



DYNAMIC TORQUE MEASUREMENT

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INTRODUCTION

Accurate and reliable information regarding transient torque characteristics of induction motors has long been a need of the designing engineer. He has been able to get reliable, steady-state speed-torque characteristic by means of the well-known prony brake or electric dynamometer, but he has had no convenient means by which he is able to determine the transient or dynamic torque characteristics. Knowledge of the transient torque characteristics is especially important in the design of induction motors, which will be subject to severe and frequently starting duty.

The dynamometer and prony brake methods of measuring steady-state torque are not at all ideal when complete speed torque curves are desired. Unless the motor is tested at a reduced voltage, serious overheating usually results. This overheating is especially serious in the smaller motors, which overheat much more quickly than larger motors. Therefore, from this point of view a method for measuring torque, which requires that the motor only be subjected to full voltage at reduced speeds for a short period of

time is very desirable. The method to be described in this thesis, while essentially a method for measuring the transient or dynamic torque, can be adopted to give results which approach the steady-state by increasing mass of the rotating parts, thereby reducing the acceleration resulting from a given torque.

CHAPTER I

HISTORICAL SURVEY

One of the earliest methods used to measure the transient torque of an induction motor was described by Dr. Steil in 1921 (appendix A). In his experiments to determine the effects of different rotor-slot combinations, he loaded the induction motor with a large flywheel. The torque developed by the motor to accelerate the flywheel was mechanically recorded as a function of time, by a recording dynamometer. The speed of the motor shaft was likewise recorded as a function of time on a recording tachometer. These two were graphically combined to obtain the desired speed-torque curves. Steil used a very large flywheel load on his motor so that the acceleration was small and therefore the results he obtained were very similar to the steady-state characteristics.

In 1924 a torsion meter was developed by Moullin (appendix A) which was superior to the recording dynamometer used by Dr. Steil, in that the recording was done electrically instead of mechanically. The Moullin Instrument consisted of a pair of choke coils, so mounted on a section of the motor

shaft that a very small angular deflection in that section of shaft would shorten or lengthen the air-gap in the core of the two choke coils, thus producing a change in the inductance of the coils, which is a function of the shaft deflection, and hence, a function of the load being transmitted. A small alternating current generator was used to furnish voltage for the coils. The current passing thru the choke coils at constant impressed voltage and frequency being dependent upon the inductance of the choke coils, served as a measure of the torque acting on the shaft.

Mr. G.R.Anderson (Appendix A) in 1929 developed a method of measuring torque, which was somewhat similar to the two methods just described. Mr. Anderson used a helical spring to couple a large flywheel to the motor shaft. The deflection of the spring and the speed of the motor shaft was recorded electrically. The spring was provided with damping sleeves to eliminate its natural period of vibration. This apparatus will not record very rapid change in torque, but it is very easily calibrated and hence, fairly accurate. quantitative results can be obtained where the torque is without

rapid variations.

The three methods just described have serious drawbacks, in that they all require a certain angular displacement, between the rotor and flywheel load before any torque is recorded. Such displacement produces an inherent error in the instantaneous torque recorded. The use of a piezo-electric crystal in the coupling between the motor and the flywheel has recently been suggested by Dr. Lund (Appendix A).

During the past few years there have been several theses written here at the Institute describing various schemes for making dynamic torque measurements. None of them have been fully successful, because of certain limitations in the mechanical and electrical construction of the apparatus involved. The scheme investigated by Messrs. Byrne and Mason (Appendix A) using the motor rotor as the flywheel load and calculating the electric torque from the acceleration of the rotor appears to be the most ideal method that has been proposed by anyone. The scheme employed by Byrne and Mason was suggested by Prof. V. Karapetoff in a discussion of a method to measure the retardation

of large generators given at an A.I.E.E. Convention in 1926 (Appendix A). Karapetoff suggested that a separately excited direct current generator be used to furnish an electromotive force proportional to the rotor speed. If this electromotive force is impressed upon a static condenser, the charging current of the condenser is proportional to the rate of change of the impressed voltage, and hence, proportional also to the acceleration of the rotor. The Byrne-Mason investigation of this method was not at all complete, and it is the purpose of this thesis to describe further investigations, which the writer has carried upon this general scheme.

CHAPTER II

THEORY OF METHOD OF TORQUE MEASUREMENTS

If a rotating body is acted upon by an unbalanced torque, there will be a change in speed or acceleration, which is directly proportion to the magnitude and sense of the applied torque. Now, if we neglect the friction and windage torques, which act upon its rotor, the acceleration of an induction motor, when starting or reversing without external load is a direct measure of the electrical torque developed. The development of a convenient and reliable method of measuring angular acceleration is therefore the important problem in this research.

The current i_c which flows in an ideal static condenser of capacity C when an electromotive force e_c is impressed upon its terminals is:

$$i_c = C \frac{de_c}{dt} \quad (1)$$

A direct current generator having separate excitation gives a voltage output, which is proportional to the speed of the rotor. Thus, if we let n be the speed of the armature of the direct current generator we can write:

$$i_c = C \frac{dn}{dt}$$

where $\frac{dn}{dt}$ is the angular acceleration α therefore:

$$i_c = C\alpha$$

But we have shown that if we neglect friction and windage

$$T = I\alpha$$

where I is the combined moment of inertia of the rotating bodies and T is the driving torque.

Thus, if a static condenser is excited by the output of a separately excited direct current generator, which is driven by an induction motor, the condenser current will be a measure of the acceleration of the motor and hence the torque:

$$T = \frac{I}{C} i_c$$

$$T = K i_c$$

This equation is truly a theoretical equation, because there are other parameters of the electric circuit beside the static condenser, which modify the results. The inductance and resistance of the armature must be considered before calibration of the apparatus can be made, but at the present, we will consider only the theoretical equation.

This method of measuring acceleration is very difficult to perfect, because voltage ripples of very small magnitudes produce condenser currents

of rather large values. For example, referring to equation (1), if our starting period is 1 sec. our condenser current will be:

$$i_c = CE$$

where E is the voltage of generator at normal speed. Now, if a 60 cycle ripple having a magnitude of .1% of E is present in the generator voltage, a 60 cycle ripple i'_c in the condenser current will result.

$$i'_c = C \frac{E}{1000} 2\pi \times 60 = .377 CE$$

$$i'_c \doteq .4i_c$$

Thus, it is evident that ripples in the voltage wave of the D.C. generator must be reduced to minimum. It appears that high frequency voltage ripples produce much more trouble than do the lower frequency ripple of the same magnitudes. This, however, is not the actual case, because the inductance and resistance of the armature offer much higher impedance to high frequency currents than they do to low frequency currents.

CHAPTER III

APPARATUS

Two distinct types of direct current generators were studied as possible sources of low ripple direct current. The first type to be considered was the homopolar. This type of generator is probably ideal from the standpoint of low ripple, since the usual commutator is replaced by a pair of slip-rings, but the fact that the maximum voltage that can easily be obtained from a homopolar generator having a reasonable size and operating at 1800 R.P.M. is less than 1 volt, makes this type of generator impractical, unless the use of some form of an amplifier is to be permitted. The writer, however, desired to have the apparatus as simple as possible, and therefore, the use of an amplifier was not considered.

It is interesting to note in connection with the use of a homopolar generator that since this research was begun, Messrs. Dannett & Redfearn of the Metropolitan Vickers Electrical Company have published (Appendix A) a description of an accelerometer using a homopolar generator and amplifier. The test results that they show in their article are very similar to those shown in

Chapter VI, of this thesis.

For this research, however, a bipolar generator having a drum wound armature was selected as the most convenient type of generator. The design and construction of this generator will be discussed in Chapter IV. The completed generator coupled to a 15 Horse Power test motor is shown in figure 1.

Other apparatus required for making dynamic torque measurements of an induction motor include the following:

Several static condensers of assorted capacity - the total capacity being about 400 mfd.

A choke coil of about .100 henries inductance and as low resistance as possible.

A magnetically operated 3 phase reversing switch for use in the motor supply line.

An oscillograph having at least two D'Arsonval type vibrators and a shutter-controlled transient switch to operate the solenoid of the motor reversing switch.

A connection sketch of the apparatus is shown in figure 2.

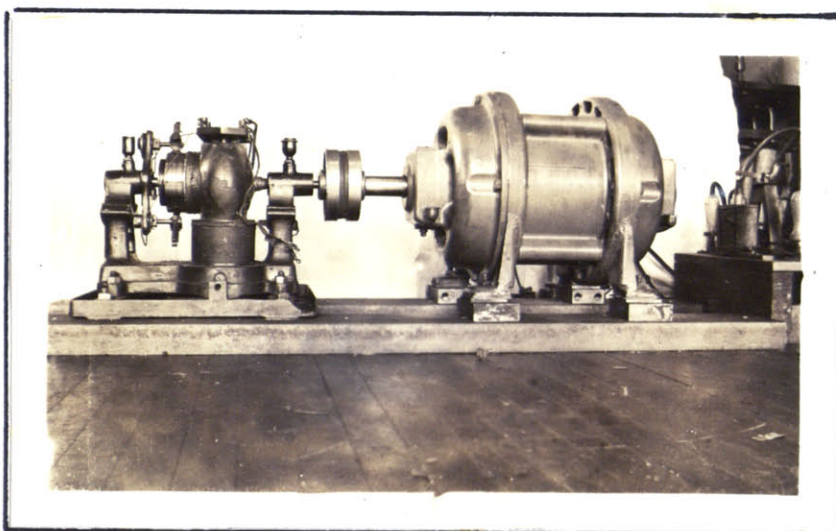
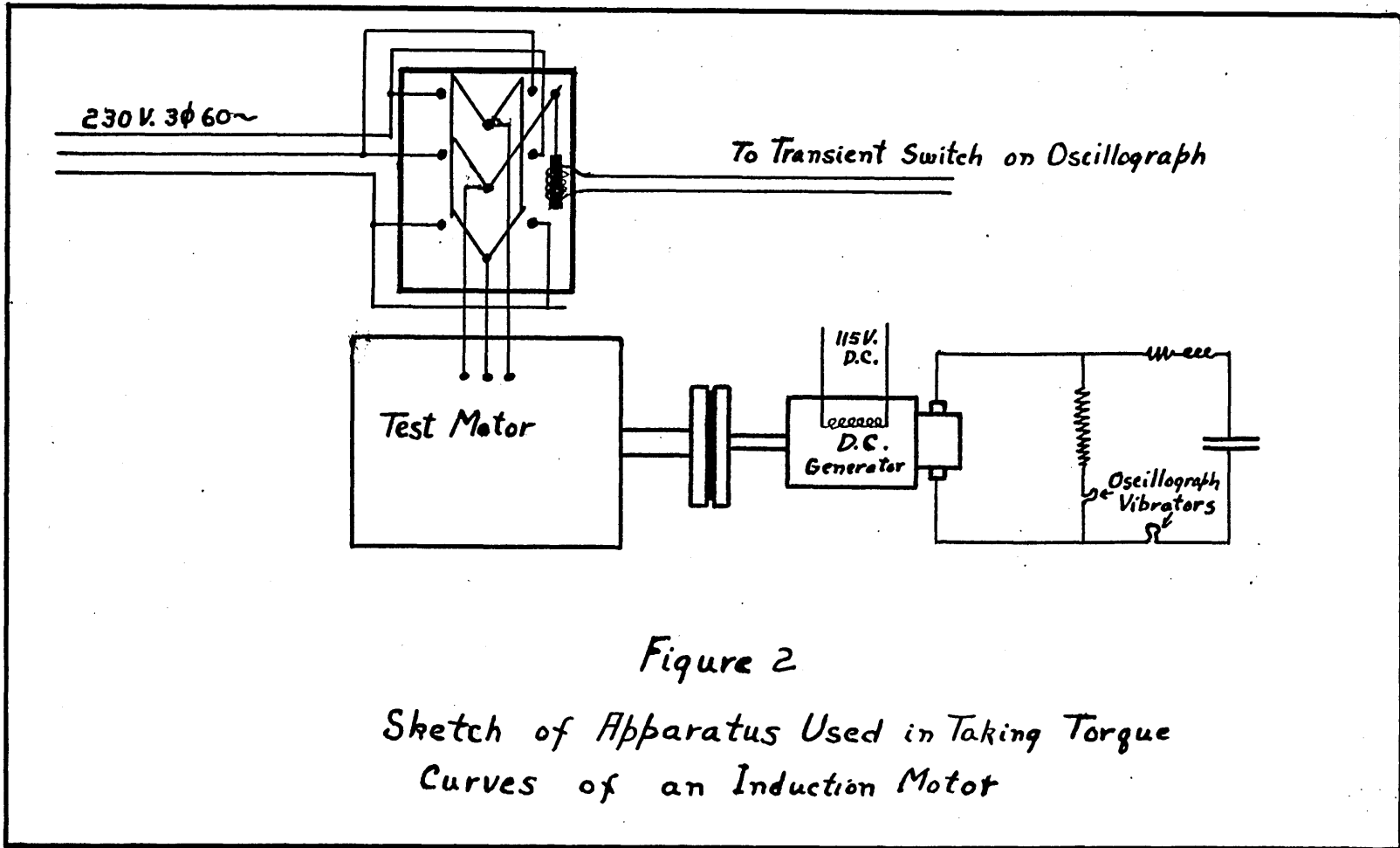


Figure 1
Showing Special Generator
Coupled to a 15# Induction Motor



H.E. Edgerton has suggested that a cathode-ray oscillograph be substituted for the ordinary vibrator type oscillograph. If the beam deflection along the horizontal axis is proportion to the voltage output of the generator and if the deflection along the vertical axis is made proportional to the condenser current, the beam will trace a speed-torque curve, when the motor is started or reversed. Several curves taken with a cathode-ray oscillograph are shown in Chapter VI (Curves 12 and 13).

CHAPTER IV

DESIGN, CONSTRUCTION AND TEST OF GENERATOR

The design and construction of a direct current generator to have an output of about 100 volts, which must be almost entirely without ripple, is by no means a simple task. The present writer, however, has been greatly assisted by the experiences of Messrs. Byrne and Mason (Appendix A), who designed and constructed several generators in their attempt to get a voltage output without ripple. The best generator constructed by Byrne and Mason showed a voltage ripple of about 3/4%. Their torque measurement made with this machine indicated that this ripple would have to be reduced to about 1/10%, if the method of measuring torque is to be useful in the study of motor torque characteristics during speed changes. With this in mind, the writer has analyzed the original Byrne-Mason design and made tests upon their machine.

The Byrne-Mason generator having been constructed from an old 2-pole Holtzer-Cabot generator which had 144 segments in the commutator, is rather ideal from the standpoint of commutation and commutator ripple. The simple 2-pole construction is preferred to a multiple pole construction, not only from the standpoint of manufacture, but also from the desire to have

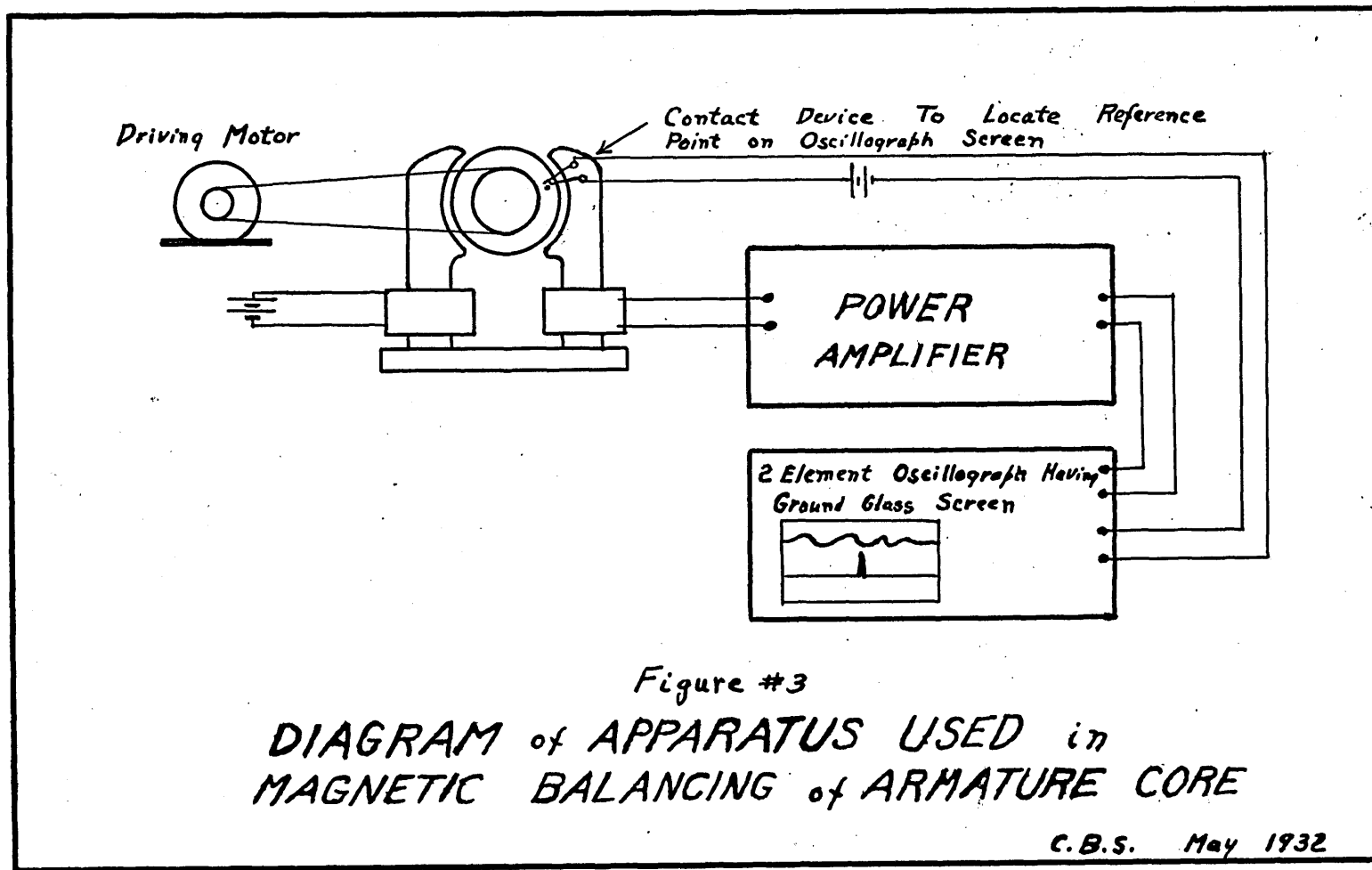
a constant flux density under the main poles. The use of interpoles in the generator is not warranted, because the current carried by any armature coil during commutation is very small. The wide zones between main pole tips and the use of narrow brushes also decrease the need of interpoles.

