OSCILLATORY and TRANSIENT

PHENOMENA

in

DYNAMO CIRCUITS

by

James W. Macfarlane, Wh. Sc.,Dipl. R.T.C.

VOLUME I

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N O T E

Volume I of this thesis contains only the text, the Tables and Figures appearing in Volume II.

C O N T E N T S.

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OSCILLATORY & TRANSIENT PHENOMONA IN DYNAMO CIRCUITS

CHAPTER 1 - Introduction.

Oscillatory phenomena occurring in dynamo circuits, as in the case of the low frequency self-excitation of A.C. commutator apparatus or in the oscillatory discharge of welding or other types of D.C. dynamo, may be very troublesome. On the other hand, the principles involved may find useful employment in constructions such as the low frequency, self exciting, multi-phase commutator dynamos used for adjusting or barring, at very low, (but stable) speeds, of printing presses, paper mill calendars, and charging the baskets of hydro-extractors and sugar centrifugals. Dynamos of this class manufactured by the General Electric Co. of America are now in common use for many purposes and a paper describing such machines is included in The Transactions of the American Institution of Electrical Engineers[1] ,

([1] Hull, Vol.52, June,1933.)

Any new matter which can be brought to light by research must be of considerable interest and importance to engineers engaged in the design of dynamo-electric machinery. It may be suggested that very little of a novel nature remains to be discovered and that all the observed phenomena have already been explained with the aid of simple mathematics, (based mainly on the sinusoidal theory, that is, on linear differential equations with constant coefficients,) but that this cannot be the case and that any mathematical formula available can only be used generally to indicate what may happen under ideal conditions, is fully realised when the many assumptions which have to be made in order to handle the/

the formulae when deduced, are listed.

In practically all mathematical analysis used in connection with electrical machinery it is usual to assume that:-

(a) The effects of magnetic saturation are negligible.

(b) There is little or no eddy or iron loss in the field structure under flux changes.

(c) In commutator apparatus the effect of the m.m.f. of, or the loss in, the coils under commutation is negligible.

(d) The parameters of the dynamo circuits remain constant.

In everyday practice these assumptions are not even approximately true and if a dynamo is generating an oscillatory e.m.f., the loss in the commutated coils and the variation of the effective resistances and inductances may be so great as entirely to mask the calculated results.

Further, it is usual to assume that linear differential equations with constant coefficients are sufficient to give approximate solutions with corresponding numerical results and this assumtion is found to be reasonable provided the dynamo is not generating and maintaining oscillations of fixed amplitude. Generally, the linear equation has been found to give fairly accurate results, particularly for the amplitude if this is not oscillatory; or if oscillatory, having a large damping decrement.

If the e.m.f., or current in a dynamo circuit is oscillating and if it is correct to use the linear equation, then the prediction from this is that these quantities vary sinusoidally with time. That this prediction is seldom even approximately true is well known/

known, and brief consideration of the 2nd order equation shows why this should be the case.

$$\frac{d^2 i}{dt^2} + P\frac{di}{dt} + Qi = 0$$

is a linear differential equation of the 2nd order and the constant P for an ideal dynamo circuit is made up of resistance, self and mutual inductance terms. If sustained oscillations exist in this circuit, then, assuming Q positive, P must be equal to, and remain at, zero throughout, otherwise the oscillation would increase indefinitely or be damped out. This is an impossible condition and therefore the stable oscillations of defined amplitude which occur in practice, cannot follow a sinusoidal law, and therefore the linear theory fails to give even an approximate solution, particularly if P is negative and of relatively high numerical value within the oscillatory limit.

A paper on the maintenance of oscillations by Le Corbeiller[2],

([2] I.E.E., Journal, Vol. 79, Sept., 1936,)

goes into this matter very fully and it is pointed out that the inadequacy of the linear theory had already appeared to Lord Rayleigh as early as 1883[3],

([3] "On Maintained Vibrations" Vol. 15, p.229,)
(Philosophical Magazine,)

but that by adding to the linear equation a term protional to a higher power of the velocity, then the first stable oscillations of definite amplitude and frequency could be presented mathematically. The resulting equation is, of course, no longer linear, and its approximate solution includes a fundamental vibration and harmonics. A method of producing oscillations with the /

the assistance of a valve generator is given in Le Corbeiller's paper and if the volt-ampere characteristic of the generator is known approximately, a graphical method of solution of the equation, that is of obtaining the shape and periodicity of the resulting oscillation, is available. It is not the intention here to go more fully into this matter but only to emphasise the failure of the linear theory under oscillatory conditions, but it may be useful to mention the more nearly P approaches zero from the negative side, Q remaining positive, the more nearly will the resulting oscillation approach the sinusoidal.

