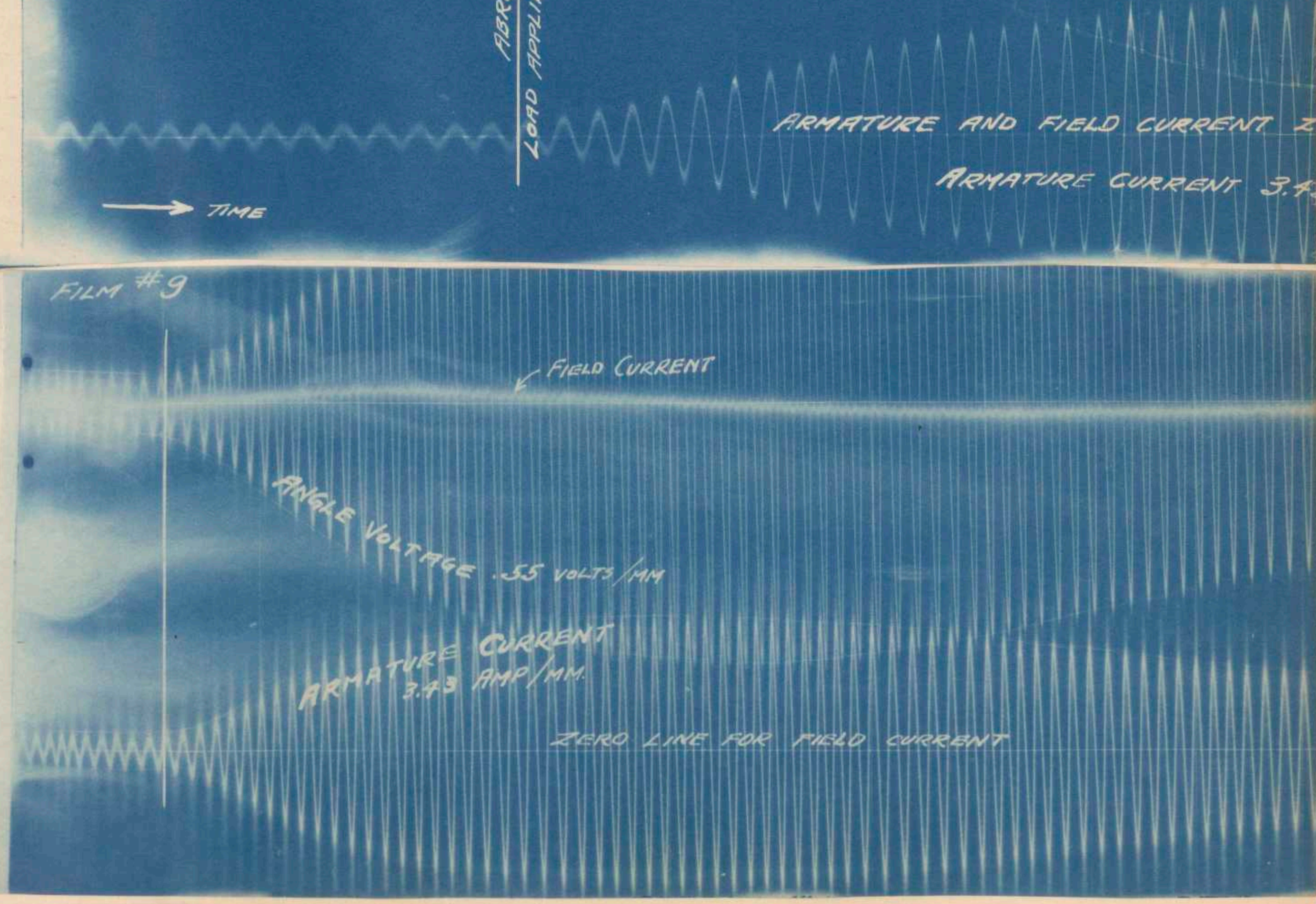
	Before	After	
V	232	228	volts
I	4.6	42	amperes
KW	1.68	15.6	kilowatts
I_f	12.6	12.6	amperes
E^o	1.5	15.1	volts
E_{dc}	200	194	volts
I_{dc}	0	59	amperes

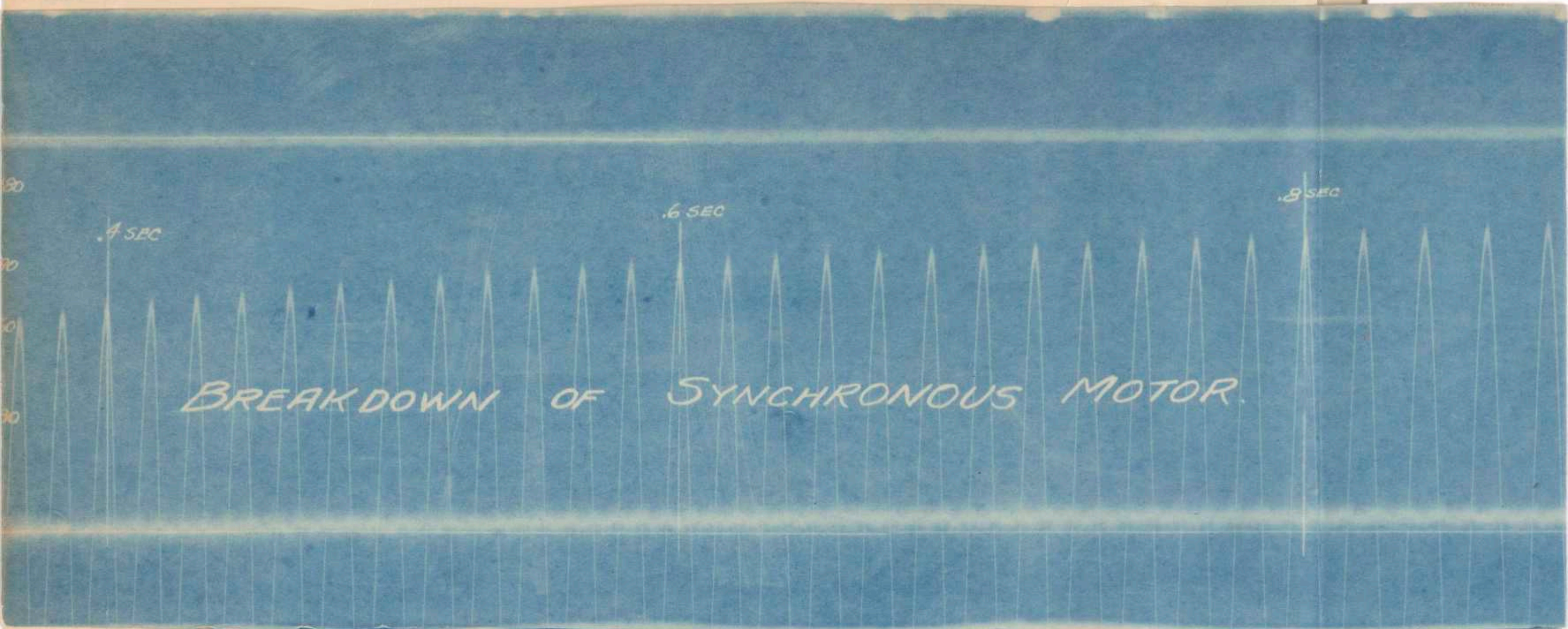


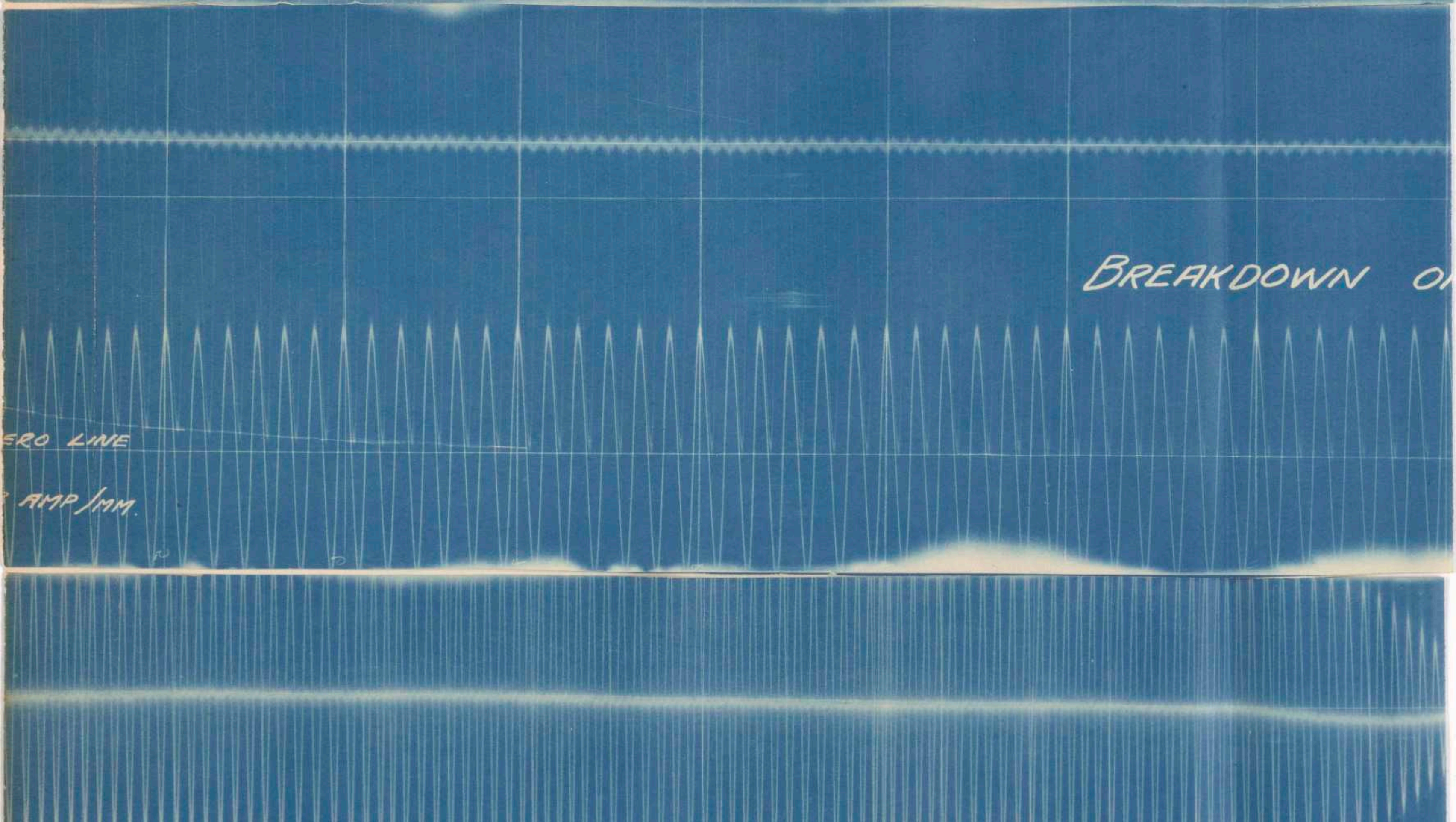
230 V
29.5 MM
16 VOLTS
27.9 MM
43.5 A
21.0 M.M.
ZERO LINE FOR ANGLE VOLTAGE.
ZERO LINE FOR VOLTAGE & CURRENT.
CALIBRATION
#6
EDGERTON
MAR. 1927

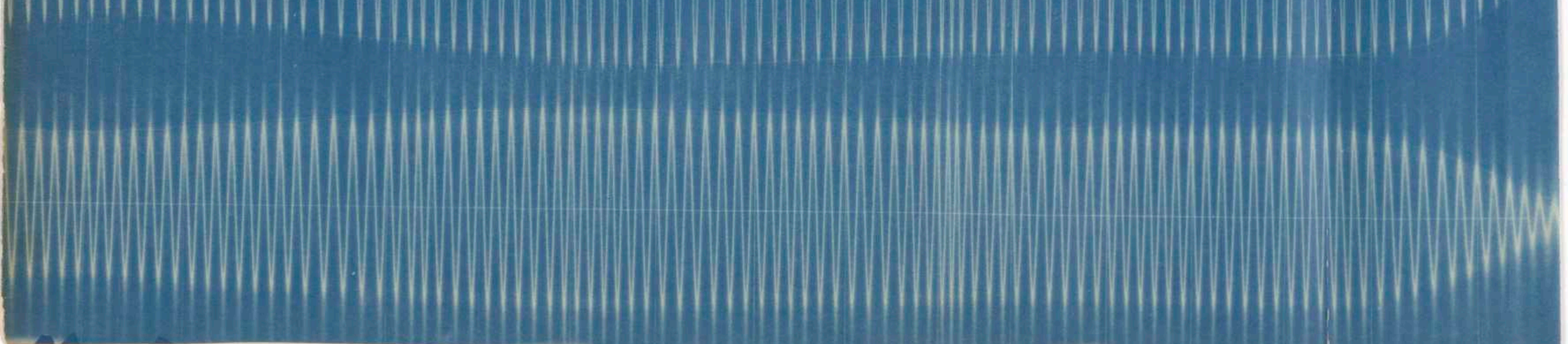

FILM #7
FIELD CURRENT ZERO LINE
.43 AMPS/MM.
LOAD APPLIED
.2 SEC.
ROTOR DISPLACEMENT
ANGLE IN DEGREES
→ TIME
FIELD CURRENT
ANGLE VOLTAGE ZERO LINE.
.55 AMPS /M.M.

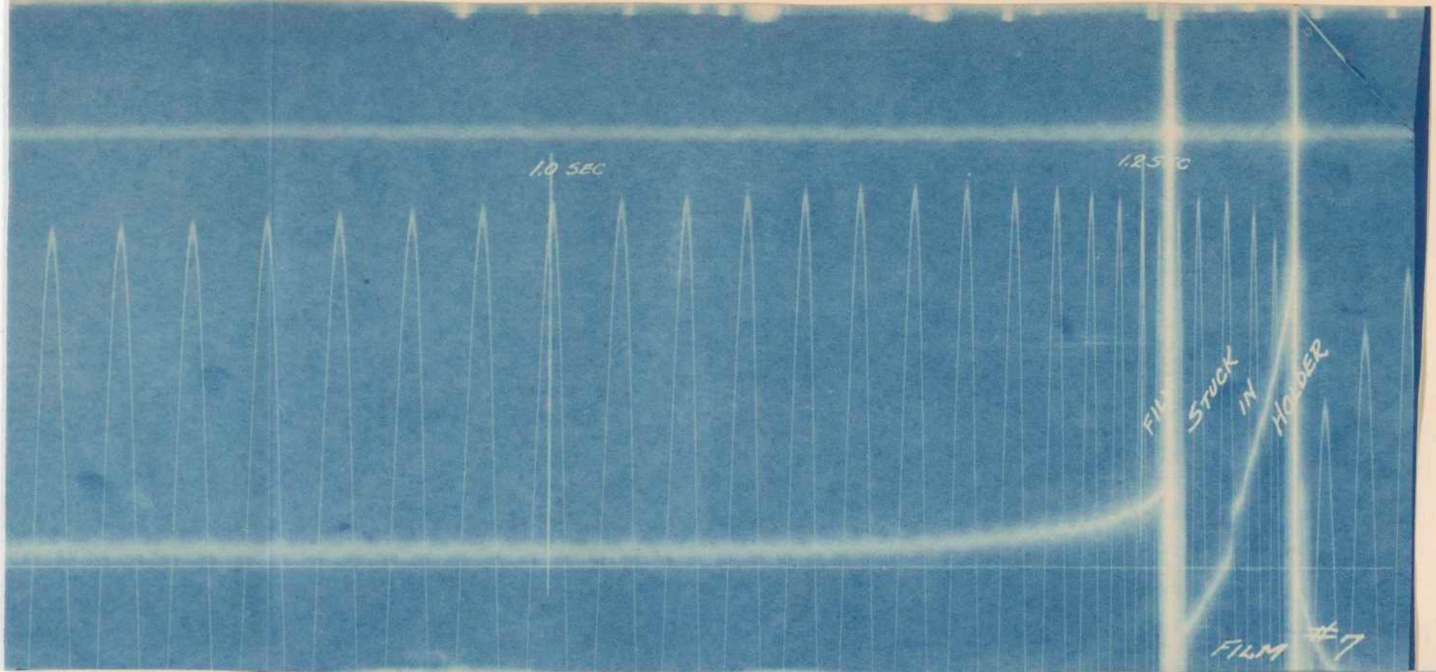

FILM # 8
FIELD CURRENT
.26 AMP/MM
12.6 A.
ABRUPT SHAFT
LOAD APPLIED HERE
ANGLE VOLTAGE ZERO LINE
.55 VOLTS /MM
ARMATURE AND FIELD CURRENT Z
ARMATURE CURRENT 3.4
→ TIME

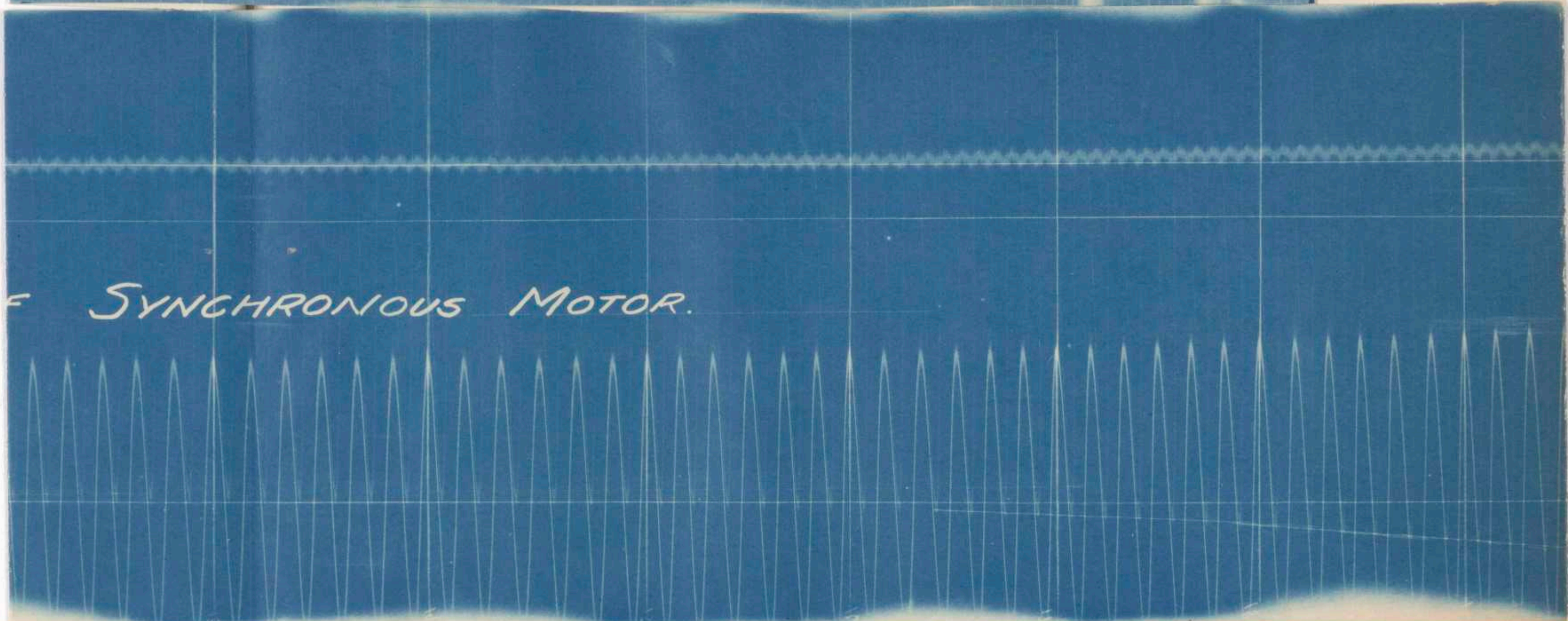

FILM #9
FIELD CURRENT
ANGLE VOLTAGE .55 VOLTS/MM
ARMATURE CURRENT
3.43 AMP/MM.
ZERO LINE FOR FIELD CURRENT

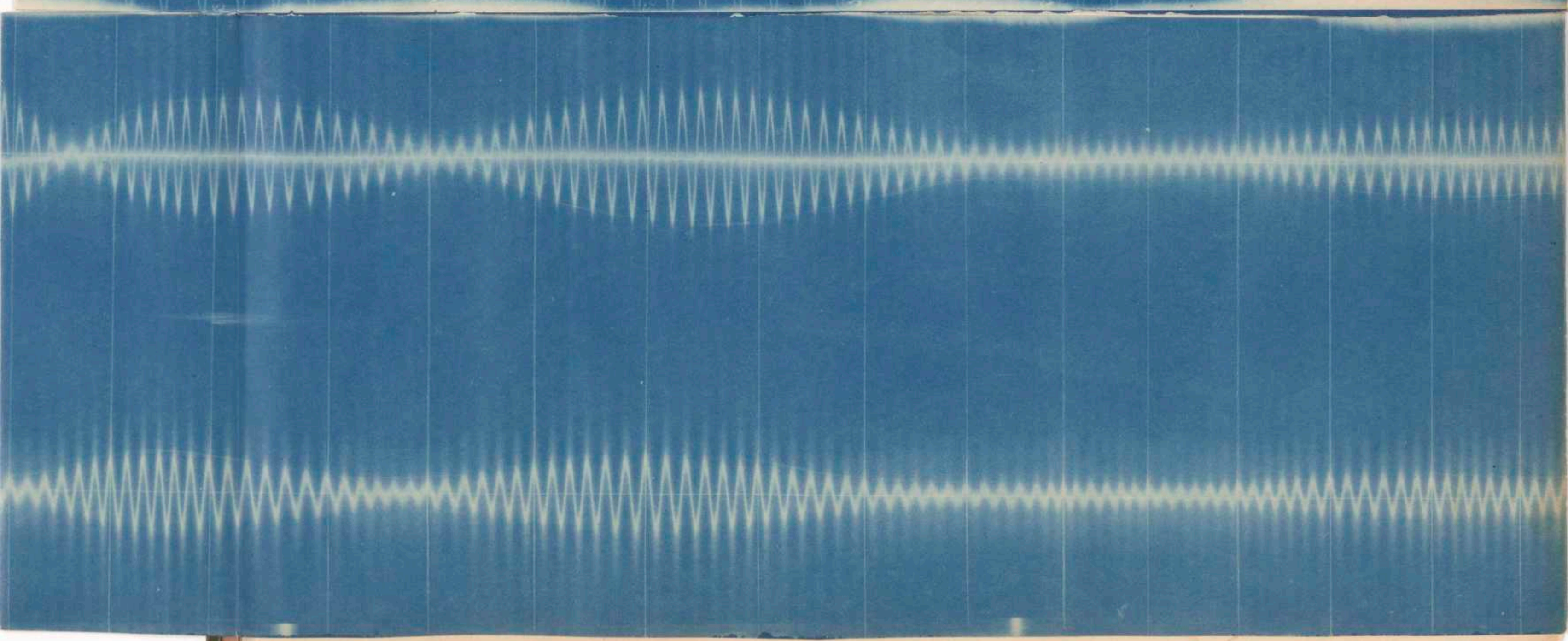

.4 SEC
.6 SEC
.8 SEC
BREAKDOWN OF SYNCHRONOUS MOTOR

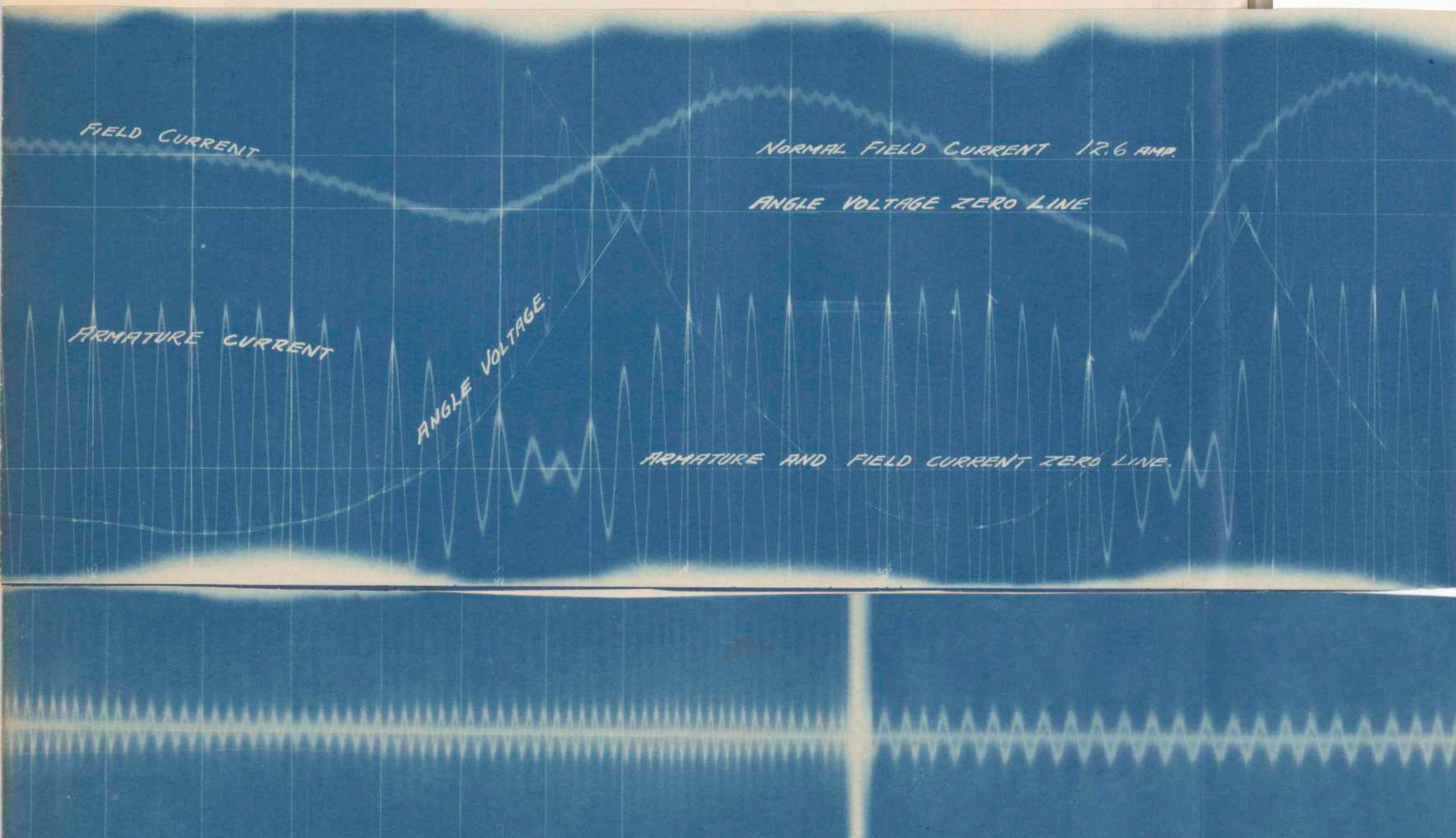

BREAKDOWN
ERO LINE
AMP/MM

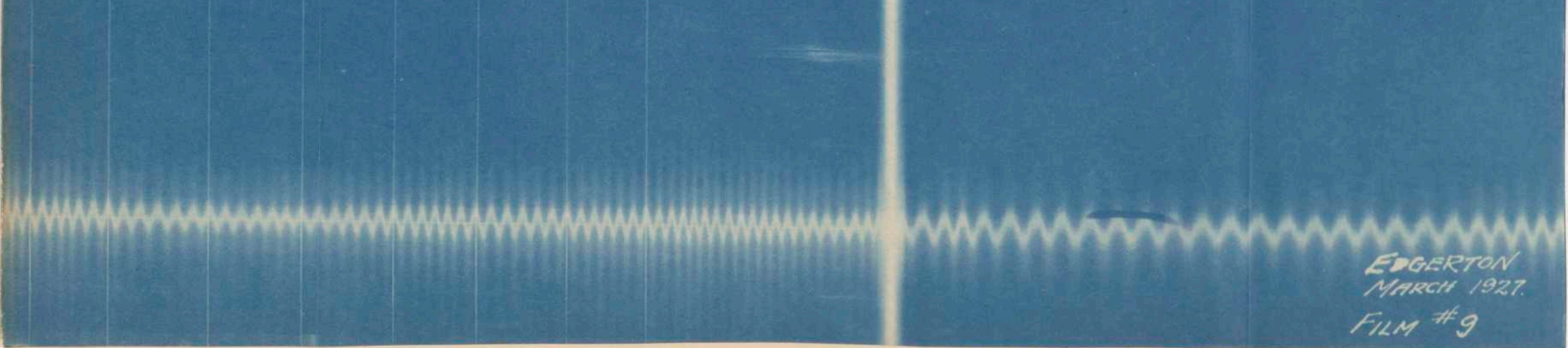


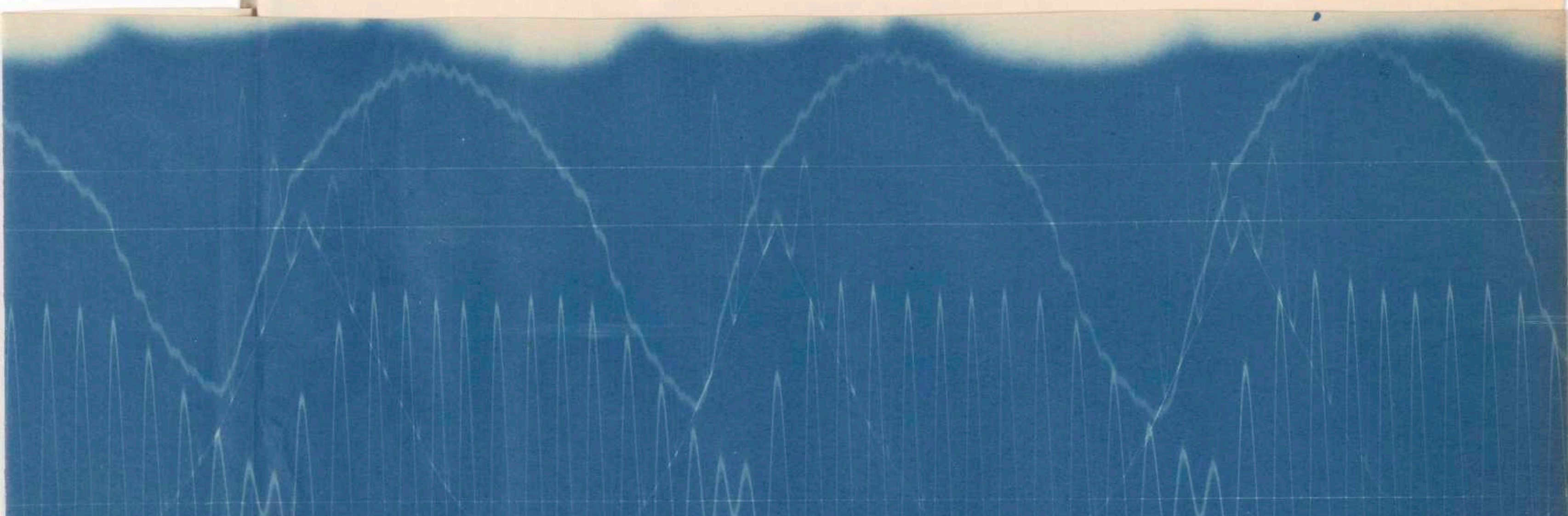

1.0 SEC
1.25 SEC
FILM STUCK IN HOLDER
FILM #7

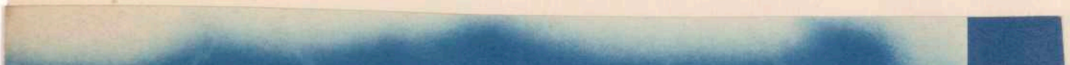

F SYNCHRONOUS MOTOR.

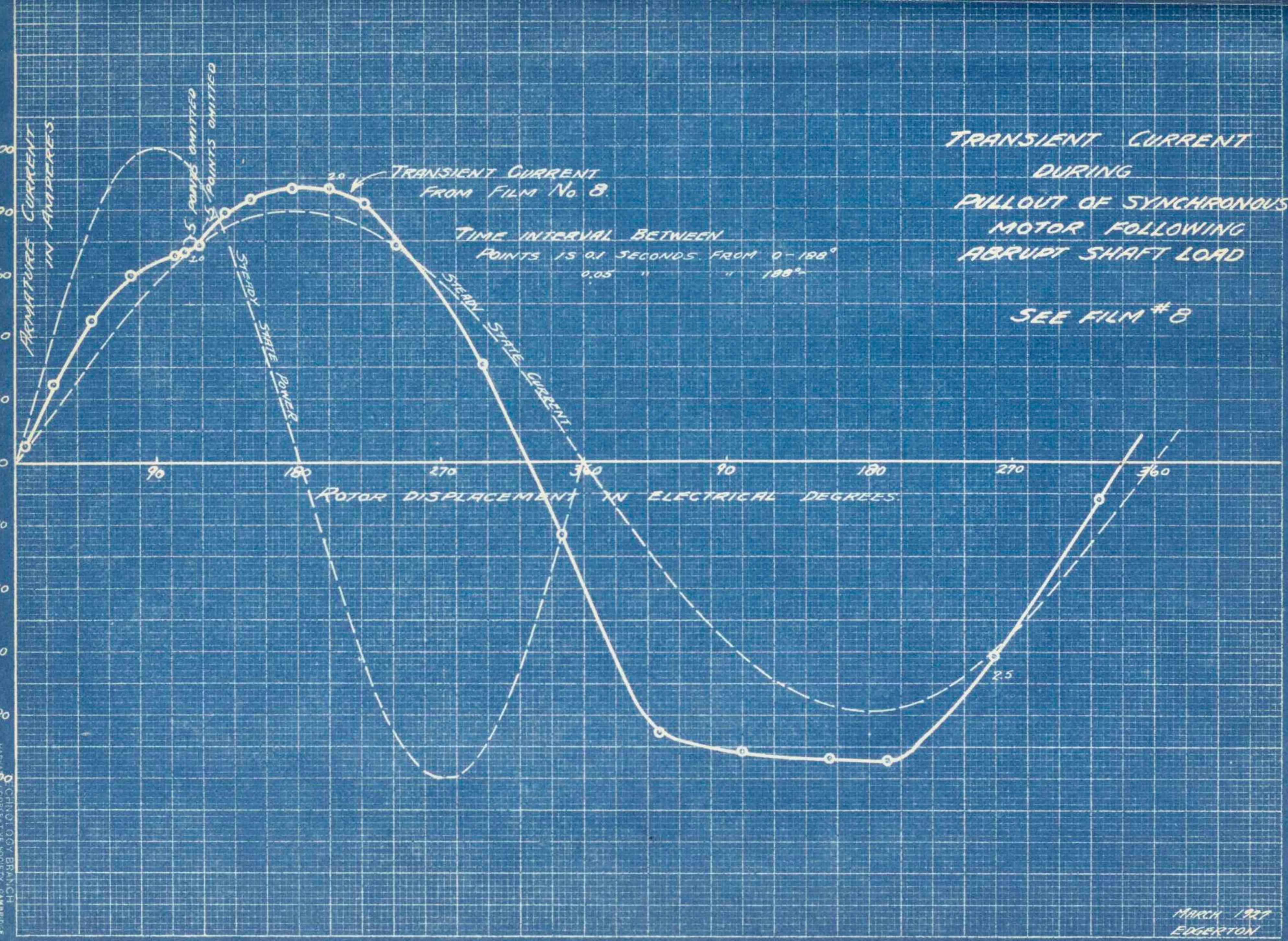



FIELD CURRENT
NORMAL FIELD CURRENT 12.6 AMP.
ANGLE VOLTAGE ZERO LINE
ARMATURE CURRENT
ANGLE VOLTAGE
ARMATURE AND FIELD CURRENT ZERO LINE.