Some of the mechanical features of the old generator were not quite ideal, namely, sleeve bearings and a long slim shaft. The improvement of either or both of these features would require a complete mechanical reconstruction. A short shaft having a large diameter and supported on roller bearing appears to be the most ideal construction. However, the writer has not been able to attribute any ripple in his machine directly to either of these undesirable mechanical features. Calculations of the angular twist of the generator shaft shows that an angular acceleration of 600 radians per second causes the commutator to deflect approximately .23 of a degree from the angular position of coupling.

The writer's tests on the Byrne-Mason Generator show that there is considerable pulsations in the main air-gap flux due to rotation of the armature. In order to observe this flux pulsations, the armature was rotated slowly by an auxiliary driving motor. One field coil

was excited from a storage battery supply and the second field coil was used as an exploring coil— it being connected thru a suitable amplifier to an oscillograph element as shown in the diagram of Figure 3. The set-up of apparatus used in making this and subsequent tests on the new armature core is shown in the Figure 4. It is evident from Figure 3 that any pulsation in the main air-gap flux due to armature rotation will induce an electromotive force in the "exploring" field coil. The general form of this electromotive force as observed in the oscillograph is shown in Figure 5.

The only known cause of such a pulsation in main air-gap flux is some form of magnetic unbalance in the armature core. It has long been known by electric motor manufacturers that the magnetic properties of laminated steel depends upon the direction of magnetization with respect to the grain or direction of rolling. The permeability of the average punching is higher when magnetization is in the direction rolling than it is when the punching is magnetized perpendicular to the direction of rolling. Ripple produced by



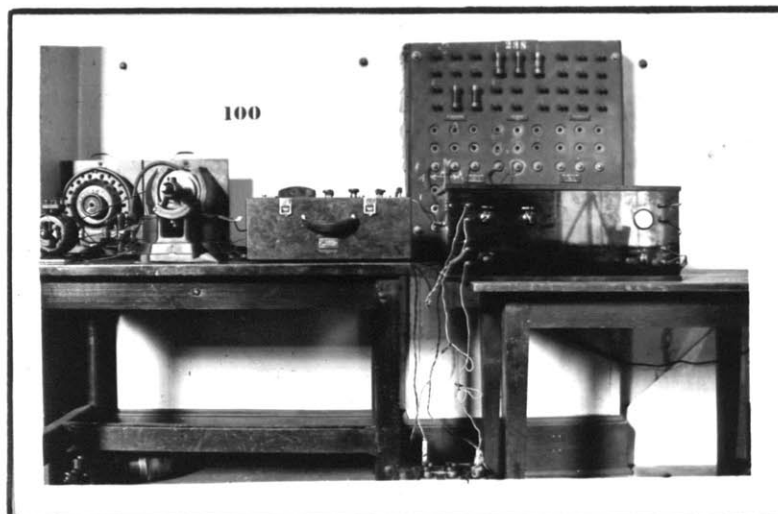


Figure 4
Apparatus Used in Making Magnetic Tests
upon Armature Cores

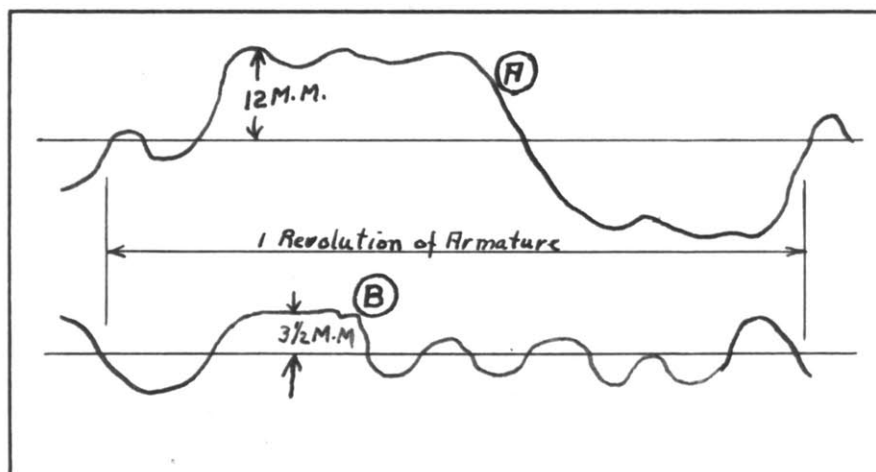


Figure 5
Sketch of Flux Variations as Viewed
on Oscillograph Screen.
"A" Curve of the Byrne-Mason Armature
"B" Curve of Writer's "Balanced" Core

this magnetic characteristic is usually called Grain Ripple. In the production of commercial motors and generators very little account is taken of the grain in the armature-core punchings because the ripple produced thereby is not of commercial importance. In view of the fact that the Byrne-Mason Generator shows very pronounced grain ripple, similar in wave form to the ripple in their voltage output and also the fact that they make no mention of any special effort to eliminate the affect of grain in their armature core, the present writer has considered that the principle source of ripple in their generator is grain of the core punchings.

With this in mind, the present investigator has followed the design of Byrne and Mason, except where it seems desirable to deviate from it, in order to reduce the affect of the grain.

Since the use of slots is to be avoided, some form of surface winding is the most desirable. Simplex wave winding, having a coil pitch of 143 in both front and back, was selected. The general scheme of the winding is shown in sketch of armature and field structure on page 2/ figure 6.

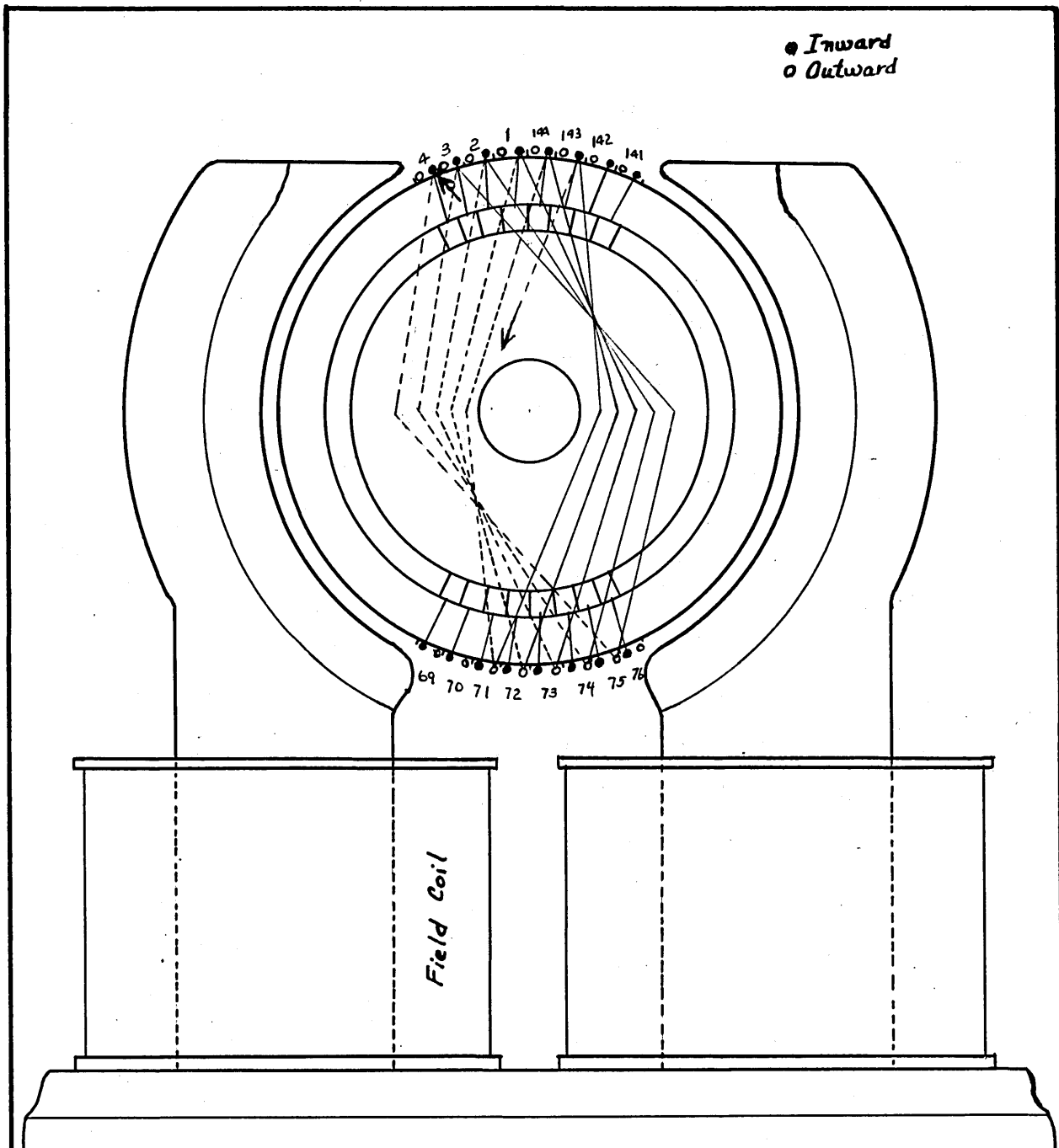


Figure 6
 SKETCH of ARMATURE and FIELD STRUCTURE
 Showing Scheme of Winding
 Details
 Type - Simplex Wave Winding
 Coil Pitch, front and back = 143
 Commutator Pitch = 143

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The calculation of the number of conductors was based upon the saturation point of the field poles. Using a cross-section of approximately 5 square inches and 90,000 lines per square inch as the maximum flux density, we find that we have a total flux of about 450 Kilolines. Desiring 115 volts at 1800 R.P.M., the number of conductors determined by the formula:

$$\# \text{ Cond.} = \frac{\text{Emf} \times 10^8 \times 60 \times \# \text{ Circuits}}{\text{R.P.M.} \times \# \text{ poles} \times \text{Total Flux}}$$

is found to be 855. There being 144 segments in the commutator, it was decided to use 6 conductor per commutator segment, or three turns per coil, making a total of 864 conductors. #28 (12.6 mil dia.) Enamel single silk covered wire was selected as the most convenient wire to use.

It was decided to use the best grade of commercial laminated iron for the armature core. 100 annealed punchings of X-5 iron, 25 mils. thick were obtained from the General Electric Company. The dimension of the punchings as shown in figure 7 were determined as a matter of convenience and desired maximum flux density. The armature core-length was made 2-1/2 inches. This length was the most desirable

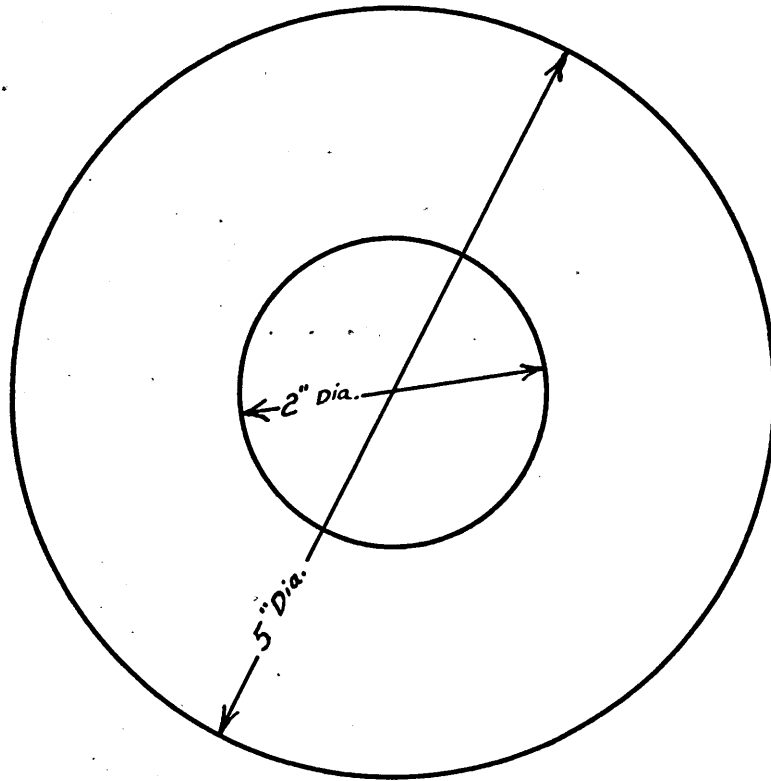


Figure 7
DETAIL of CORE PUNCHING

Material:

**Annealed X-5 Iron
.025" Thick**

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in view of the fact that the pole faces were 3-1/4 inches long.

The assembly of the core was somewhat of a problem. It was finally decided to stack the punchings on a brass core and clamp them together by means of a pair of brass end plates screwed on the brass core, such as is shown in figures 8 and 9. The punchings were assembled with a sheet of thin paper between each one. The paper not only served to insulate the punchings from each other, but it also increased the mechanical friction of one upon the other. The friction between the laminations and end plates is important in preventing turning on the core, since it was impossible to provide key and key-way on the brass core. The laminations were stacked so that the effect of the grain of the metal would be eliminated in the final assembly. In order to accomplish this, each lamination was so stacked, that its grain was 45° to the right of the one stacked before. The scheme of stacking is shown in figure 8.

After the core was assembled and pressed on the shaft with commutator as shown in figure 9., the assembly was put in the field structure and

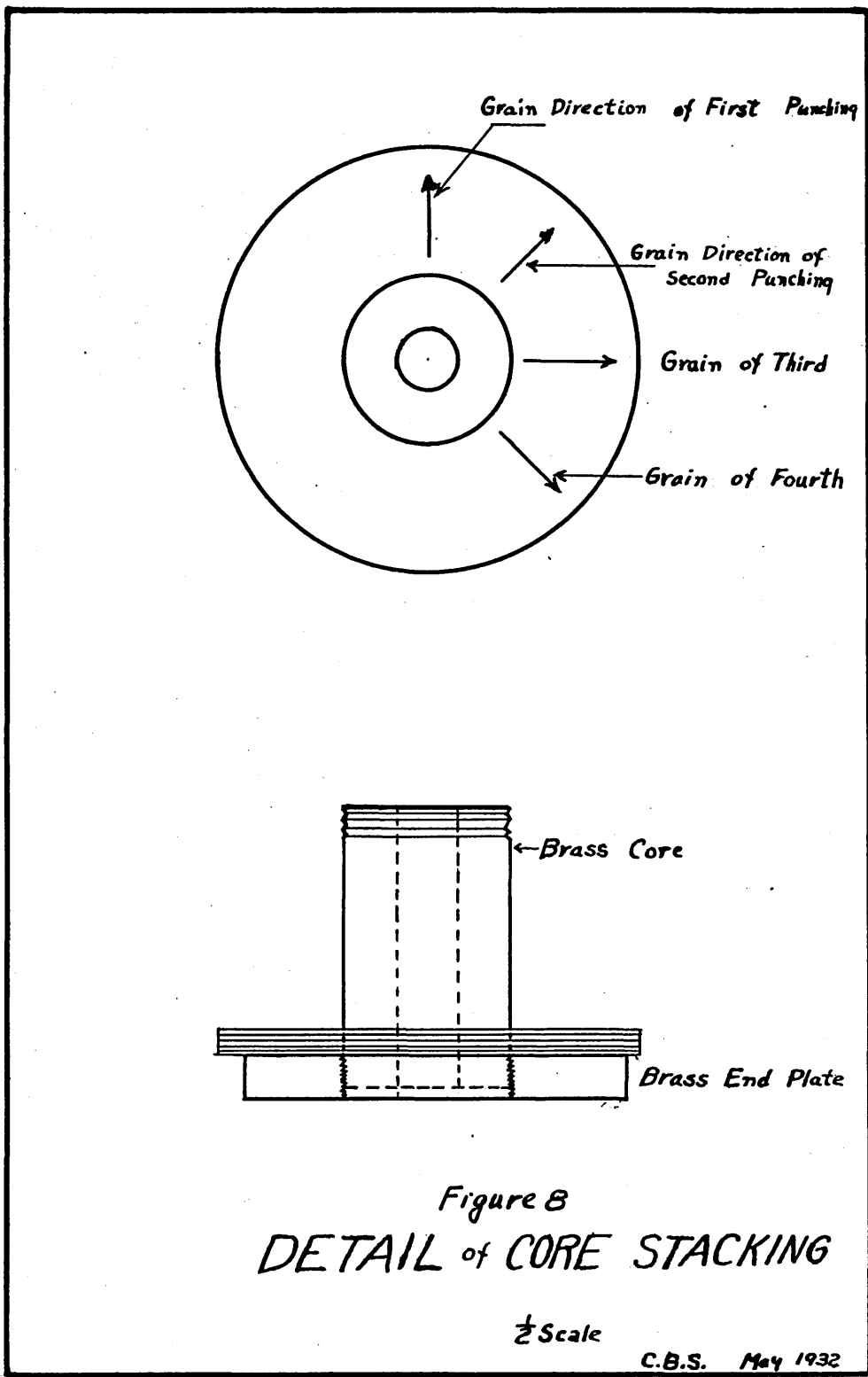


Figure 8
DETAIL of CORE STACKING

$\frac{1}{2}$ Scale

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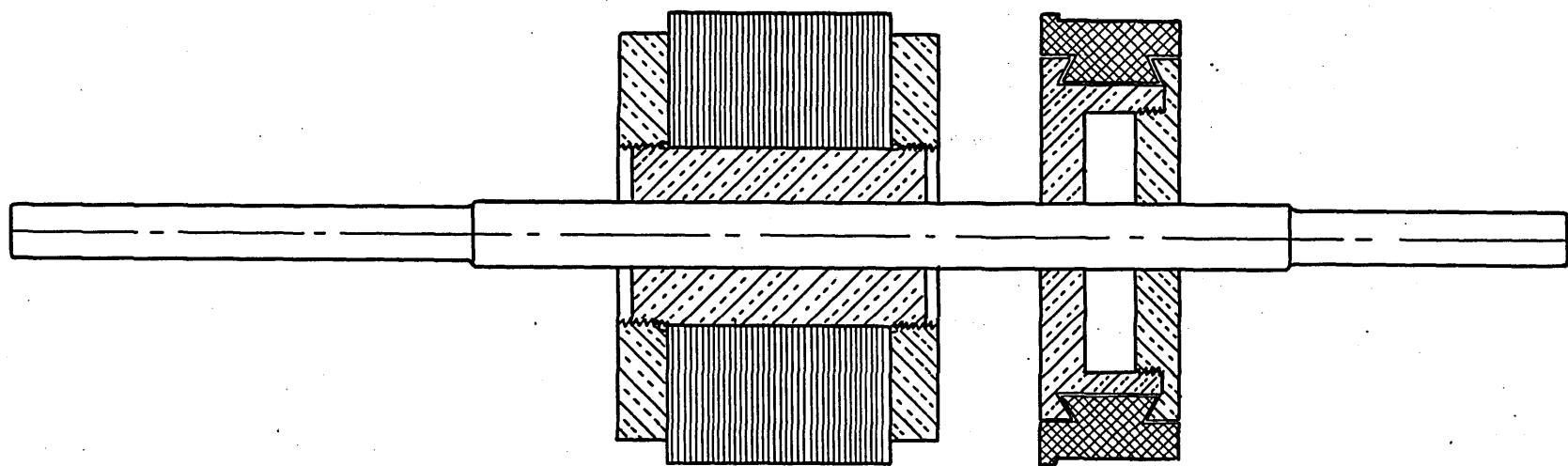


Figure 9
Assembly of Core and
Commutator

Scale 1" = 2"

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tested for magnetic symmetry in the set-up, as shown in figure 4 and diagram of figure 3.