The well known case of a low-frequency, self-exciting oscillatory circuit amploying a commutator machine is that of a series dynamo connected to a condenser, or a separately excited motor acting as such, and appears to have been first mentioned by Fitzgerald in a paper to the Physical Society in 1892[4],

([4] This paper has not been preserved in the Proceedings of the Society, but a report of it was published in La Lumiere Electrique, 1892.)

and later by Rüdenberg[5],

([5] Phys Zeits., 1907, p.668, also 1908, p.556.)

and B. van de Pol[6],

([6] "On Relaxed Oscillations," Zeitschrift für Hochfrequenz-technik, 1927, Vol.114,p.29.)

but it has occurred to the writer with his experience of special D.C. machines, and from his inspection of the possible values of P for dynamo circuits that there are at least 3 other methods for producing low-frequency oscillations from dynamos without the use of condensers. These 3 methods are enumerated below /

below. The experience referred to has been gained from two classes of machines recently introduced.

Class A. Self regulating or drooping characteristic dynamos for supplying the individual welding arc.

Class B. Constant current power dynamos.

These two classes are not as yet commonly known or fully developed and it is therefore proposed to mention briefly their leading features and their more important design details.

The 3 methods of producing low frequency oscillations from dynamos referred to above are:-

(1) Excitation of the field winding from the armature circuit through an impulse transformer.

(2) Insertion of a mutual inductance between the armature and field circuits of a shunt dynamo.

(3) By means of a forcing frequency in phase with the free frequency of the dynamo circuit.

In Chapter 2 of this thesis it is proposed to demonstrate mathematically that 1, 2, & 3 above are possible, and further it is proposed to obtain expressions for the static and dynamic volt-ampere characteristics of both welding and constant current dynamos, using these to predict the maximum amplitude of discharge during loading changes, and as an indication when oscillations may be produced and maintained. It will further be indicated that similar methods to those employed with constant current power dynamos for ensuring rapid response and rigid current supply can be applied to the excitation of alternators of any capacity resulting in the rapid response compounded alternator without special/

special regulators, and incidentally limiting the transient overshoot or short circuit current when a fault occurs in the feeders, without the use of reactors in these circuits. Alternators are mentioned here in order to point out that the principles uncovered in this investigation may have a much wider importance and application than it is possible to deal with in this thesis.

Before passing to Chapter 2 it may be useful to summarise the possible applications of this enquiry. These are mainly:-

(a) It will, in some cases, help to explain the tendency to self-excite in some classes of A.C. commutator machines.

(b) It will explain the self-excitation of low-frequency generators, such as the Hull[1] generator.

(c) In welding dynamos of reasonable design, it will be shown that calculations made by means of the linear theory can give reasonable results in estimating the transient departure from the prescribed static characteristic, and also indicate any tendency to self-excite in this type of machine.

(d) In constant current dynamos of the most recent design, calculations based on the linear theory will show any tendency to oscillate, and also indicate the cure. It is important to know in these machines the likely overshoot of the current when switching from the maximum to the minimum load, and a reasonable approximation may be obtained by the use of the simple theory.

(e) It will indicate alternative methods to those /

those now existing for improving the regulation of alternators and other machines.

NOTES ON THE TEXT & LIST OF MACHINES.

During this investigation 8 generators have been discussed, and 6 of these actually subjected to test, while the design and performance particulars of the remaining 2 were available. In order to identify these machines the scheme shown in TABLE 1. was adopted.

Throughout the text the symbol $\underline{\underline{i}}$ is used to represent current, and without a suffix indicates the current in the load circuit. With suffix 1 (i_1) it indicates the exciter field or abutment current. When i is used with suffix 2 (i_2) it always indicates the main generator secondary or field circuit.

The Heaviside operator p is used throughout in place of $\frac{d}{dt}$.

LIST OF SYMBOLS.

i or I	Current	Amps.
e or E	Electro-Motive force.	Volts.
r or R	Resistance.	Ohms.
L	Self Inductance.	Henries.
M	Mutual Inductance.	"
Z	Impedance = R + Lp	Ohms.
f	Frequency.	Cycles/sec.
ω	$= 2\pi f$.	
K	E.M.F. constant.	
v	E.M.F. due to residual magnetism.	Volts.
t	Time.	Seconds.
p	Heaviside operator = $\frac{d}{dt}$.	