EDGERTON
MARCH 1927.
FILM #9




EDGERTON MAR '27
FILM #8


TRANSIENT CURRENT
DURING
PULLOUT OF SYNCHRONOUS
MOTOR FOLLOWING
ABRUPT SHAFT LOAD
SEE FILM #8
TRANSIENT CURRENT
FROM FILM No. 8.
TIME INTERVAL BETWEEN
POINTS IS 0.1 SECONDS FROM 0-188°
0.05 " " 188°-
ARMATURE CURRENT
IN AMPERES
5 POINTS OMITTED
POINTS OMITTED
STEADY STATE POWER
STEADY STATE CURRENT
ROTOR DISPLACEMENT IN ELECTRICAL DEGREES
100
80
60
40
20
0
20
40
60
80
100
90
180
270
360
90
180
270
360
2.0
2.0
2.0
2.5
MARCH 1927
EDGERTON

FILMS NOS 10 and 11

For these films the excitation for the synchronous motor was obtained from a separately excited motor-generator set. In this manner it was possible to get as low a resistance as possible in the field circuit.

Film No. 10 was run so that power could be read from it. The voltage wave was taken to neutral so that it would be easier to read the values of current which were in phase.

Meter readings

	Before	After	
V	232	228	volts
I	4.5	42.2	amperes
KW	1.7	15.9	kilowatts
I_f	12.6	12.6	amperes
E^o	1	15.4	volts
E_{dc}	190	186	volts
I_{dc}	0	61	amperes

The transient power read from this film is plotted on page 52.

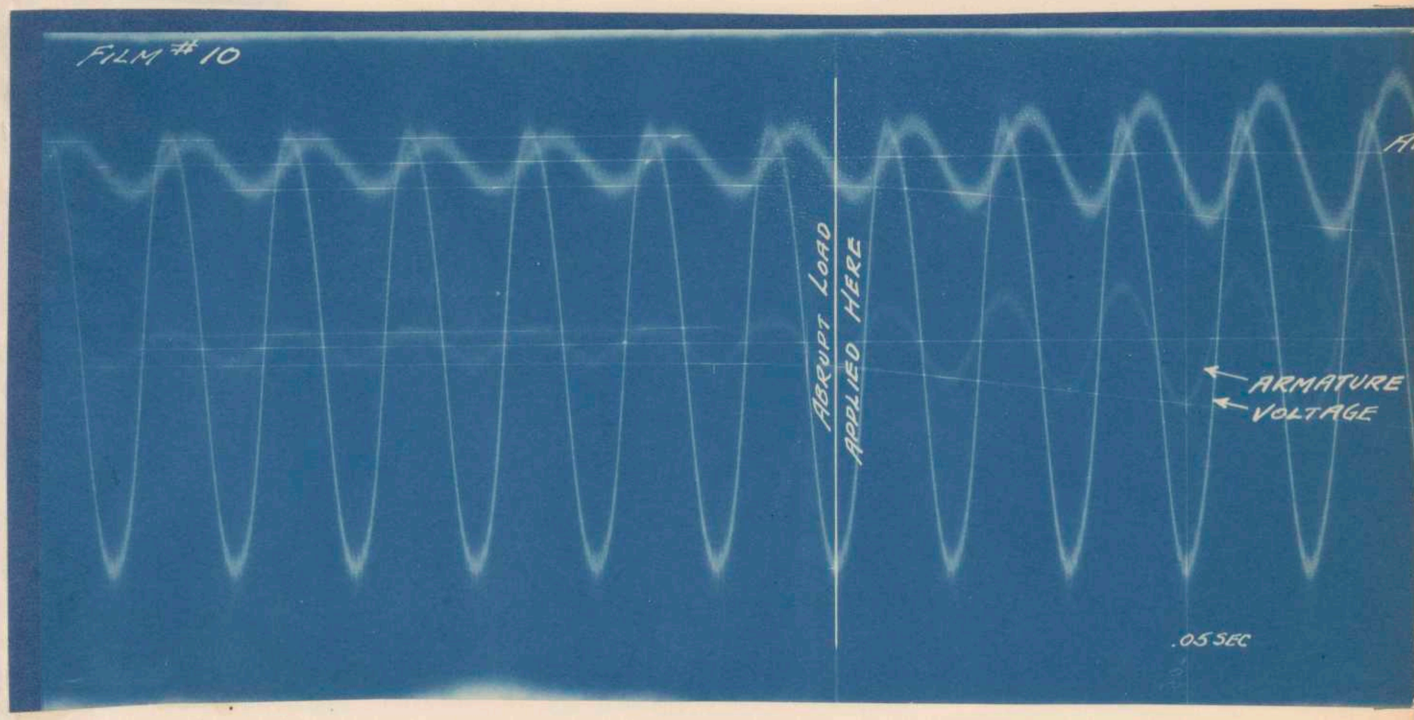
Film No. 11 is similiar to film No. 10 except the vibrator reading voltage to neutral was made to read field current.

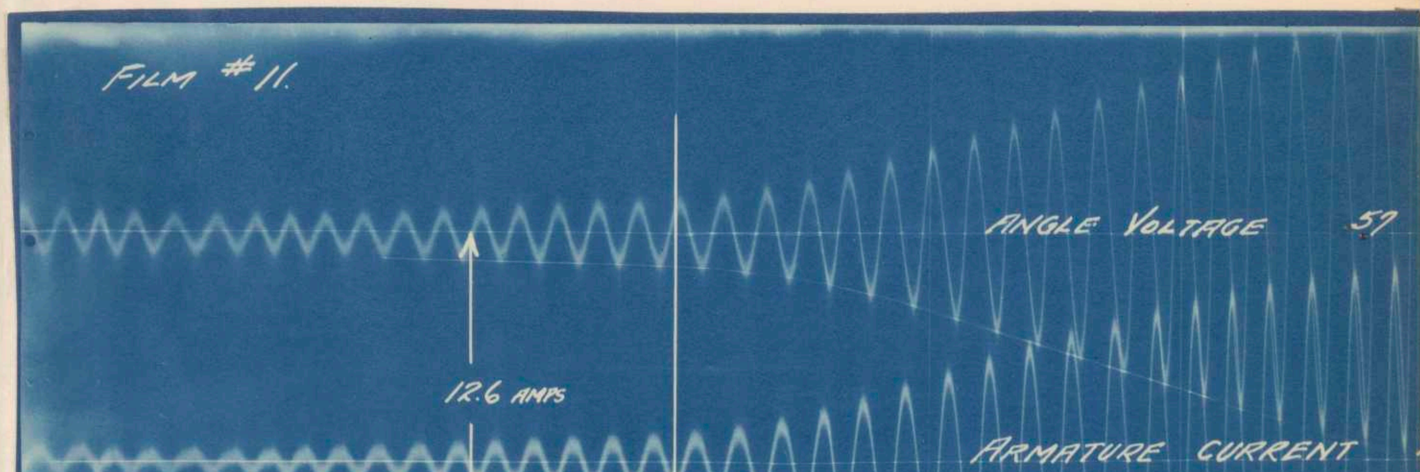
Transients from this film are plotted on page
Also a polar diagram using values from this film is shown on page 53. This was plotted on the assumption that the

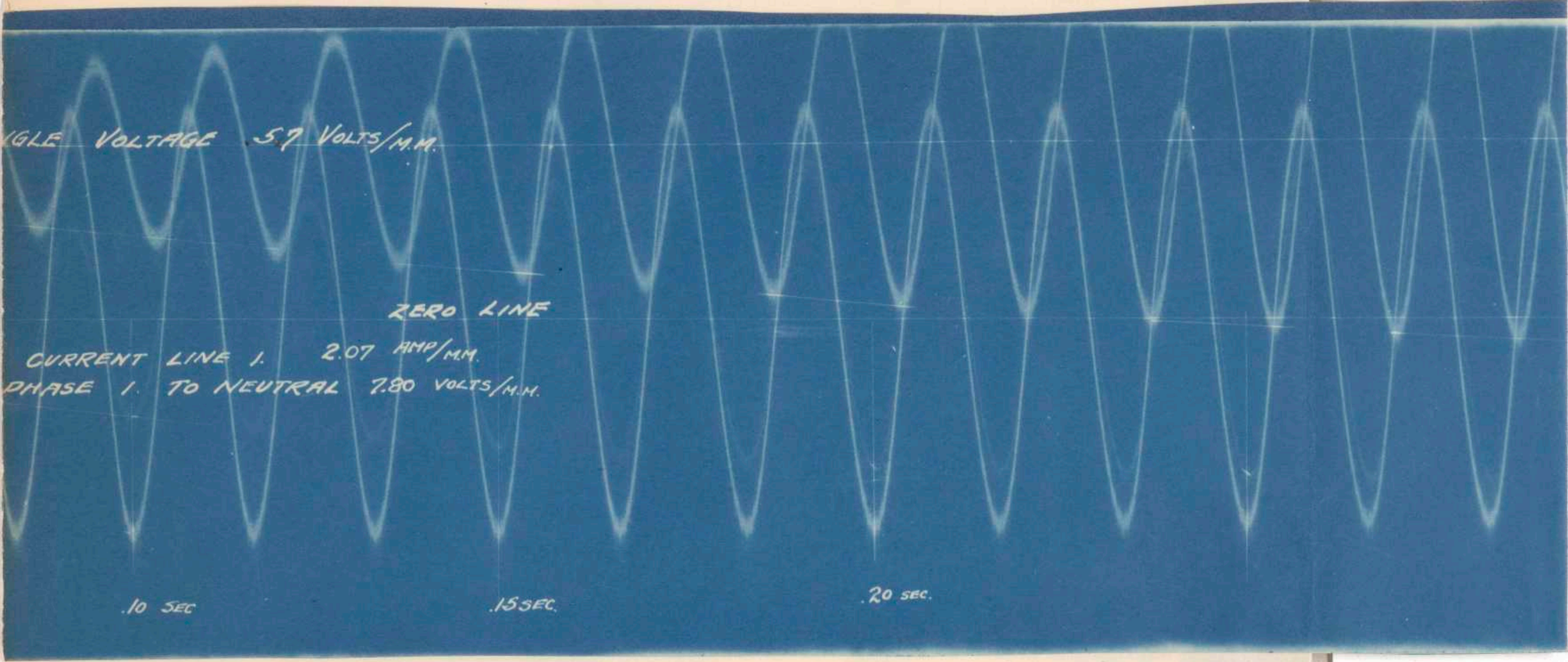
induced voltage and the field current followed the open circuit saturation curve.

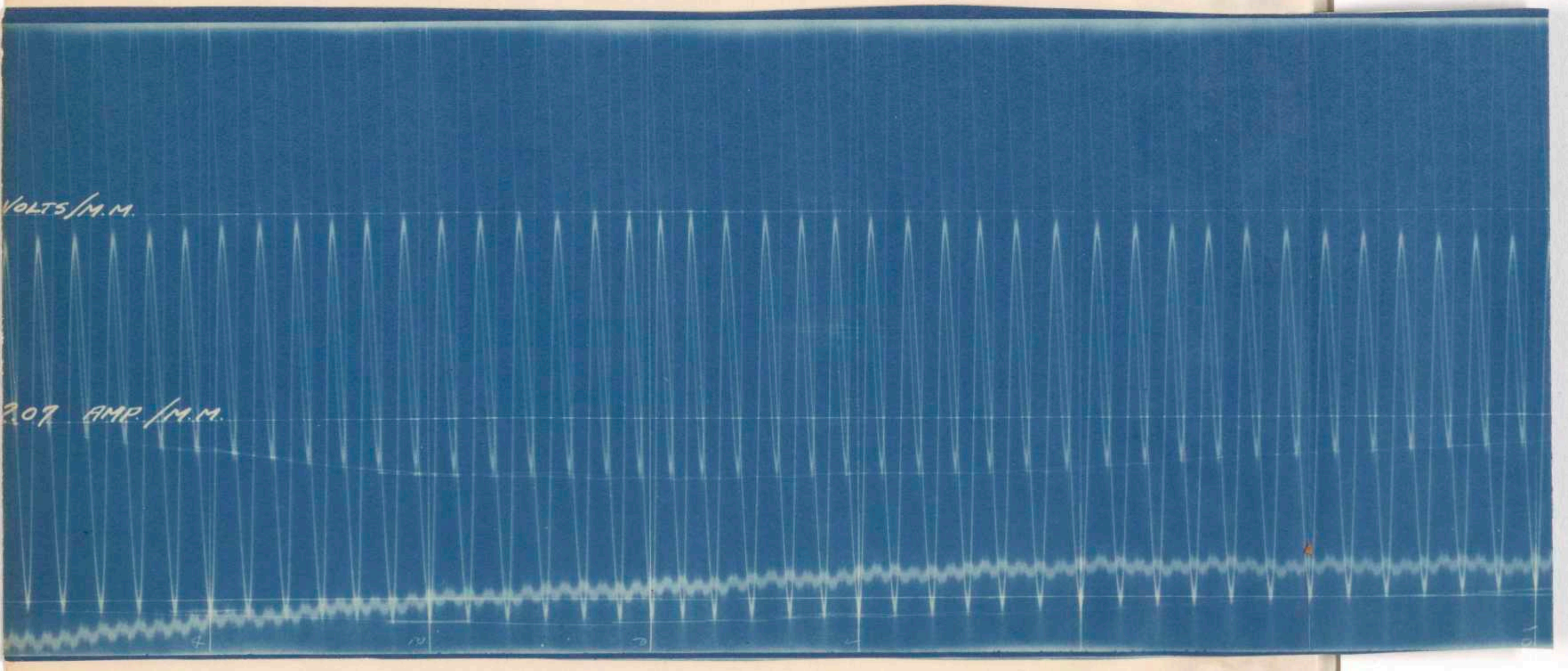
Meter readings film No. 11

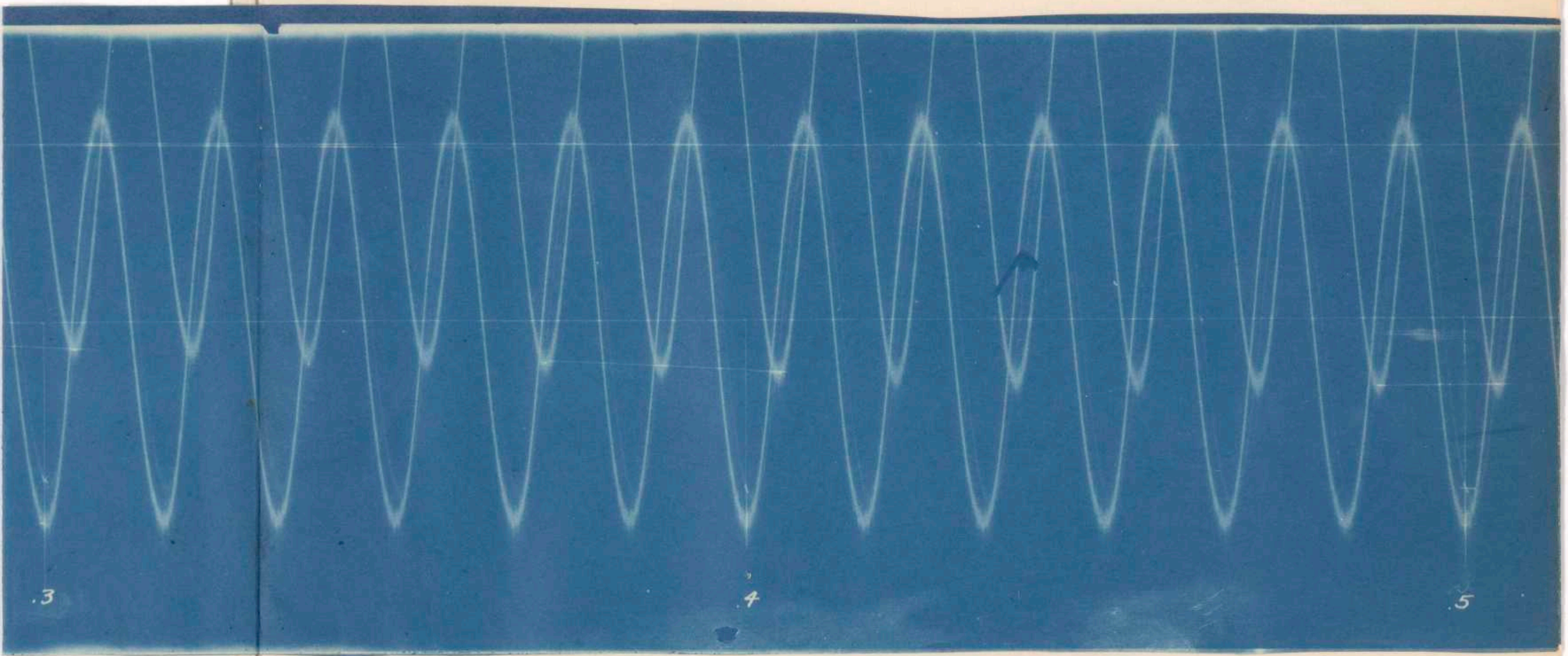
	Before	After	
V	233	230	volts
I	4.5	40	amperes
KW	1.7	15.4	kilowatts
E^{o}	1	15	volts (64.5°)
I_f	12.7	12.7	amperes
E_{dc}	190	186	volts
I_{dc}	0	55	amperes

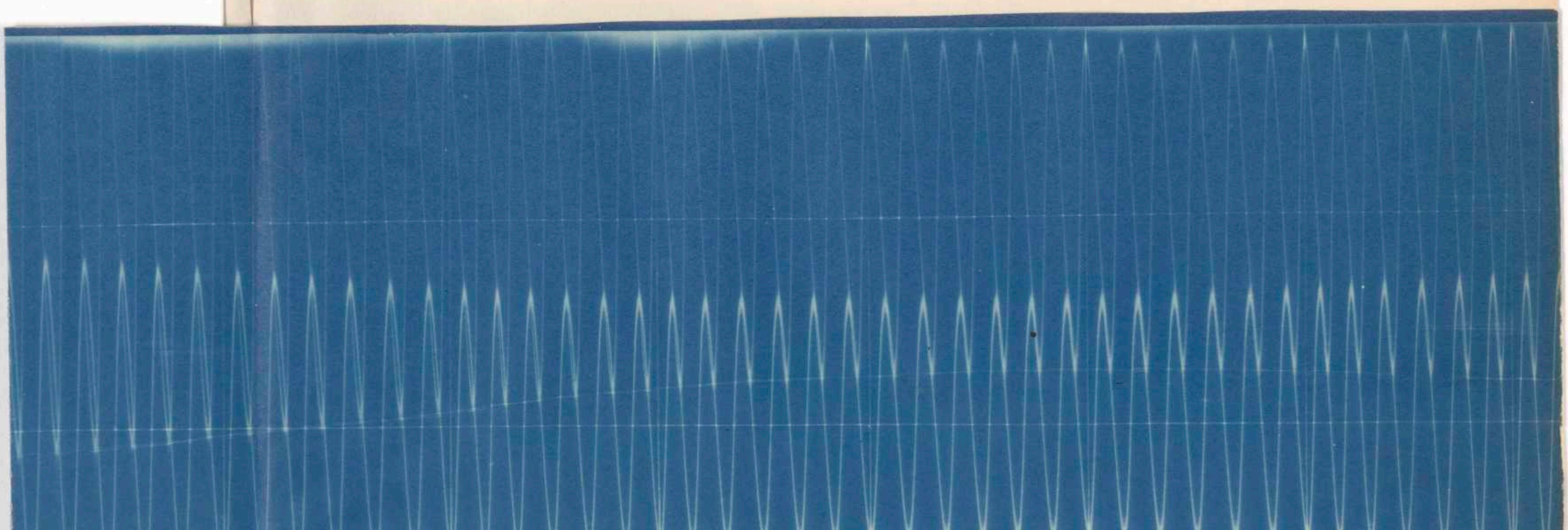

FILM # 10
ABRUPT LOAD
APPLIED HERE
ARMATURE
VOLTAGE
.05 SEC

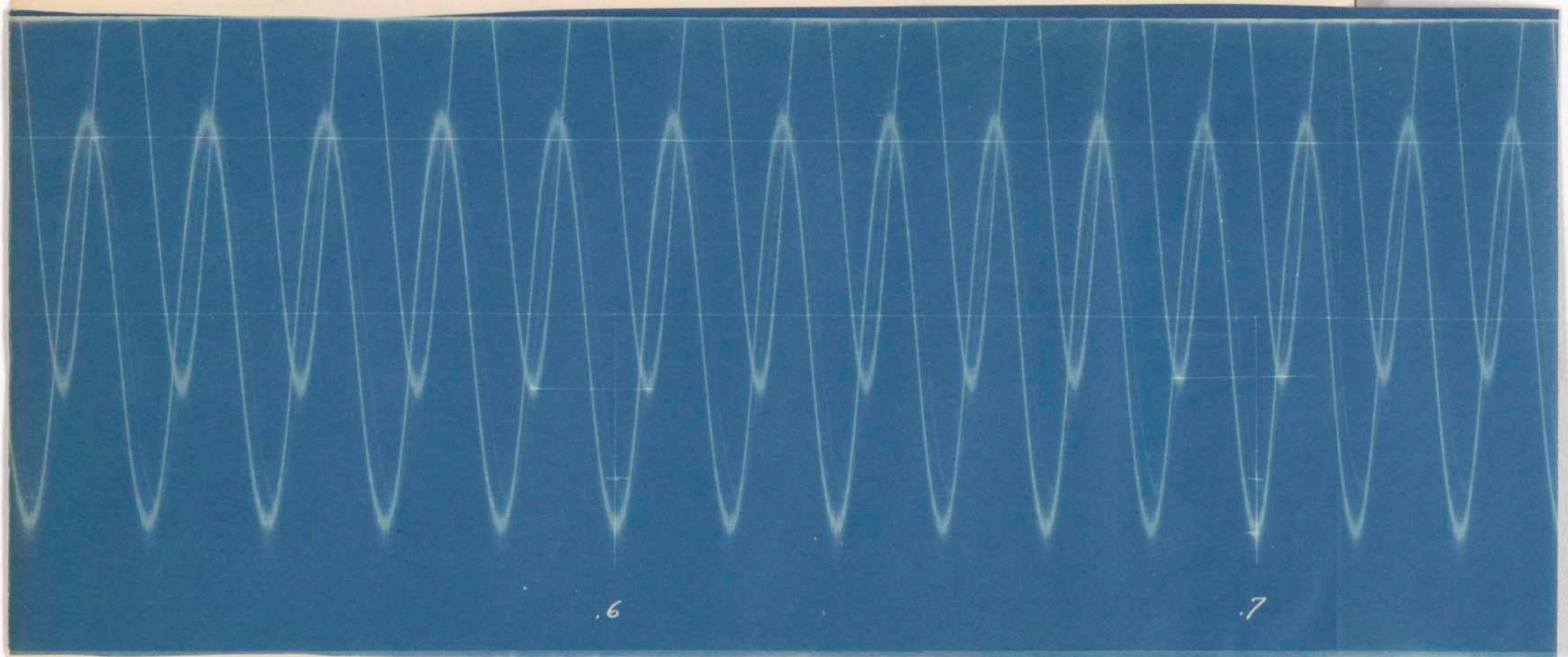

FILM # 11.
ANGLE VOLTAGE
12.6 AMPS
ARMATURE CURRENT
NORMAL FIELD
CURRENT.
FIELD CURRENT

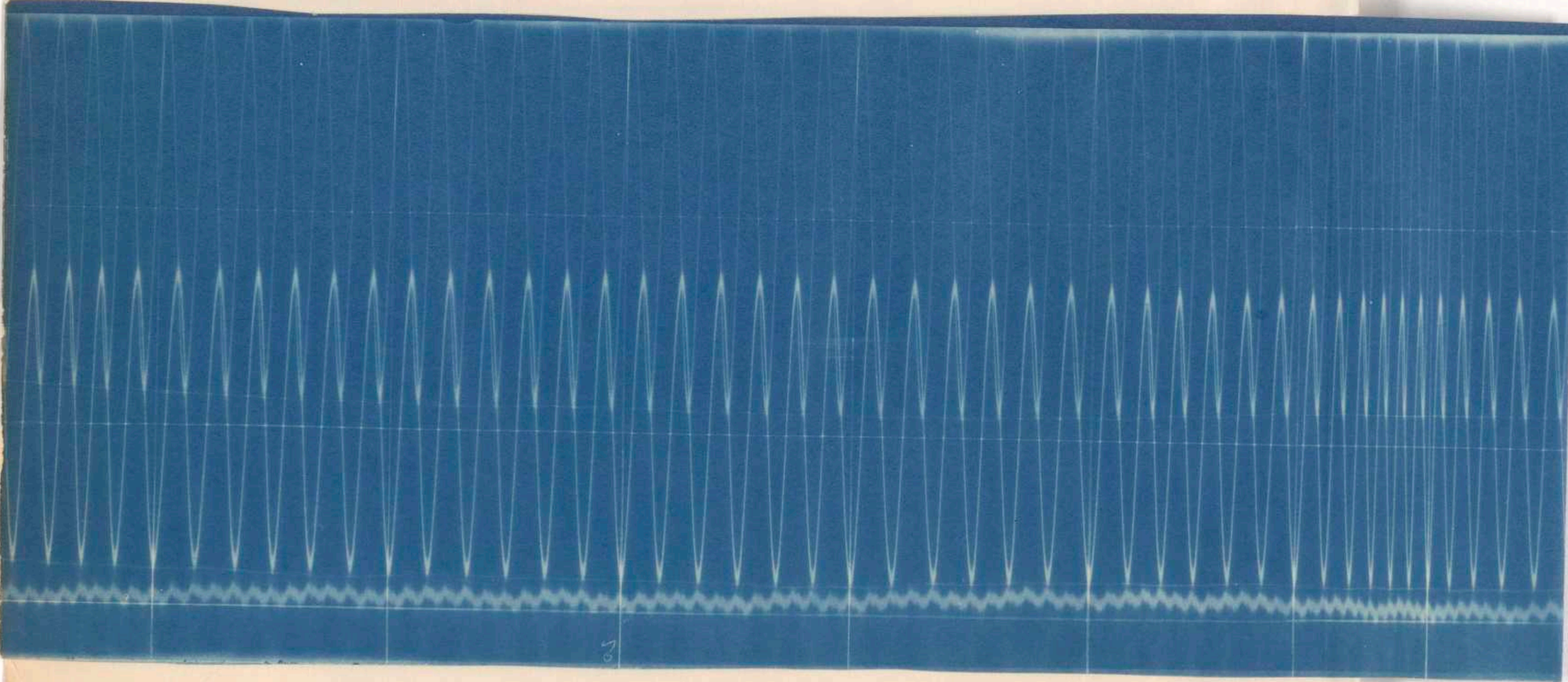

IGLE VOLTAGE 5.7 VOLTS/M.M.
ZERO LINE
CURRENT LINE 1. 2.07 AMP/MM.
PHASE 1. TO NEUTRAL 7.80 VOLTS/M.M.
.10 SEC
.15 SEC.
.20 SEC.

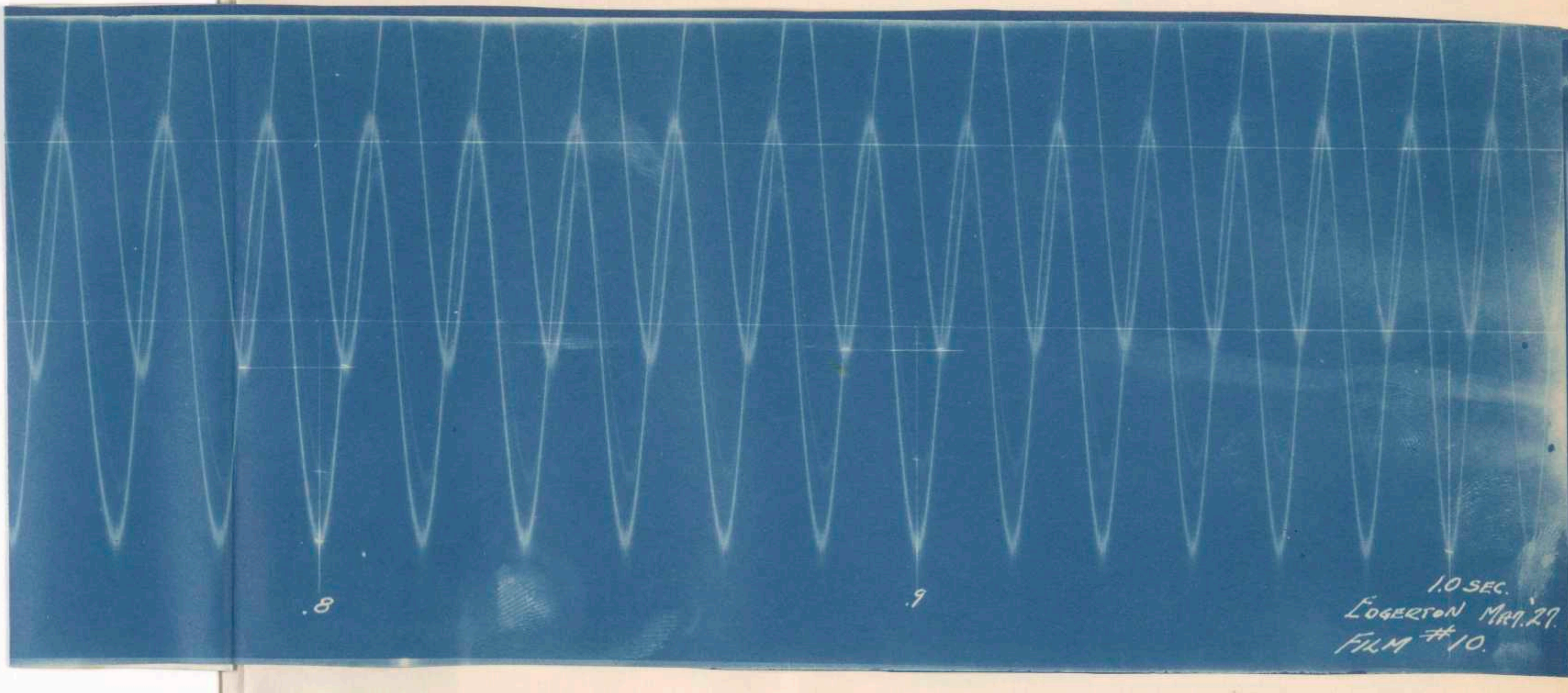

VOLTS/M.M.
2.07 AMP./M.M.