The air gap flux was not as constant as desired, so the core was torn down and reassembled, taking special care in determining the direction of the grain in each lamination. In some cases, however, it was very difficult to determine the grain, because the iron had been annealed. The second assembling gave a little better symmetry than the first, but still it was not as good as desired.

After the attempts to get a magnetically balanced core by staggered stackings had failed, the only alternative left was to file the punching so as to compensate for the grain unbalance or possible mechanical eccentricity of the individual laminations. This process of balancing was purely a cut and try process. The writer, however, after many hours of labor, was able to reduce the amplitude of the flux pulsation due to rotation to about 1/5 that which was observed in the old armature constructed by Messrs. Byrne and Mason.

The winding process was rather simple, but it was very slow and tedious. The core and armature assembly, as shown in figure 9, after it had been

magnetically balanced; was covered with several layers of untreated white linen insulating tape. The tape was securely stitched in place so that it could not slip during the winding process. The circumference of the insulated core was next divided into 144 equal "slots" by means of black cotton threads, which were stitched to the linen tape to prevent their slipping. The winding was applied as a continuous winding tapped for connections to the commutator segments. The details of the winding are shown in figure 6.

After the winding had been completed and tested for shorts, opens and grounds, the conductors were firmly bound to the core by a layer of linen cord. The completed armature was then thoroughly impregnated with an artificial resin varnish, air-dried and baked. The completed armature assembled in the field structure is shown in figure 10.

Approximately 150 hours was spent in the design and construction of the armature.

TESTS OF THE GENERATOR:

The generator as first set up with small soft carbon brushes, showed very low voltage ripple at no load, but upon the application of a small load,

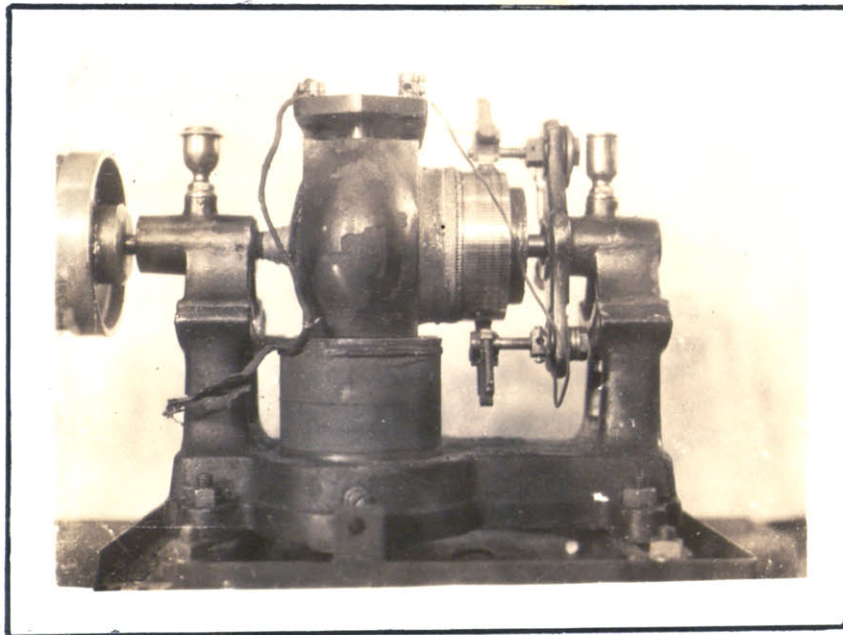


Figure 10

Special D.C. Generator

this ripple increased considerably. Such a variation in the ripple could not be tolerated in this machine, so several other types of brushes were tried. A pair of woven copper brushes, having a width of about 1-1/2 commutator bars was finally selected. These copper brushes gave a ripple, which was somewhat larger than that observed with the carbon brushes, but it did not vary in amplitude upon the application of load. The voltage wave and condenser current it produces are shown in figure 11.

The ripple in the condenser current shown in figure 11a is too large. Applications of the generator to the study of speed torque curves indicate that the ripple must be reduced in order that the torque characteristics may be studied with some degree of accuracy. In order to reduce this ripple series inductance was added in the condenser circuit. The condenser current when inductance was in the series with the condenser is shown in figure 11a and 12. The use of inductance is very undesirable from the standpoint of calibration and determination of the instantaneous torque. It is, however, necessary to reduce the condenser current ripples produced by

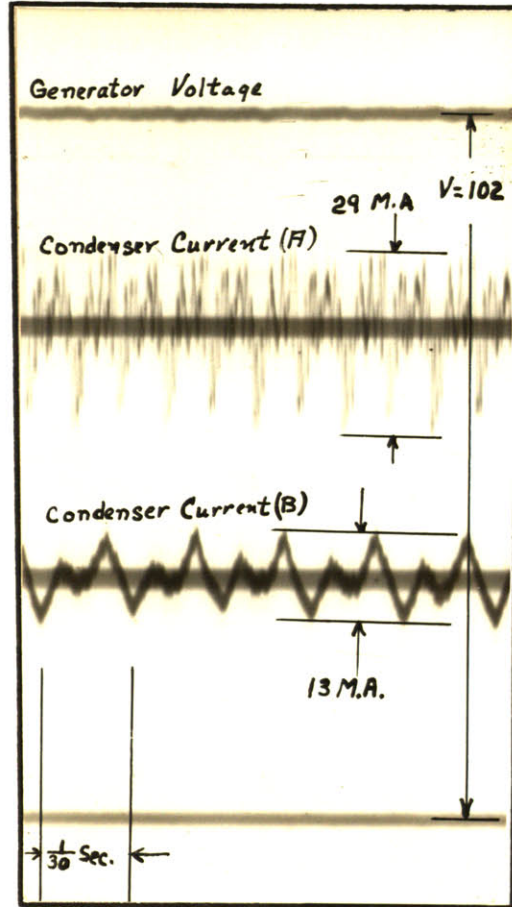


Figure 11

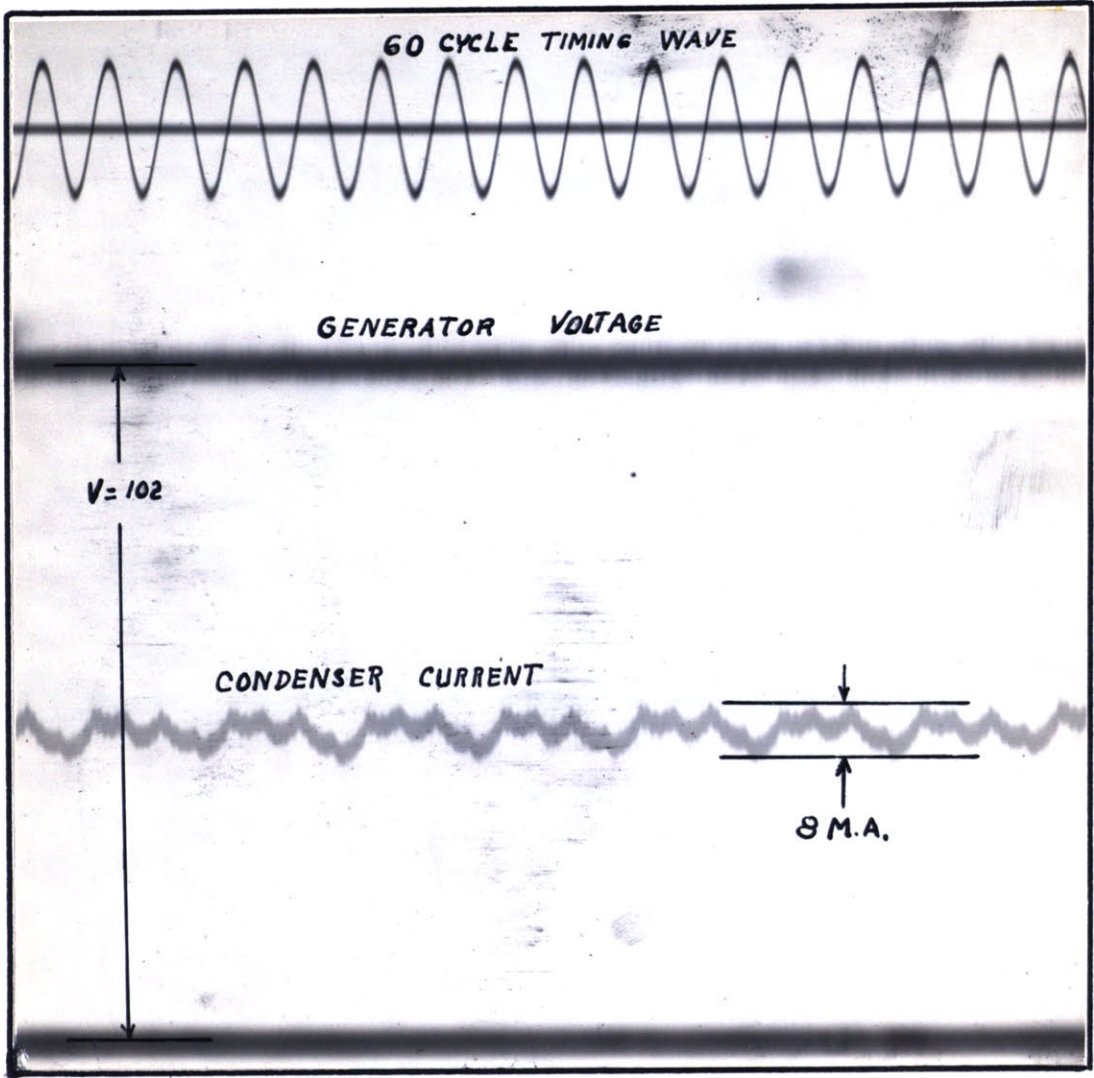
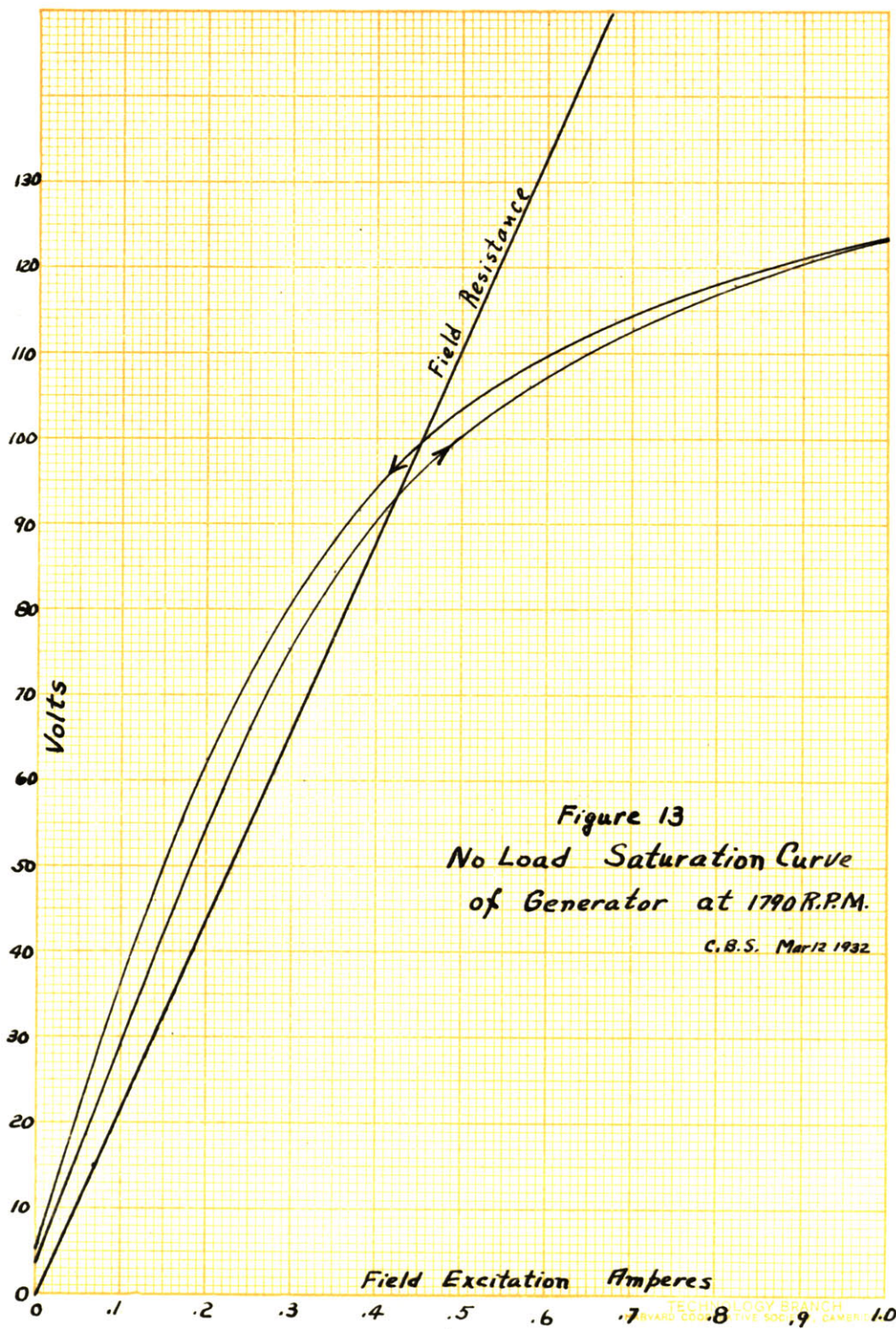


Figure 12

changes in voltage, which are not functions of the speed of the generator armature.

The electrical characteristics of the generator, aside from the voltage ripple are about as desired. The resistance at 20°C is 9.5 ohms (with copper brushes) and the inductance with fields shorted measured 20 millihenries. The no-load saturation curve at 1795 R.P.M. is shown in figure 13.



CHAPTER V

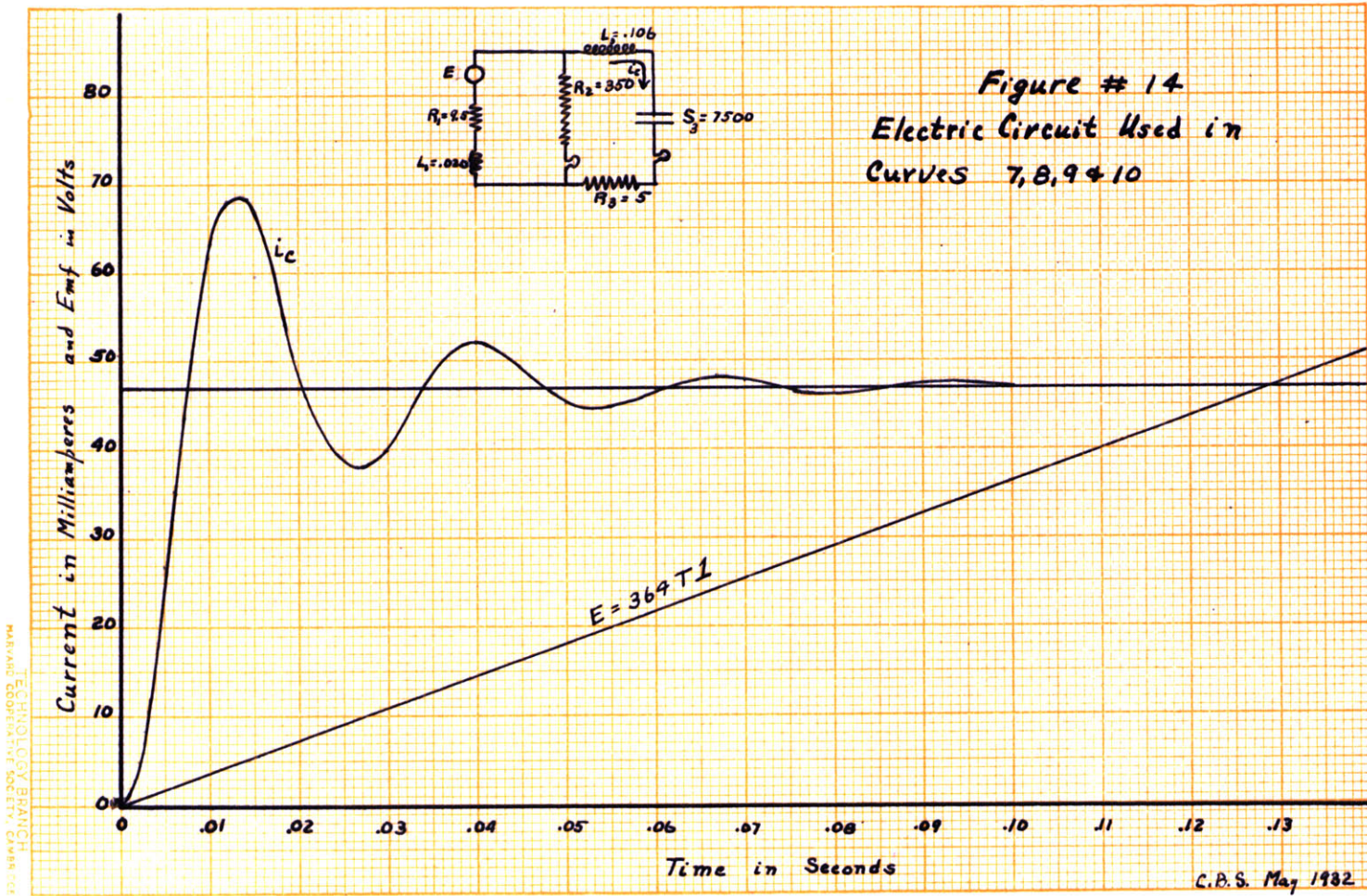
Electric Circuit and Calibration.