In addition to this list various symbols are used as integration constants, etc., and these are individually defined where used.

As far as possible capital letters have been used to denote constant quantities, while small letters generally refer to variables.

CHAPTER 2.

Section 1.

CONSIDERATION OF THE POSSIBILITY OF PRODUCING AND MAINTAINING OSCILLATIONS BY A DYNAMO, THE FIELD OF WHICH IS EXCITED FROM ITS ARMATURE THROUGH AN IMPULSE TRANSFORMER.

Fig. 1 shows a skeleton diagram of the connections required, and it is assumed that :-

(1) The dynamo speed is constant.

(2) The field structure is laminated, and therefore the total e.m.f.,(e), generated by the armature may be taken as proportional to the field current.

(3) The e.m.f. due to residual magnetism can be represented by a small constant voltage $\underline{\underline{v}}$.

(4) The assumptions a,b,c, and d, on p.6 of Chapter 1 apply here.

Let:- i, i_2 , be the currents flowing in load, and field circuits respectively.

e, the total generated e.m.f.

R, R_2 , the resistances of the load and field circuits respectively.

L, L_2 , the inductances of the load and field circuits respectively.

The e.m.f., $\underline{e}$ is proportional to the m.m.f. on each pole of the dynamo, i.e. :-

$$e = K i_2 + v.$$

where K is constant.

Considering Fig. 1 , the e.m.f. $\underline{\underline{e}}$ is consumed by :-

(1) The impedance of the main circuit.

(2) The mutual inductive reactance of the field /

field circuit on the armature.

Therefore :-

$$K i_2 + v = Z i + M p i_2 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

also

$$0 = Z_2 i_2 + M p i \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

and from (2),

$$i_2 = -\frac{M p i}{Z_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where M is the mutual inductance of the impulse transformer, and may be positive or negative.

Eliminating $\underline{\underline{i_2}}$ from equation (1) we have :-

$$-K M p i + Z_2 v = Z Z_2 i - M^2 p^2 i$$

Introducing the values of Z and Z_2, gives :-

$$-K M p i + Z_2 v = (R + Lp)(R_2 + L_2 p) i - M^2 p^2 i .$$

and reducing we have :-

$$p^2 i + Ppi + Q(i - S) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where

$$P = \frac{R L_2 + R_2 L + K M}{L L_2 - M^2} ,$$

$$Q = \frac{R R_2}{L L_2 - M^2} ,$$

and

$$S = \frac{v}{R} .$$

$\underline{\underline{i_2}}$ can be obtained in terms of $\underline{\underline{i}}$ and $\underline{\underline{p i}}$ by eliminating $\underline{\underline{p i_2}}$ from equation (2). It has already been pointed out, (Chapter 1, p.3), that this analysis is valueless if maintained oscillations are present, except to show the possibility of producing these, and as the term containing P in equation (4) demonstrates this possibility there is no need to carry the analysis further in this instance. It should be noted that the term L_2 contains the inductance of the dynamo field, and therefore :-

$(L L_2 - M^2)$ and Q must always be positive. For P to be zero or negative :-

$$R L_2 + R_2 L + K M \; /$$

$$R\,L_2 + R_2 L + K\,M$$

must be zero or negative. There is little doubt that for some negative value of M this condition can be satisfied. Take for example generator A, (Table 1.) the parameters of which are known, and combine them with those of a chosen transformer so that the resistances and inductances of the completed circuits, as indicated in Fig. 1, can be used. If transformer figures are chosen at random, and P becomes zero, (Q remaining positive,) for a definite value of the circuit resistance R, then undoubtedly maintained oscillations will occur in practice with this combination.

To simplify the calculation, assume that the self-inductances of the primary and the secondary of this transformer are the same as those of the armature and field circuits of the generator, which are approximately $\frac{1}{10^3}$ and $\frac{2}{10}$ henries respectively. The primary and secondary resistances of the transformer may be taken as $\frac{5}{10}$ and $\frac{5}{10^3}$ ohms respectively. If the transformer is assumed to have a perfect magnetic circuit, (no leakage,) then :-

$$M = \sqrt{LpLs} = -\frac{1{\cdot}41}{10^2} \text{ henries.}$$

The complete circuit parameters for Fig. 1, (P equal to zero,) are now :-

$$R = ?\ \text{ohms.} \qquad R_2 = 1{\cdot}5\ \text{ohms.}$$

$$L = \frac{2}{10^3}\ \text{henries.} \qquad L_2 = \frac{4}{10}\ \text{henries.}$$

and from the open circuit characteristic of this machine, (Fig. 126,)

$$K = \frac{120\ \text{volts.}}{15\ \text{amps.}} = 8 \text{ approximately.}$$

(neglecting saturation.)