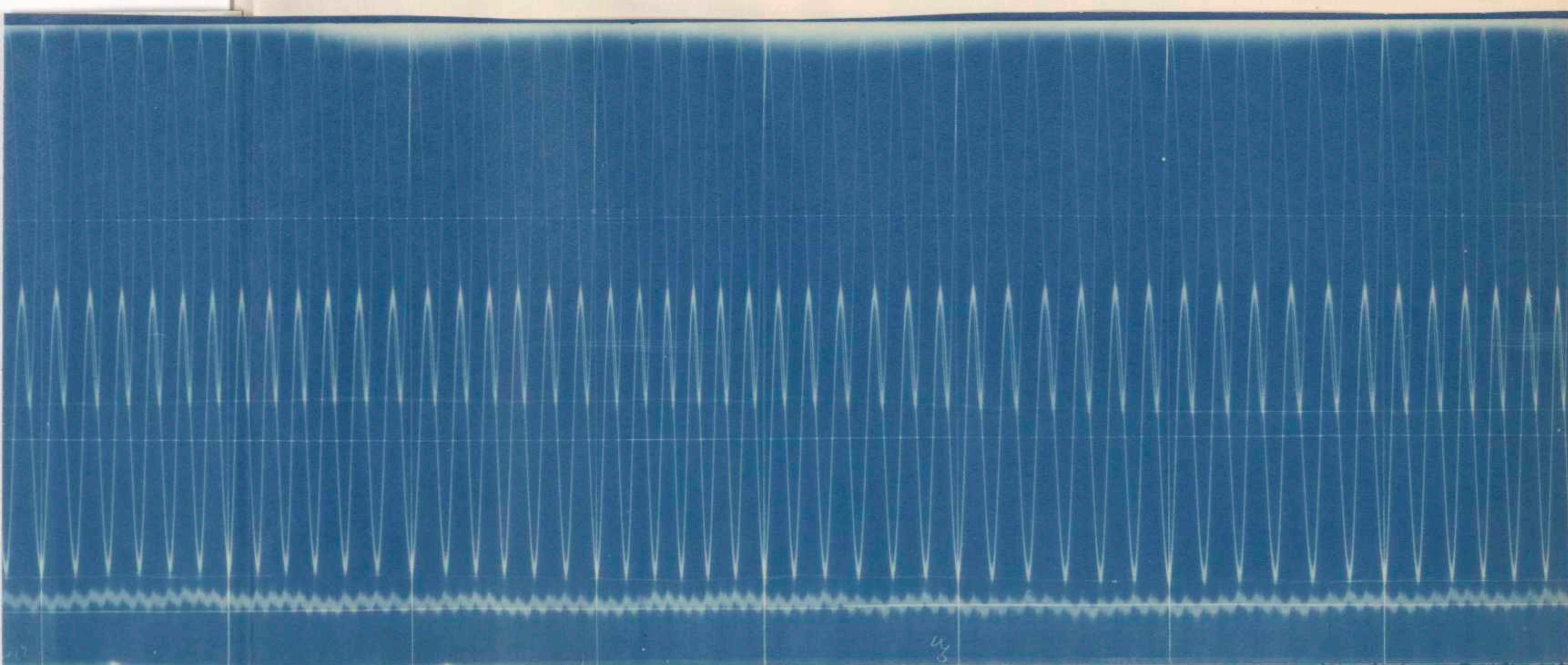

.3
.4
.5

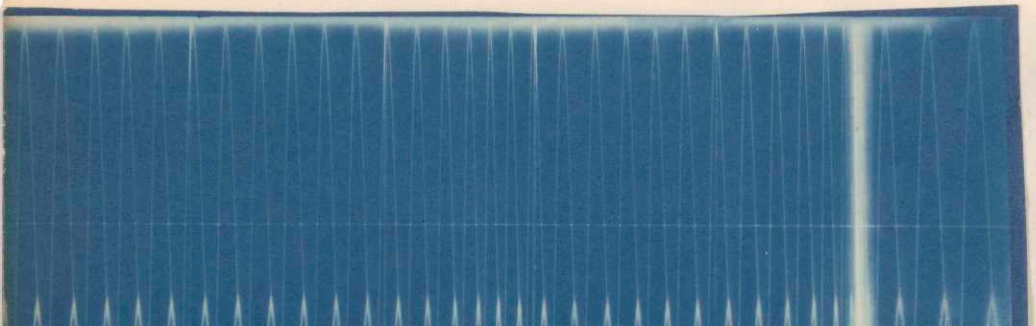

10

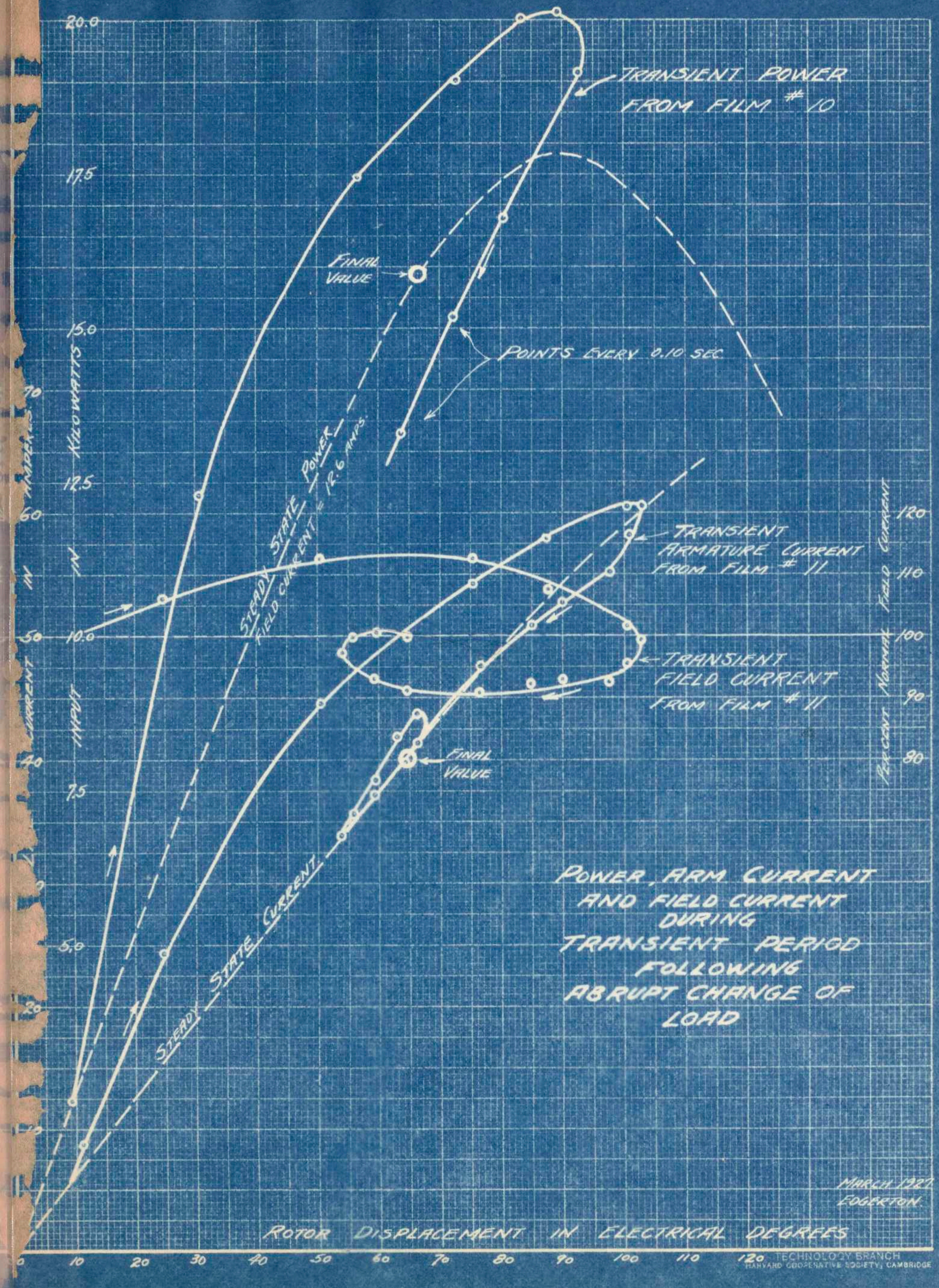

.6
.7

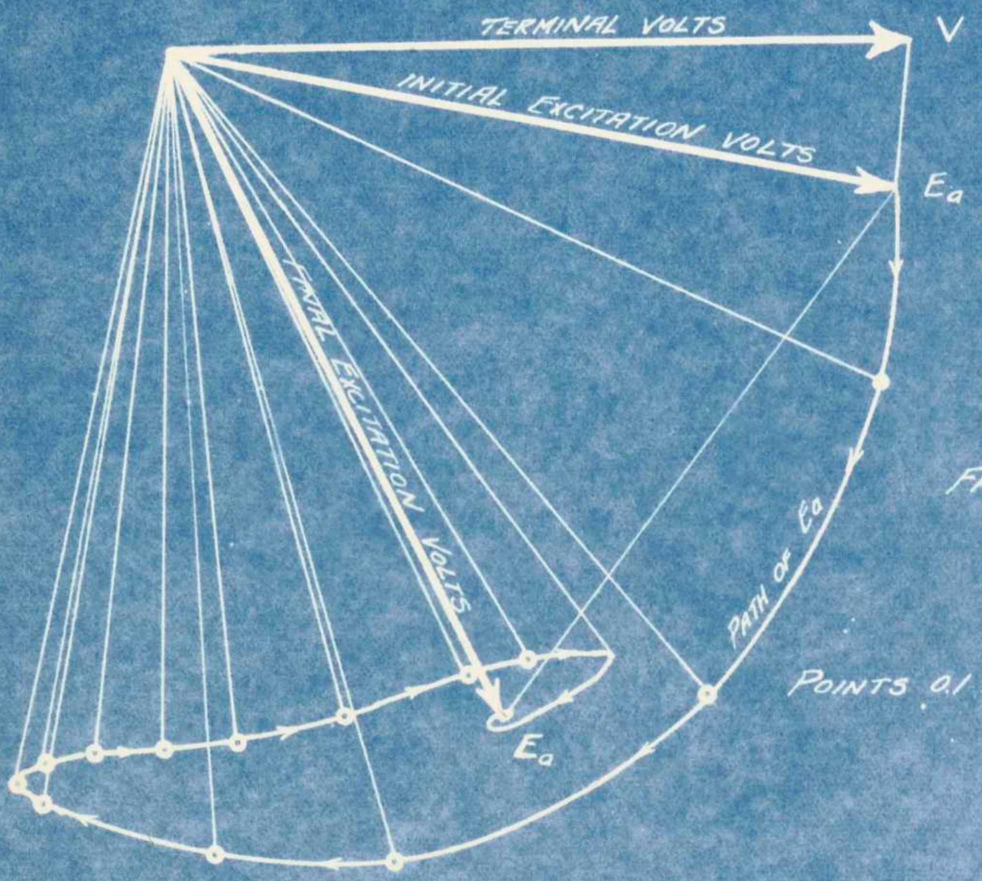



.8
.9
1.0 SEC.
EDGERTON MAY 27.
FILM #10.




FILM #11
EDGERTON
MAR. 1927.


TRANSIENT POWER FROM FILM # 10
FINAL VALUE
POINTS EVERY 0.10 SEC
STEADY STATE POWER
FIELD CURRENT = 12.6 AMPS.
TRANSIENT ARMATURE CURRENT FROM FILM # 11
TRANSIENT FIELD CURRENT FROM FILM # 11
FINAL VALUE
STEADY STATE CURRENT
POWER, ARM CURRENT AND FIELD CURRENT DURING TRANSIENT PERIOD FOLLOWING ABRUPT CHANGE OF LOAD
MARCH 1927
EDGERTON
ROTOR DISPLACEMENT IN ELECTRICAL DEGREES
INPUT IN KILOWATTS
PERCENT NORMAL FIELD CURRENT
20.0
17.5
15.0
12.5
10.0
7.5
5.0
60
50
40
120
110
100
90
80
0
10
20
30
40
50
60
70
80
90
100
110
120
TECHNOLOGY BRANCH
HARVARD COOPERATIVE SOCIETY, CAMBRIDGE



FROM FILM No.11

POINTS 0.1 SEC. APART

VECTOR DIAGRAM OF
SYNCHRONOUS MOTOR
DURING
TRANSIENT PERIOD,
DUE TO ABRUPT CHANGE OF LOAD.

EDGERTON
APRIL 1927

FILMS NOS 29, 31, & 32

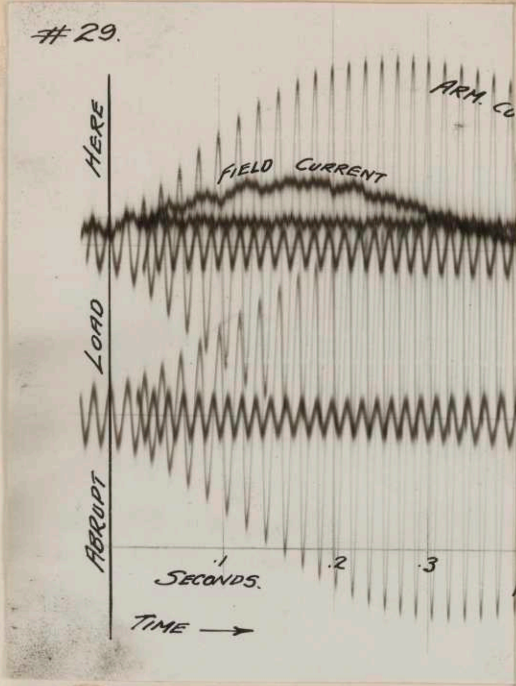
These films are radically different from any of the other films although laboratory conditions were apparently the same. The magnitudes were greater and the maximum abrupt shaft load less. The reason for this was probably due to the source of power.

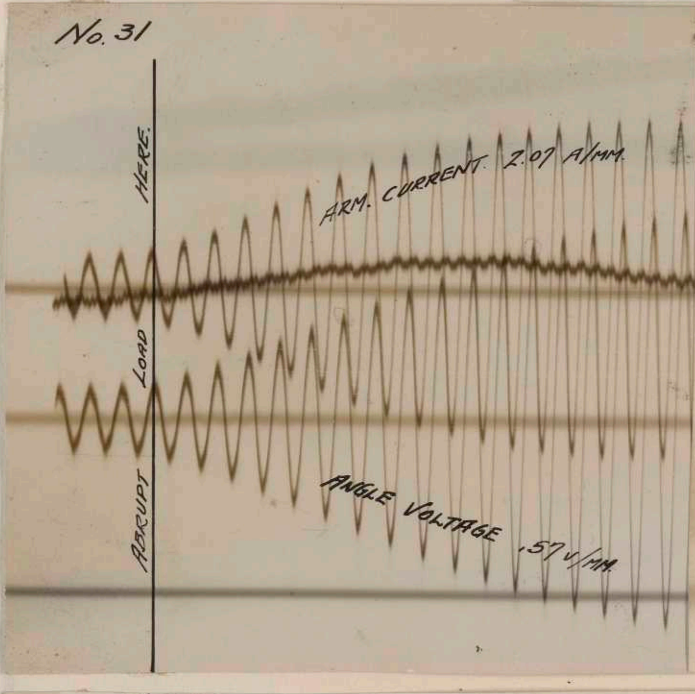
A separately excited exciter was used for this group of films so that no more resistance than necessary would be in the field circuit. Three different values of field current were used as shown below on the tabulation of meter readings.

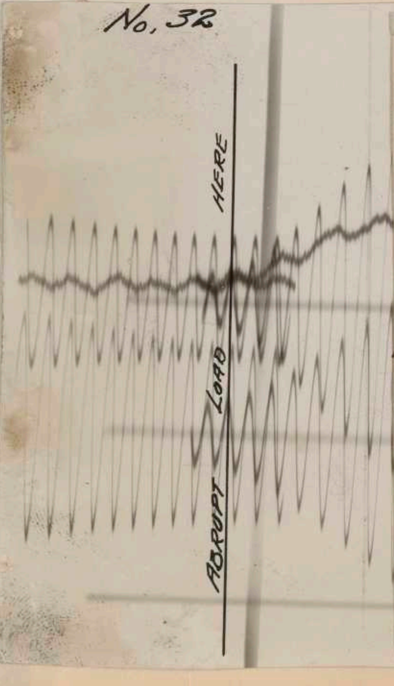
Meter readings

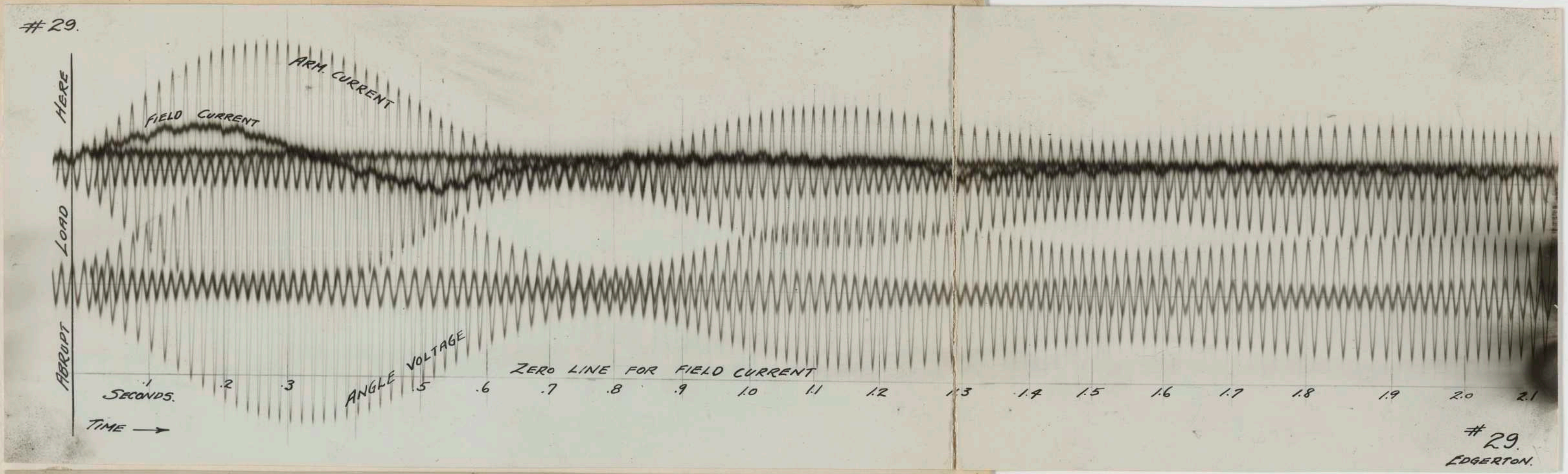
	Before	After 29	After 31	After 32	
V	232.5	232	232	232	volts
I	4.5	18.8	17.8	20.9	amperes
KW	1.4	7.4	6.88	8.2	kilowatts
E^o	1	6.2	7.15	7.82	volts
I_f	~~14.3~~	14.3 (115%)	11.2 (85%)	12,3 (100%)	amperes
E_{dc}		128	122	138	volts
I_{dc}		39.5	38	44.2	amperes

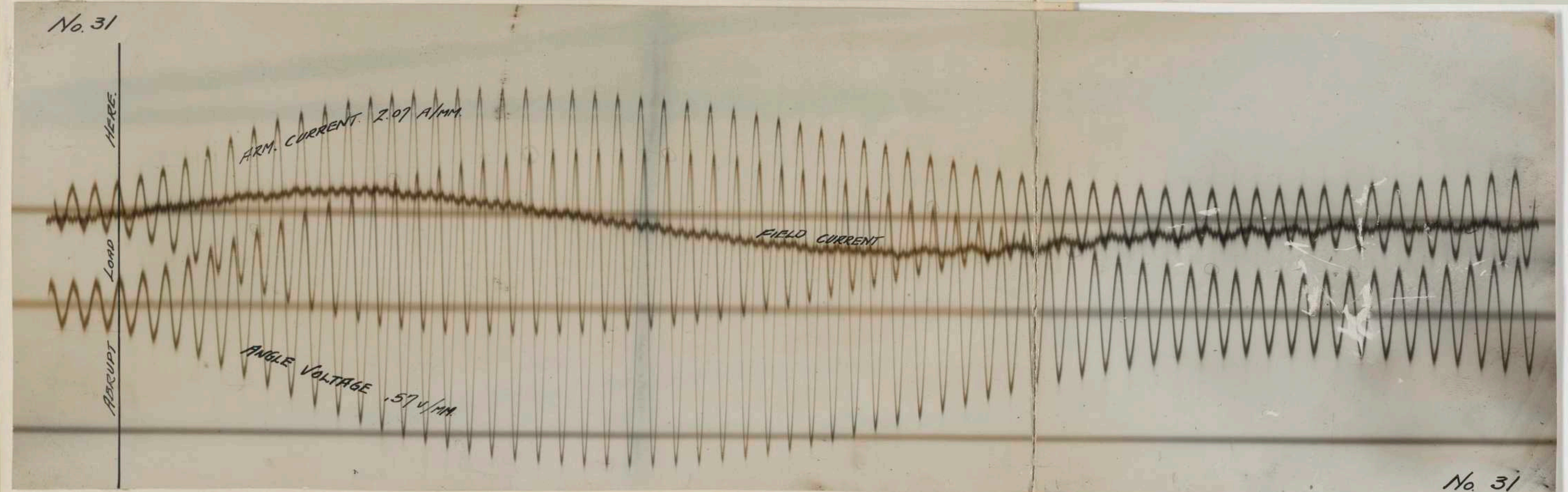
Values of displacement angle plotted against time are shown on page 56. They show the extreme swing of the angular displacement.

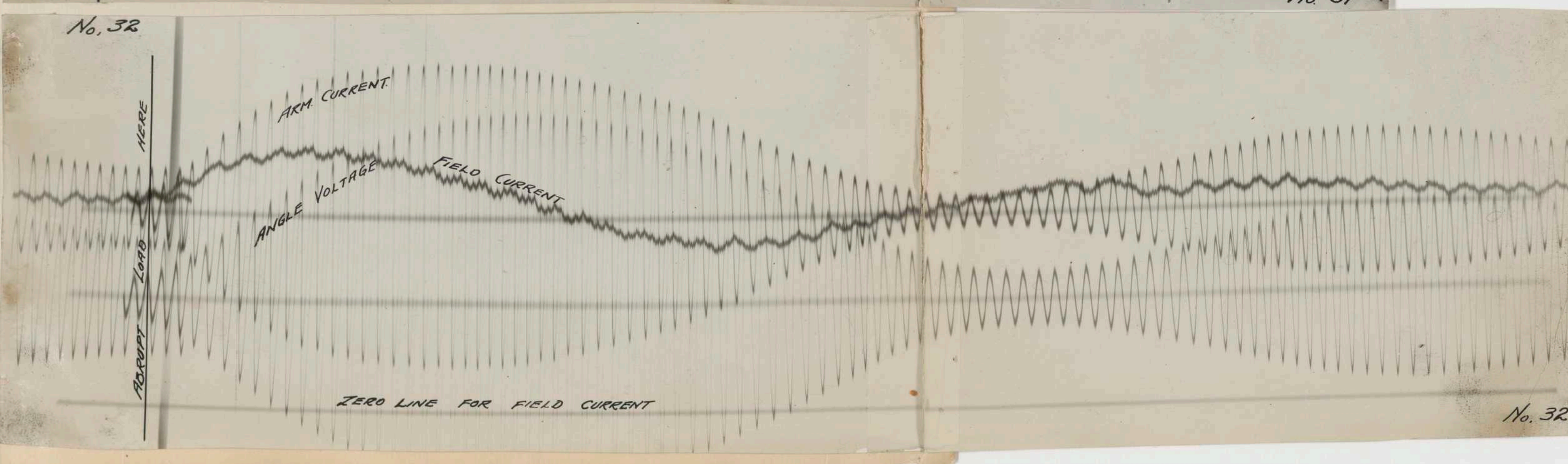

#29.
ABRUPT LOAD HERE
FIELD CURRENT
.1
.2
.3
SECONDS.
TIME →

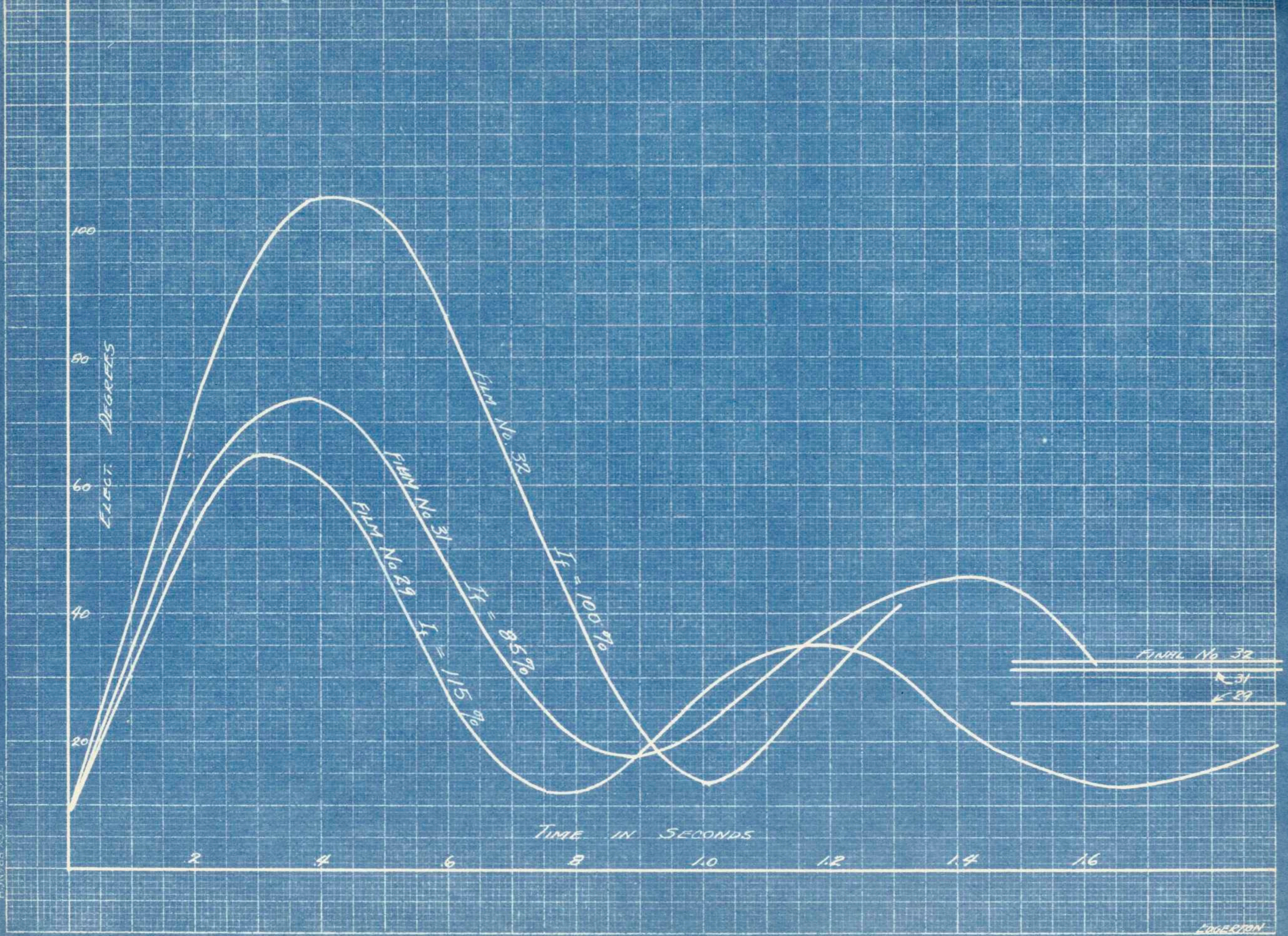

No. 31
ABRUPT LOAD HERE.
ARM. CURRENT. 2.07 A/MM.
ANGLE VOLTAGE .57 V/MM.


No. 32
ABRUPT LOAD HERE


#29.
ARM. CURRENT
FIELD CURRENT
ABRUPT LOAD HERE
ANGLE VOLTAGE
ZERO LINE FOR FIELD CURRENT
.1 .2 .3 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1
SECONDS.
TIME →
#29.
EDGERTON.


No. 31
ARM. CURRENT 2.07 A/MM.
ABRUPT LOAD HERE.
FIELD CURRENT
ANGLE VOLTAGE .57 v/MM.
No. 31


No. 32
ARM. CURRENT.
ABRUPT LOAD HERE
ANGLE VOLTAGE
FIELD CURRENT
ZERO LINE FOR FIELD CURRENT
No. 32


ELECT. DEGREES
100
80
60
40
20
FILM No 32 If = 100 %
FILM No 31 If = 85 %
FILM No 29 If = 115 %
FINAL No 32
31
29
TIME IN SECONDS
.2
.4
.6
.8
1.0
1.2
1.4
1.6
EDGERTON

FILMS NOS.

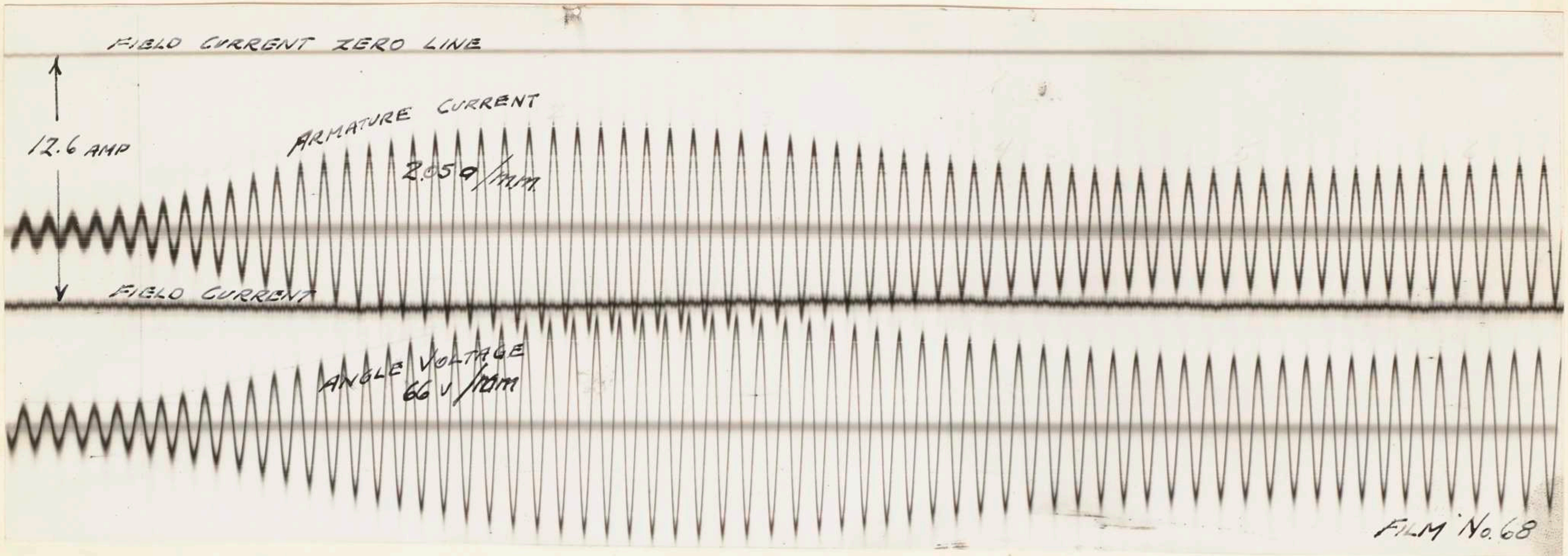
67 68 69 74 75

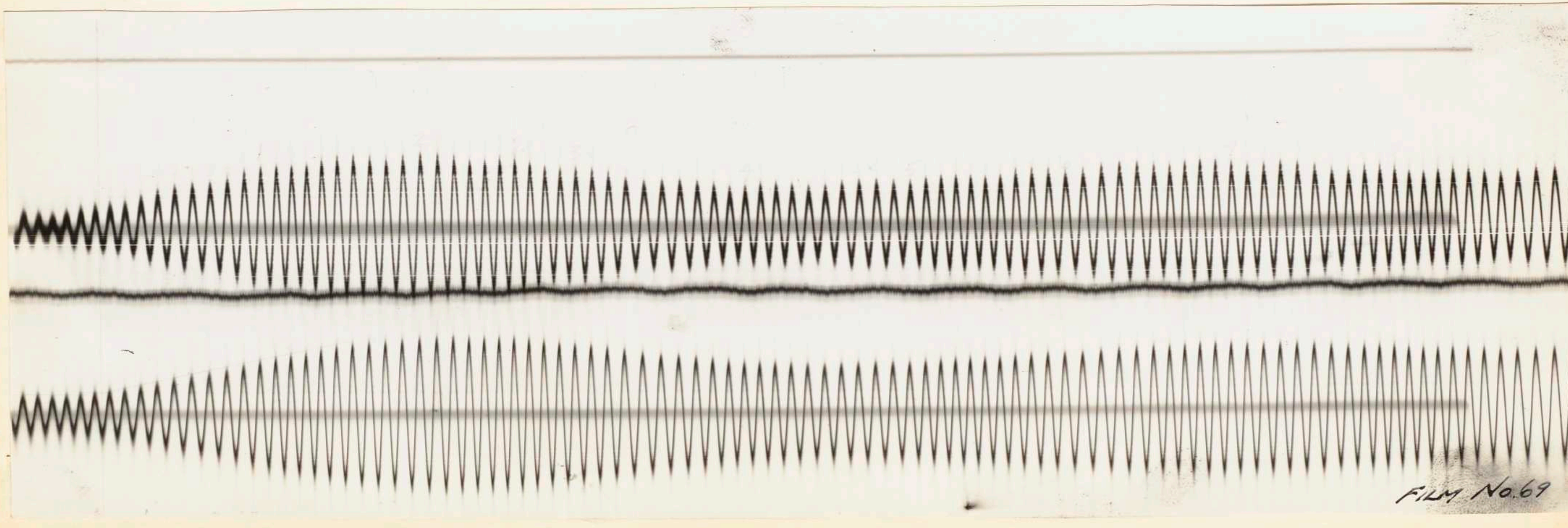
The exciter supplying field current for the synchronous motor was held at 100 volts at its terminals. Of this 60 volts drop occurred across the synchronous motor field and 40 volts across the field resistance.

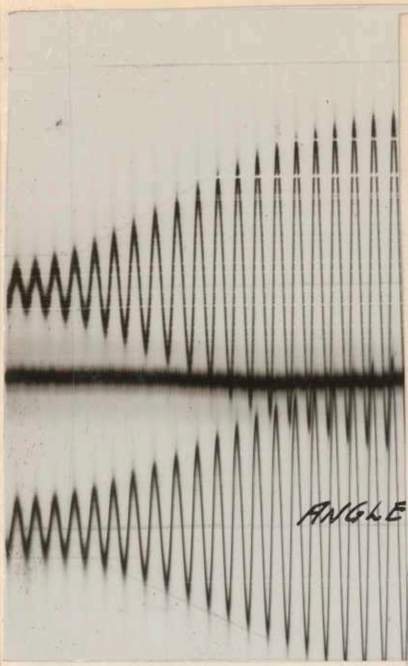
Meter readings.

	Before	After				
Film No.		67	68	69	74	75
V	228	226	227	227	226	225
I	3.5	32.8	23.8	15.5	38.5	41.5
KW	1.6	12.7	9.5	6.2	14.3	14.95
I_f	12.6	12.6	12.8	12.6	12.6	12.6
E^o	1	12	8.6	6	13.8	15.0
E_{dc}	190	185	185	143	196	204
I_{dc}	0	50.4	35.8	18.8	53.5	55.3

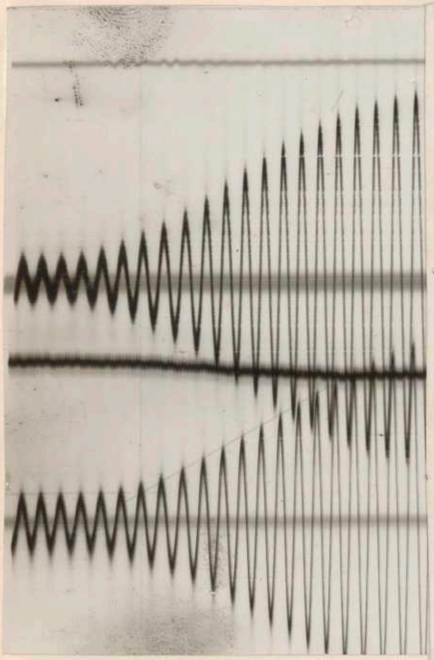
The curves on page 60 show the values of angle plotted against time for these films.