The ideal electric circuit as described in chapter II containing only a static condenser and an electromotive force which varies as the speed of the rotor cannot be realized in actual practice. The armature of any direct current generator has appreciable inductance and resistance. The armature built by the writer has 9.5 ohms resistance and 20 millihenries inductance. Both this resistance and inductance has considerable effect upon the electric circuit and it is desirable that both these parameters be kept as small as possible.

The inductance of the armature windings has not presented the most serious difficulty in the electric circuits used in this investigation. The inductance which has been added in the condenser circuit to smooth out the condenser current ripples has caused much more difficulty. The writer desired to build a generator which would be entirely without ripple in its voltage output, but this was

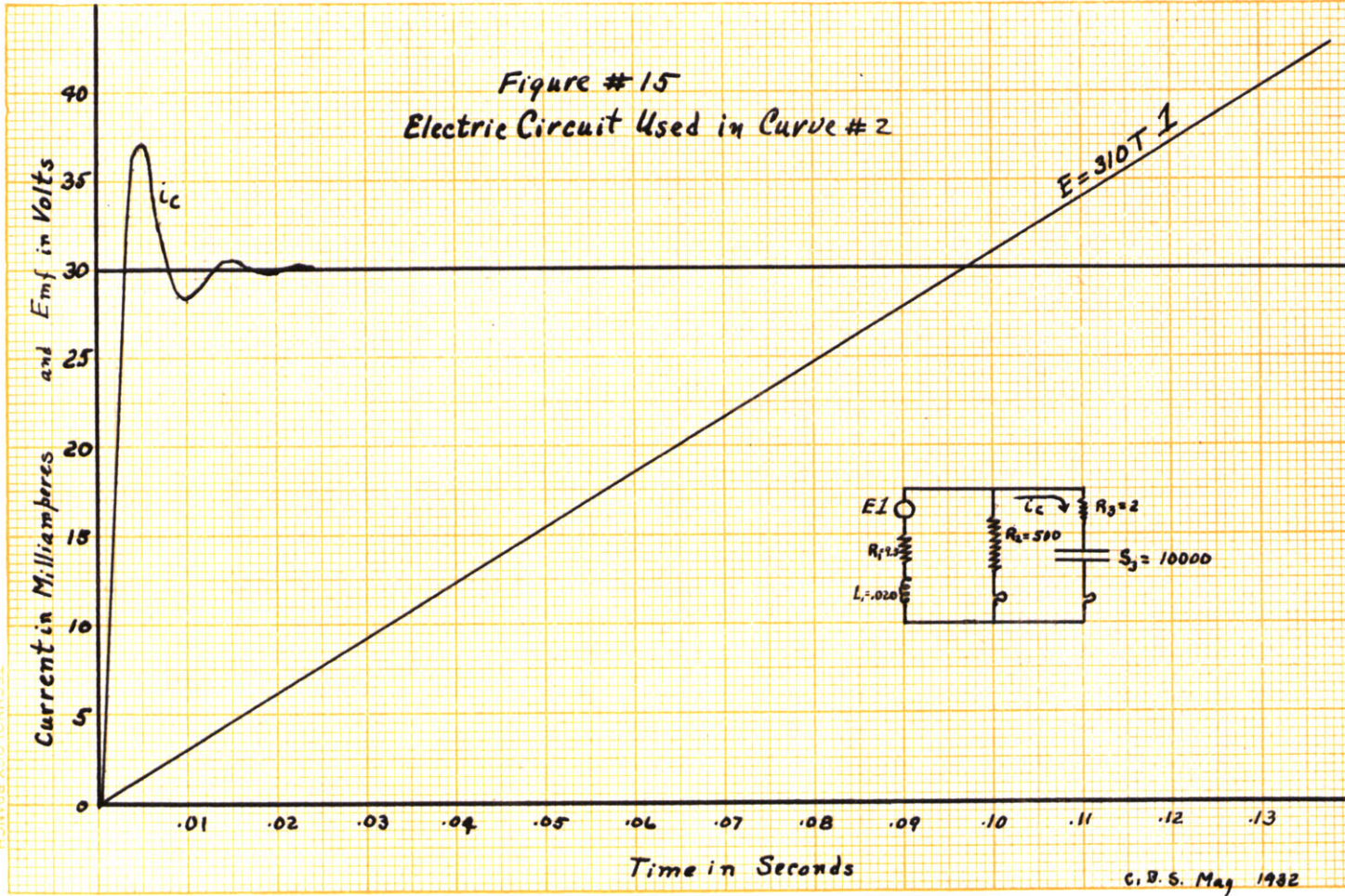
not accomplished to the extent desired. Reference to figure 11 will show that while the voltage ripple is very small the resulting current ripple is large. Attempts were made to design a tuned filter to remove this current ripple, but when consideration was made of the fact that the generator speed would vary from zero to some normal value, say 1800 R.P.M., and that the frequency of the condenser current ripple would vary over a similar range the idea of a tuned filter was discarded. Tests were then made with a simple inductance coil in series with the condenser. These tests showed that the current ripple could be greatly reduced by such an arrangement. Most of the oscillograms shown in chapter VI have been taken with some inductance in the condenser circuit.

The condenser current resulting from the application of an electromotive force proportional to time to a circuit of this type is shown in figure 14. Figure 15 shows the current in a similar circuit in which no filter inductance has been used. The oscillations of current in figure 15 are not very objectionable. The oscillations in figure 14 are, however, much more objectionable and can only be tolerated as the lesser of two evils— low



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current ripple and large oscillations or highly damped oscillations and large current ripples.

The calculation of the condenser current of figure 14 by operational methods is as follows:

$$i_1 (R_1 + R_2 + L_1 p) - i_2 R_2 = E = 364 t$$

$$-i_1 R_2 + i_2 (R_2 + R_3 + L_3 p + \frac{S_3}{p}) = 0$$

$$Z_{12}(p) = \frac{D(p)}{M_{12}(p)} = \frac{(R_1 + R_2 + L_1 p)(R_2 + R_3 + L_3 p + \frac{S_3}{p}) - R_2^2}{R_2}$$

Putting values of Parameters in:

$$Z(p) = \frac{(0.00212 p^2 + .24 p + 127)(p + 21300)}{350 p}$$

$$i_c = \frac{1}{Z(p)} \times 364 t \mathcal{I} = \frac{364}{p} \cdot \frac{1}{Z(p)} \mathcal{I}$$

$$i_c = k \left(\frac{1}{p} \cdot \frac{p}{(ap^2 + bp + c)} \cdot \frac{1}{p+d} \right) \mathcal{I} \quad \begin{cases} k = 127300 \\ a = .00212 \\ b = .24 \\ c = 127 \\ d = 21300 \end{cases}$$

By Borel's Theorem:

$$i_c = \frac{k}{a} \cdot \frac{1}{a\beta} \int_0^t (1 - e^{-d(t-\lambda)}) e^{-\frac{b\lambda}{2a}} \sin \beta \lambda d\lambda \quad \left\{ \beta = \sqrt{\frac{c}{a} - \frac{b^2}{4a^2}} \right.$$

$$i_c = \frac{k}{cd} - \sqrt{\frac{c}{a}} \frac{k}{cd\beta} e^{-\frac{b}{2a}t} \sin(\beta t + \tan^{-1} \frac{2a\beta}{b}) + \frac{k e^{-\frac{b}{2a}t}}{ad\beta \sqrt{d^2 - \frac{db}{a} + \frac{c}{a}}} \sin(\beta t - \tan^{-1} \frac{2a\beta}{2ad-b}) - \frac{k e^{-dt}}{ad(d^2 - \frac{db}{a} + \frac{c}{a})}$$

$$i_c \times 10^3 = 47 - 48.4 e^{-56.6t} \sin(238t + 76.5^\circ) + .56 e^{-56.6t} \sin(238t - 0^\circ 30') - .0062 e^{-21300t}$$

The Last Term is Very small and can be neglected.

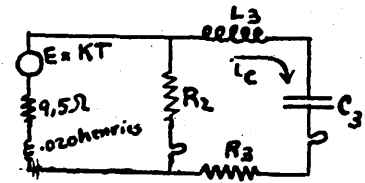
$$\therefore i_c \times 10^3 = 47 - 48.5 e^{-56.6t} \sin(238t + 77^\circ)$$

The above solution is of the circuit used for the oscillograms of curves #7,8,9& 10. Figure 15 shows the condenser current which results in a circuit such as used for curve #2 from an impressed electromotive force which increases directly as time. The table on the following page shows the parameters of the electric circuits used in taking the other oscillograms of chapter VI. The current which results from an electromotive force $E = Kt$ has been calculated for several of these circuits.

CALIBRATION:

The calibration of the apparatus involves the determination of two constants, first the moment of inertia of the rotating bodies and second the acceleration^{scale} for the particular electric circuit used. The moment of inertia can be determined by a number of different methods. In appendix B the moment of inertia of the armature of the D.C. motor of curve #6 has been determined by the retardation method. The torsional pendulum method can also be used, but this method requires that the armature be removed from the frame. The moment of inertia of the induction motor rotors used in this investigation have been determined from the maker's specifications.

Table of Electric Circuit Parameters
For Test Curves of Chapter VI



Curve Number	R_2	R_3	L_3	C_3	Condenser Current in Milliamperes	Calibration of current Vibrator
1	550	2	0	165 mfd.	$.162K - .189K e^{-288t} \sin(470t + 58.5^\circ)$	26 Ma/inch
2	550	2	0	100 mfd.	$.098K - .107K e^{-288t} \sin(645t + 66^\circ)$	
3+5	350	29	250 mh.	165 mfd.	$.160K - .182K e^{-74t} \sin(131t + 61^\circ)$	30 Ma/inch
4	350	2	0	165 mfd.	$.160K - .187K e^{-288t} \sin(470t + 58.5^\circ)$	30 Ma/inch.
6	350	9	207 mh.	383 mfd.	$.370K - .400K e^{-35t} \sin(99t + 71.0^\circ)$	
7,8,9+10	50	5	106 mh.	133 mfd.	$.129K - .133K e^{-56.6t} \sin(238t + 76.5^\circ)$	29 Ma/inch
11	350	5	106 mh.	383 mfd.	$.370K - .380K e^{-57t} \sin(142t + 82^\circ)$	29 Ma/inch
12	∞	3	8 mh.	390 mfd.		
13	∞	3	8 mh.	225 mfd.		
14	∞	6	55 mh.	250 mfd.		
15	∞	15	210 mh.	125 mfd.		
16	∞	6	55 mh.	383 mfd.		
17	∞	10	114 mh.	383 mfd.		

The acceleration constant of the electric circuit can likewise be determined in several ways. Probably the most evident method is by use of the parameters of the electric circuit and the solutions for current such as are shown on the preceding pages. This method is not as convenient as a simple method proposed by Dannatt and Redfearn using only constants which can be easily determined directly from the oscillograms. The acceleration scales of the oscillograms of chapter VI have been calculated by this method directly from the speed-time and acceleration-time curves of the oscillograms.

The calibration by this method is obtained from the following equation:

$$\alpha = \frac{eV V_0}{A}$$

Where:

α = Acceleration scale in radians per sec.² per inch.

A = Area between acceleration-time and axis, between the limits t_1 & t_2 , in sq. inches.

V = Difference in machine speeds at t_1 & t_2 as obtained from the speed-time curve in rad./sec.

V_0 = Speed of oscillograph camera in inches per sec.

The speed-torque taken with the cathode ray oscillograph cannot be calibrated by the above method, but they must be calibrated thru the electric circuit and the deflection constants of the tube. The oscillograms of curves 12 to 17 have not been so calibrated because the deflection constants of the cathode ray tube were not determined at the time the pictures were taken.

CHAPTER VI

TEST RESULTS.

On the following pages of this chapter there are shown some of the test results of this research. The oscillograms of curves 1 to 11 show speed-time and torque-time curves for several types of induction motors and a standard D.C. motor. The pictures of curves 12 to 17 show the speed-acceleration or rather the speed-torque curves of some of these motors as determined by a cathode ray oscillograph used in the manner that was outlined in chapter III. The special features of each oscillogram together with the type of motor involved will be found on each curve.

The first curves that were taken by the writer were of a motor starting from rest such as shown in curve 5. Reference to this curve will show that there are very large pulsations in the recorded torque for a few cycles just after the motor is thrown on the line. This is probably due to electrical transients in the stator windings. In order to eliminate this condition Dannatt & Redfearn have suggested that the motor be rotating in a negative sense when the line

switch is closed. In their investigations they used a small auxiliary motor to drive the test motor backwards. This driving motor was disconnected from the test motor just before the power was applied to the test motor.

The writer was not able to use a driving motor in such a manner because of difficulty in disconnecting it from the test motor at the proper time. The scheme finally adopted was that of complete reversal of the test motor. This probably sets up greater transients in the stator than does the ordinary starting operation, but by the time the motor reaches zero speed these disturbances are of very small magnitude and therefore they should have very little effect upon the torque curve from zero to synchronous speed. Some of the tests were made with a 24 to 60 cycle reversal and others were made with a 50 to 60 cycle reversal, but those which used the simple 60 to 60 cycle reversal seem to give the best results.

The ripple in the condenser current and hence in the torque curve of the oscillograms has caused much trouble in this research. The only method by which the writer was able to reduce the ripple required the addition of an inductance in the condenser circuit. As pointed out in chapter V

this is very undesirable from the standpoint of oscillations in the electric circuit. Curves 3 & 4 show a 50 to 60 cycle reversal of a type KF motor. These two curves were taken under similar conditions. The only difference being that curve 3 was taken with a 250 mh. inductance coil in the condenser circuit while no such coil was used in the circuit when the other curve was taken. We see that the average values of torque agree very closely on the two curves, but the ripple in curve 3 makes it of very little value in analyzing the motor characteristics. It will also be observed that the torque curve of 3 does not agree with its speed curve. From this curve it would appear that a decrease in torque causes an increase in speed and that an increase in torque causes a decrease in speed. On curve 4, however, we see that an increase in torque causes a corresponding increase in speed as we know must be the case. The discrepancy in curve 3 is due to the inductance in series with the condenser. The condenser current does not respond instantly to a change in the generator voltage, but lags behind by some phase angle.

It is interesting to note several features of the motor characteristics which these two curves and the other curves bring to light. In the first

Upon comparing the values of torque obtained from the oscillograms of curves 1 to 11 with the manufacturer's guarantees we find that the results of the oscillograms are at least in line with those from the guarantees. On the type KG motor (curve 1) the guarantee shows a starting torque of 278% or 122 #ft. This agrees very well with the value we would estimate from the oscillogram.

On the type KF motor (curves 2 to 5) we found that our test values are slightly lower than those quote by the maker. A starting torque of 208% or 91 #ft. should be expected while our tests show starting torques of 80 to 90 #ft.

The tests of the type K motor gives us values which are slightly in excess of those quoted by the manufacturer. Curves 7 to 10 show a maximum torque of about 123 #ft., as compared with a guarantee of 115 #ft. maximum torque. Curve 11 shows the type K motor on half voltage reversal. Here we get a maximum torque of 34 #ft. which is about 27½% of the torque observed on full voltage reversal. We should expect this relation to be 25%. If we take into account the regulation of the line voltage at the terminals of the motor we find that the torques have almost exactly the relation of the square of the terminal volts.

place it will be observed that the induction motors overshoot synchronous speed, and second that the torque increases for values of slip greater than unity. This increase in torque for large values of slip can be fairly well accounted for by the action of the double rotor bars in the type KF motor (see appendix C for dimensions of rotor bars). Such values of torque in the type K motor cannot be so justified because this type of motor has a solid rotor bar of rectangular cross-section. It is probable that the ^{increase} in torque for large values of slip is due in part to increased eddy currents in the rotor punchings.

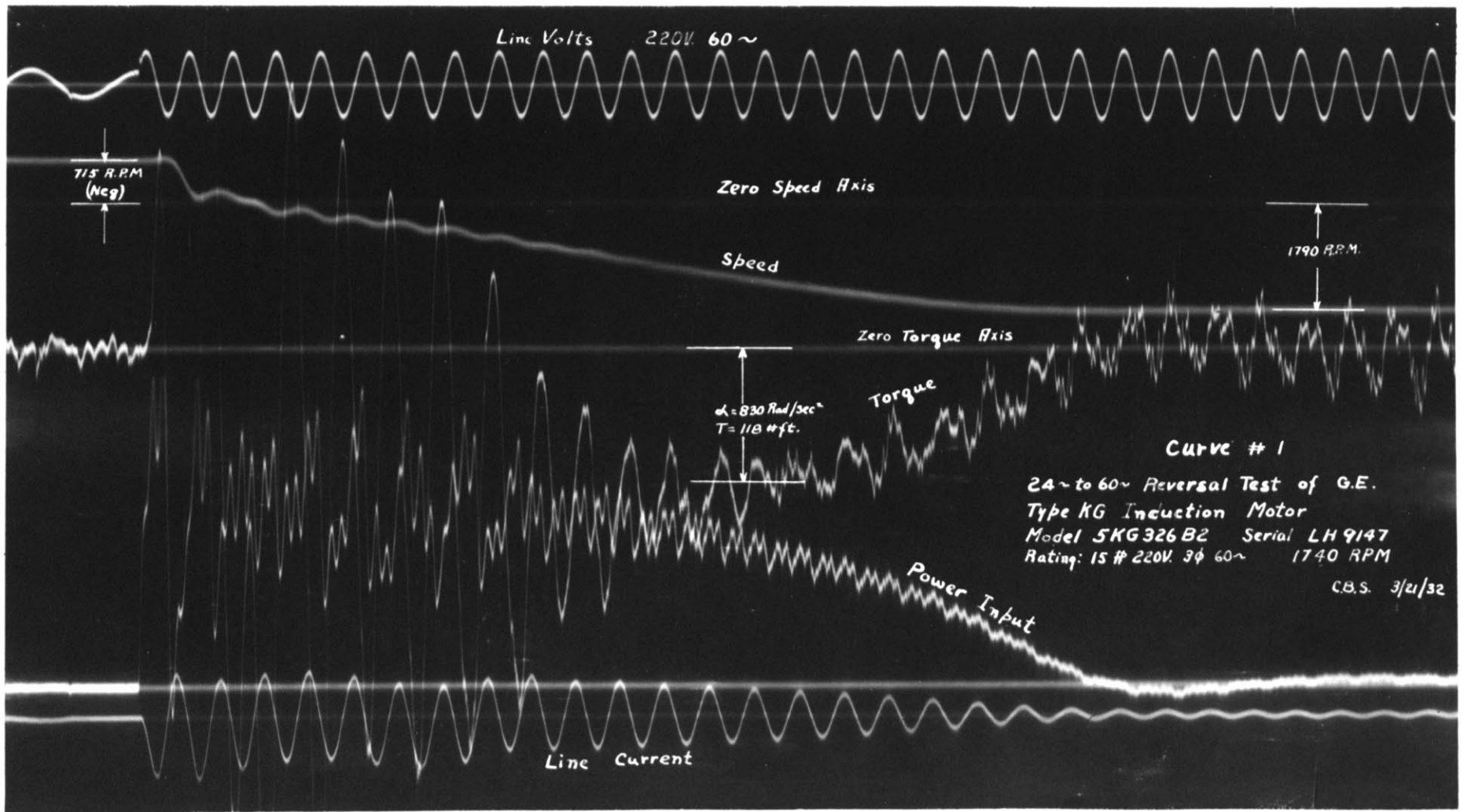
Now to go back to the overshooting of synchronous speed, we find that this has happened to some extent in all the induction motors tested. The steady-state induction motor theory has nothing to indicate that such a condition of "hunting" can exist. It must be remembered that here we have a transient phenomenon rather than a steady-state phenomenon and we must not expect the theory to hold exactly. In connection with this the reader is referred to the work of M.M.Sanghavi (appendix A) in which the effect of acceleration on the performance of induction motors has been studied.