For $P = 0$.

$$R\,L_2 + R_2 L + K\,M = 0.$$

hence,/

hence,

$$R = \frac{2.75}{10} \text{ ohms.}$$

Using this value of R, we have now,

$$P = 0. \qquad Q = 690.$$

$$\sqrt{4\,Q} = 52.5 \qquad f = 8.35 \text{ cycles/sec.}$$

Although the linear theory indicates correctly that this dynamo will maintain oscillation, the frequency found by this means, (8.35 cycles/sec.,) is not necessarily correct, and may not even approximate to this value in practice.

As mentioned above, the figures used in this example were selected entirely at random, and a transformer with suitable constants is best found by experiment. When tests are made it is necessary to ensure that the field winding of the dynamo is coupled in the correct direction for excitation. It should also be noted that rocking the dynamo brushes back from the neutral will tend to help excitation and will further provide a limited control on the mutual inductance $\underline{\underline{M}}$, particularly if the dynamo is equipped with compensating windings.

CHAPTER 2.

Section 2.

CONSIDERATION OF THE POSSIBILITY OF PRODUCING AND MAINTAINING OSCILLATIONS IN A SHUNT WOUND DYNAMO CIRCUIT WITH MUTUAL INDUCTANCE BETWEEN THE ARMATURE, OR LOAD, CIRCUIT AND THE FIELD WINDING.

Figures 2 and 3 show skeleton diagrams of the connections. Figure 2 shows the transformer primary in the load circuit and Figure 3 shows the transformer primary in the armature circuit. These arrangements correspond to short and long shunt respectively.

It is assumed that :-

(1) Assumptions 1,2,3, and 4 of Section 1 apply.

(2) If a transient increase of the current traversing the primary of the transformer causes a decrease in that traversing the secondary, $\underline{\underline{M}}$ is positive and the windings are cumulative.

(3) If a transient increase of the current traversing the primary of the transformer causes an increase in that traversing the secondary, $\underline{\underline{M}}$ is negative and the windings are differential.

Let i, i_1, i_2, be the currents flowing in the load, armature, and field circuits respectively.

e, e_T, the total and terminal e.m.f's. generated respectively.

Z, Z_1, Z_2, the impedances of the load, armature and field circuits respectively.

R, R_1, R_2, the resistances of the load, armature and field circuits respectively.

Then considering the figure 2,/

figure 2,

$$e = Ki_2 + v = Z_1 i_1 + e_T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

also

$$e_T = Z_2 i_2 + Mpi = Zi + Mpi_2 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

and

$$i_2 = i_1 - i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

From (2) and (3) by eliminating i_2, we have,

$$i_1 = \left(\frac{Z - Mp}{Z_2 - Mp}\right) i + i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

From (1) and (3),

$$K(i_1 - i) + v = Z_1 i_1 + Z_2(i_1 - i) + Mpi \quad \ldots\ldots\ldots\ldots \quad (5)$$

Substituting the value of i_1 from (4) in (5) and reducing, we obtain,

$$p^2 i + Ppi + Q(i - S) = 0 \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

in which

$$P = \frac{RL_1 + R_1 L + RL_2 + R_2 L + R_1 L_2 + R_2 L_1 - 2R_1 M - KL + KM}{LL_1 + LL_2 + L_1 L_2 - 2L_1 M - M^2},$$

$$Q = \frac{RR_1 + RR_2 + R_1 R_2 - KR}{LL_1 + LL_2 + L_1 L_2 - 2L_1 M - M^2},$$

$$S = \frac{R_2 v}{RR_1 + RR_2 + R_1 R_2 - KR}.$$

For the connection shown in Figure 3, (long shunt conditions,) the constants P, Q, and S, become,