FIELD CURRENT ZERO LINE
12.6 AMP
ARMATURE CURRENT
2.05 a/mm.
FIELD CURRENT
ANGLE VOLTAGE
66 v/mm
FILM No. 68

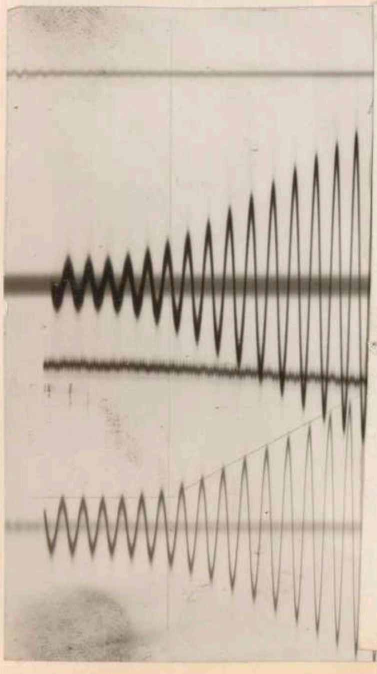

FILM No. 69



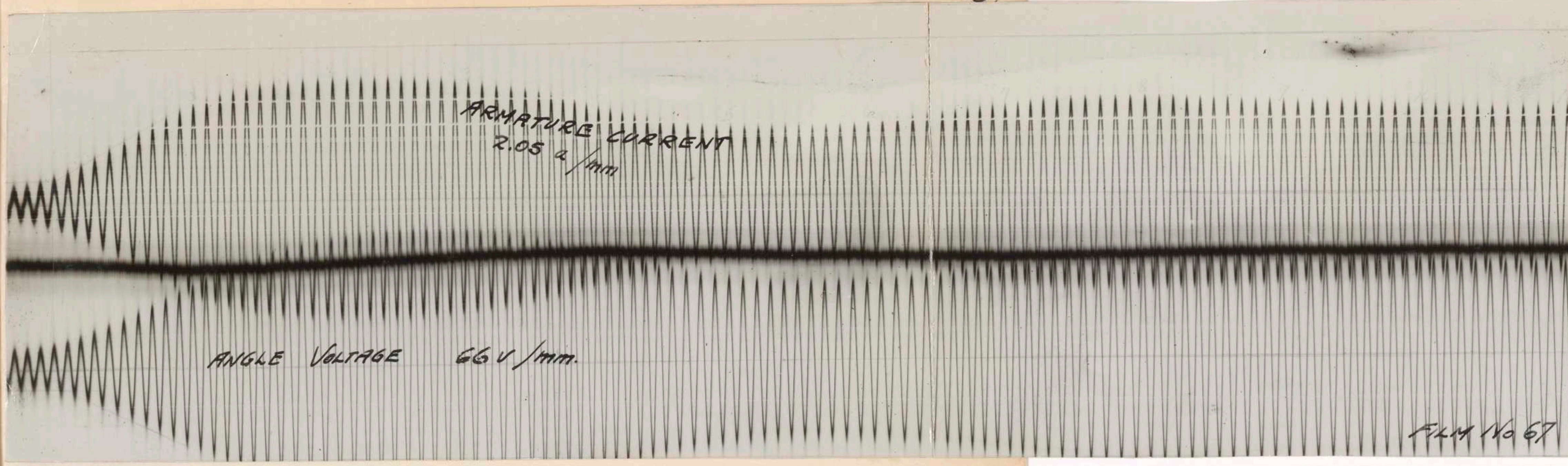
FILM No 67

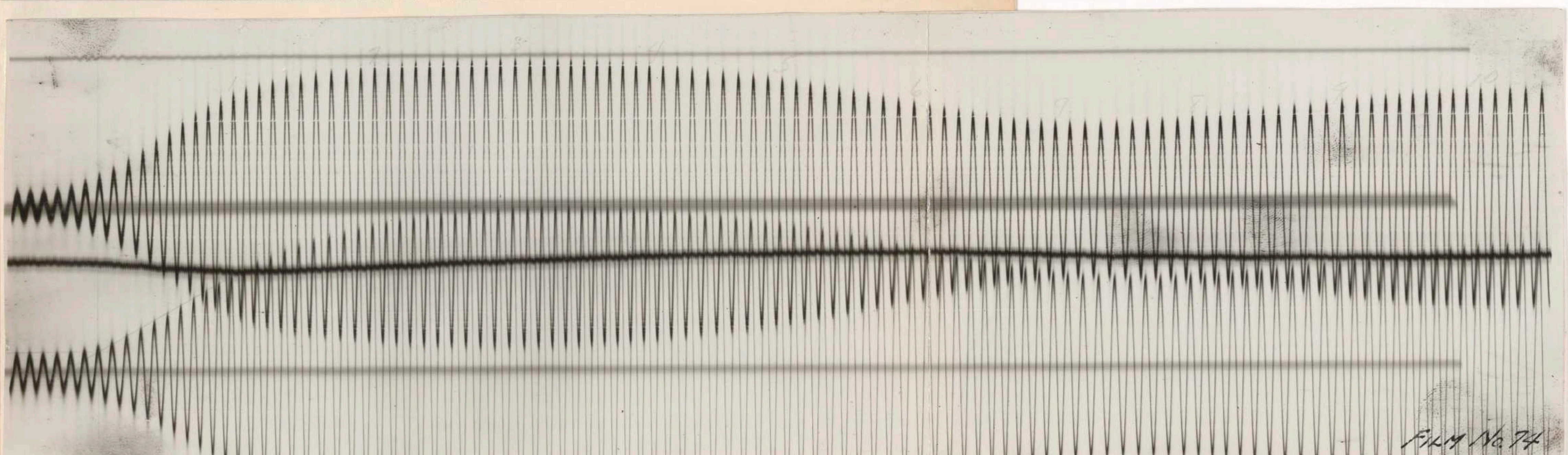


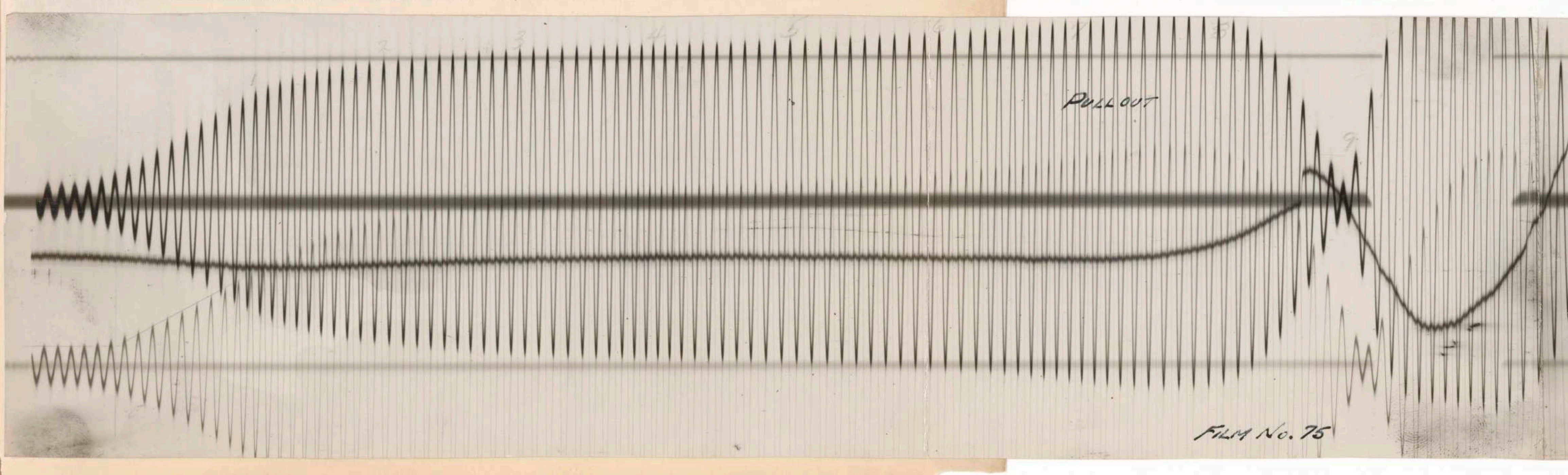
FILM No. 74

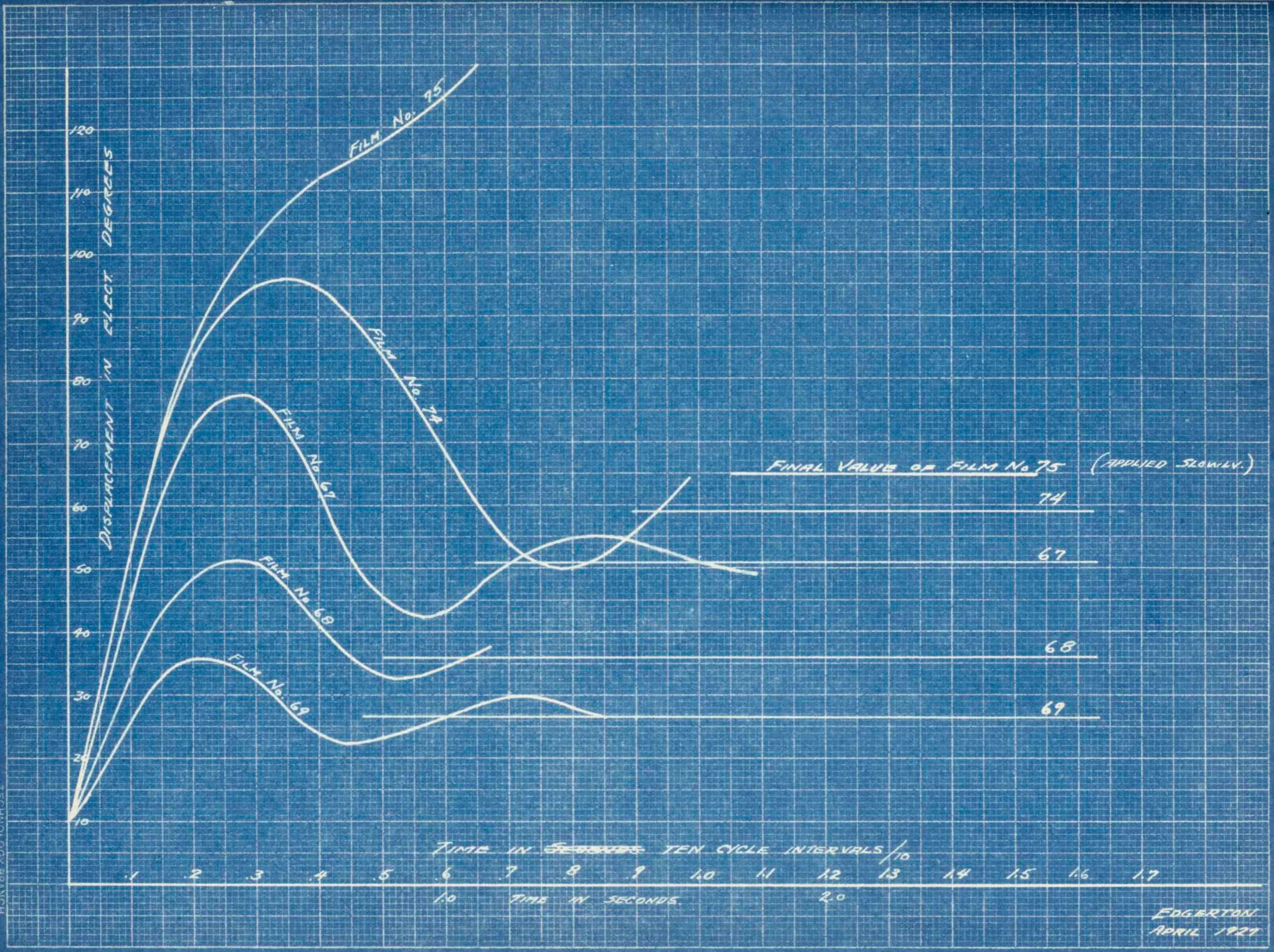


FILM No. 75.


ARMATURE CURRENT
2.05 a/mm
ANGLE VOLTAGE 66 V/mm.
FILM No 67


FILM No 74


PULLOUT
FILM No. 75



FILM No. 75
FILM No. 74
FILM No. 67
FILM No. 68
FILM No. 69
DISPLACEMENT IN ELECT. DEGREES
120
110
100
90
80
70
60
50
40
30
20
10
FINAL VALUE OF FILM No. 75 (APPLIED SLOWLY.)
74
67
68
69
TIME IN ~~SECONDS~~ TEN CYCLE INTERVALS /10
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
1.0 TIME IN SECONDS 2.0
EDGERTON
APRIL 1929

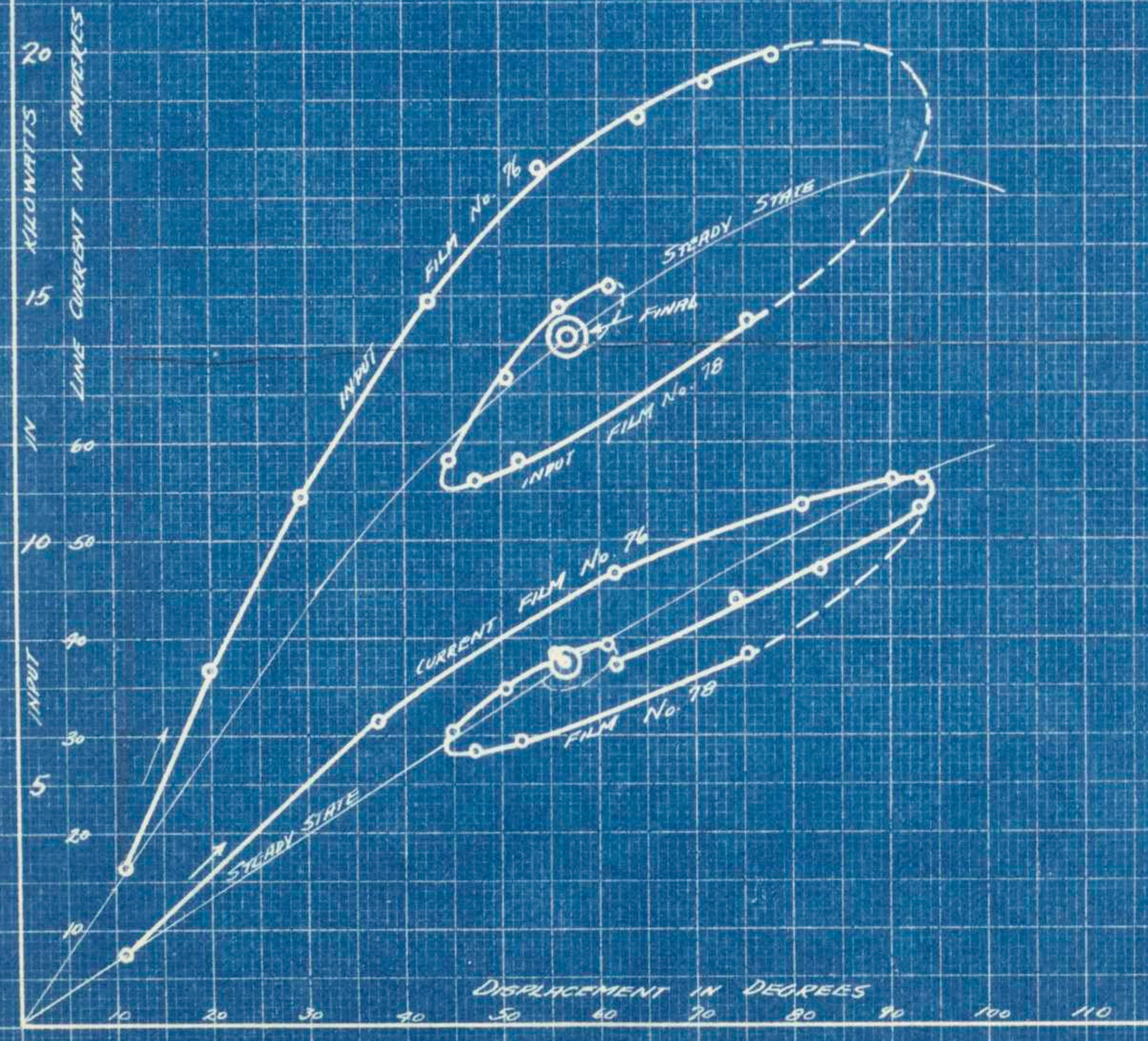
FILMS NOS 76 77 & 78

These films are four foot ones and were taken with the same conditions as the previous series. The drum was speeded up and the vibrator recording field current was changed so that it recorded voltage to neutral in the same phase that current was read.

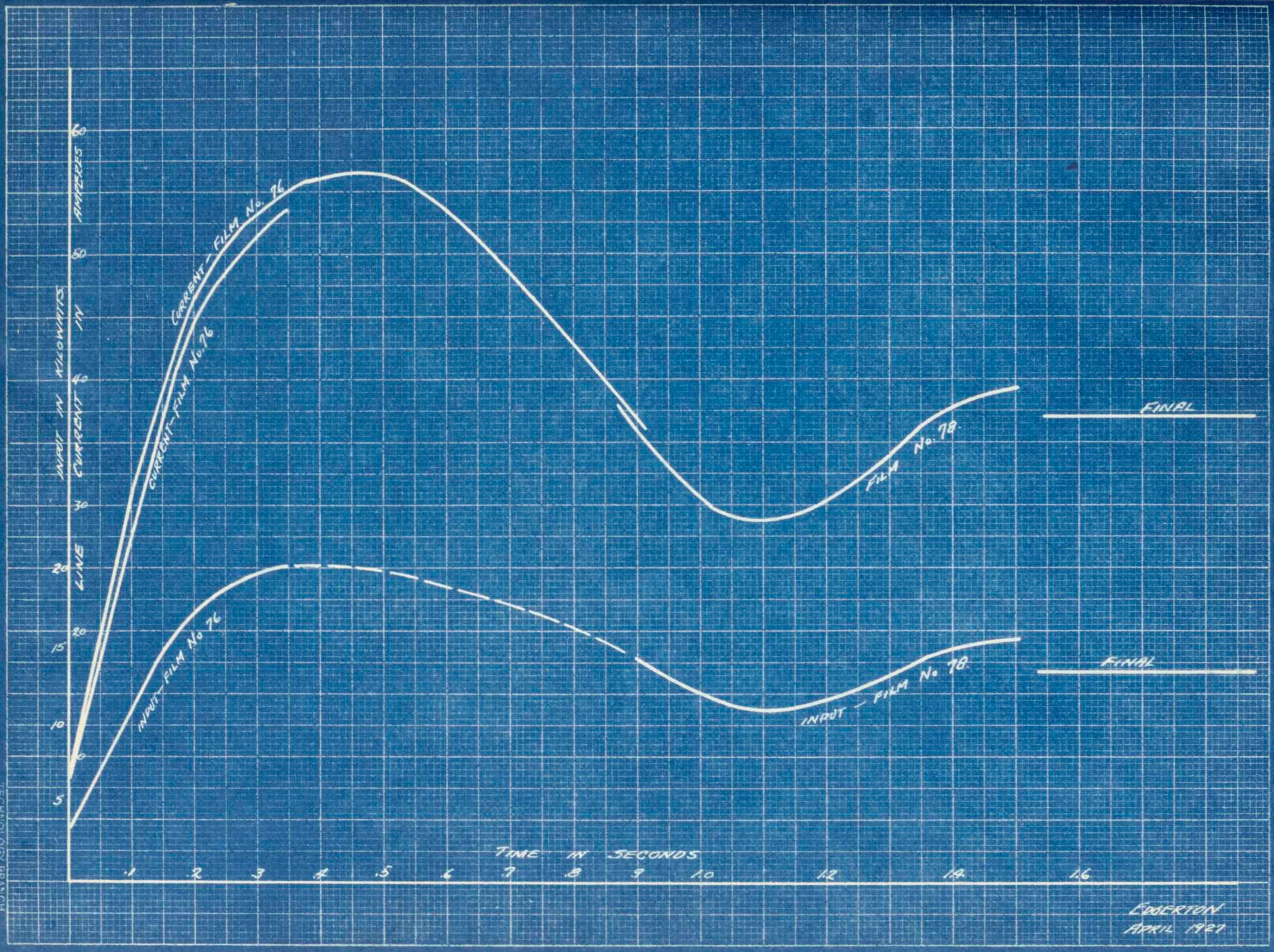
Points calculated from data on the films are shown plotted on the following page.

Meter readings.

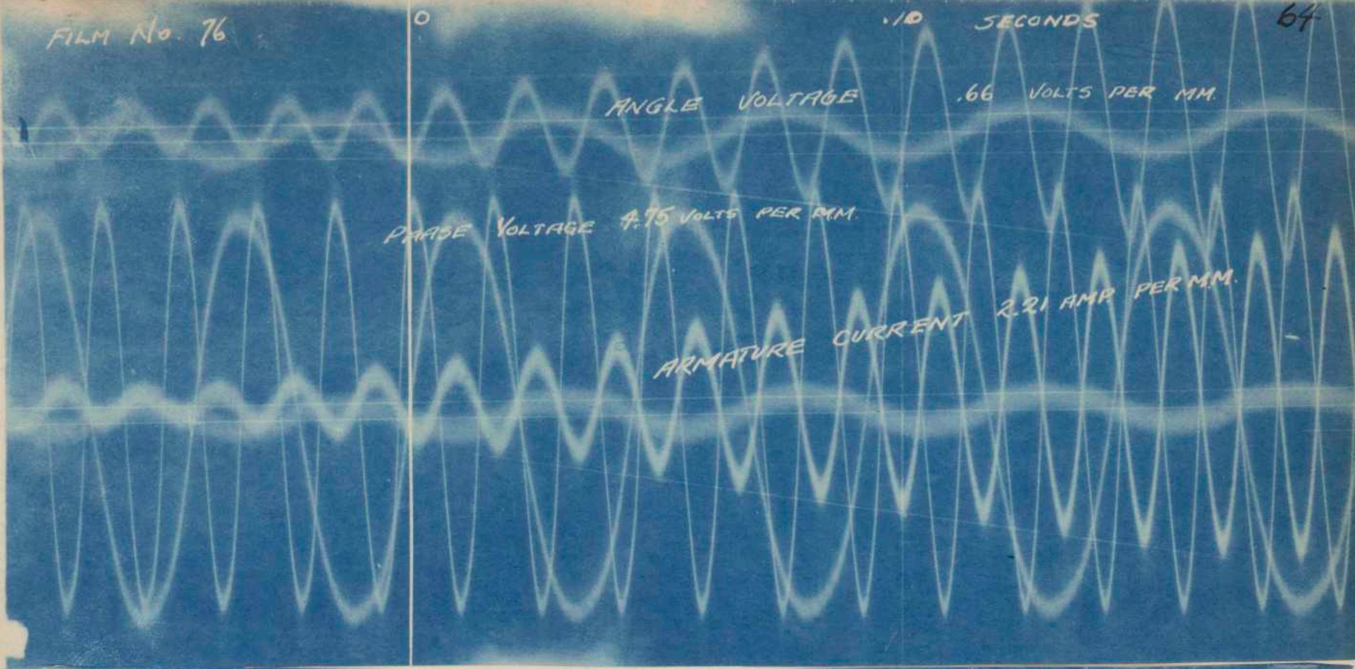
	Before	After			
film no.		76	77	78	
V	228	226	225.5	226	volts
I	4	37.5	37.2	37.5	amperes
KW	1.5	14.1	14.0	14.2	kilowatts
E^o	1	13.4	13,4	13.45	volts
I_f	12.6	12.6	12.6	12.6	amperes
E_{dc}	190	182	182	182	volts
I_{dc}	0	57.2	57	57.2	amperes

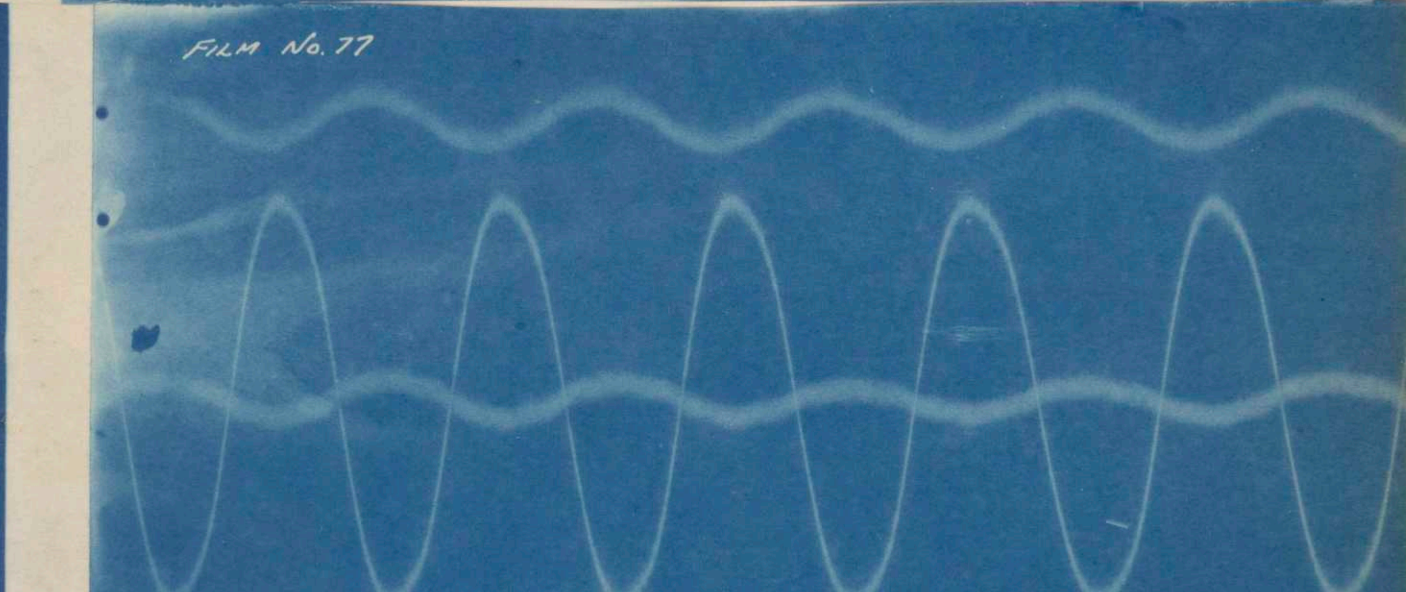


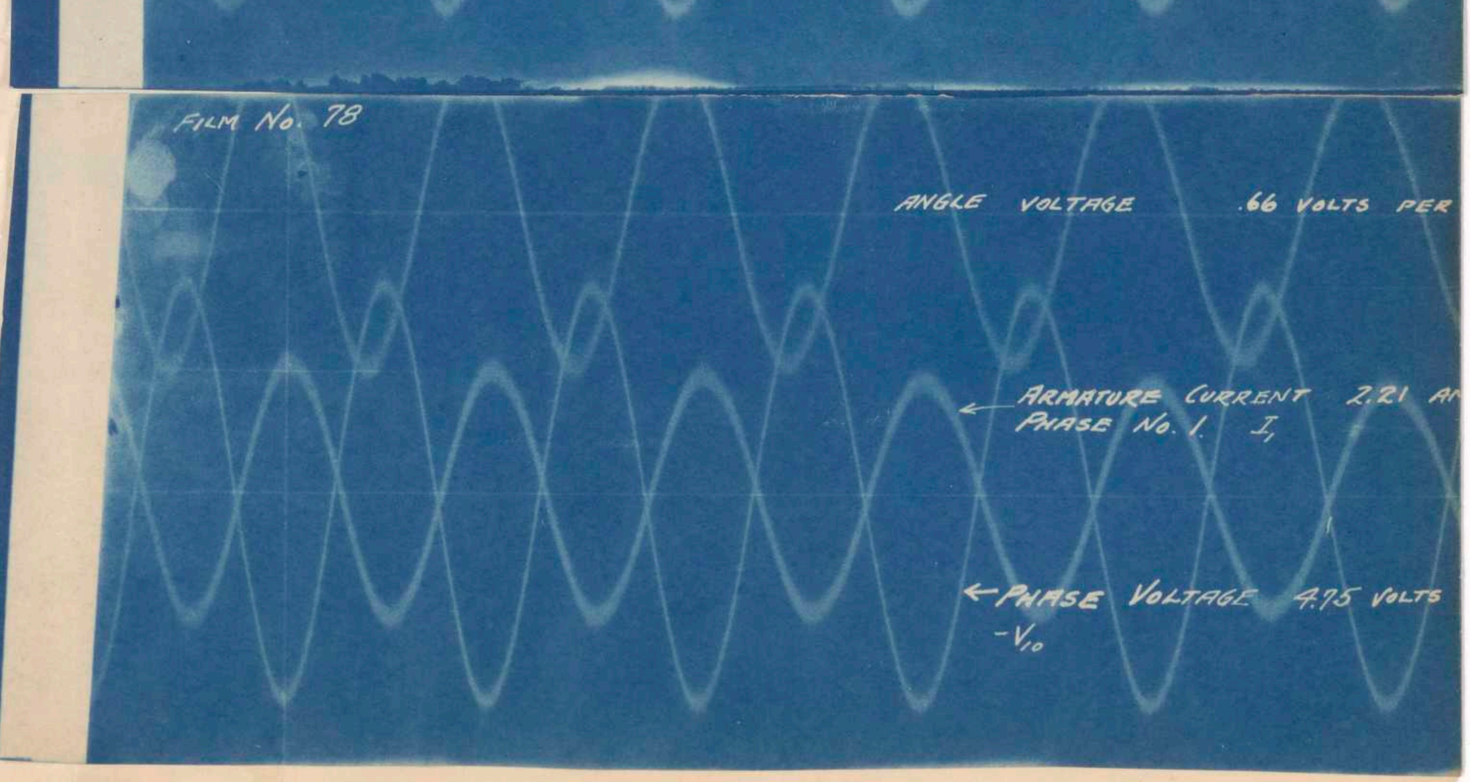
EDGERTON
APRIL 1927

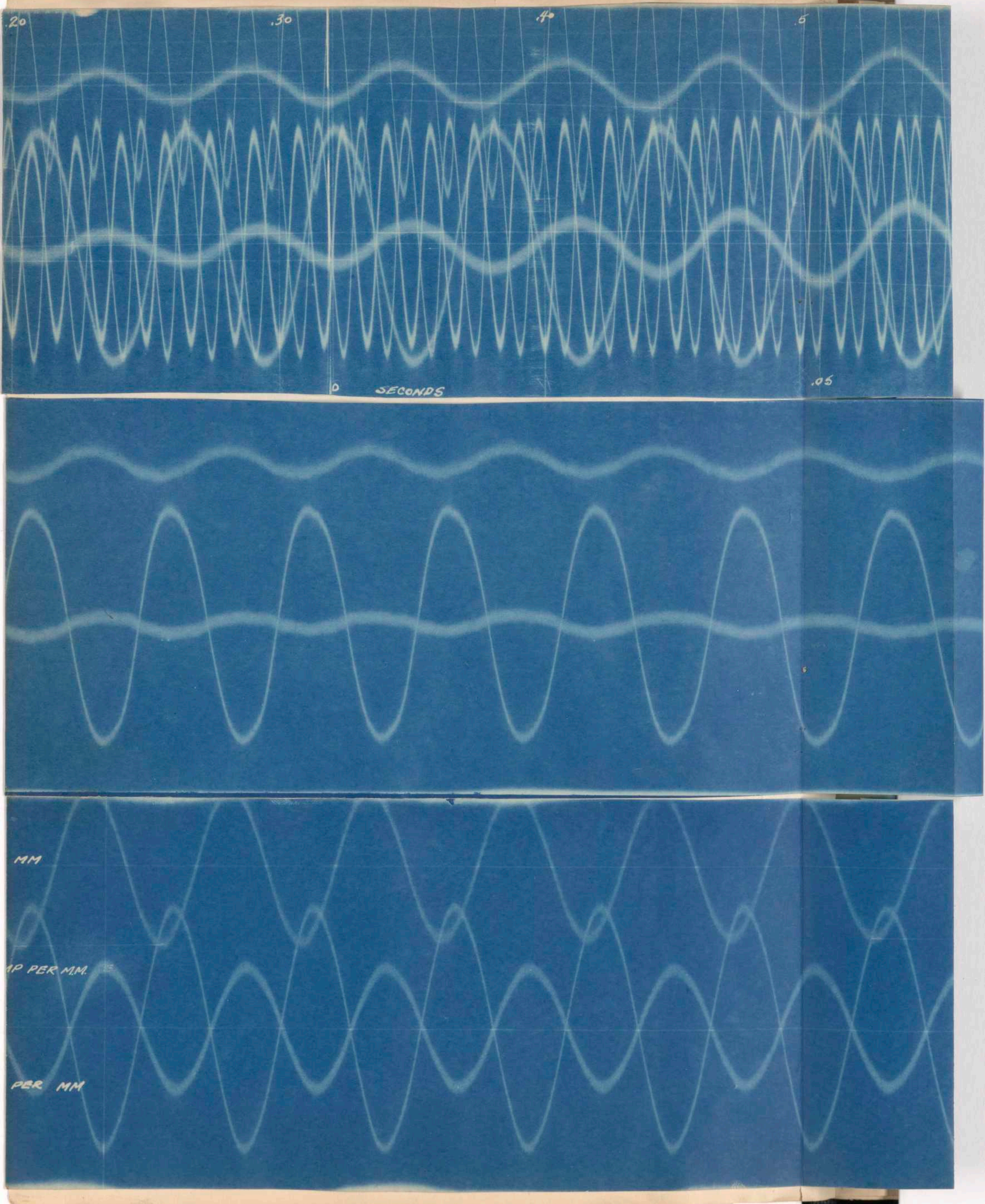


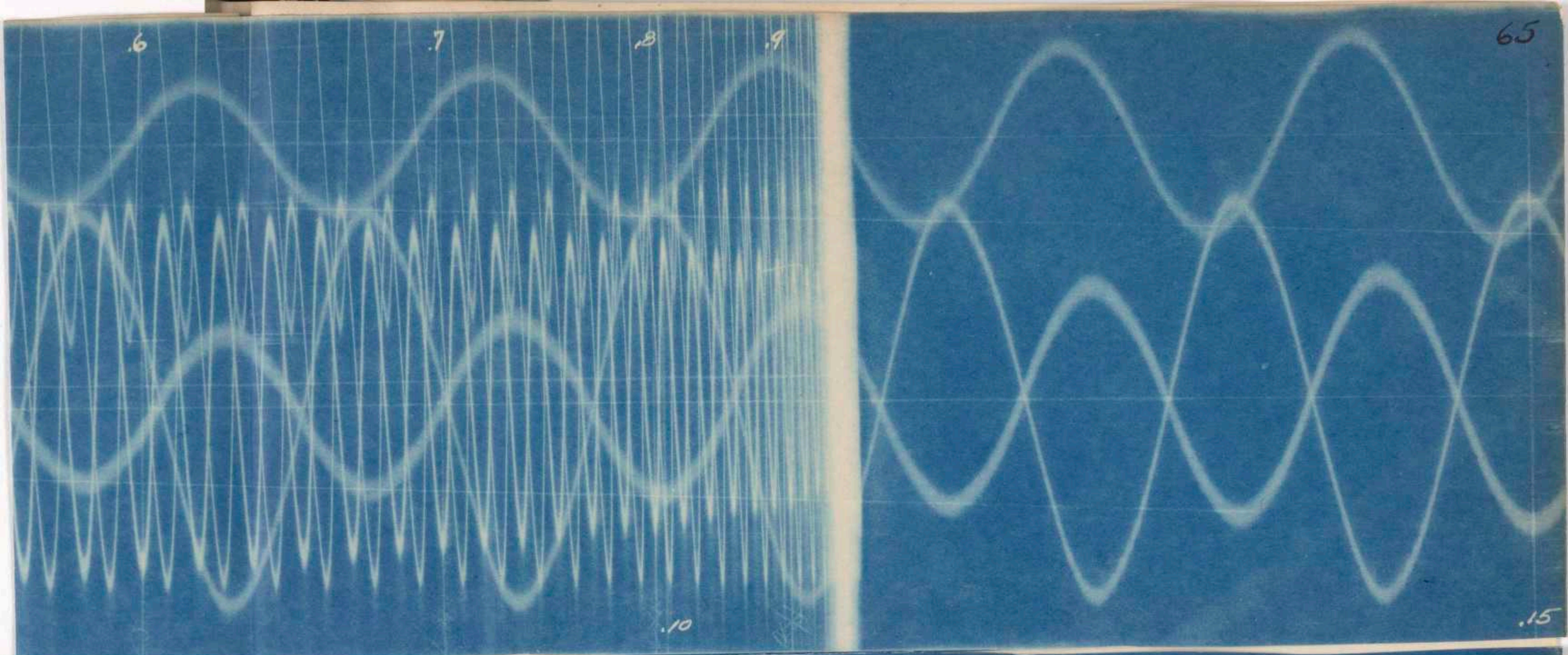
INPUT IN KILOWATTS
LINE CURRENT IN AMPERES
CURRENT - FILM No. 76
CURRENT - FILM No. 76
FILM No. 78
FINAL
INPUT - FILM No 76
INPUT - FILM No. 78
FINAL
TIME IN SECONDS
EDGERTON
APRIL 1927