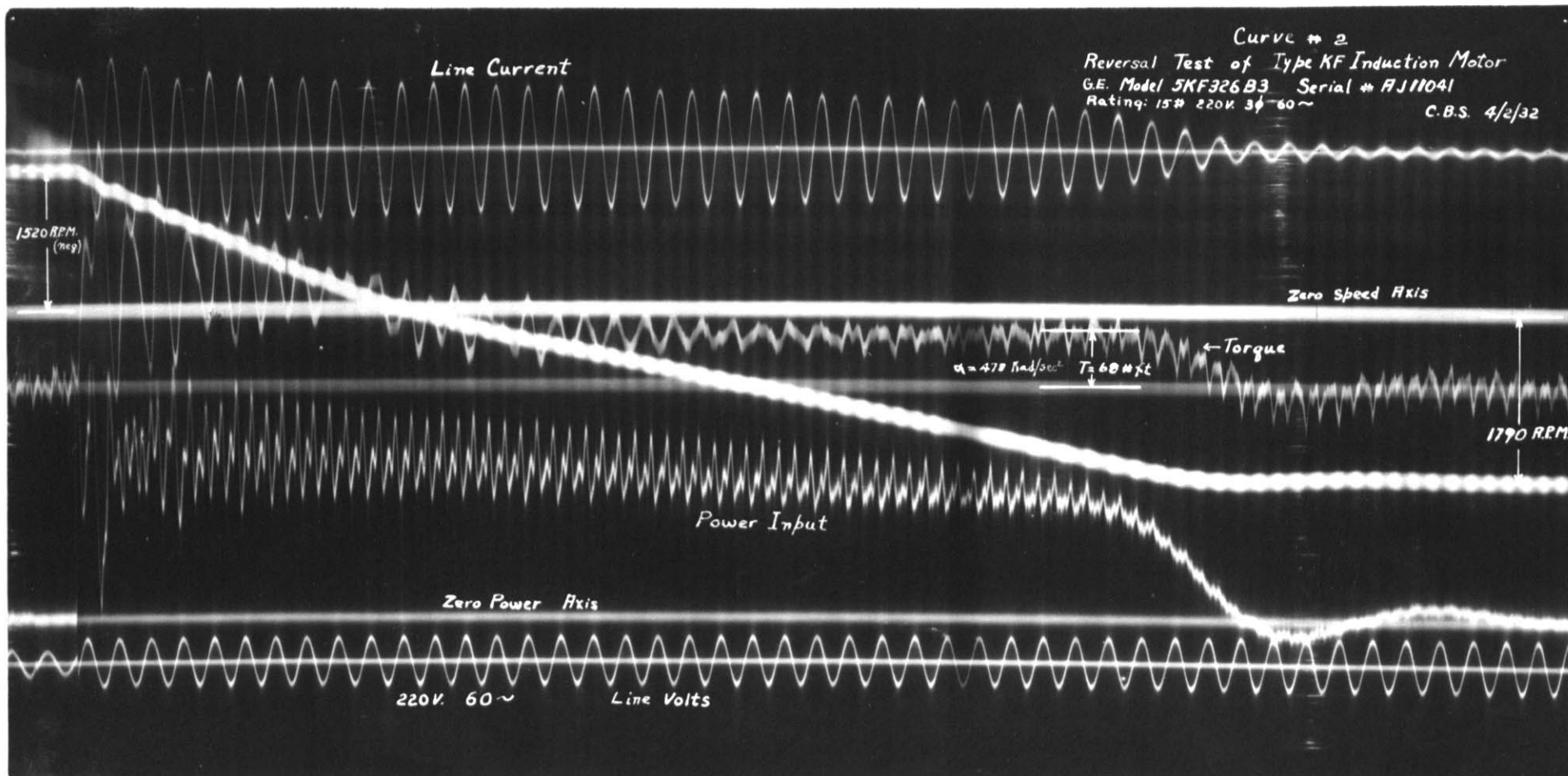
The results of tests made on a D.C. motor are shown on curve 6. Here we find that the torque curve agrees fairly well with the armature current curve. The maximum armature current is 146 amperes or 400% of full load current and we find that the maximum torque is 180 #ft. or 392% of full load torque. While this comparison is without refinements it shows that the recorded torque is very nearly correct.

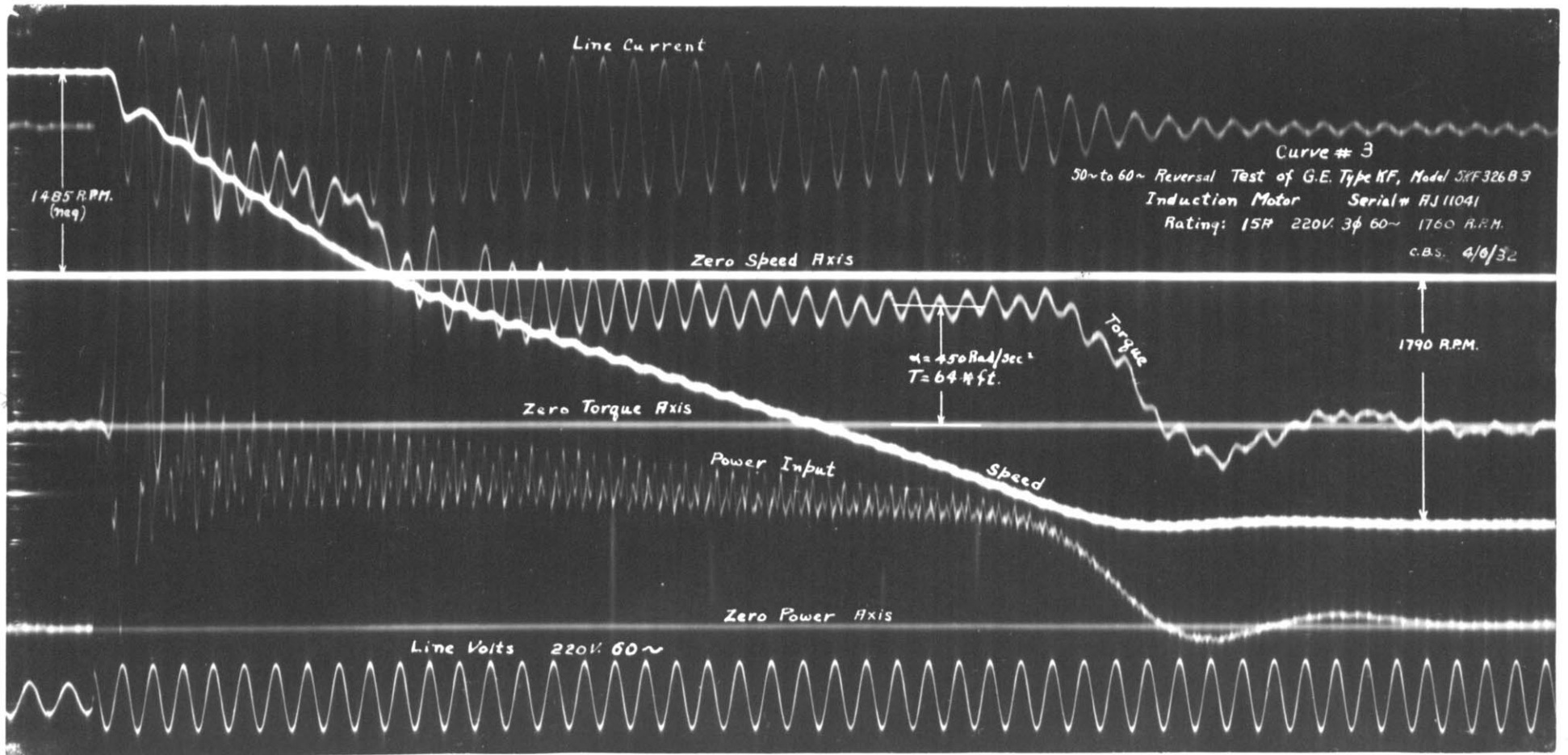
Curves 12 to 17 have been taken with a cathode ray oscillograph as has been explained before. Curves 13 to 17 are all of the type K motor. The full voltage tests show ripple similar to that on the time oscillograms. The half voltage reversal speed-torque curves taken in this manner are without much ripple and they should be of value in the study of induction motor characteristics.

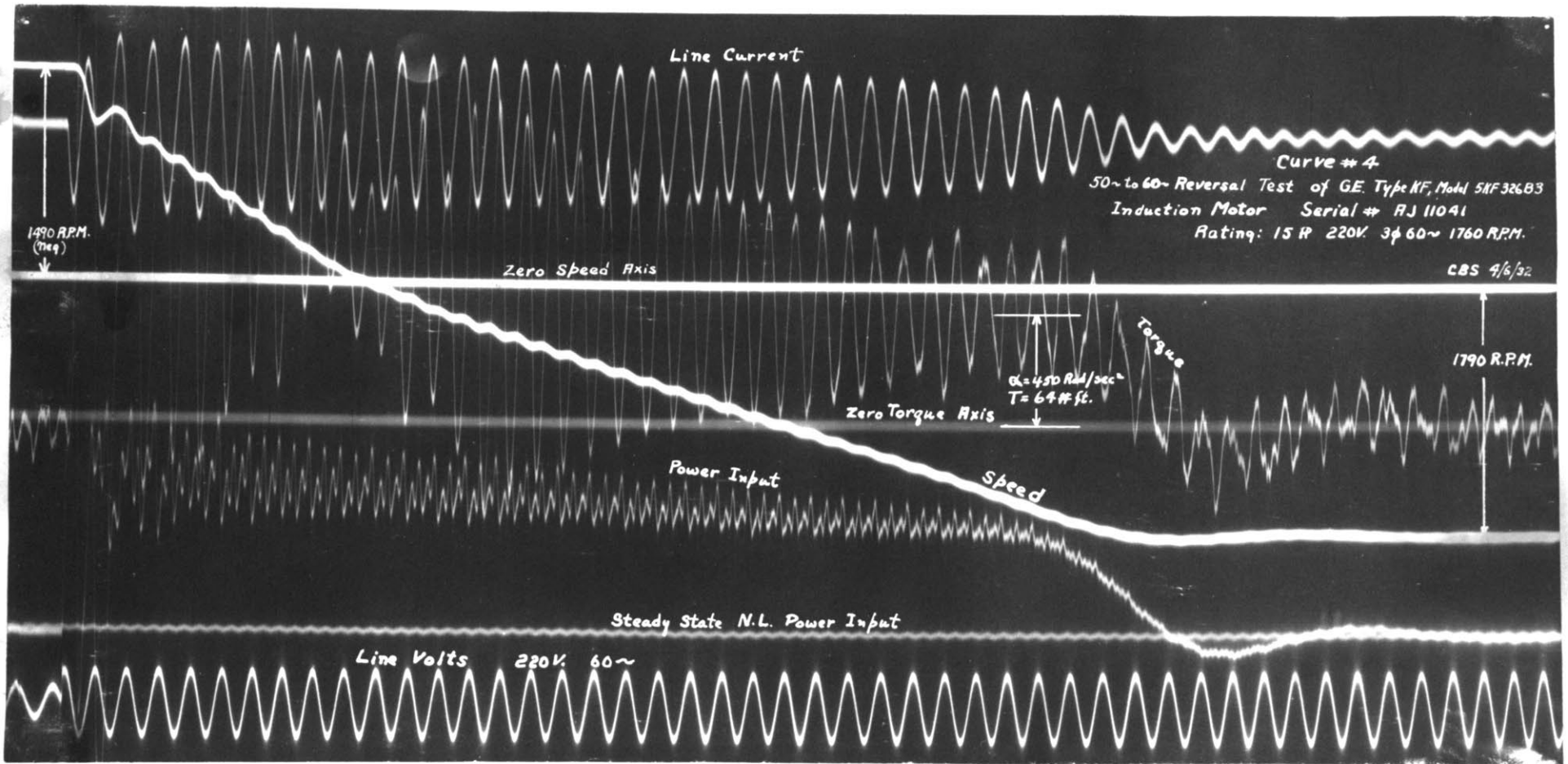
The cause of the violent pulsations in the torque curve after a full voltage reversal has not been completely determined. The high speed moving pictures shown in curves 18 & 18a were taken of the coupling of a type K motor on full voltage reversal in order to study the steps in the speed-time and the deflection of the coupling. The speed-time curve has been plotted from these pictures (curve 19)

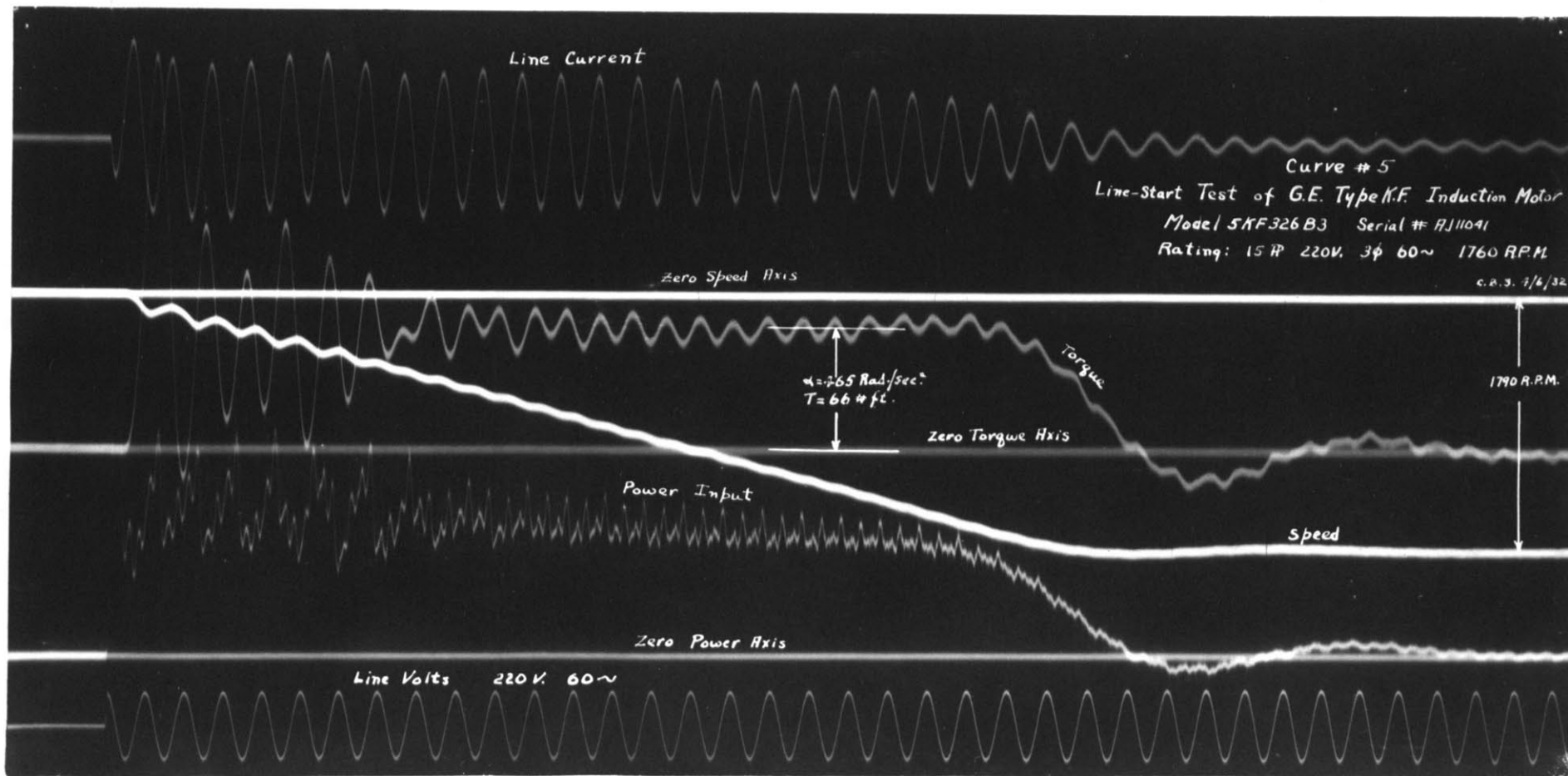
and we see that it agrees in general shape to the speed curves of the oscillograms of curves 7 to 10. A coupling shift can be observed just after reversal of the power. This shift is small and does not appear to oscillate. It would be well to note at this time that a solid coupling between the motor and the generator is to be desired, but with the line-up facilities available in the laboratory at present the use of solid coupling is almost impossible. All the tests curves shown in this thesis have been made with the generator coupled to the test motor thru a semi-flexible web coupling.