$$P = \frac{RL_1 + R_1 L + RL_2 + R_2 L + R_1 L_2 + R_2 L_1 + 2RM - KL + KM}{LL_1 + LL_2 + L_1 L_2 + 2LM - M^2},$$

$$Q = \frac{RR_1 + RR_2 + R_1 R_2 - KR}{LL_1 + LL_2 + L_1 L_2 + 2LM - M^2},$$

$$S = \frac{R_2 v}{RR_1 + RR_2 + R_1 R_2 - KR}.$$

If $\underline{\underline{M}}$ is made zero in the above expressions for P, the value of both short and long shunt couplings becomes/ the same and this is the value for a plain shunt dynamo. It is of interest to notice that P cannot in this case /

case become zero. From this it is inferred that a shunt dynamo cannot maintain oscillations of itself. As demonstrated in Section 1 (p.10) the denominator of P cannot be negative and the expression for the numerator in the case of a plain shunt dynamo is :-

$$RL_1 + R_1L + RL_2 + R_2L + R_1L_2 + R_2L_1 - KL \ .$$

This expression contains only one negative term, KL, but in such a machine where v is small,

$$K = R_2 \quad \text{(approx.)}$$

and the resulting expression,

$$RL_1 + R_1L + RL_2 + R_1L_2 + R_2L_1$$

is essentially positive.
Although a shunt generator may produce an oscillatory discharge under sudden changes of load it would thus appear that this condition cannot be maintained, whereas when mutual inductance is present between the armature and shunt circuits an inspection of the values that P may attain makes the maintenance of oscillation not only possible, but probable.

Theoretically also the series dynamo cannot produce and maintain oscillations without external aid, for if,

$$e = Ki = Zi \ \ldots\ldots\ldots\ldots\ldots \ (a)$$

is the equation for the total e.m.f. generated in the armature of a series dynamo, then,

$$Lpi + (R - K)i = 0 \ \ldots\ldots\ldots\ldots \ (b)$$

Differentiating (b) we have,

$$p^2 i + \left\{\frac{R - K}{L}\right\} pi = 0 \ \ldots\ldots\ldots\ldots \ (c)$$

from which it will be noted that,

$$Q = 0$$

hence oscillatory discharge or maintained oscillations are not possible.

Reverting to the values of P, Q, and S, derived from equation (6) for the long shunt (Fig. 3) and making/

making R and L each zero, that is, short circuiting the dynamo terminals, the numerator of P becomes :-

$$R_1 L_2 + R_2 L_1 + KM,$$

naturally, a similar expression to that obtained in Section 1.

As before, take for example, generator A the parameters of which for neutral brush position are as follows :-

$R_1 = 3.5.$ ohms.		$L_1 = \frac{1}{10^3}$	henries.
$R_2 = 1$ ohm.		$L_2 = \frac{2}{10}$	henries.

and using the figures for the transformer assumed previously (p.11,) the circuit parameters become :-

SHORT SHUNT.		LONG SHUNT.	
$R = ?$	$L = \frac{1}{10^3}$	$R = ?$	$L = 0$
$R_1 = \frac{3.5}{10^2}$	$L_1 = \frac{1}{10^3}$	$R_1 = \frac{4}{10^2}$	$L_1 = \frac{2}{10^3}$
$R_2 = 1.5.$	$L_2 = \frac{4}{10}$	$R_2 = 1.5$	$L_2 = \frac{4}{10}$
$M = -\frac{1.41}{10^2}$		$M = -\frac{1.41}{10^2}$	

In a shunt machine, K is approximately R_2. If, however, the generator A was run at its normal speed of 3000 r.p.m., the field winding, if directly connected across the brushes, would be seriously overloaded, but this may be easily overcome in practice by running the machine at a much lower speed.

SHORT SHUNT for P = 0,

$$R(L_1 + L_2) + R_1 L + R_1 L_2 + R_2 L_1 - 2R_1 M + KM = 0$$

and $Q = \dfrac{RR_1 + R_1 R_2}{LL_1 + LL_2 + L_1 L_2 - 2L_1 M - M^2}$, always positive.

LONG SHUNT for P = 0

$$R(L_1 + L_2 + 2M) + R_1 L_2 + R_2 L_1 + KM = 0$$

and $Q = \dfrac{RR_1 + R_1 R_2}{LL_1 + LL_2 + L_1 L_2 - 2LM - M^2}$, always positive.

It is clear that in both these cases, the value of/

of P can be zero and Q is always positive, therefore maintained oscillations are to be expected.