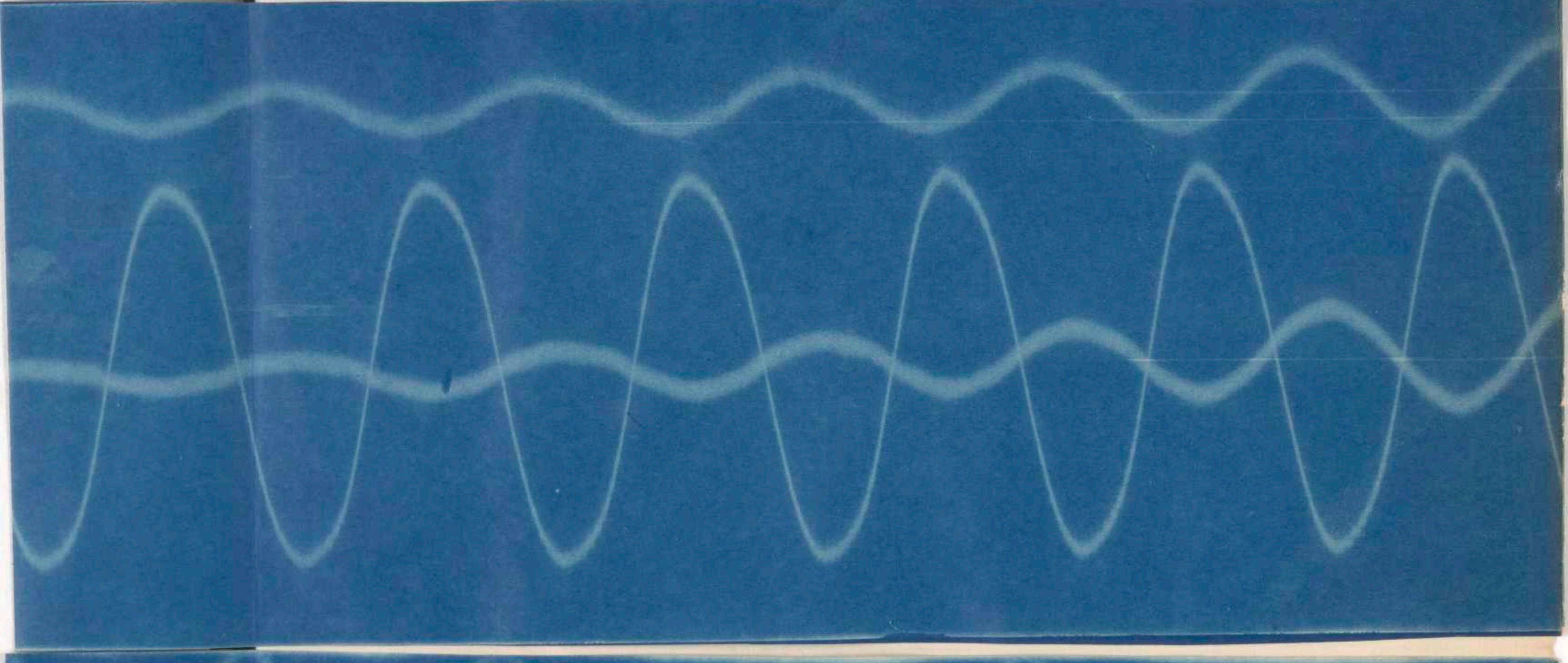

FILM No. 76
0
.10 SECONDS
ANGLE VOLTAGE .66 VOLTS PER MM.
PHASE VOLTAGE 4.75 VOLTS PER MM.
ARMATURE CURRENT 2.21 AMP PER MM.

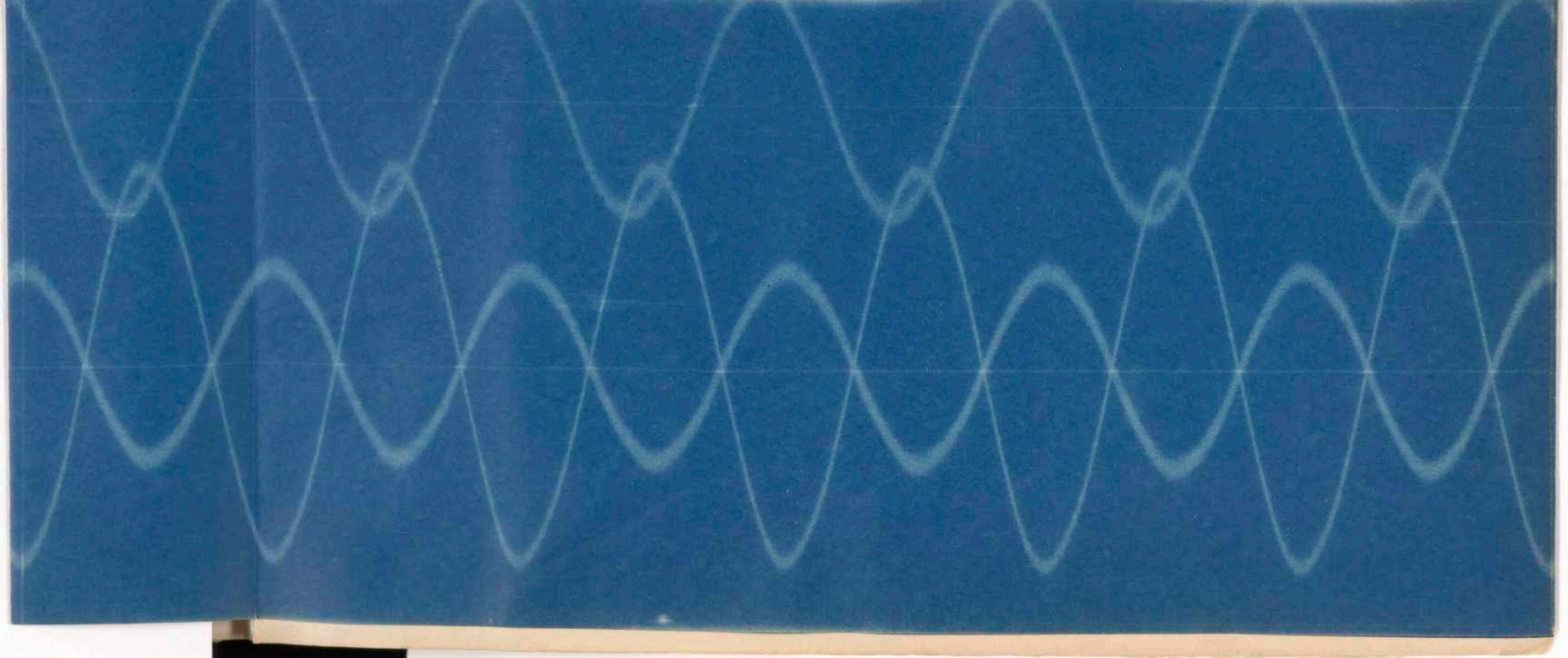

FILM No. 77

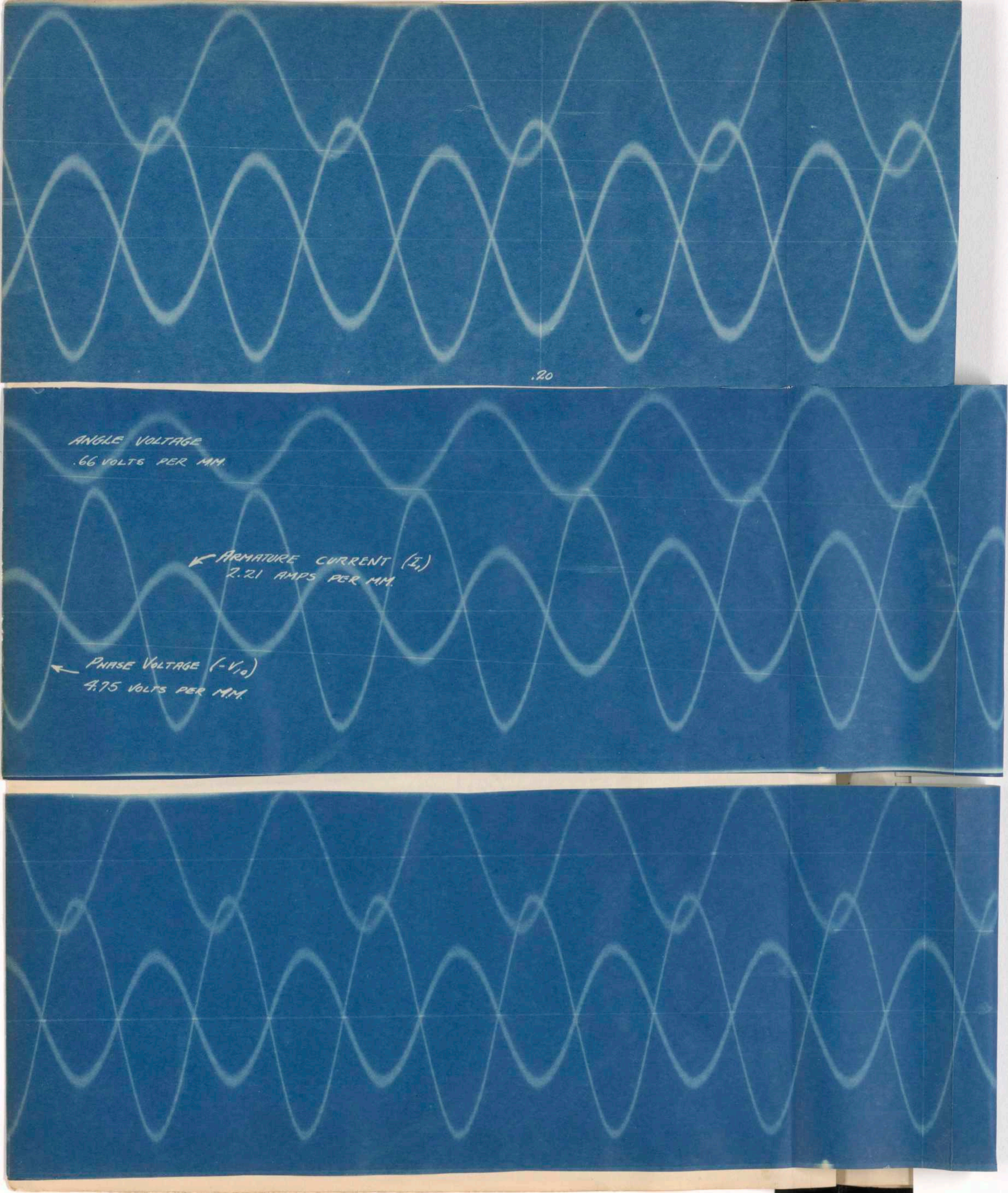

FILM No. 78
ANGLE VOLTAGE .66 VOLTS PER
ARMATURE CURRENT 2.21 A
PHASE No. 1. I_1
← PHASE VOLTAGE 4.75 VOLTS
$-V_{10}$

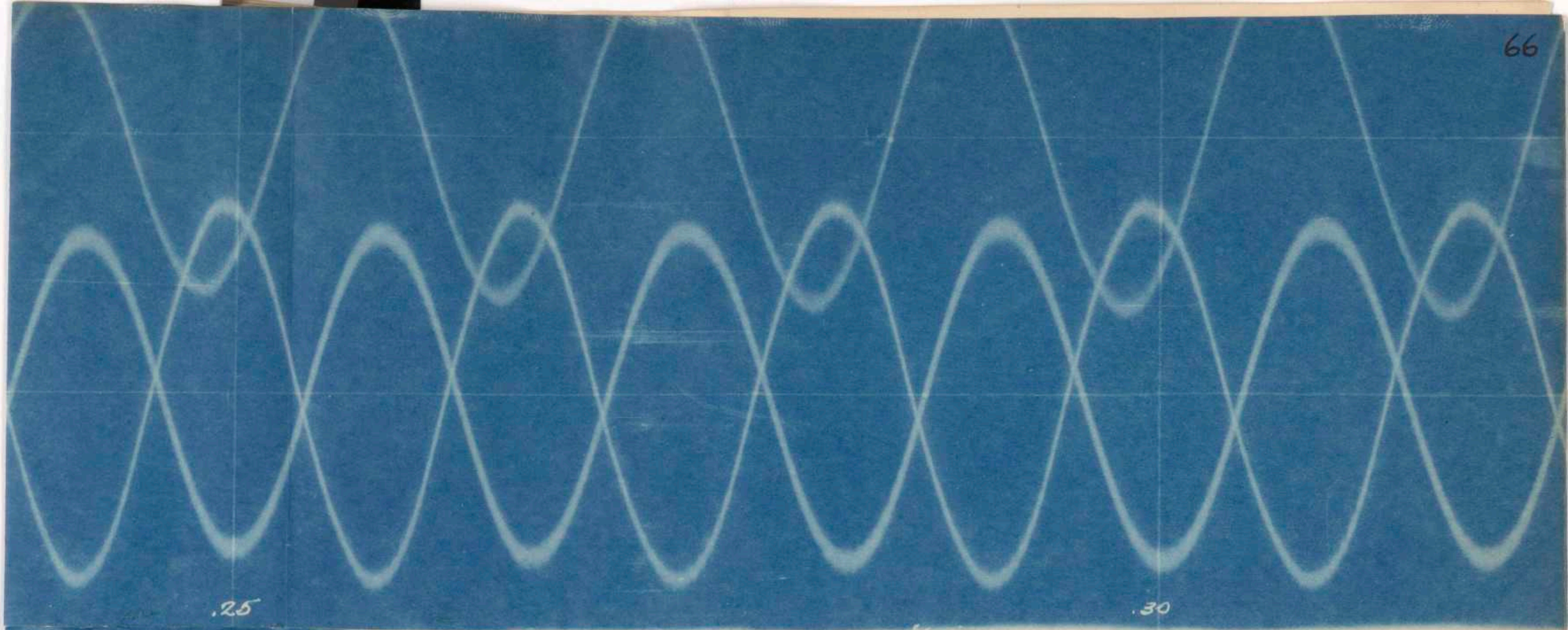

.20
.30
.40
.5
0 SECONDS
.05
MM
PER MM.
PER MM

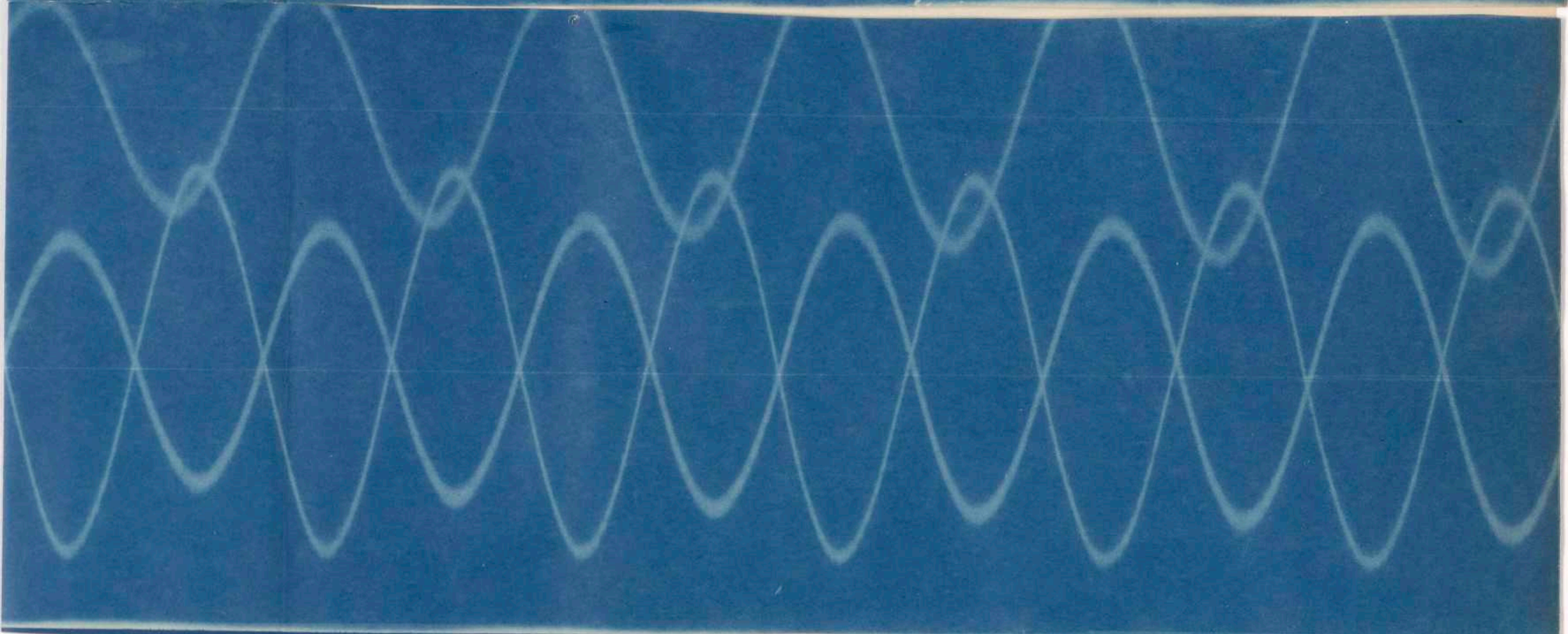

.6
.7
.8
.9
.10
.15

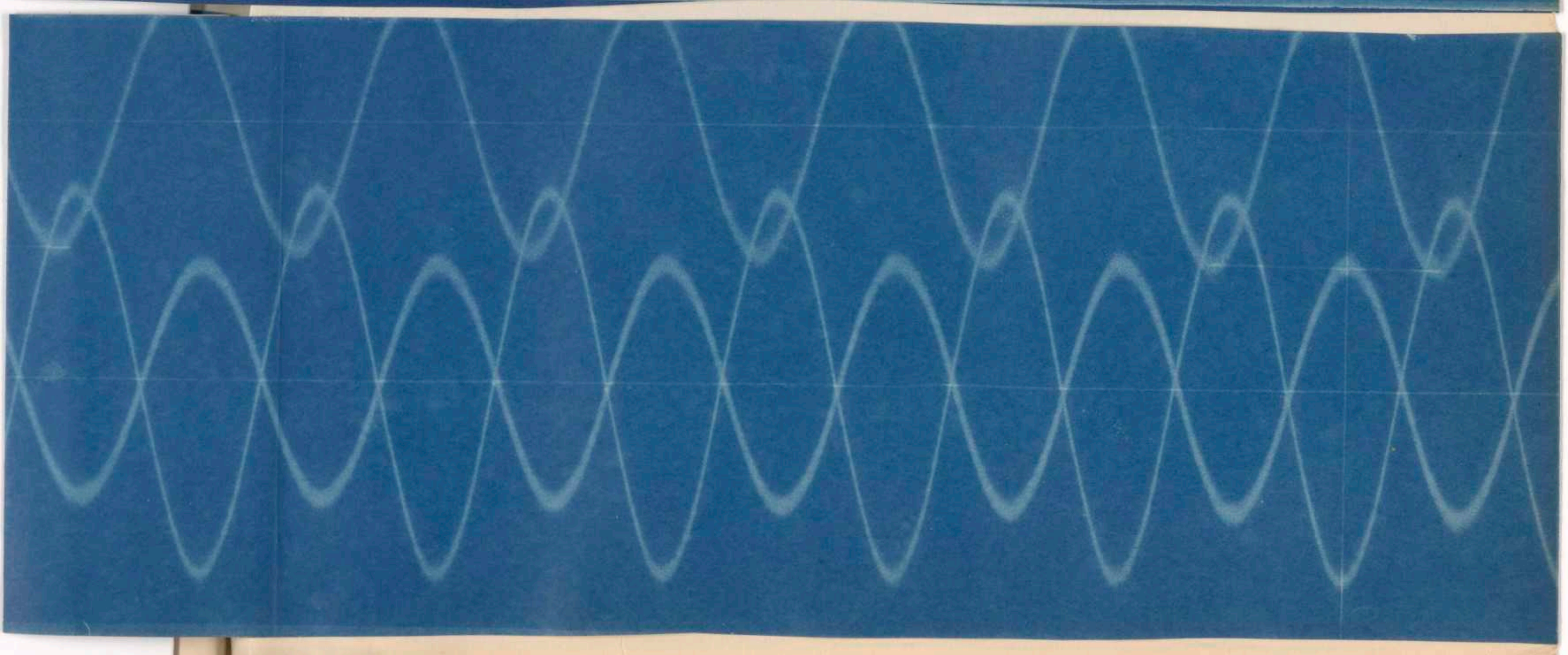


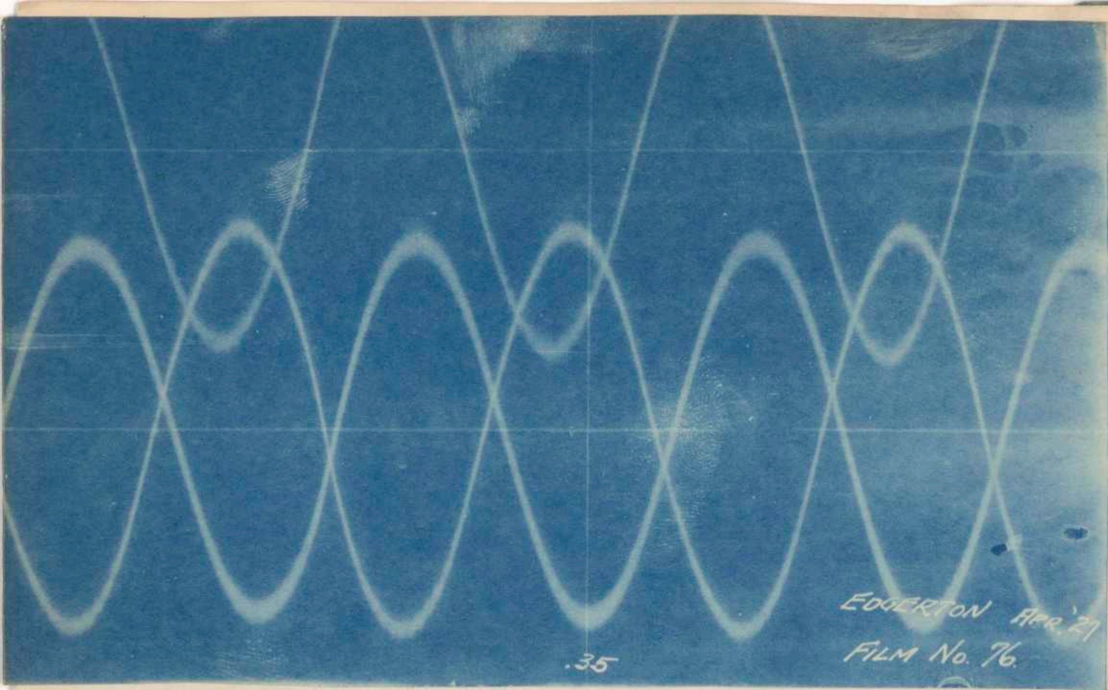



.20
ANGLE VOLTAGE
.66 VOLTS PER MM.
ARMATURE CURRENT (I_1)
2.21 AMPS PER MM.
PHASE VOLTAGE ($-V_{10}$)
4.75 VOLTS PER M.M.

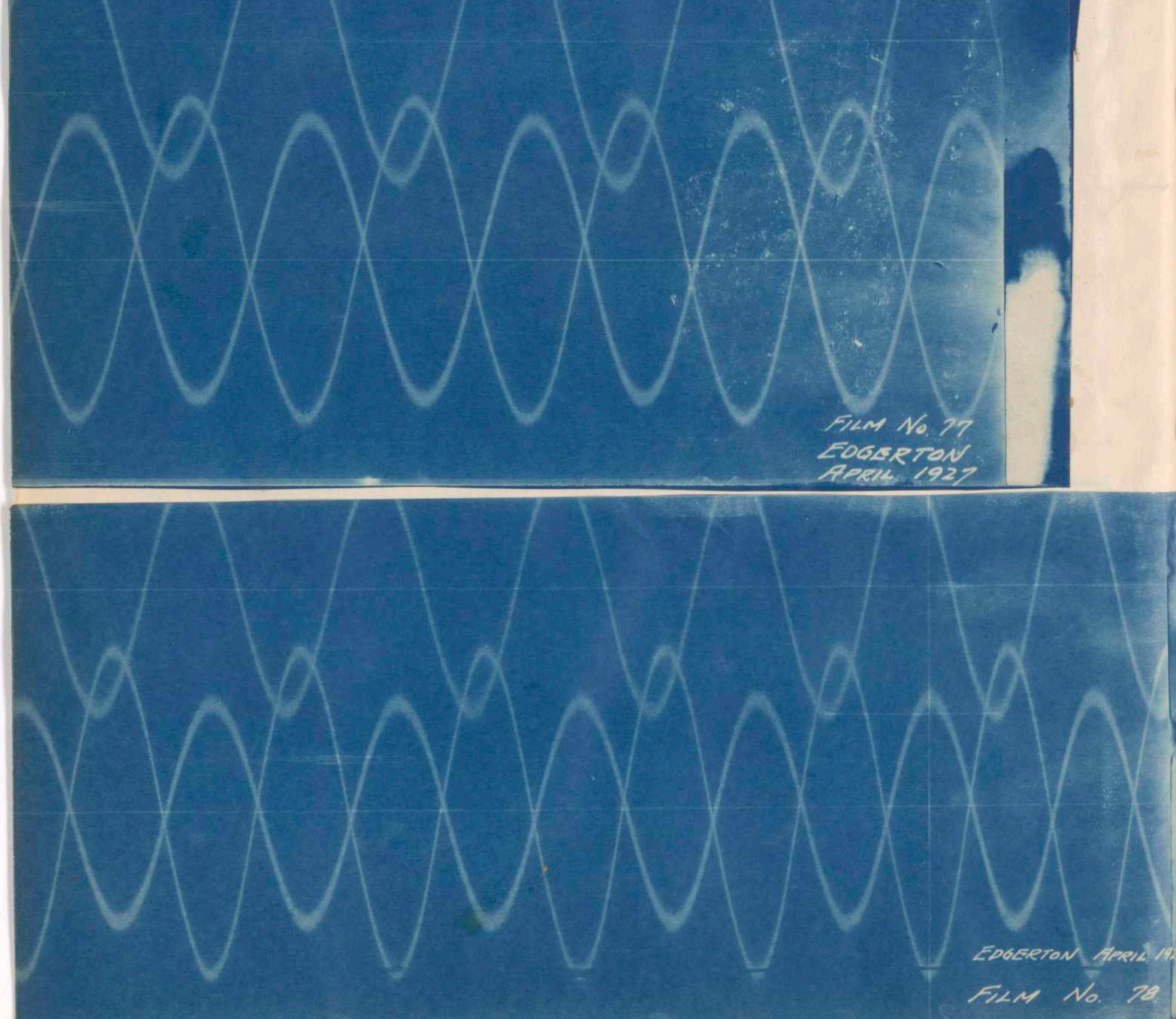

.25
.30






EDGERTON APR.'27
FILM No. 76.
.35


FILM No. 77
EDGERTON
APRIL 1927


EDGERTON APRIL 192
FILM No. 78

FILMS NOS 83 - 91 INCL.

No field resistance was used for these tests. The exciter was placed directly across the field circuit and the voltage varied to get the normal field current of 12.6 amperes. This was done in order to get as near a balanced condition in the rotor as possible.

The films record line current, angle voltage, and field current against time. The values of angle were taken from the films and plotted on page 73 , which follows. This is the set of curves which was checked by the solution on the integraph.

TRANSIENT

POWER ANGLE CHARACTERISTICS AGAINST

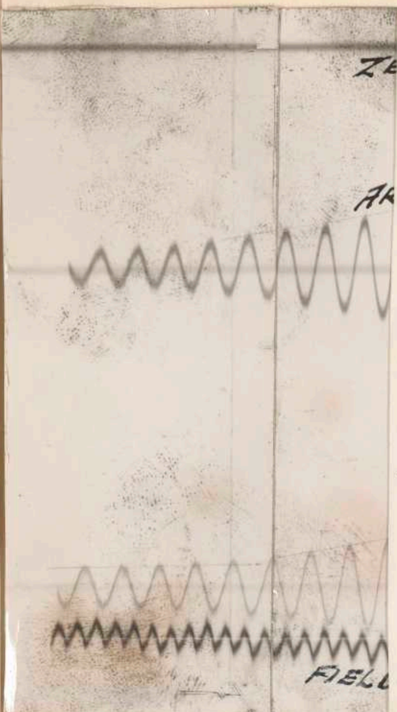
TIME.

Tests made
4-30-1927

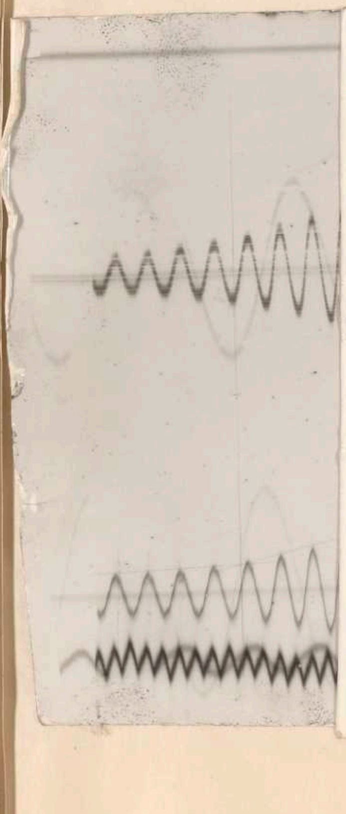
Meter readings were taken after oscillogram except for films no. 90 and 91 since these record breakdown.