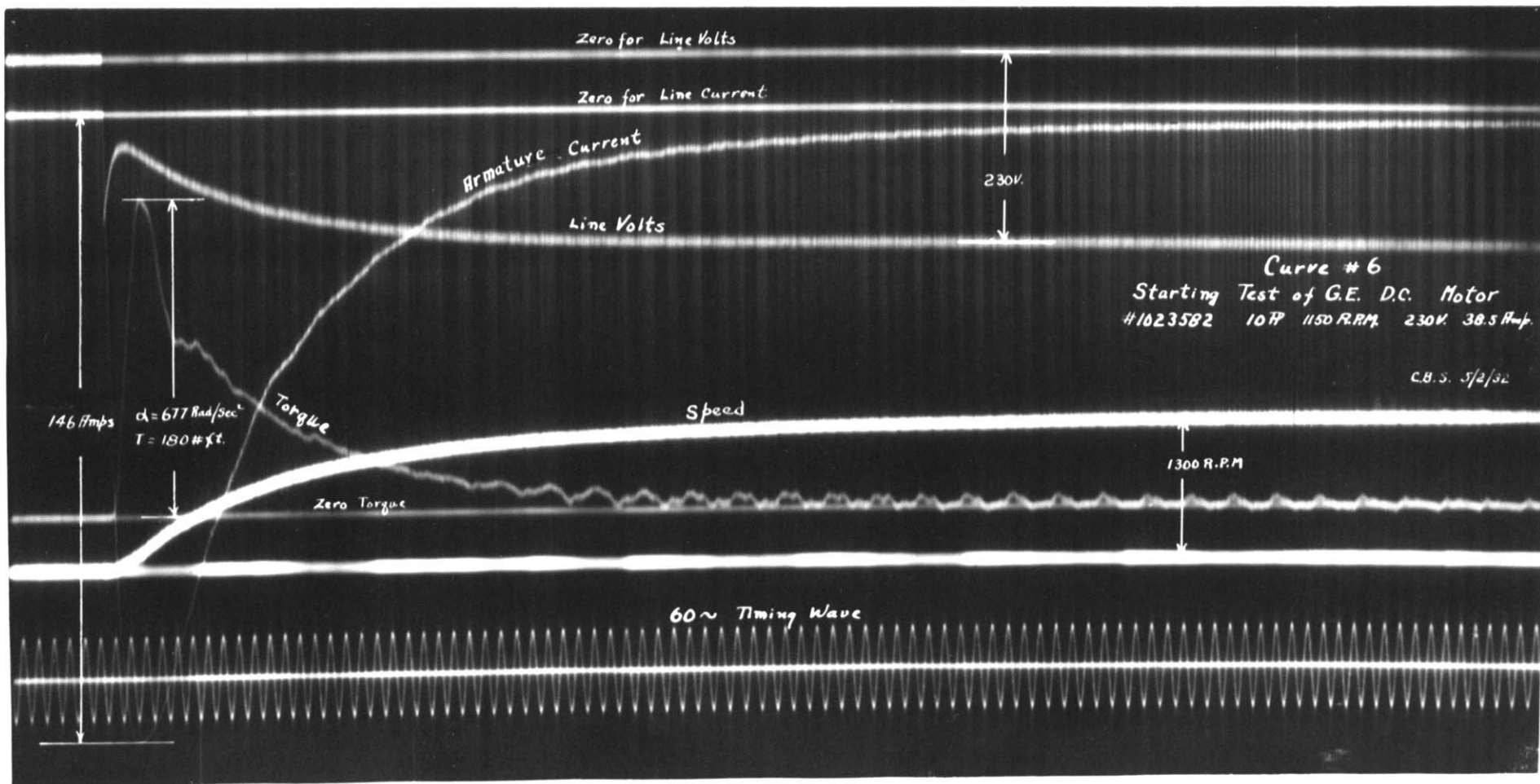


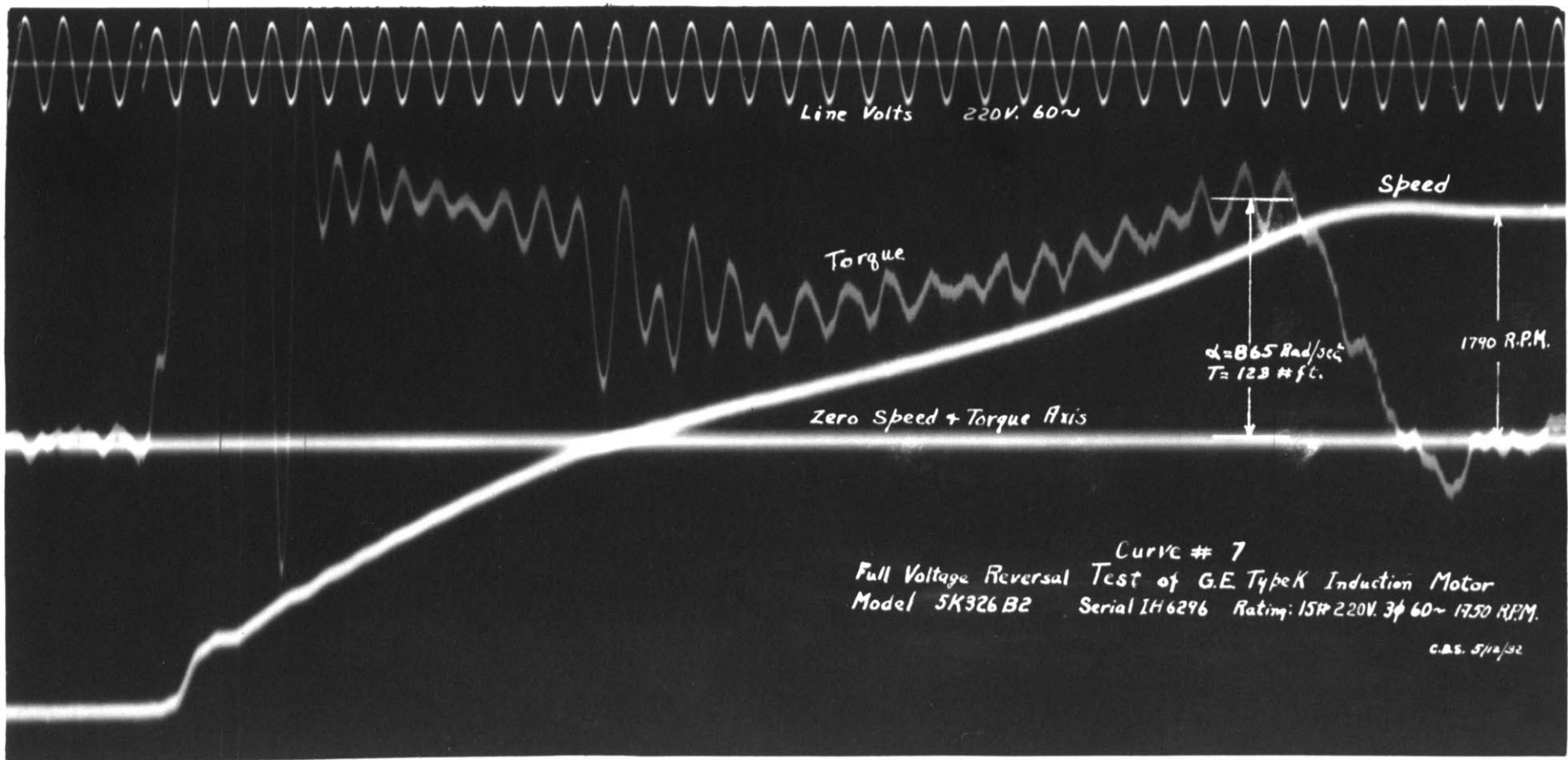


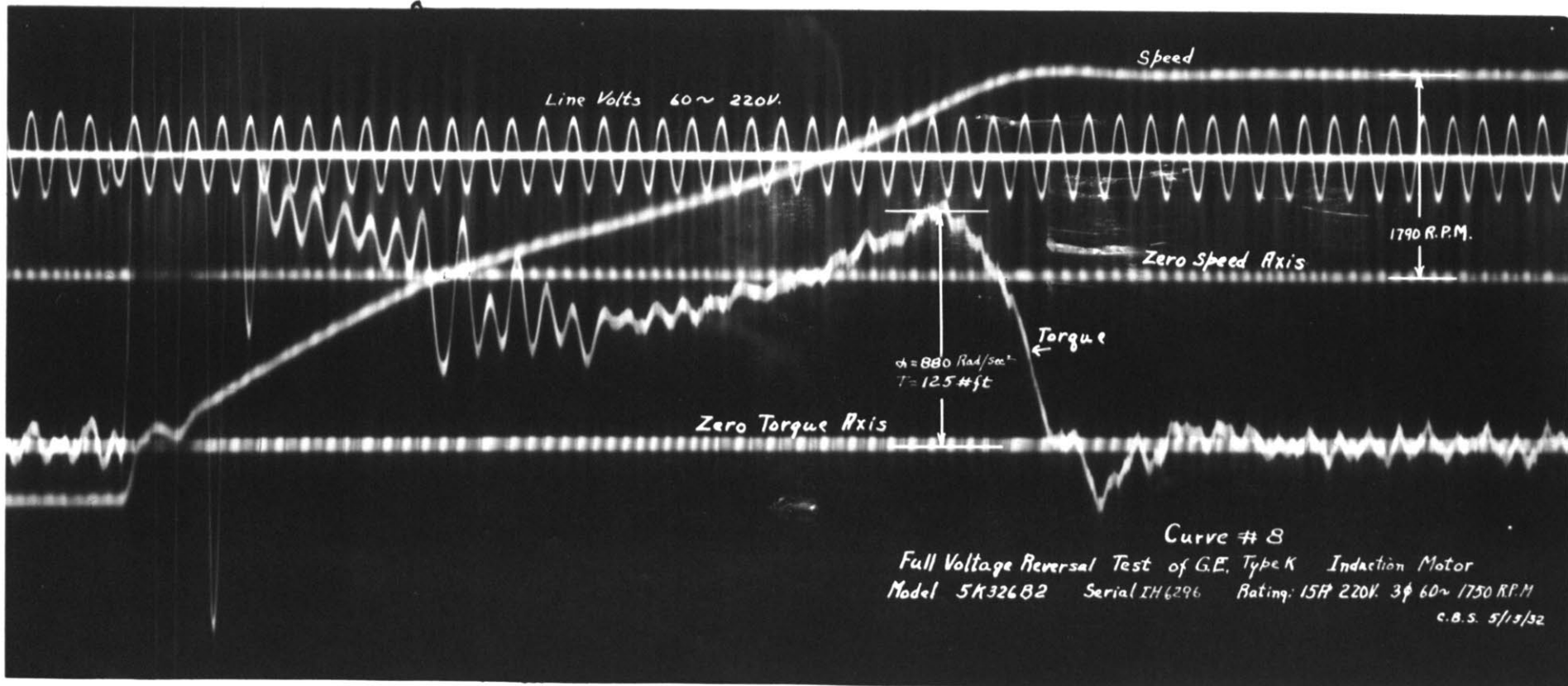


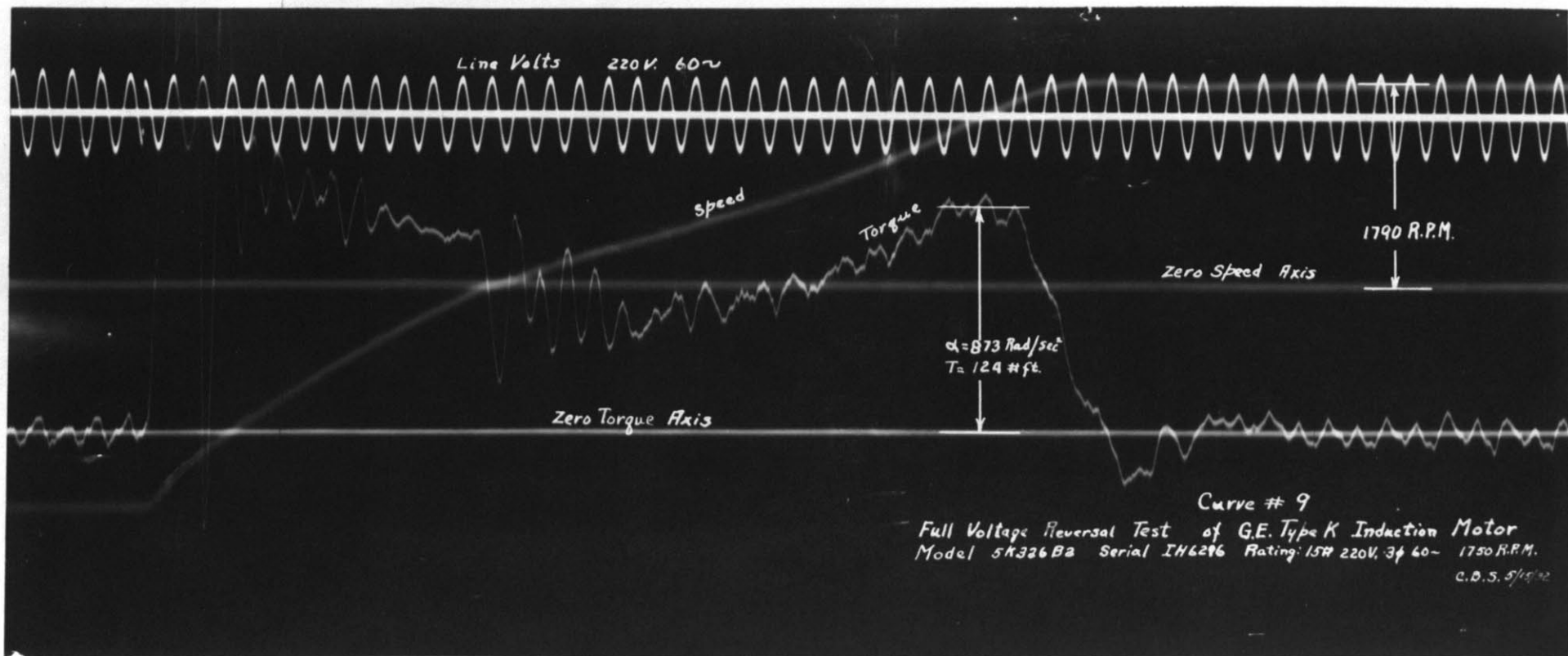


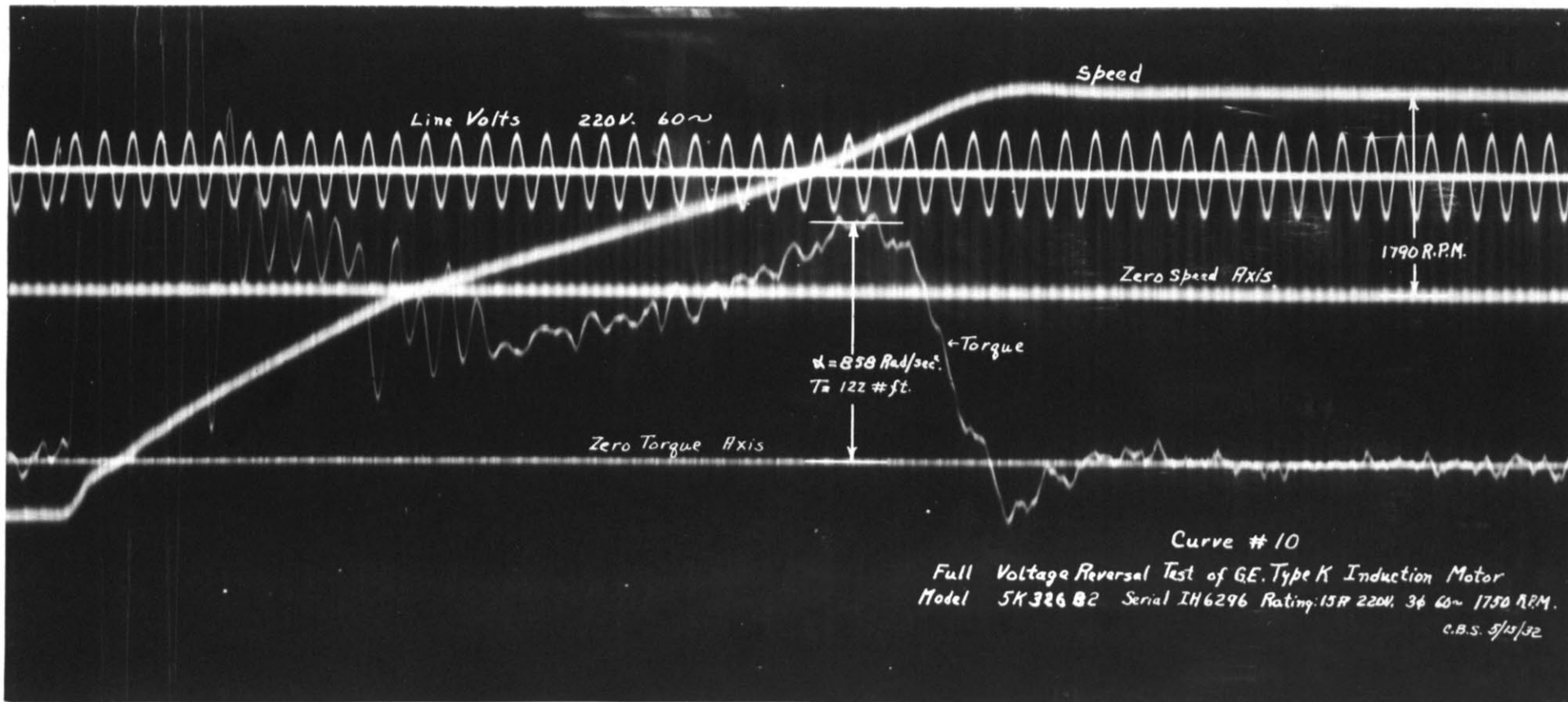




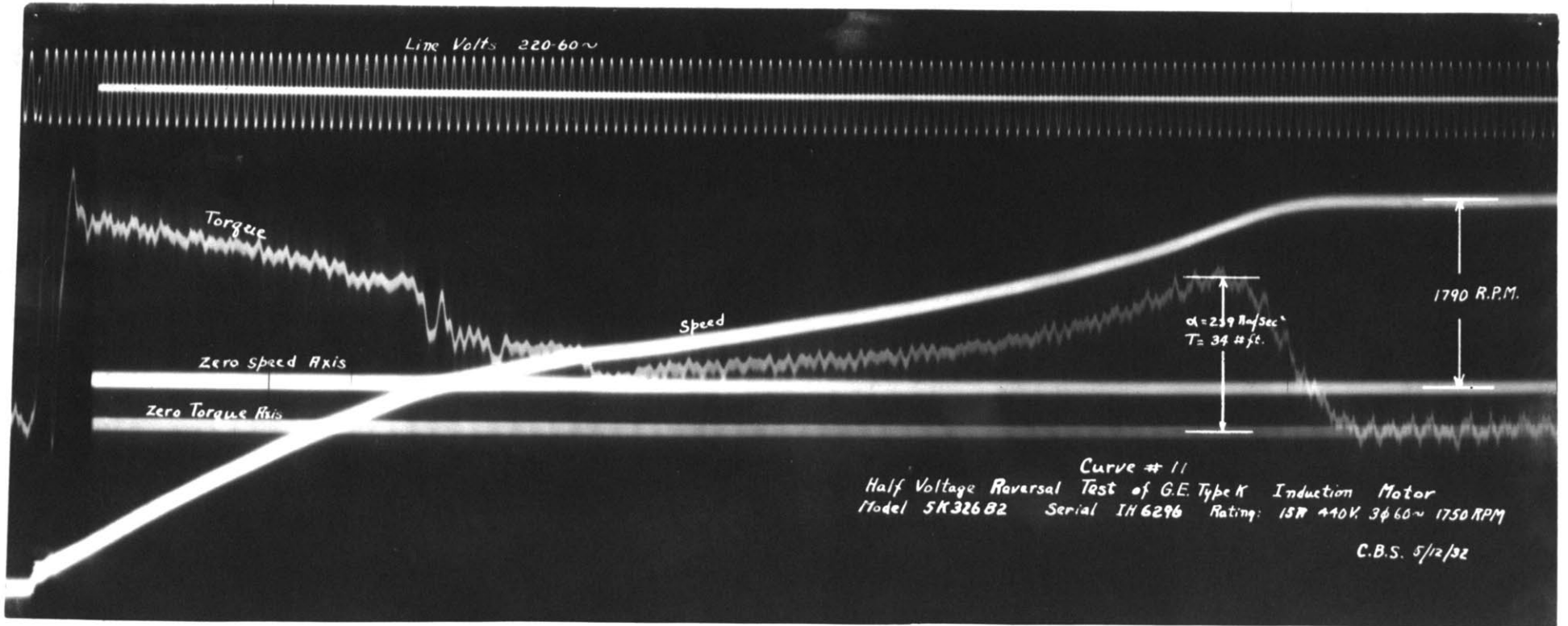








Line Volts 220-60~



Torque

Speed

Zero Speed Axis

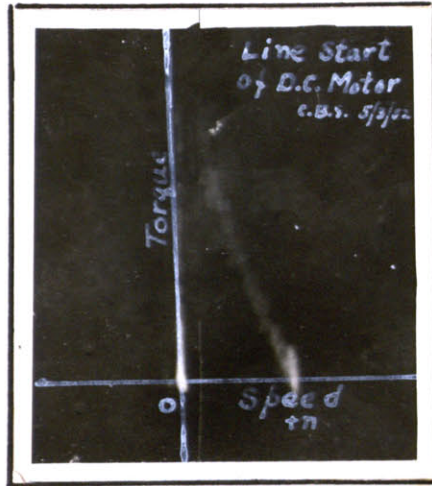
Zero Torque Axis

$\alpha = 239 \text{ R.P.M./sec.}$
 $T = 34 \text{ #ft.}$

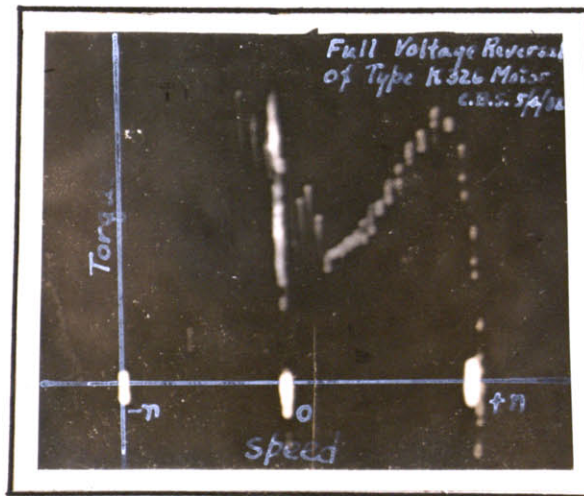
1790 R.P.M.

Curve # 11
Half Voltage Reversal Test of G.E. Type K Induction Motor
Model 5K32682 Serial IH 6296 Rating: 157 440V. 3 ϕ 60~ 1750 RPM

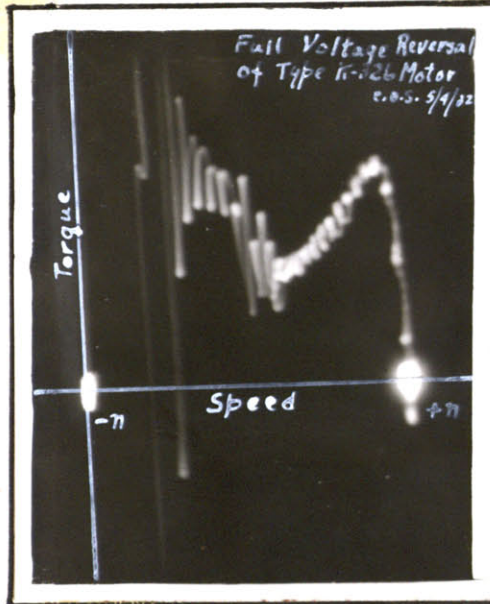
C.B.S. 5/12/32



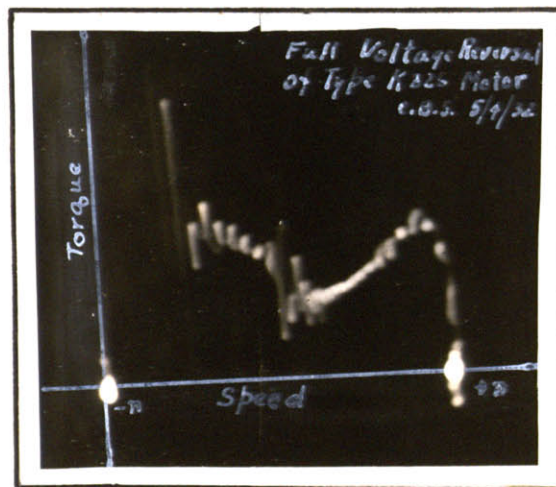
Curve # 12



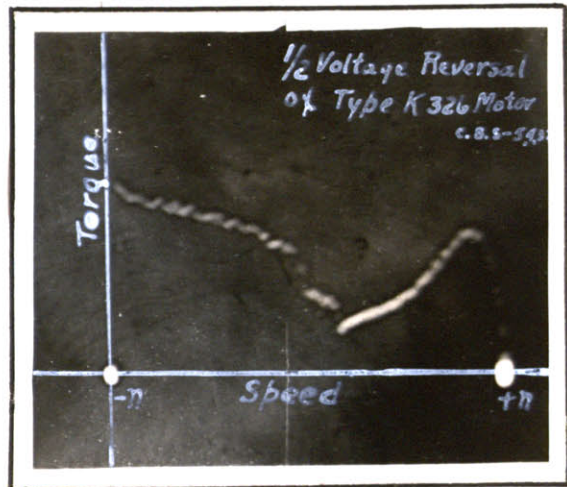
Curve # 13



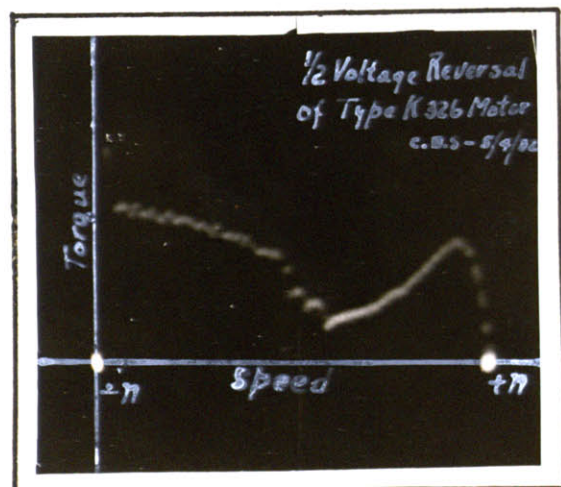
Curve # 14



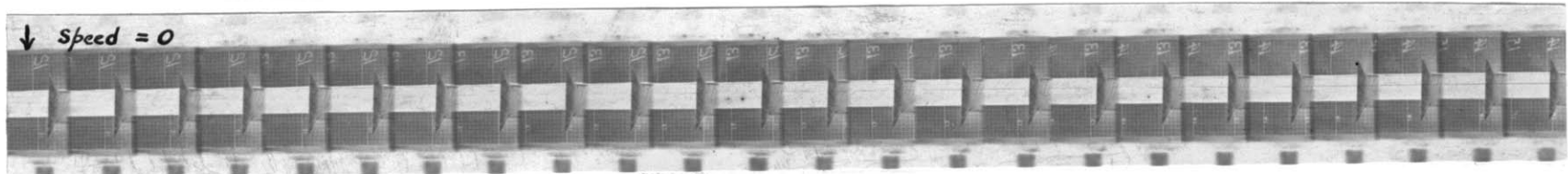
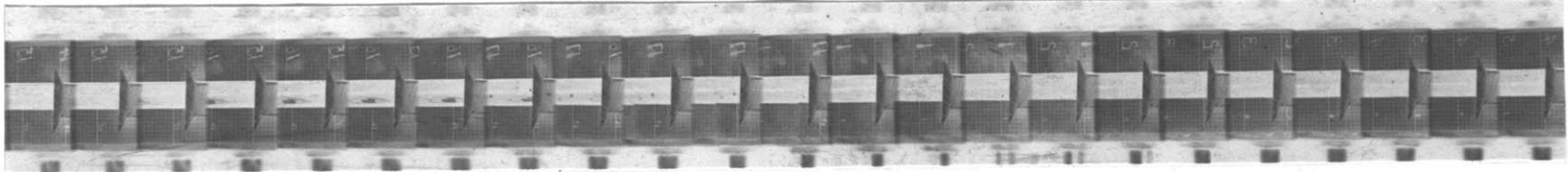
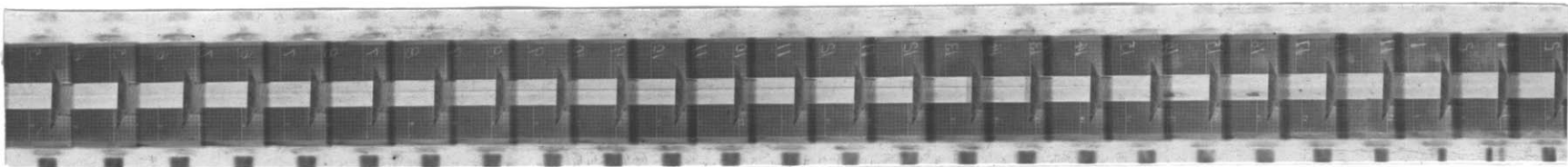
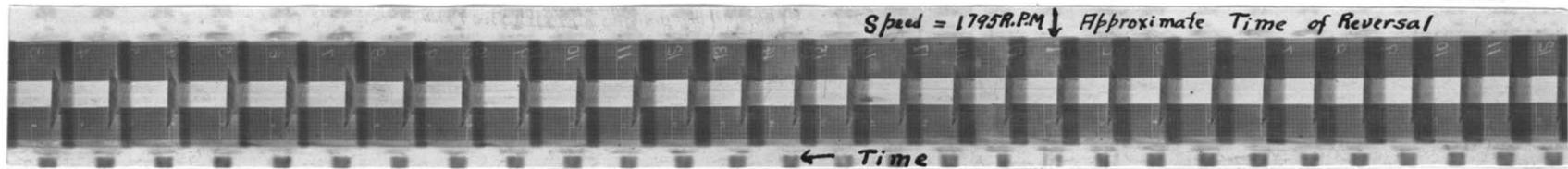
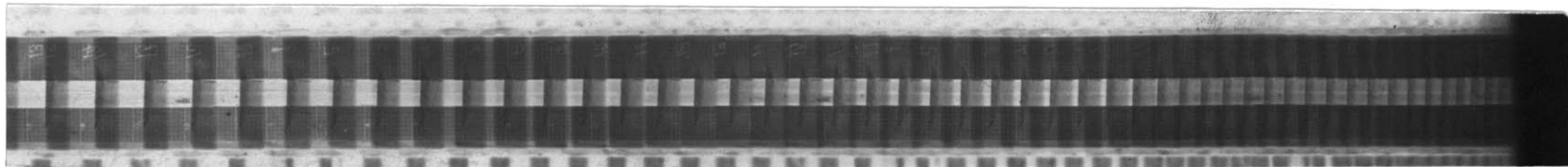
Curve # 15



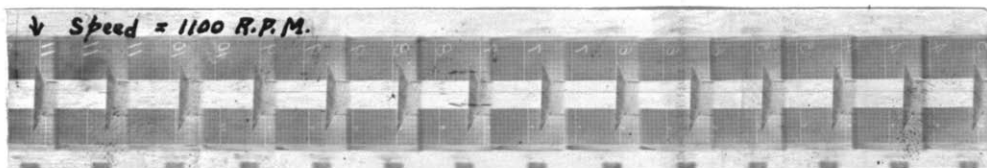
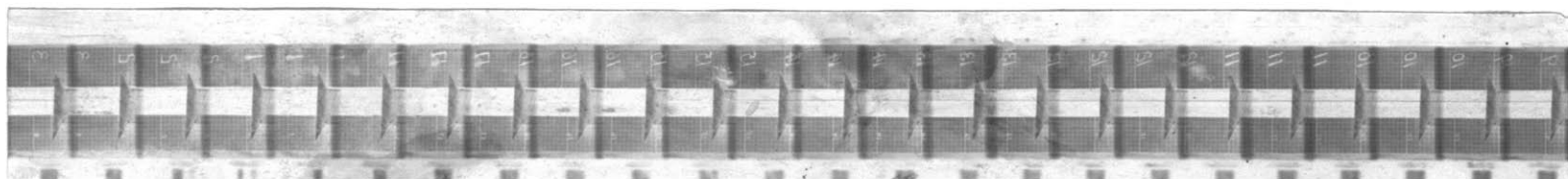
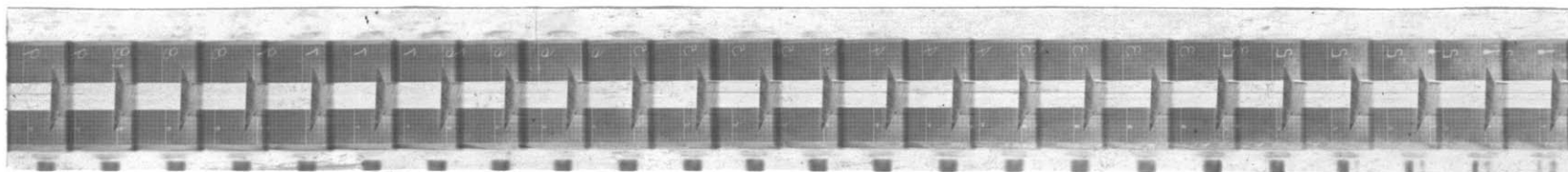
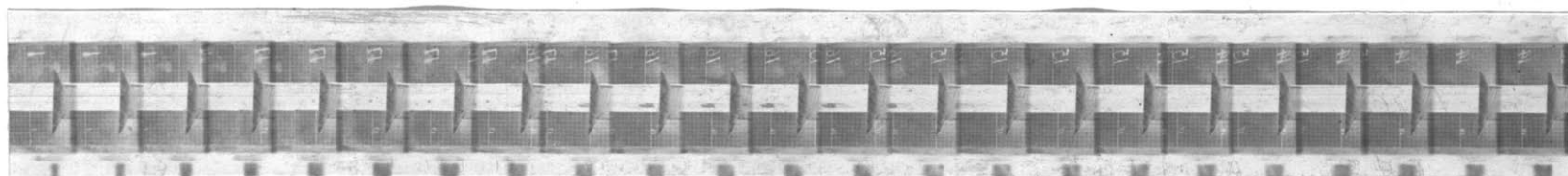
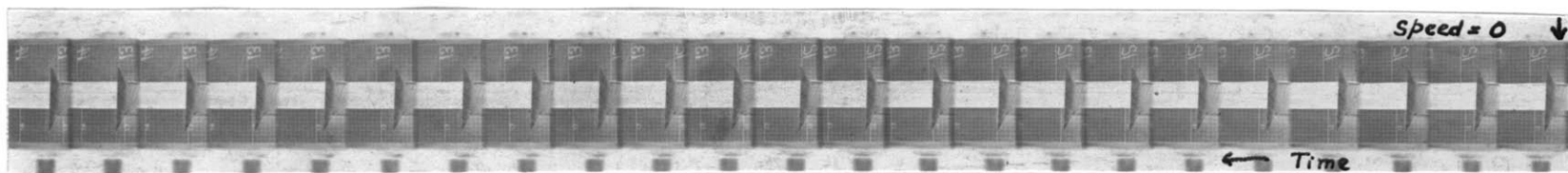
Curve # 16



Curve # 17

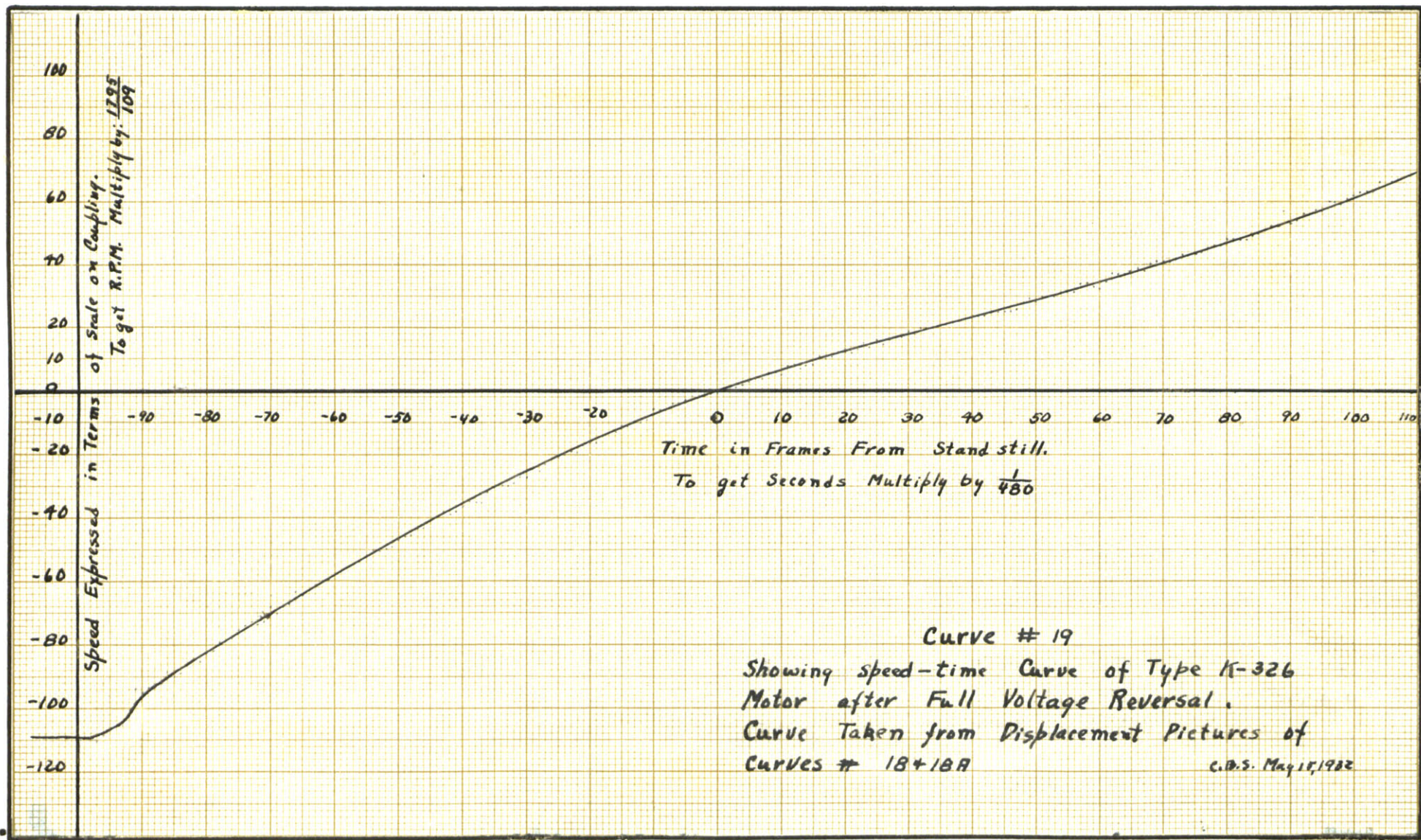


Curve # 18
Pictures Showing Displacement of Rotor of Type K-326
Induction Motor After Full Voltage Reversal. Time
between Each Frame = 1/480 Second.
Continued on Curve #18a



Curve # 18A
Continuation of Displacement Pictures
from curve # 18

May 15, 1932



CONCLUSIONS

In this investigation it has been shown that dynamic torque measurements can be made by means of an electric accelerometer such as developed in this research. While the accuracy of the torque measurements by this method have not been definitely established it has been shown that these measurements are in close agreement with the steady-state values at a few points on the torque curve.