Film No.	V	I_a	W_1	W_2	I_f	E^o	D.C. E	D.C. I	comp. angle
83	228	19	20.2 x.2	17.5 x.2	12.4	7	190	27.8	29
84	228	23.4	12.4 x.4	10.7 x.4	12.6	8.7	189	35	36.5
85	227	29.2	15.9 x.4	12.9 x.4	12.6	10.8	185.5	45.5	45.5
87	227.5	36	19.8 x.4	14.8 x.4	12.7	12.9	189	55	55
88	226	39	21.7 x.4	15.4 x.4	12.7	14.2	188	57.3	60.5
89	228	42.5	23.4 x.4	15.7 x.4	12.8	15.2	184	59	65.8
#90	228	43	23.8 x.4	16.2 x.4	12.8	15.4	189	61.5	66.5
#91	228	42.5	23.75 x.4	16.1 x.4	12.7	15.3	189	61	66

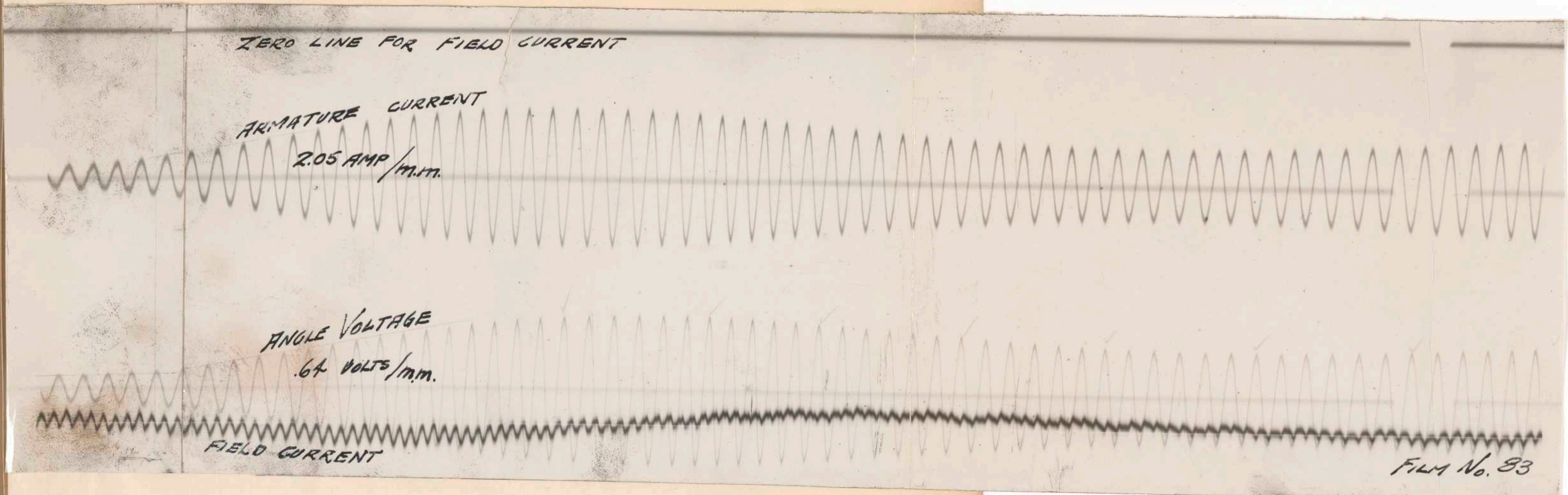
The abrupt load for these cases was sufficient to pull the motor out of synchronism.

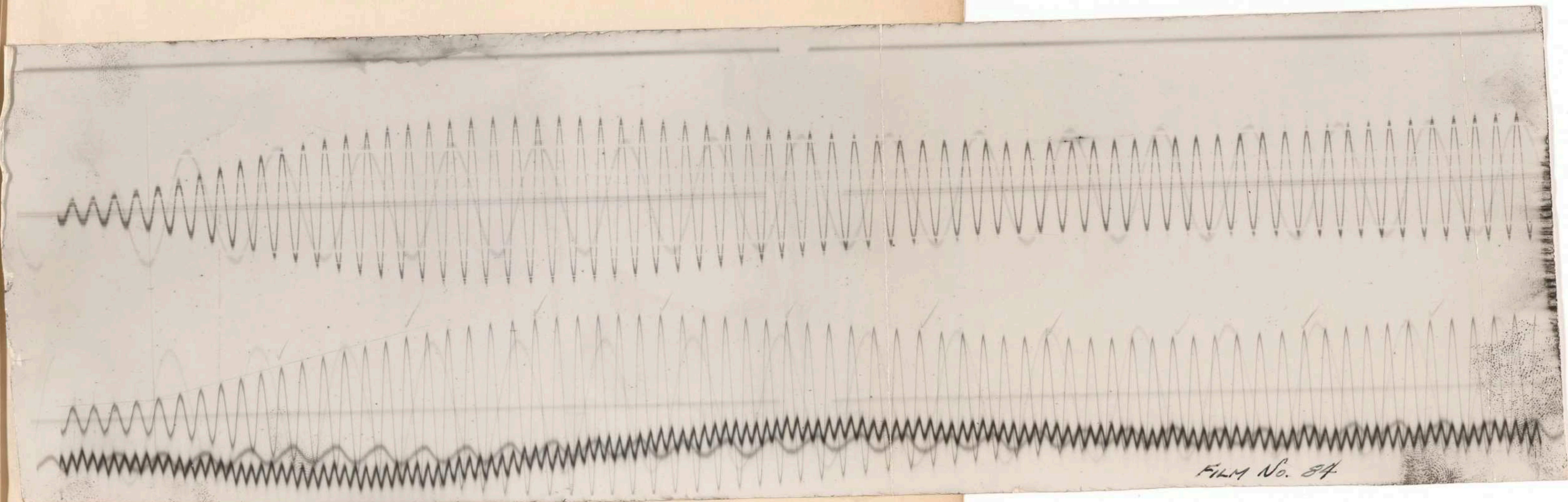


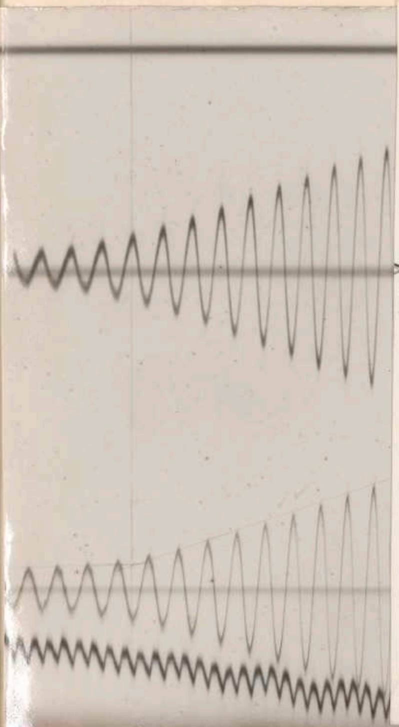
FILM No. 83.



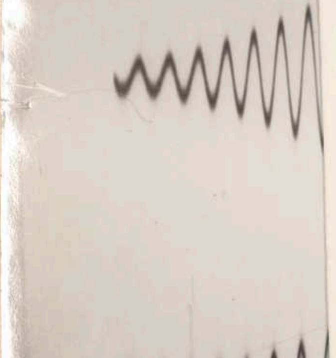
FILM No. 84


ZERO LINE FOR FIELD CURRENT
ARMATURE CURRENT
2.05 AMP/m.m.
ANGLE VOLTAGE
.64 VOLTS/m.m.
FIELD CURRENT
FILM No. 83

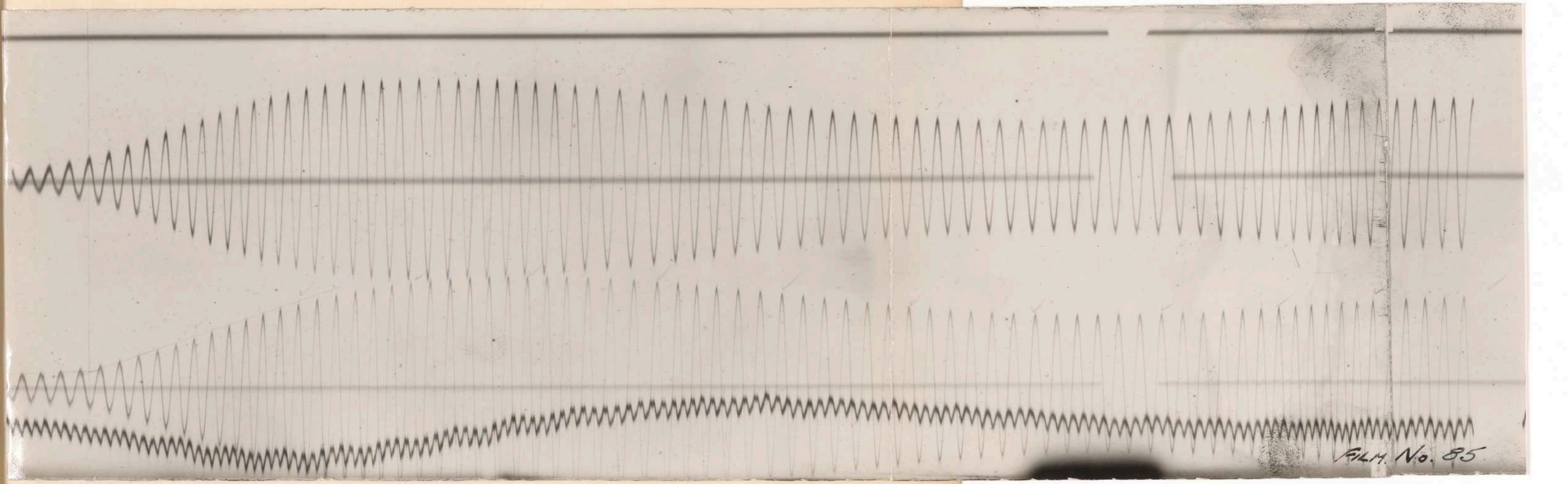

FILM No. 84

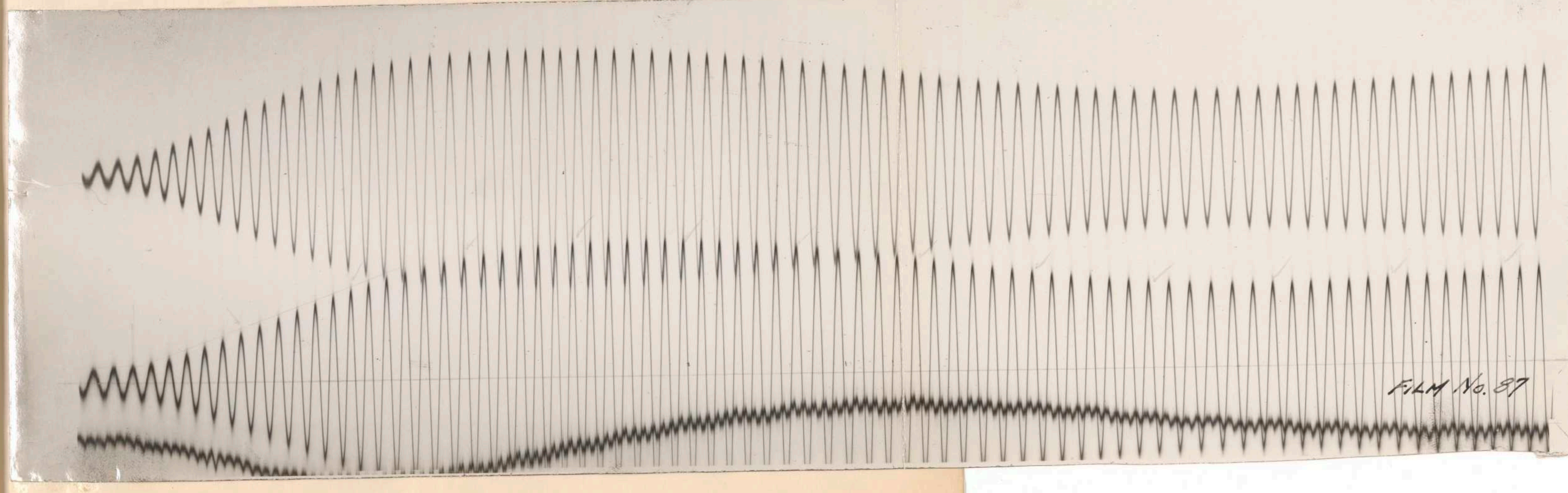


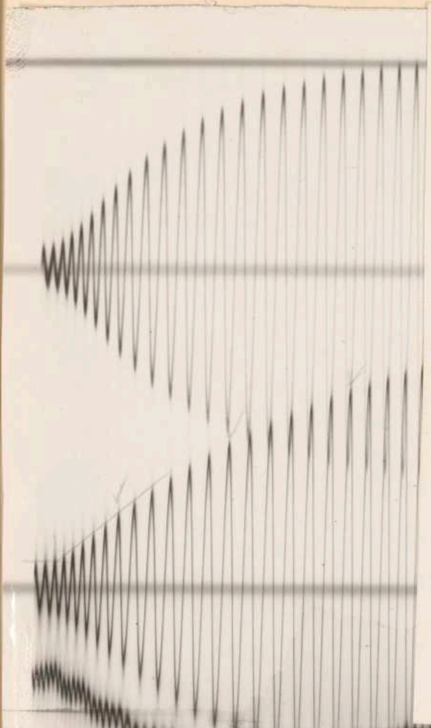
FILM No. 85



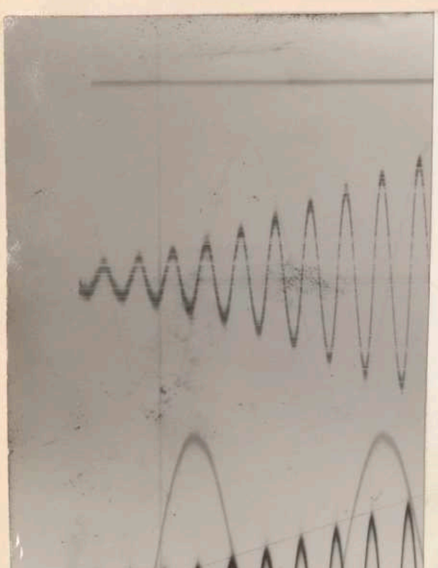
FILM No. 87


FILM. No. 85

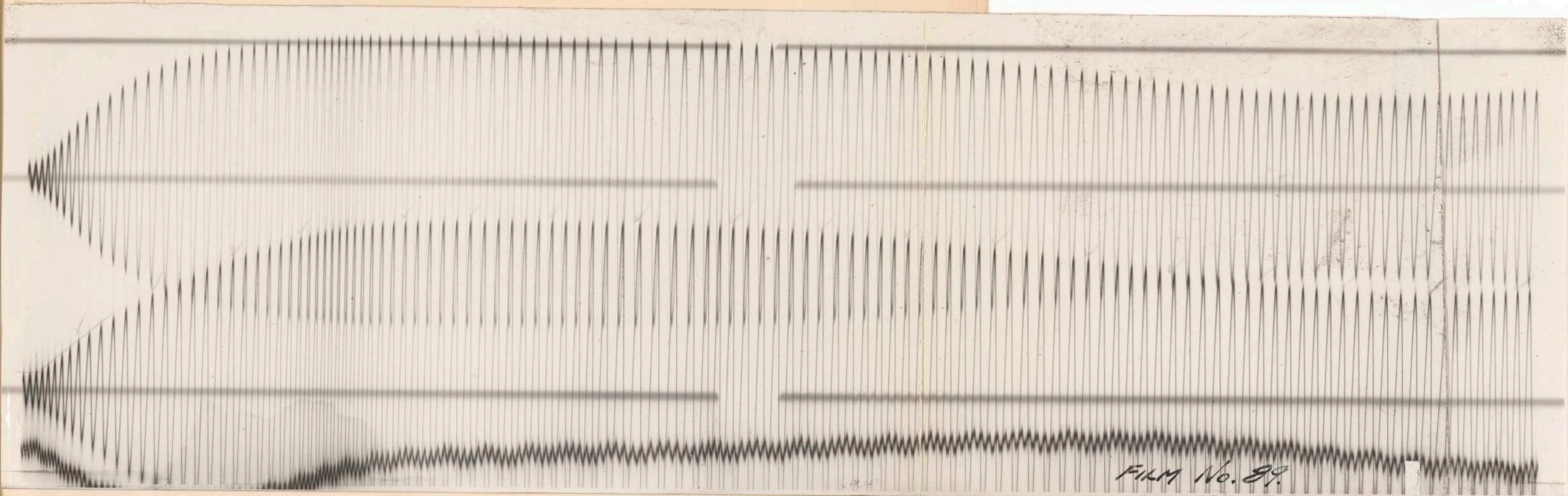

FILM No. 87

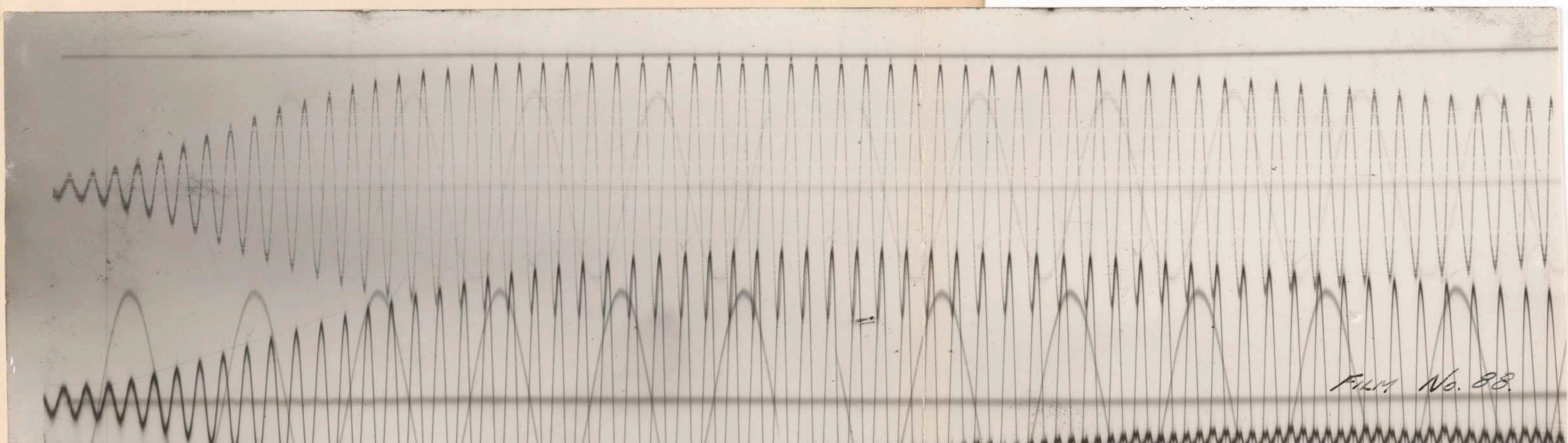


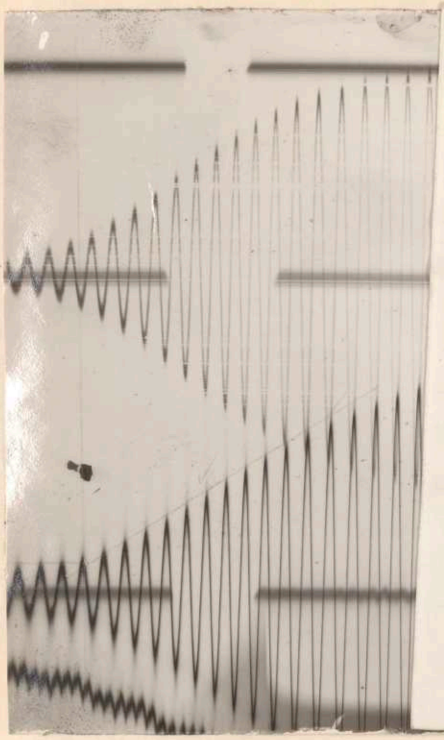
FILM No. 89



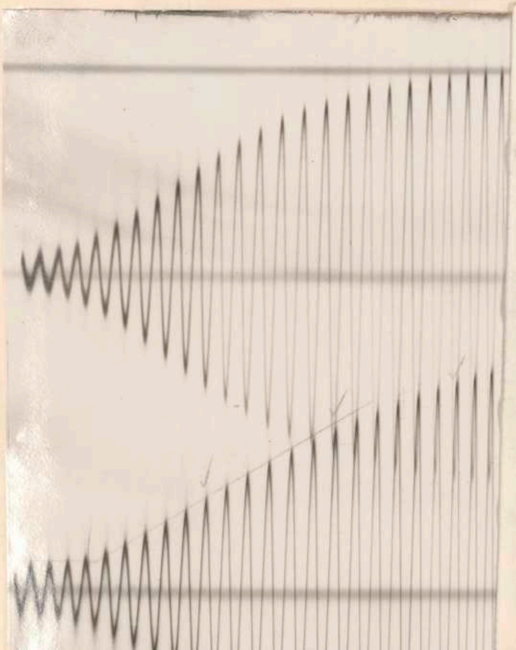
FILM No 88


FILM No. 89.

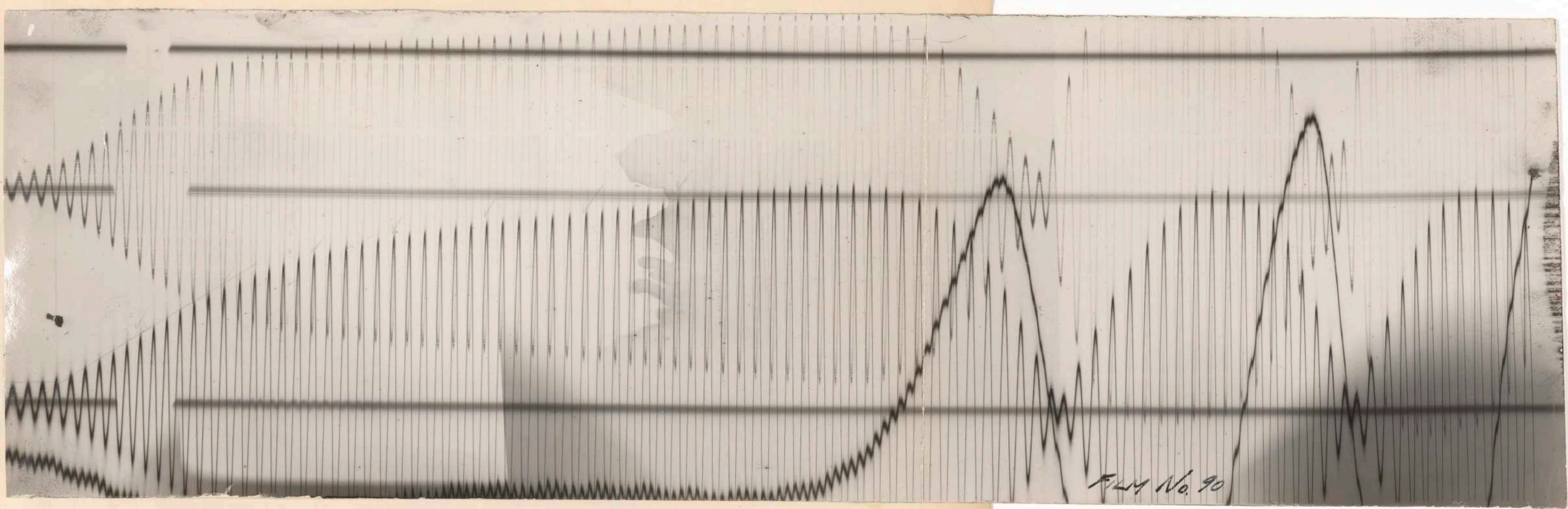

FILM No. 88.

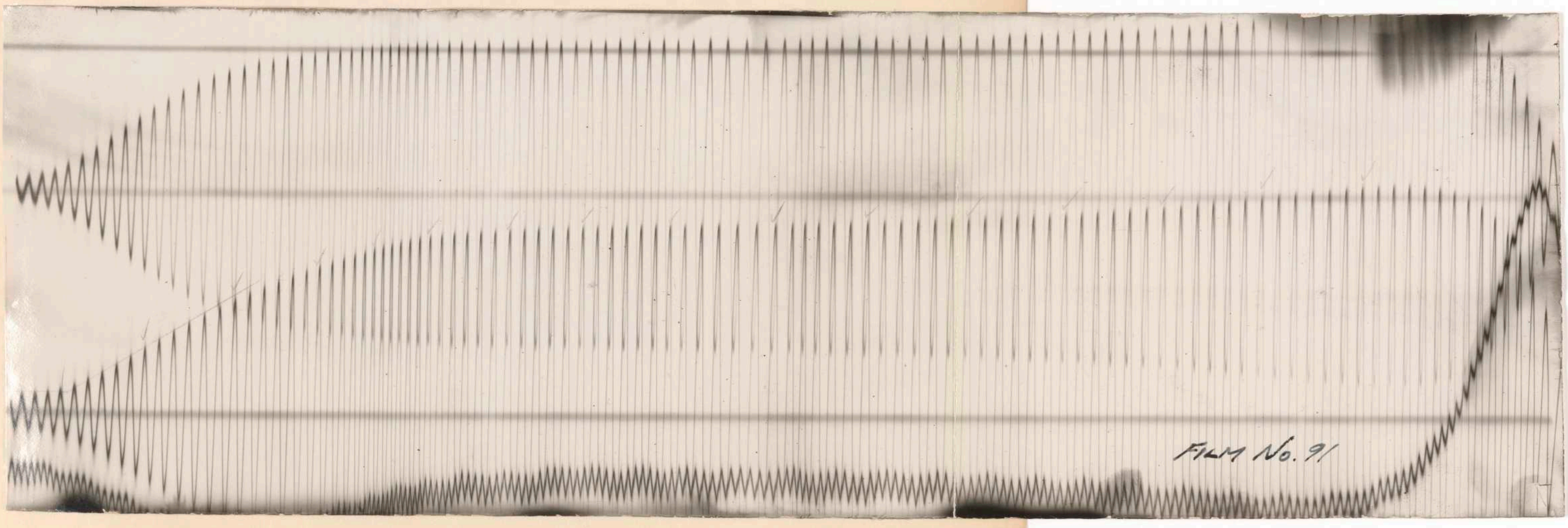


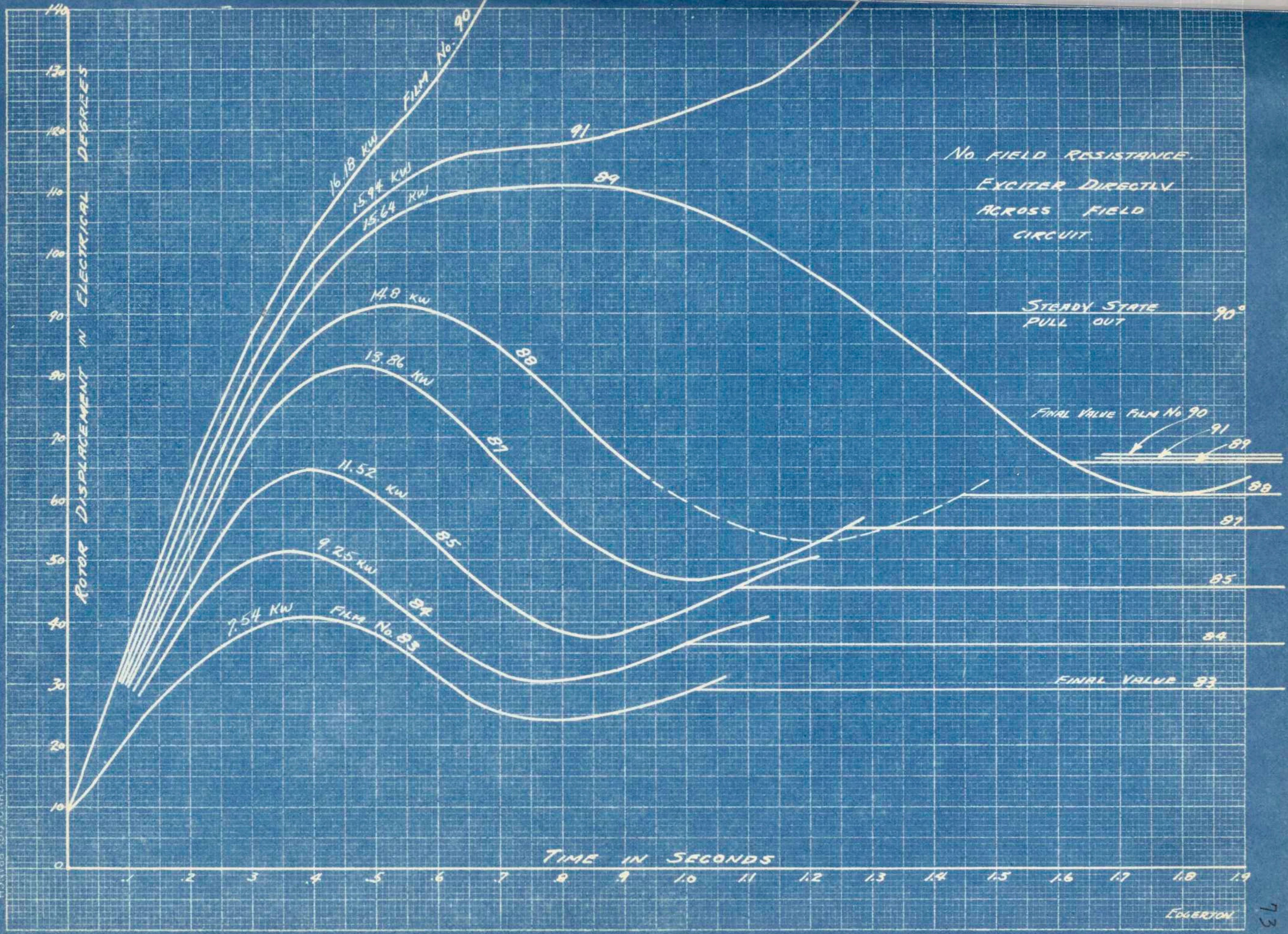
FILM No. 90



FILM No. 91

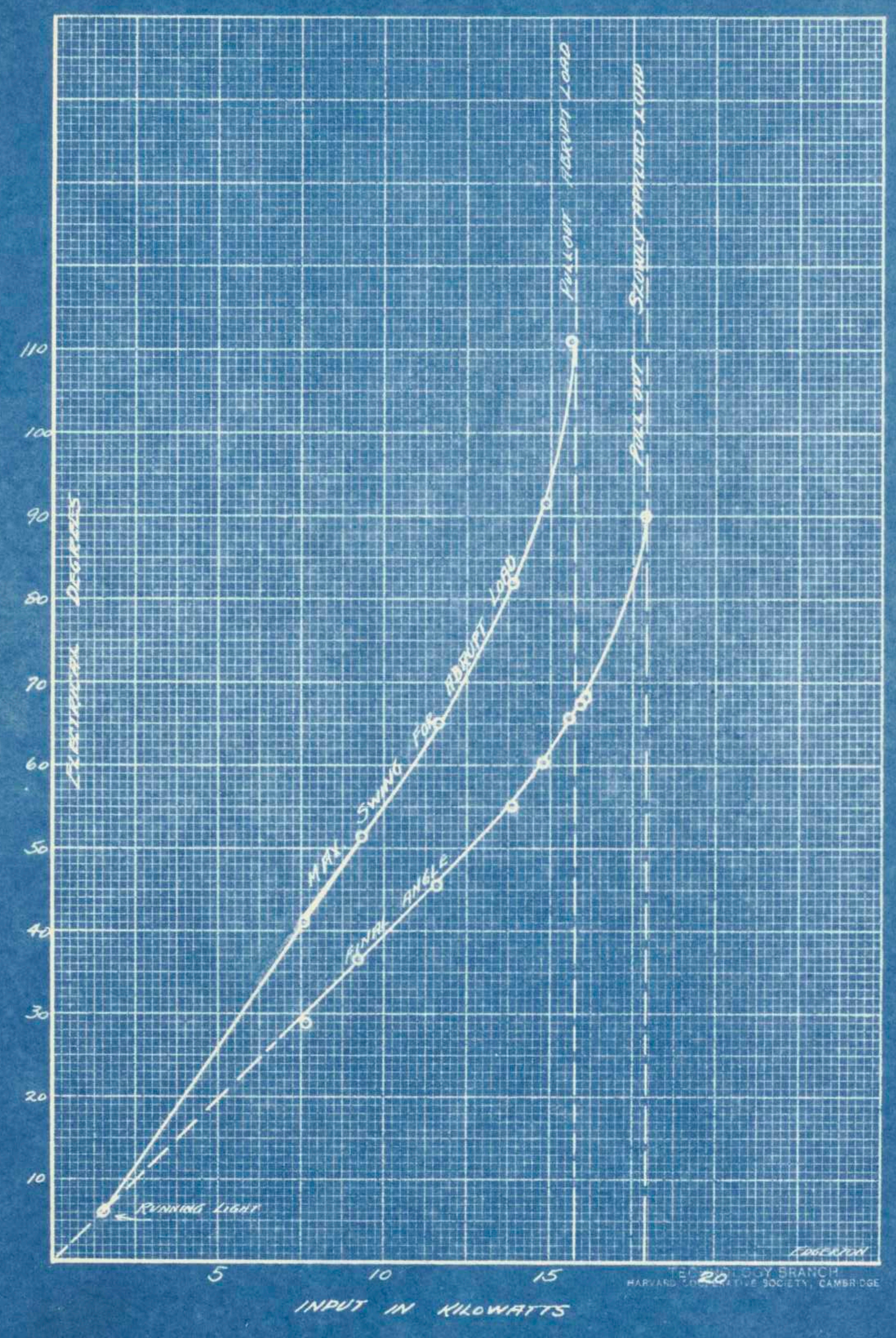

FILM No. 90


FILM No. 91



No field resistance.
Exciter directly across field circuit.
Steady State Pull out 90°
Rotor Displacement in Electrical Degrees
Time in Seconds
Film No. 90
16.18 KW
15.94 KW
15.64 KW
91
89
14.8 KW
88
13.86 KW
87
11.52 KW
85
9.25 KW
84
7.54 KW Film No. 83
Final Value Film No 90
91
89
88
87
85
84
Final Value 83
Edgerton

73


ELECTRICAL DEGREES
10
20
30
40
50
60
70
80
90
100
110
5
10
15
20
INPUT IN KILOWATTS
RUNNING LIGHT
MAX SWING FOR ABRUPT LOAD
RUNNING ANGLE
PULLOUT ABRUPT LOAD
PULL OUT SLOWLY APPLIED LOAD

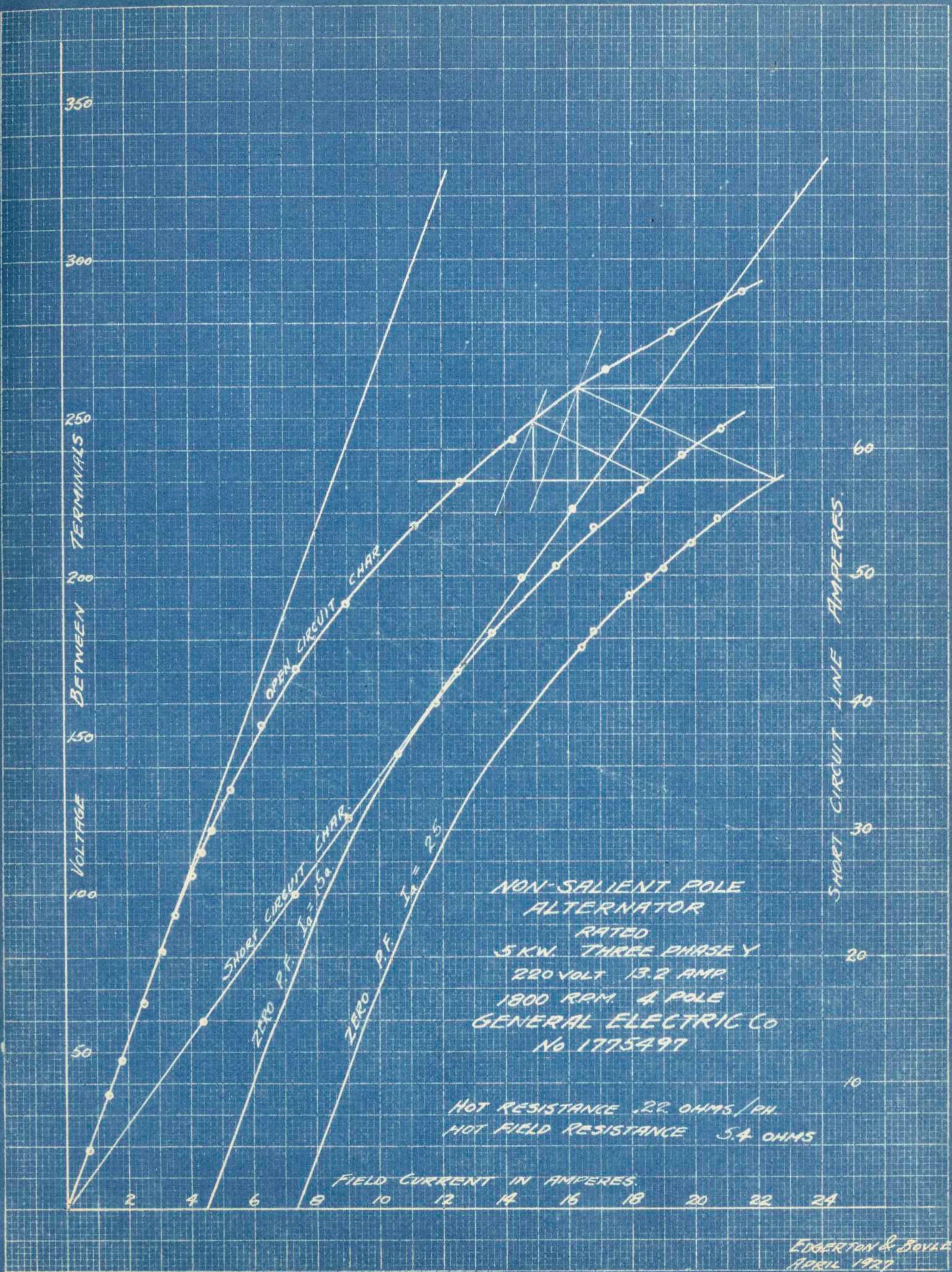
SECTION IV

STEADY STATE TESTS.