The tests taken with the motor starting or reversing at half voltage indicate that better results would be obtained if the acceleration resulting from a given torque could be reduced. This would require the addition of a flywheel load to the motor shaft. By lengthening the acceleration period we would reduce the effect of the current transient of the stator circuit and get results which are more nearly the steady-state values. It is desirable, however, that the dynamic torque tests of a motor be made with an acceleration which is nearly the same as the acceleration the motor will have in actual service. If a motor is designed to start heavy loads it should be tested with a rather large flywheel, but if it is designed to start light loads in a short time it should be tested with a small flywheel.

The cathode ray oscillograph offers a very convenient means by which the speed-torque curves of an induction motor can be recorded directly. So far as the writer knows curves 12 to 17 of chapter VI are the first speed-torque curves to be recorded by this method. While the speed-torque curve gives a good overall picture of the motor operating characteristics, the writer believes that the speed-time and torque-time curves are more desirable in the detail study of motor performance.

While the generator and electric circuit used in this research are not ideal, the writer believes that fairly reliable torque measurements can be made with the generator and the electric ^{circuit} _^ as shown on figure 14 of chapter V.

If speed-torque curves are to be determined by means of the cathode ray tube it is highly desirable that a new generator be constructed to give an output of 200 volts or more. The resistance, inductance and voltage ripple should be kept at a minimum.

APPENDIX A

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APPENDIX B

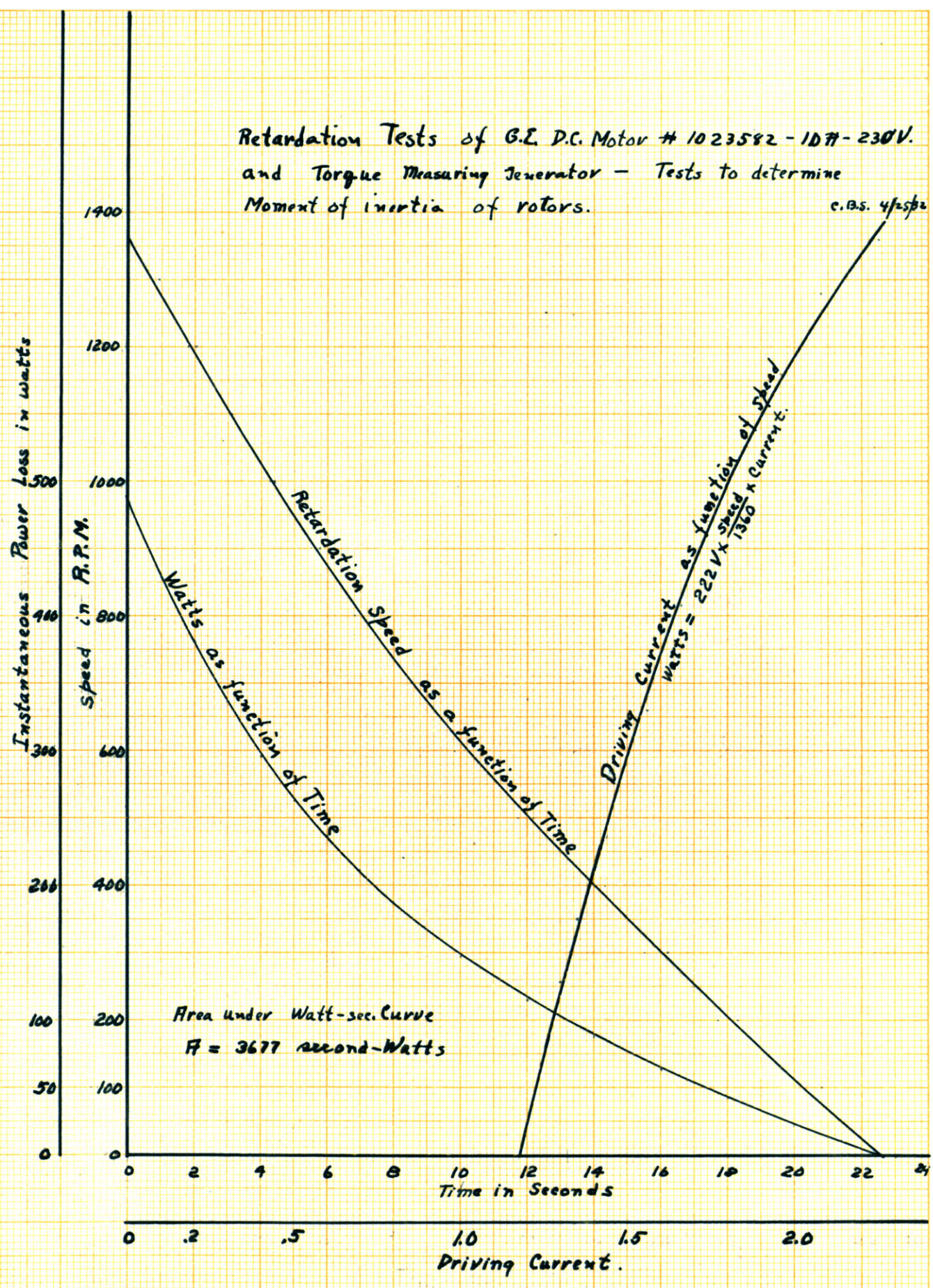
DETERMINATION OF THE MOMENT OF INERTIA
OF THE ROTATING PARTS.

The moment of inertia of a rotating body can be conveniently determined by means of the retardation tests and rotational loss curves. While the accuracy of the results obtained in such a manner is not exceedingly high it is usually well within the limits of commercial testing.

The moment of inertia of the special generator and the direct current motor used in curves 11 & 12 of chapter VI has been determined by this method. The figure on the following page shows the curves used. The retardation speed as a function of time and the driving current as a function of speed curves were determined by test. The instantaneous retardation watts have been determined from these curves and plotted as a function of time. The area under this watts curve represents the stored energy in the rotating body when $t = 0$. This is also equal to $\frac{1}{2}IW^2$. By taking proper care of units we find that;

$$I = \frac{2 \times 7375 \times 3677}{\left(\frac{1360 \times 2\pi}{60}\right)^2} = .266 \text{ \#(mass) sec}^2\text{ft.}$$

Retardation Tests of G.E. D.C. Motor # 1023582 - 107-230V.
 and Torque Measuring Generator - Tests to determine
 Moment of inertia of rotors.



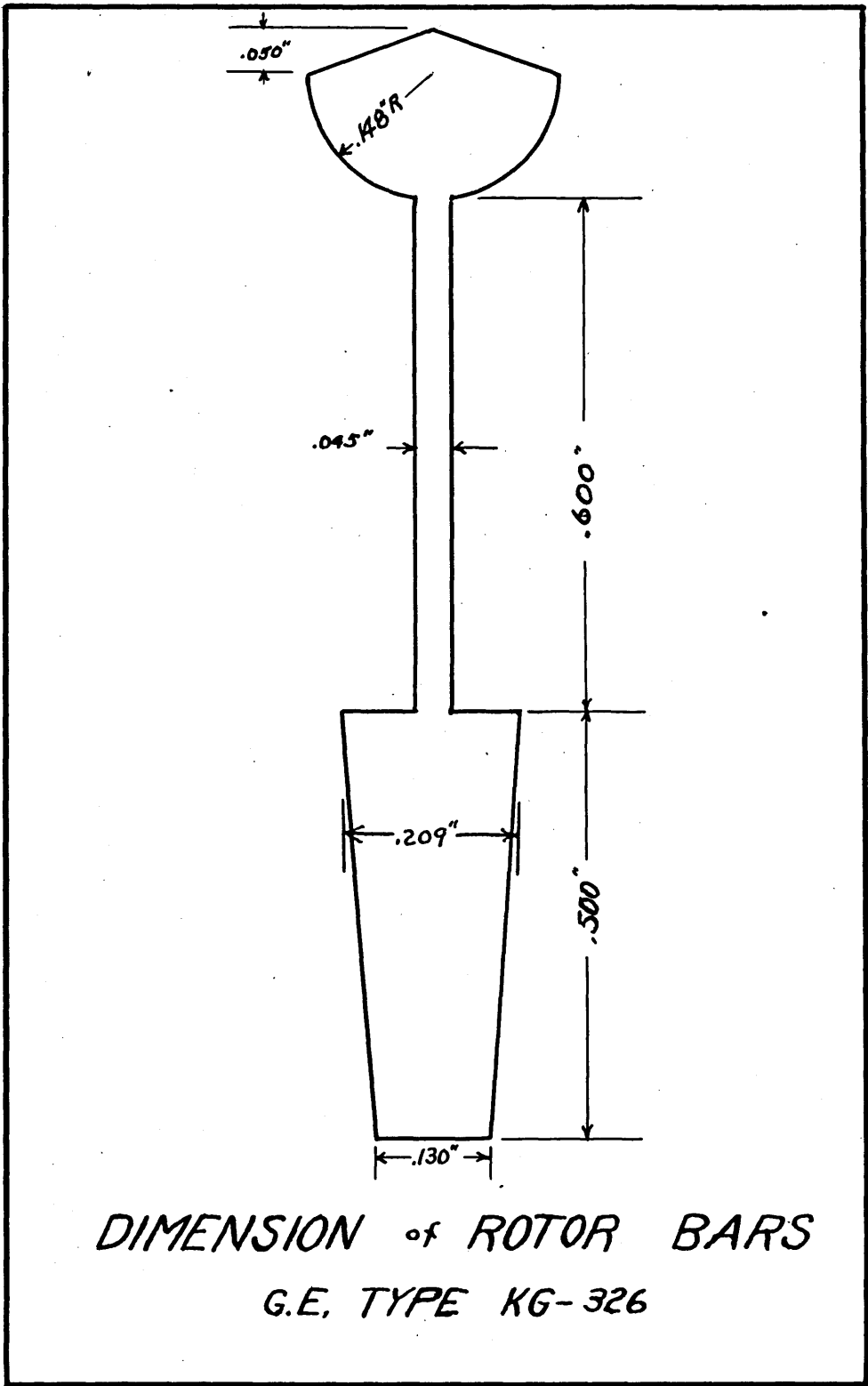
The moment of inertia of the induction motor rotors has been taken from the maker's design data. For the size rotors used in these tests we find that the WR^2 is 3.934 for the types used in this investigation. By adding to this the WR^2 of the armature of the special ^{generator} and coupling we get a total WR^2 of 4.57 . This gives us the moment of inertia as $I = .142 \text{ # sec}^2 \text{ ft.}$

APPENDIX C

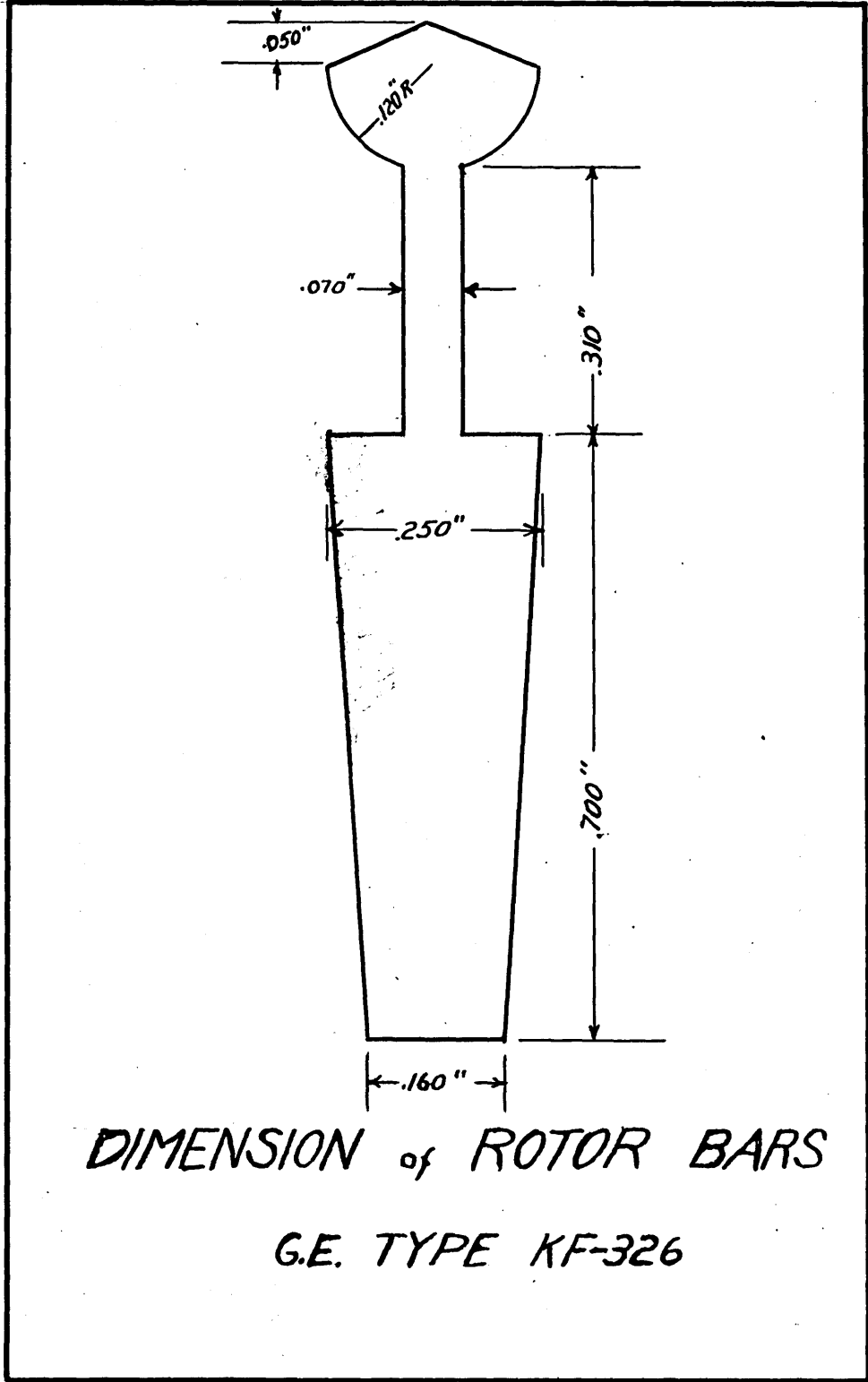
TEST MOTORS

The following figures show the dimensions of the rotor bars used in the several test motors. The type K motor is an up-to-date single squirrel-cage rotor general purpose motor having a considerable hump in the speed-torque^{curve} at about 25% slip. The types KG and KF are modern double squirrel-cage rotor line-start motors. The type KF gives normal starting torque with low starting current while type KG gives high starting torque with low starting current.

A complete set of the manufacturer's characteristic curves for these motors will be found in the appendix to the Byrne & Mason Thesis.

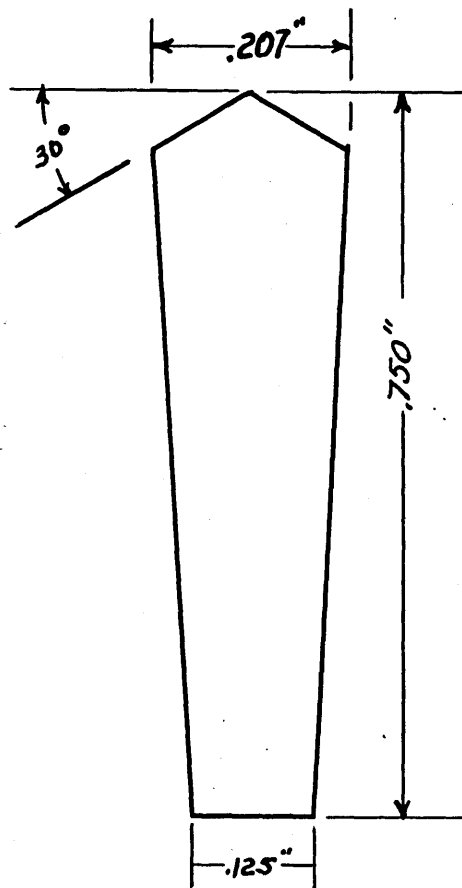


DIMENSION of ROTOR BARS
G.E. TYPE KG-326



DIMENSION of ROTOR BARS

G.E. TYPE KF-326



DIMENSION
of
ROTOR BARS
G.E. TYPE K-326