These steady state tests were made to determine the constants of the machine and also to find its steady state operating characteristics.

OPEN AND SHORT CIRCUIT CHARACTERISTICS
ZERO POWER FACTOR TESTS.

These are the usual tests made on a synchronous machine to determine its electrical characteristics. The zero power factor tests were made at two different currents and these showed that the Potier triangle for each was similiar. The results of these tests follow on the next page.



350
300
250
200
150
100
50
VOLTAGE BETWEEN TERMINALS
60
50
40
30
20
10
SHORT CIRCUIT LINE AMPERES
OPEN CIRCUIT CHAR.
SHORT CIRCUIT CHAR.
ZERO P.F. Ia = 15a.
ZERO P.F. Ia = 25
2
4
6
8
10
12
14
16
18
20
22
24
FIELD CURRENT IN AMPERES.
NON-SALIENT POLE
ALTERNATOR
RATED
5 KW. THREE PHASE Y
220 VOLT 13.2 AMP.
1800 R.P.M. 4 POLE
GENERAL ELECTRIC Co
No 1775497
HOT RESISTANCE .22 OHMS/PH.
HOT FIELD RESISTANCE 5.4 OHMS
EDGERTON & BOYLE
APRIL 1927

Test data for
open circuit characteristic

I_f	E
.75	19.0
1.38	36.2
1.8	47.5
2.5	65.9
3.05	81.9
3.52	93.2
4.05	105.8
4.4	113.6
4.7	120.0
5.06	127.5
5.31	133.0
6.30	153.5
7.15	166.5
7.4	171.0
8.17	181.5
9.0	191.8
9.85	201.5
11.18	216.0
12.48	228.3
14.22	243.0
15.42	252.2
17.2	265.6
18.07	270.0
19.22	277.7

Short circuit
characteristic data.

I_f	I_a
9.61	33.1
11.56	39.5
14.55	49.9
16.15	55.3

The speed was held at
1800 rpm for all tests.

Data for Zero power factor.

I_f	E	I_a
18.0	194.5	25
16.8	182	25
16.5	178	25
18.55	199	25
19.0	202.4	25
19.95	210	25
20.75	218	25

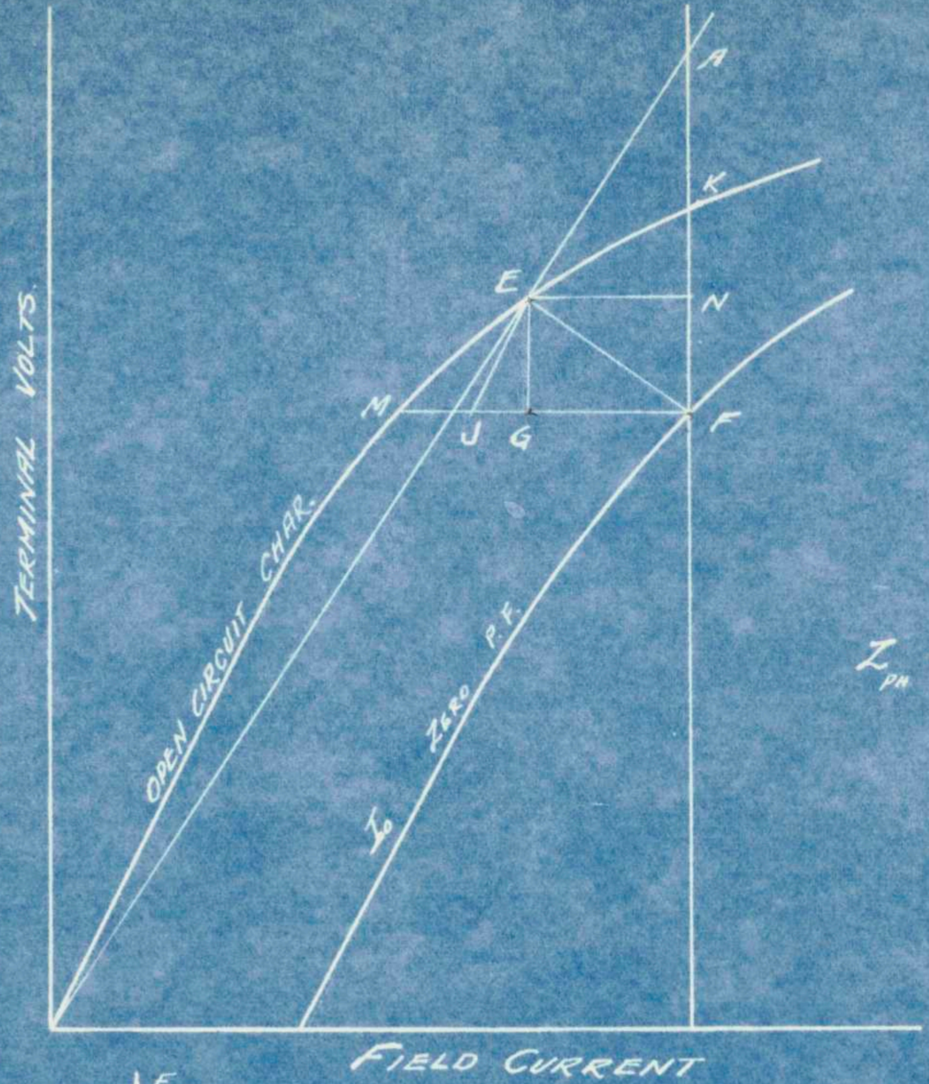
I_f	E	I_a
10.6	144	15
11.8	160	
12.55	170	
13.6	182	
15.6	203	
16.8	215	
18.3	227.5	
19.6	238	
20.8	246	

CALCULATION OF SYNCHRONOUS REACTANCE FROM TEST DATA.

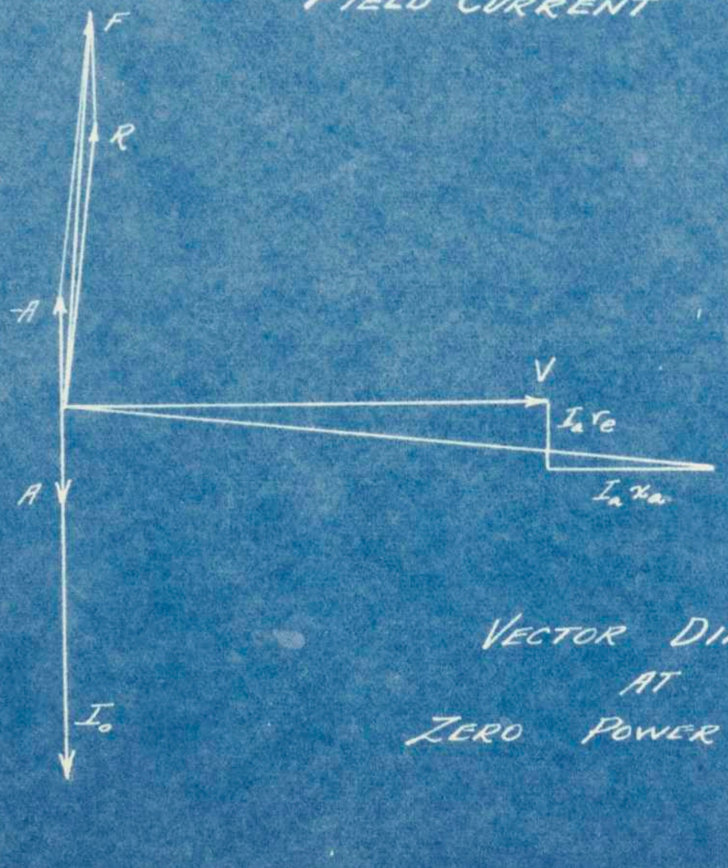
As long as the straight line portion of the magnetization curve is used the synchronous reactance is constant. On the saturated portion of the curve the synchronous reactance is less than on the straight line saturation. From the open circuit characteristic it is obvious that this machine is well saturated (about 35 % saturation).

The method used for calculating the synchronous impedance requires the open circuit and zero power factor characteristic. Figure 1 page 79 shows the form of these curves. The voltage AF divided by the zero power factor current gives the synchronous impedance for point E. This is based on the fact that the magnetic circuit is working on the straight line saturation OEA and that if this saturation remains, the voltage will rise AF volts when the current is removed. Since the resistance is small compared to the reactance the impedance is practically the same as the reactance.

The values of synchronous impedance thus obtained by the two different values of zero power factor current differ only slightly. Page 80 gives a plot of synchronous impedance against field current for the two zero power factor tests.

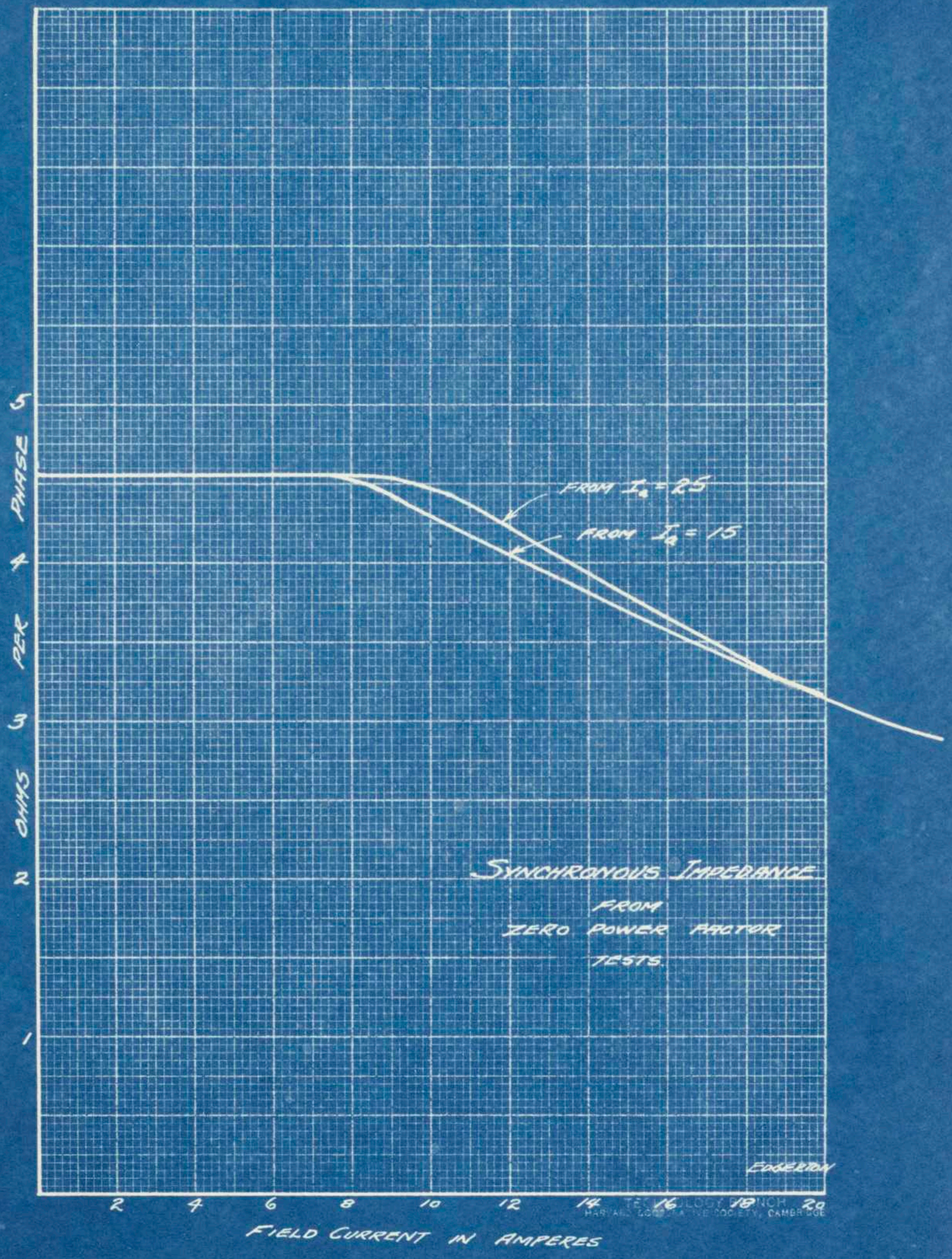


$$Z_{ph} = \frac{E_{AF}}{\sqrt{3}\ I_o}$$



VECTOR DIAGRAM
AT
ZERO POWER FACTOR

EDGERTON



OHMS PER PHASE
5
4
3
2
1
FROM I_a = 25
FROM I_a = 15
SYNCHRONOUS IMPEDANCE
FROM
ZERO POWER FACTOR
TESTS.
EDGERTON
2 4 6 8 10 12 14 16 18 20
FIELD CURRENT IN AMPERES

ARMATURE LEAKAGE REACTANCE

Armature leakage reactance was found by the potier triangle method. The triangle EFG , page 79 figure 1 , represents the condition at zero power factor with a current of I amperes flowing in the armature. The vector diagram on this same page is the vector diagram of a synchronous machine at zero power factor. The voltage EG represents the drop in voltage due to armature leakage since at zero power factor the leakage drop is in phase with the voltage and the armature reaction is in quadrature thus directly opposing the magnetizing action of the field poles.

Armature leakage reactance is then ;

$$x_a = \frac{V_{EG}}{I\sqrt{3}} = \frac{29.5}{25 \times 1.73} = 0.63 \text{ ohms per phase}$$

The factor $\sqrt{3}$ enters since terminal voltages were measured and this is a wye connected machine.

Armature reaction likewise is ;

$$A = I_a \frac{I_{GF}}{I} = I_a k = I_a \frac{6.2}{25} = .248\ I_a$$

where I_a is any armature current. A is in units which correspond to field current.

CAMPARISON TO A TURBO ALTERNATOR

In order to compare this machine with the usual turbo alternator it was rerated so that its synchronous impedance equalled 100 percent. This gives,

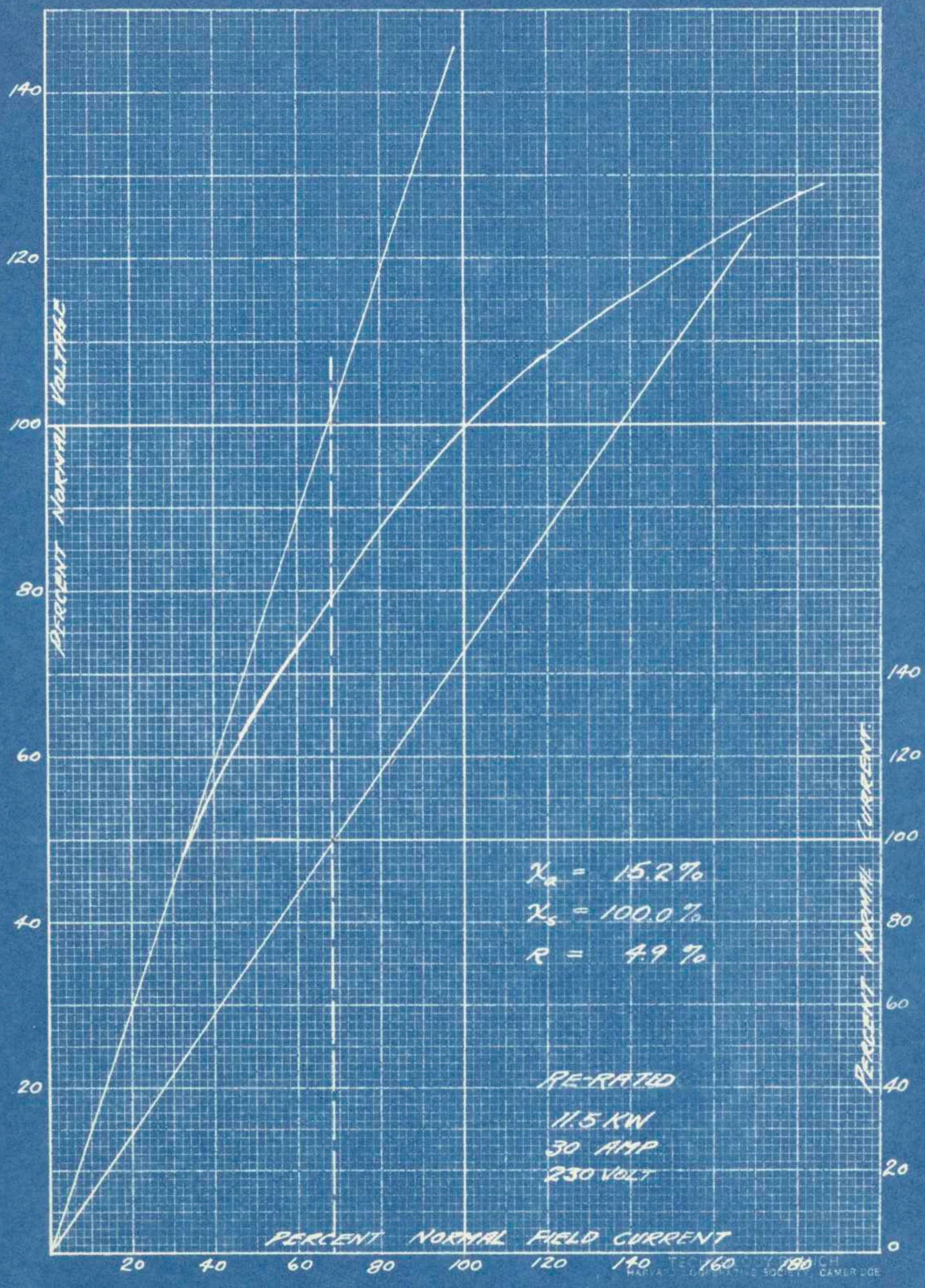
x_s = 100 %

x_a = 15.2 %

r = 4.9 %

This changes the rating to 11.5 kilowatts, 30 amperes, and 230 volts.

Curves showing the characteristics follow on the next page.



PERCENT NORMAL VOLTAGE
140
120
100
80
60
40
20
PERCENT NORMAL CURRENT
140
120
100
80
60
40
20
0
X_a = 15.2 %
X_s = 100.0 %
R = 4.9 %
RE-RATED
11.5 KW
30 AMP
230 VOLT
PERCENT NORMAL FIELD CURRENT
20
40
60
80
100
120
140
160
180

MOMENT OF INERTIA

The moment of inertia was determined in a manner similiar to that used by Johnson[1]. The two element chronograph of which a photograph appears on the next page was connected so that one element gave time intervals and the other gave the deviation from synchronism.

An ordinary metronome was rigged up with a contact and mercury cup to give the time interval. A laboratory slip counter was used to obtain the deviation from synchronism. The slip counter consists of two discs, one driven by the machine under test and the other by a small synchronous motor. A contact between the two parallel discs gives an electrical contact for each one revolution difference in speed.

Johnson gives the formula :

$$\text{Loss in Kw} = \frac{4\ WR^2\ \pi^2\ S}{32.2 \times 3600 \times 33000 \times 1.34} \cdot \frac{dS}{dt}$$

where

W = weight in pounds

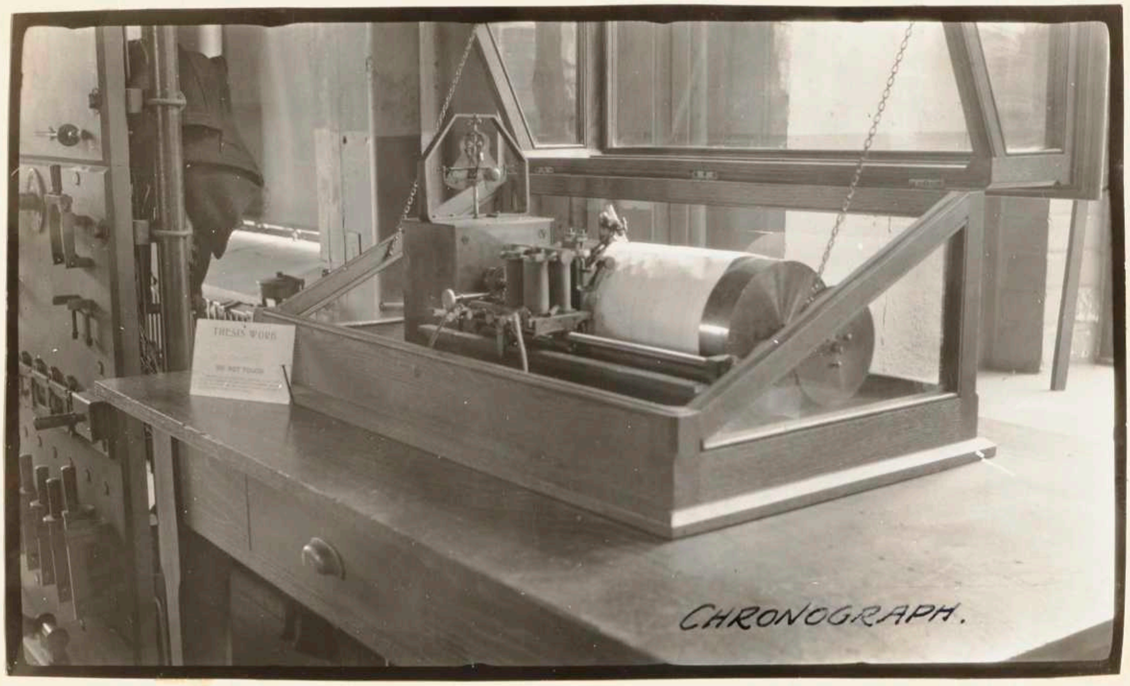
R = radius of gyration in feet

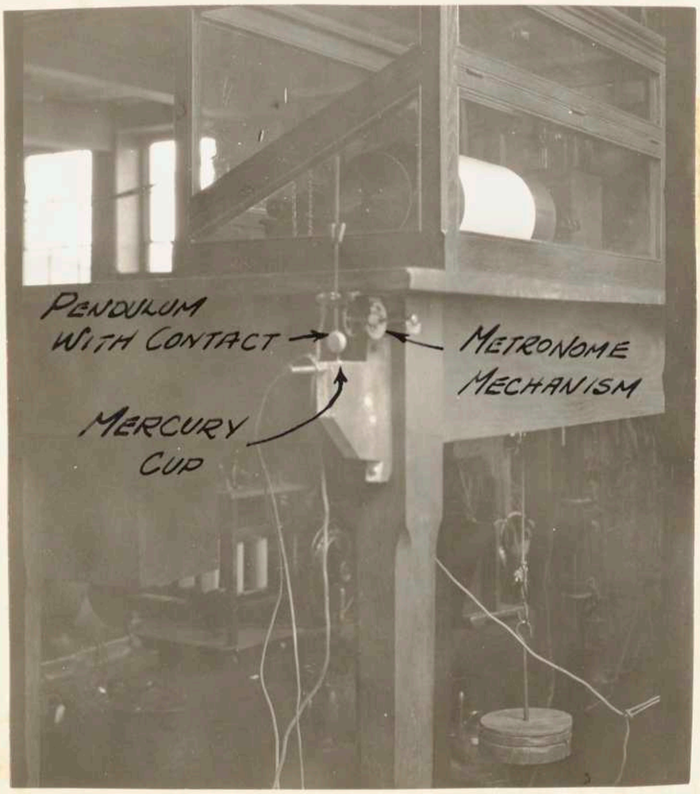
S = rev. per minute.

$\frac{dS}{dt}$ = rate of retardation in rev. per minute per minute.

The loss in Kw was obtained from the wattmeter readings when running with no load and normal excitation on the field. $\frac{dS}{dt}$ was obtained from the slope of the retardation

A.I.E.E. Journal June 1926 page 546.


THESIS WORK
DO NOT TOUCH
CHRONOGRAPH.


PENDULUM
WITH CONTACT
METRONOME
MECHANISM
MERCURY
CUP

test from the chronograph. S was taken as synchronous speed. Thus all quanities but WR^2 can be measured. Solving for WR^2 in the previous given formula gives the moment of inertia in pound $feet^2$.

CALCULATION OF MOMENT OF INERTIA

Loss in Kw = 1.38 (windage, friction and iron loss in one machine)

$$\frac{dS}{dt} = 1724 \text{ rpm}^2 \quad \text{(from chronograph record)}$$

S = 1760 (synchronous speed)

Then,

$$WR^2 = \frac{1.38 \times 32.2 \times 3600 \times 33000 \times 1.34}{4\pi^2 \times 1760 \times 1724} = 58.8 \text{ lb ft}^2$$

When $\frac{dS}{dt}$ is expressed in electrical degrees per sec. per sec. as $d^2\theta/dt^2$ and assuming that S equals 1800 rpm and does not vary, the loss in Kw becomes:

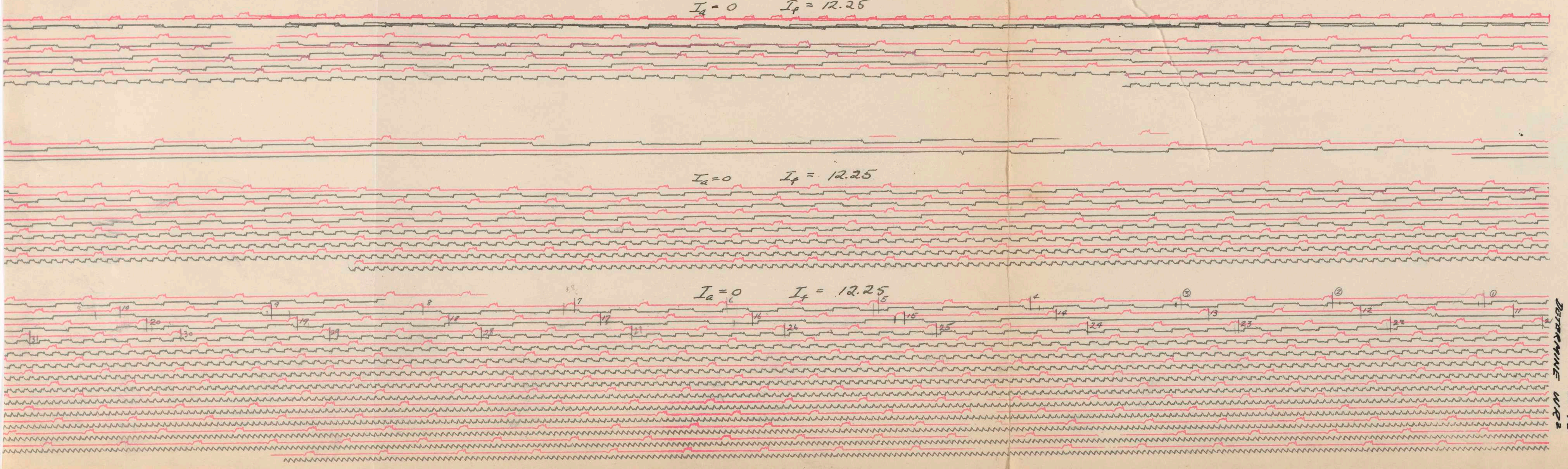
$$Kw = .0041 \frac{d^2\theta}{dt^2}$$

.0044 $\frac{d^2\theta}{dt^2}$

This is the form that is convenient to use with machine power equations since the units are the same.

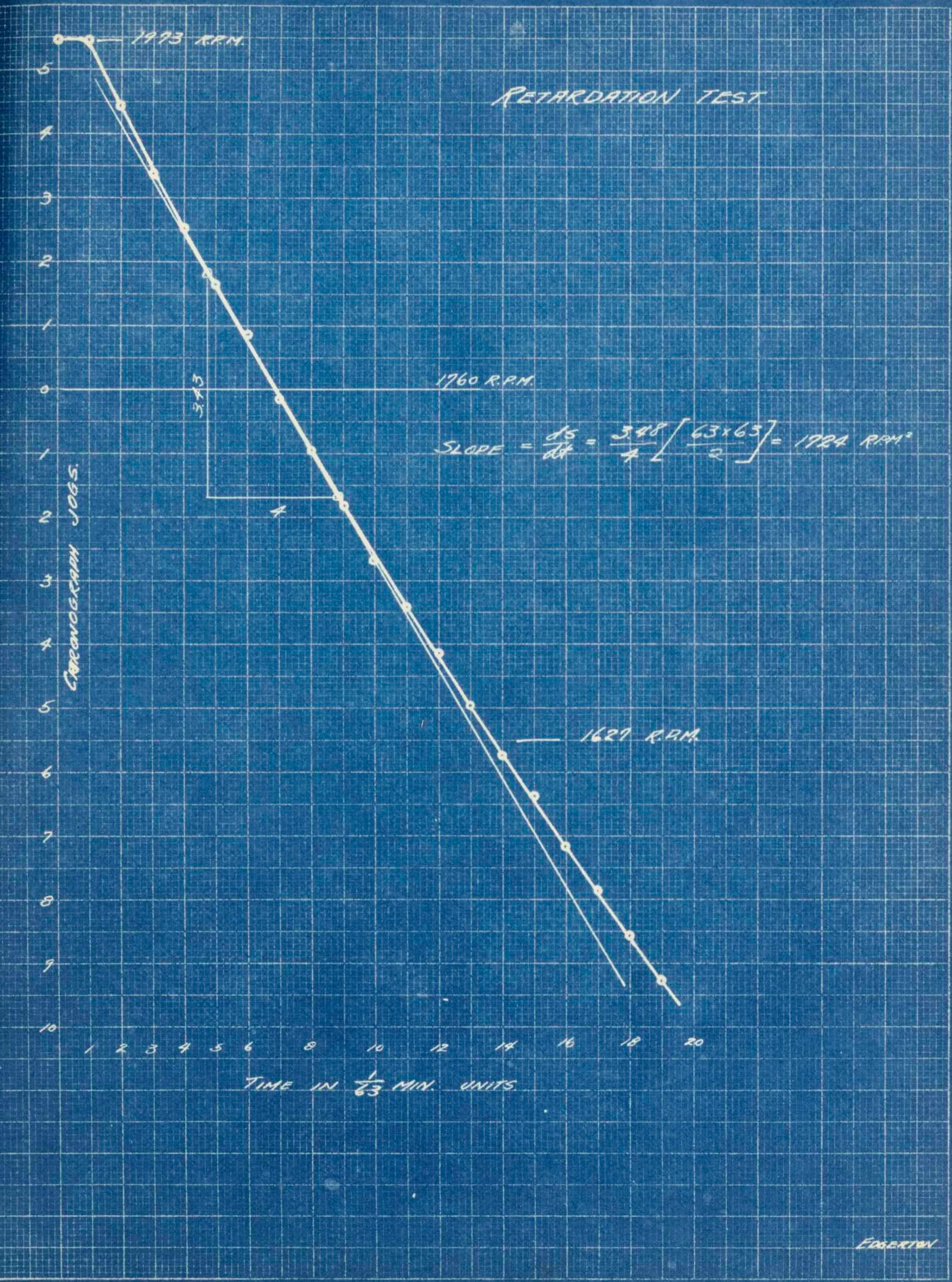
It must be remembered that since this is a four pole machine, 360 mechanical degrees equal 720 electrical.

TIME INTERVAL 63 PER. MIN. [COUNT ALTERNATE IMPULSES]



THIS ONE USED TO DETERMINE WR^2

CHRONOGRAPH RECORD OF RETARDATION TEST.



1993 R.P.M.
RETARDATION TEST
1760 R.P.M.
3.48
4
SLOPE = ds/dt = 3.48/4 [63×63/2] = 1724 RPM²
1627 R.P.M.
CHRONOGRAPH JOGS.
5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 8 10 12 14 16 18 20
TIME IN 1/63 MIN. UNITS
EDGERTON

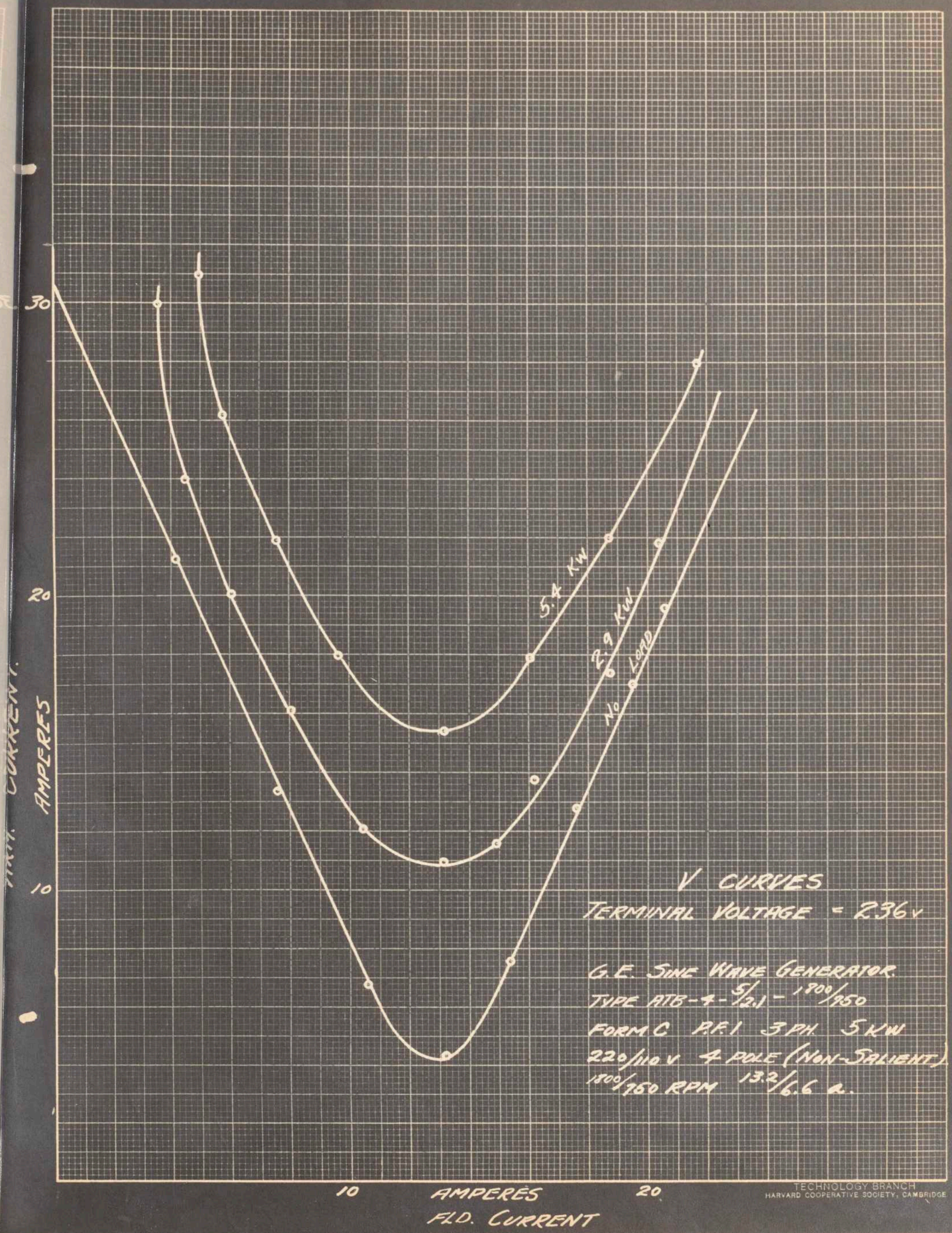
STEADY STATE
OPERATING TESTS

1. " V " CURVES.

These were taken in the usual manner by changing the field current holding the load constant and recording armature current and watts. The curves on page 90 show three "V" curves. The shaft load for each was constant.

2. POWER ANGLE TESTS

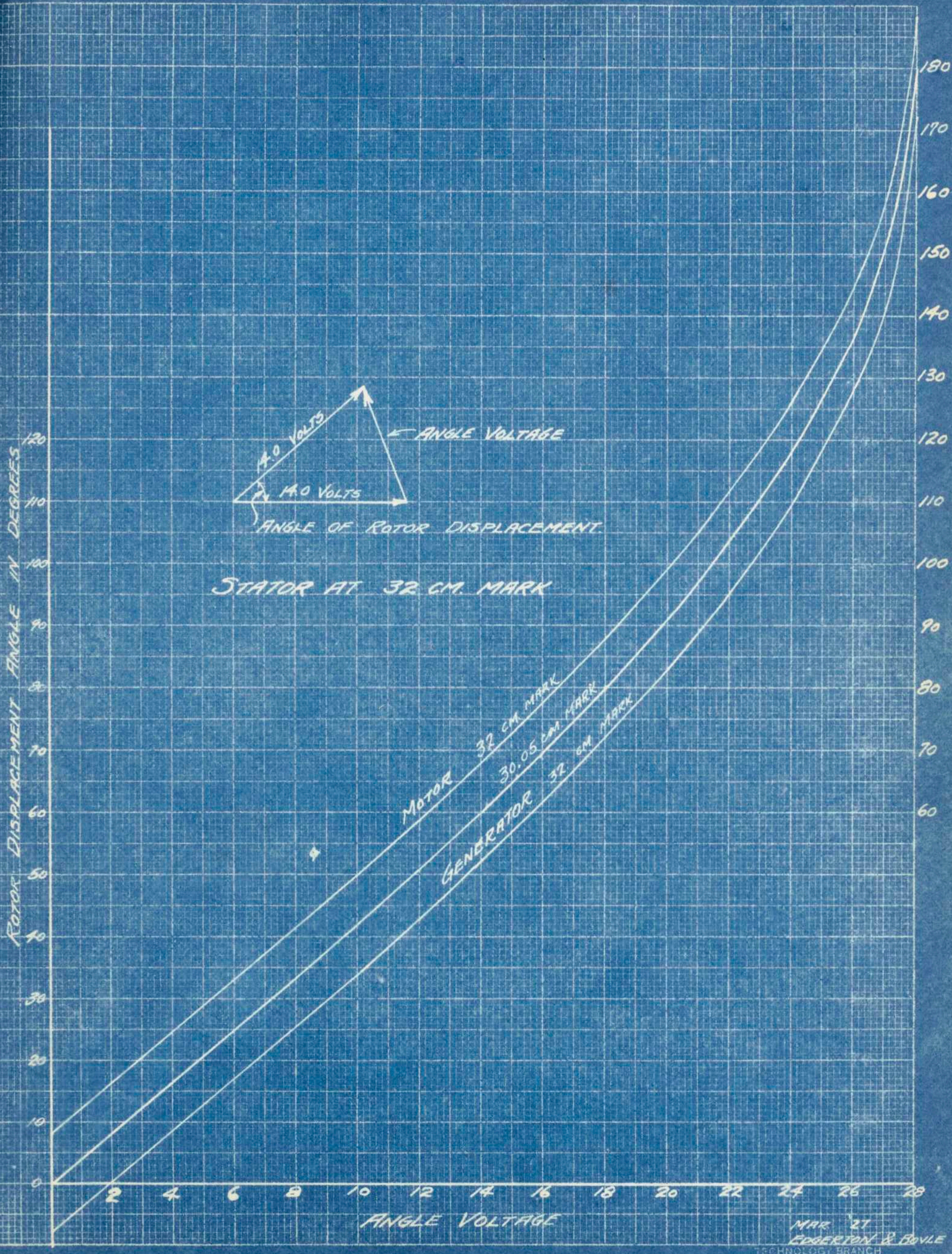
The rotor displacement angle was measured by a scheme suggested by Prof. Lyon. This method requires a direct coupled synchronous machine and the measure of angle is obtained by adding its terminal voltage vectorally to the terminal voltage of the machine under test. The auxilliary synchronous machine used was the 20 volt machine with the moveable stator. The terminal voltage of 230 volts was reduced by taking it through two 4:1 potential transformers. Excitation was adjusted on the 20 volt machine until both voltages were equal in magnitude. Then one side of each was connected which gave the vector sum. By proper selection of phase, polarity, and stator position it was possible to have

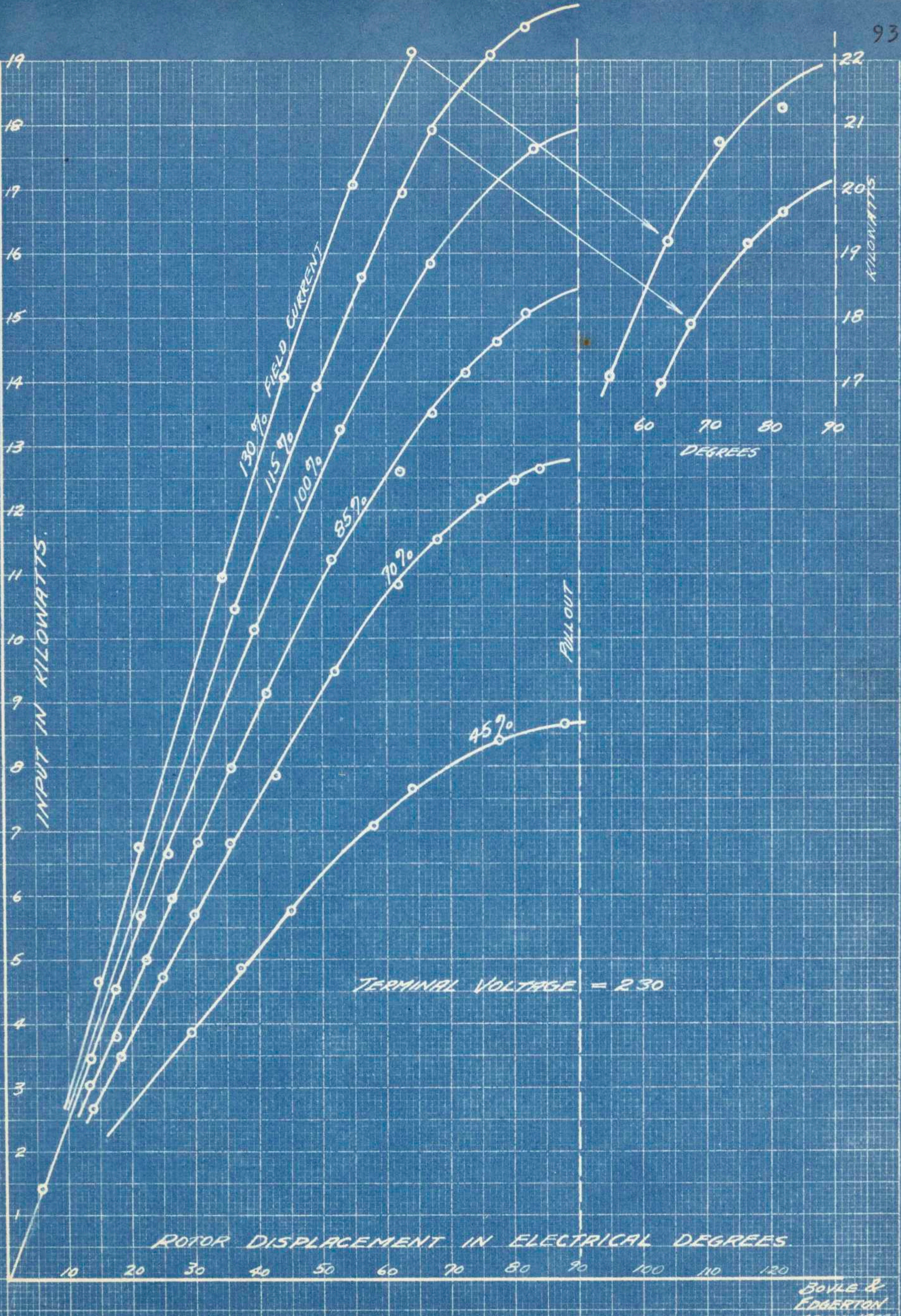

30
20
10
10
20
AMPERES
AMPERES
FLD. CURRENT
CURRENT
5.4 KW
2.9 KW
NO LOAD
V CURVES
TERMINAL VOLTAGE = 236 v
G.E. SINE WAVE GENERATOR
TYPE ATB-4-5/2.1-1800/950
FORM C P.F.1 3 PH. 5 KW
220/110 v 4 POLE (NON-SALIENT)
1800/950 RPM 13.2/6.6 a.

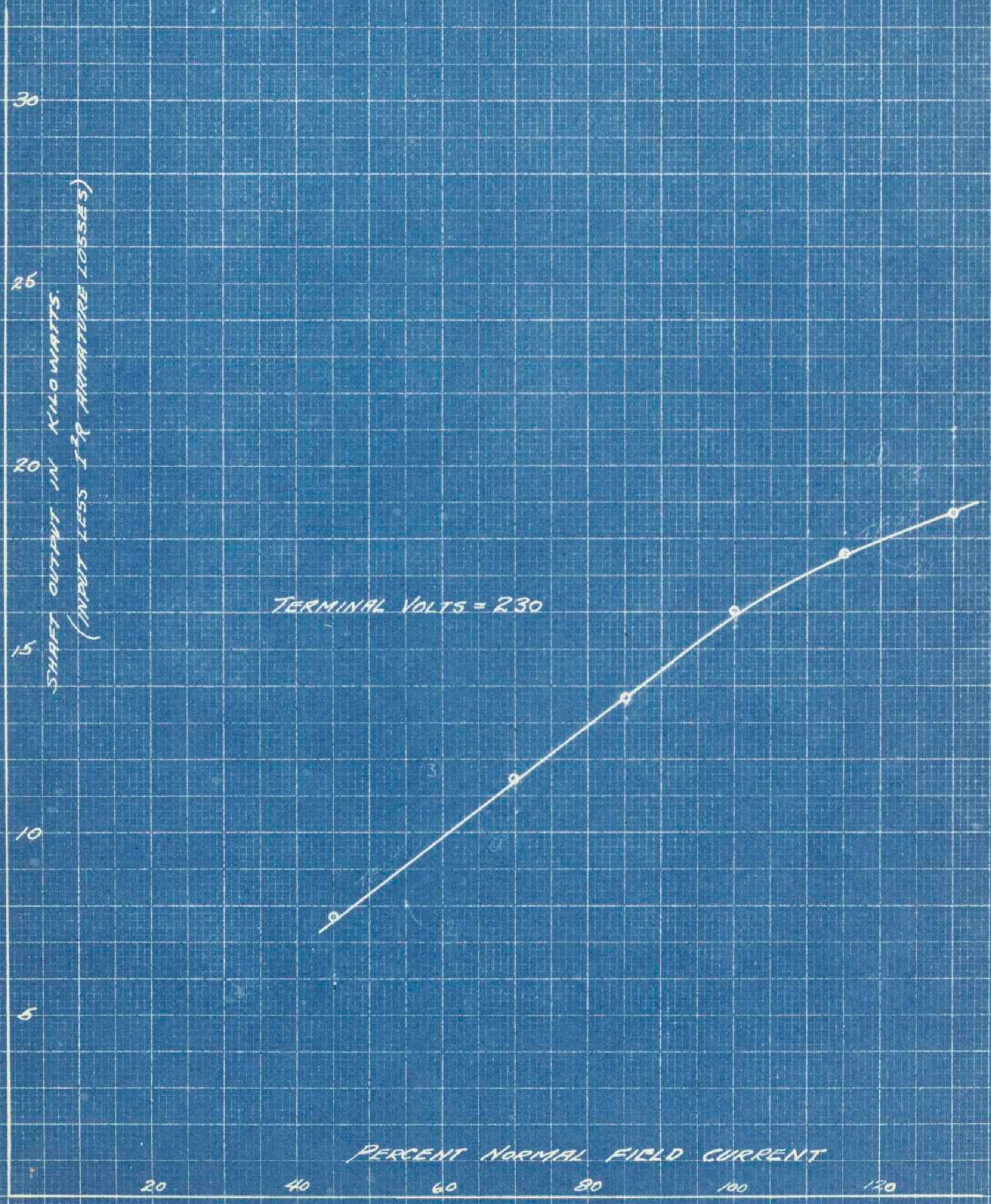
zero voltage correspond to zero angle.

From the triangle of voltages the angle can be computed. A curve of voltage against angle, page 92 , was very convenient for converting the angle voltage to electrical degrees.

For several different field currents the power was recorded against angle from no load to pullout. These are plotted on page 93. The power in this case is the electrical input and therefore includes stator iron loss and stator copper loss. It is necessary to subtract these to find the power which crosses the air gap. The iron loss from a retardation test was found to be about 200 watts at normal excitation by Mr. Boyle. This can be neglected when compared to the I^2R loss which is considerable. On page 94 there appears a curve of pullout shaft power against percent field current.


14.0 VOLTS
14.0 VOLTS
← ANGLE VOLTAGE
ANGLE OF ROTOR DISPLACEMENT
STATOR AT 32 CM. MARK
MOTOR 32 CM MARK
30.05 CM MARK
GENERATOR 32 CM MARK
ROTOR DISPLACEMENT ANGLE IN DEGREES
ANGLE VOLTAGE
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
2
4
6
8
10
12
14
16
18
20
22
24
26
28
MAR '27
EDGERTON & BOYLE


INPUT IN KILOWATTS
ROTOR DISPLACEMENT IN ELECTRICAL DEGREES
130% FIELD CURRENT
115%
100%
85%
70%
45%
PULLOUT
TERMINAL VOLTAGE = 230
DEGREES
KILOWATTS
BOYLE & EDGERTON
APRIL 1927



EDGERTON & BOYLE
APRIL 1927

3. INDUCTION MOTOR EFFECT

Two tests of this sort were made, one with the field short circuited and one with it open. Some difficulty was experienced in taking these tests because of the unbalanced condition of the rotor.

With the field winding open circuited, the shorted winding on the quadrature axis furnished enough torque to run the set although under unbalanced conditions. The slip was made large enough to cause the wattmeter needle to read the average of the pulsations. Points were taken on the speed torque curve both above and below synchronism.

Short circuiting the rotor field causes a balanced polyphase winding to exist on the rotor. Similiar tests to the ones described above were taken in this case also.

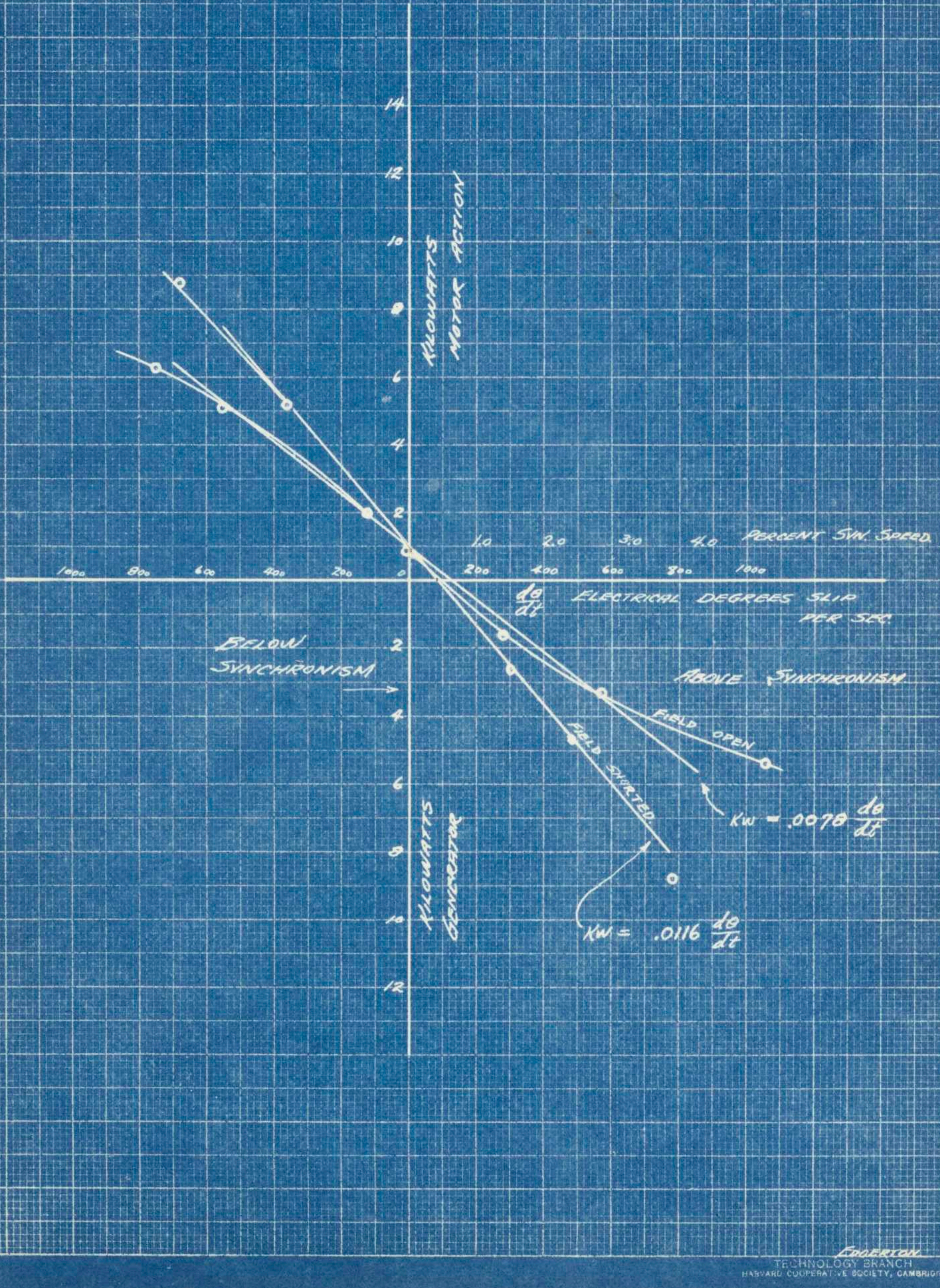
The curves for both of these tests are plotted together on the following page. They are plotted in kilowatts and electrical degrees slip per second in order to conform with other equations with which they are used.

On page 97 appear the tests which showed that the rotor was a balanced polyphase one when the field circuit was shortcircuited.

INDUCTION MOTOR EFFECT

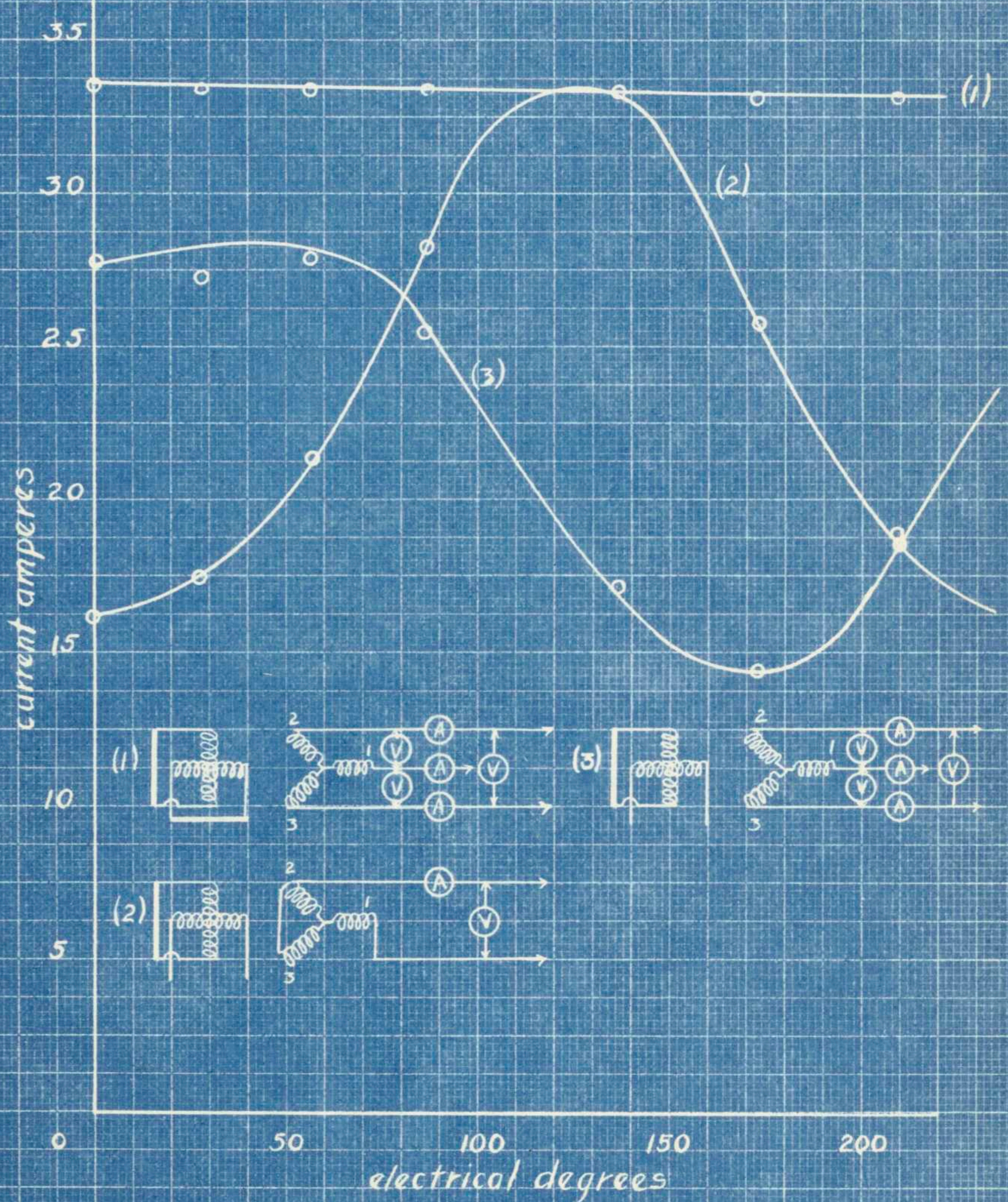
Meter readings

V	I	W_1	W_2	RPM Slip.	KW	Elect. deg. slip/sec.
	FIELD SHORTED	MOTOR ACTION			Tests made 3/4/27	
225	30.4	1.2x4	-.54x4	10	2.64	120
224	36.0	1.65	-.21	26	5.76	312
222	46.8	2.4	+.25	57	10.6	685
221	50.2	2.7	+.42	66	12.48	793
					Tests made 3/29/27	
223	27.8	.85	-.72	0	.72	0
222	35.0	1.52	-.22	30	5.2	360
222	42.5	2.10	+.12	56	8.9	673
221	51.8	2.6	-	-	-	-
	FIELD SHORTED	GENERATOR ACTION				
223	34.2	.63	-1.28	-25	-2.60	-300
224	40.0	.48	-1.66	-40	-4.64	-480
224	52.4	.22	-2.48	-65	-9.04	-781
225	57	.2	-2.65	-64	-9.68	-768
	FIELD WINDING OPEN CIRCUITED		MOTOR ACTION			
225	30.0	1.07	-.57	10	2.0	120
223	37.5	1.58	-.27	46	5.15	552
224	41.5	1.75	-.18	62	6.28	744
		GENERATOR ACTION				
226	34	.73	-1.13	-24	-1.6	-288
227	39.4	.66	-1.48	-47	-3.28	-564
226	50	.56	-1.92	-84	-5.44	-1006


14
12
10
8
6
4
2
0
2
4
6
8
10
12
KILOWATTS MOTOR ACTION
KILOWATTS GENERATOR
1000 800 600 400 200 0 200 400 600 800 1000
1.0 2.0 3.0 4.0 PERCENT SYN. SPEED
$\frac{d\theta}{dt}$ ELECTRICAL DEGREES SLIP PER SEC.
BELOW SYNCHRONISM
ABOVE SYNCHRONISM
FIELD OPEN
FIELD SHORTED
$KW = .0078 \frac{d\theta}{dt}$
$KW = .0116 \frac{d\theta}{dt}$

Evaluation of σ

Terminal voltage = constant = 92.5 volts.



Boyle & Edgerton
May 6, 1927.

SECTION V

SUMMARY AND CONCLUSIONS OF TEST AND THEORY

ALSO

SUGGESTIONS FOR FUTURE INVESTIGATIONS

SUMMARY

The tests show that, at least for the machine under test, the following points are valid.

1. The electromagnetic effect of acceleration may be neglected. This means that the analysis can be made with the rotor moving at a constant slip with respect to the field poles.

2. The often mentioned theory of induced field currents does not mean a change in the synchronous motor power but is simply an induction motor current superimposed on the field current. Each is treated as though the other did not exist.

The solution of problems such as this by automatic integrating devises is greatly to be desired. In the future many difficult problems will be solved by such means. The family of solutions on page 15 was made in about three hours. The thesis is a good example of what tremendous advantage an integrating machine will prove itself to be.

Effect of Acceleration.

The effect of acceleration on the electromagnetic reactions is evident and may be an important factor in some machines. For instance, film No. 10 on page 49 shows phase current and voltage following an abrupt change of load on the shaft of a synchronous motor running at unity power factor. Consideration of both the synchronous motor and induction motor action require a lagging power factor, when the rotor is moving at a constant slip. The oscillogram shows clearly that for about the first six cycles the current leads the voltage. This was also observed in films 76, 77, and 78 which are on page 64.

Acceleration is a maximum at the first instant, then decreases to zero when the slip is constant, reverses and reaches another maximum at the end of the first swing. It is directly proportional to the ordinates of the areas ABC and CDE in fig. 7 on page 18.

This doubtless explains why the power spirals on pages 52 and 62 are higher than the steady state power at the end of the first swing. Of course experimental error is rather large and so no definite conclusions can be made.

SUGGESTIONS FOR INVESTIGATIONS

There is no limit to the various phases of the problem to be investigated. A few are listed below which may be useful to those interested in carrying on the work.

1. Solution of torque equation when the field winding is single phase. This is a specific case of an unbalanced rotor. Non-salient pole machine.

2. Same as 1 with the exception of the use of a salient pole machine.

3. Study of the effect of acceleration on a machine. This could be done on an induction motor when it changes from one load to another.

4. Investigation of instantaneous power in an induction motor with an unbalanced rotor and as a special case the single phase rotor.

5. Study of two machines having different characteristics running in parallel.

6. Development of a power oscillograph either single phase or three phase. The need for such an instrument is urgent for all future work.

BIBLIOGRAPHY

1. Principles of Alternating-Current Machinery, by R. R. Lawrence, 1921 page 361.

2. C. P. Steinmetz, Theory and Calculation of Electrical Apparatus. page 288.

3. Synchronous Motors and Converters, by Andre Blondel, Translated by C.O. Mailloux. page 122.

4. C. L. Fortescue, Colloquium on Power Transmission given at M.I.T. 1927, page 30. (Several copies are available in the Vail Library)

5. Hunting and Parallel Operation of Synchronous Machines, by V. Karapetoff, The Sibley Journal of Engineering. Vol XXXIV No. 3 page 3.

6. Induction Type Synchronous Motors, by Lawrence H. A. Carr. Journal I.E.E. Vol 60 page 165. Discussion follows article.

7. The Pulling into Step of an Induction Type Synchronous Motor, by Lawrence H. A. Carr. Journal I.E.E. Vol 61 p 692.

8. The Pulling into Step of a Synchronous Induction Motor, by H. Cotton. Journal I.E.E. Vol 63 page 211. Discussion page 609. Includes bibliography of other foreign articles.

9. Oscillations and Resonance in Systems of Parallel Connected Synchronous Machines, By H. V. Putman. Franklin Institute Journal Vol. 197 page 603

10. Design of Flywheels for Reciprocating Machinery Direct Connected to Synchronous Motors or Generators, by R. E. Doherty and R. F. Franklin. Trans. A.S.M.E. 1920 page 523.

A.I.E.E. Papers

1. Stability of High Power Generating Stations, by C. P. Steinmetz, Journal A.I.E.E. 1920 page 554.

2. Discussion, Journal A.I.E.E., 1924 page 858-885 and page 980

3. Power System Transients, by V. Bush and R. D. Booth, Journal A.I.E.E. March 1925 page 229.
   Journal A.I.E.E. July 1925 page 766.

4. Oscillographic Solution of Electro-Mechanical Systems, by C. A. Nickel, Journal A.I.E.E. Dec. 1925 page 1277
   Discussion ditto 1341.

5. Stored Mechanical Energy in Transmission Systems, by J. P. Jollyman, Journal A.I.E.E. Sept. 1925 page 948
   Discussion ditto Dec 1925 1351

6. Transmission Stability, by C. L. Fortescue. Journal A.I.E.E. Sept. 1925. page 951.

7. Discussion, Journal A.I.E.E. Jan. 1926 page 68.

8. Investigation of Transmission System Power Limits, by C. A. Nickle and F. L. Lawton, Journal A.I.E.E. Sept. 1926. p 865. Discussion in same issue page 874.

9. Practical Aspects of System Stability by Roy Wilkins, Journal A.I.E.E. Feb. 1926. page 142.

10. Stability Characteristics of Alternators, by O. E. Shirley, Journal A.I.E.E. Sept. 1926 page 813. Discussion Journal A.I.E.E. Feb. 1927 page 183.

11. Synchronizing Power in Synchronous Machines, by H. V. Putman, Journal A.I.E.E. Dec. 1926 Discussion Journal A.I.E.E. April 1927 page 380.

12 Synchronous Machines, by R. E. Doherty and C. A. Nickle. Mid Winter Convention A.I.E.E. New York Feb. 7-11 1927.