Completing the calculations for $P = 0$,

SHORT SHUNT.		LONG SHUNT.	
R	$= \frac{1.12}{10^2}$	R	$= \frac{5.9}{10^3}$
Q	$= 84$	Q	$= 100$
$\sqrt{4Q}$	$= 18.35$	$\sqrt{4Q}$	$= 20$
f	$=$ 2.9 cycles per sec.	f	$=$ 3.2 cycles per sec.

The same reservations apply here as were applied the result of the example in Section 1 (p.12.)

CHAPTER 2.

Section 3.

CONSIDERATION OF THE POSSIBILITY OF PRODUCING AND MAINTAINING OSCILLATIONS IN A DYNAMO CIRCUIT CONTAINING NO MUTUAL INDUCTANCE BY MEANS OF A FORCING FREQUENCY IN PHASE WITH FREE FREQUENCY OF THE CIRCUIT.

It has been indicated in the preceeding sections that maintained oscillatory currents are to be expected under certain conditions from the proposed circuits, and if such oscillations occur the residual magnetisms of the field systems of the dynamos in question will change with each current reversal.

It will be indicated later that even with separately excited dynamos the generation of maintained oscillations is possible if mutual inductance or a forcing impulse is present. In dynamos of ordinary construction having series windings on the poles or with brushes displaced from the neutral, mutual inductance between the armature and field windings is always present. The most convenient way in which to provide a forcing frequency in phase with the free frequency of the load or armature circuit is to transmit to the field system of the dynamo a magnetising impulse by means of a series winding in the armature or load circuit but as previously mentioned this would introduce mutual inductance which will, at least, complicate the problem. If however, the dynamo is so constructed that the shunt and series windings occupy separate magnetic systems, the interference between these windings is eliminated. Such machines are actually in use, and Figure 4 indicates a suitable arrangement.

The skeleton connection diagrams, Figures 5, and 6, are those of compound wound machines with short and/

and long shunt couplings.

It is assumed that,

(1) Assumptions 1, 2, and 3, of Section 2 apply.

(2) Mutual inductance has been eliminated by special construction, (such as indicated in Figure 4,) or by means of an injection transformer.

Let i, i_1, i_2, be the currents flowing in the load, armature, and field circuits respectively.

e, e_T, the total and terminal e.m.f's. generated respectively.

Z, Z_1, Z_2, the impedance of load, armature, and field circuits respectively.

R, R_1, R_2, the resistance of the load, armature and field circuits respectively.

L, L_1, L_2, the inductances of the load, armature, and field circuits respectively.

N, the ratio $\frac{\text{Series}}{\text{Shunt}}$ turns.

Then considering Figure 5, we have,

$$Z = R + Lp, \quad Z_1 = R_1 + L_1 p, \quad Z_2 = R_2 + L_2 p$$

Also

$$e = K(i_2 + Ni) + v = Z_1 i_1 + e_T \quad \text{.................. (1)}$$

and

$$e_T = Z_2 i_2 = Zi \quad \text{.............................. (2)}$$

and

$$i_2 = i_1 - i \quad \text{.................................. (3)}$$

By eliminating i_2 from (2) and (3),

$$i_1 = \frac{Zi}{Z_2} + i \quad \text{.................... (4)}$$

and from (1) and (3) we have,

$$K(i_1 - i + Ni) + v = Z_1 i_1 + Zi \quad \text{............... (5)}$$

Substituting the value of i_1 from (4) in (5) and reducing gives,/

gives,

$$KZi + KNZ_2 i + Z_2 v = ZZ_1 i + ZZ_2 i + Z_1 Z_2 i ,$$

giving the Z's their values and reducing gives,

$$p^2 i + Ppi + Q(i - S) = 0 \quad \dots\dots\dots\dots\dots\dots\dots\dots(6)$$

where

$$P = \frac{RL_1 + R_1 L + RL_2 + R_2 L + R_1 L_2 + R_2 L_1 - KL - KLN}{LL_1 + LL_2 + L_1 L_2} ,$$

$$Q = \frac{RR_1 + RR_2 + R_1 R_2 - KR - KNR_2}{LL_1 + LL_2 + L_1 L_2} ,$$

and

$$S = \frac{R_2 v}{RR_1 + RR_2 + R_1 R_2 - KR - KNR_2} .$$

For the connection shown in Figure 6, (long shunt conditions,) the constants P, Q, and S, become :-

$$P = \frac{RL_1 + R_1 L + RL_2 + R_2 L + R_1 L_2 + R_2 L_1 - KL - KNL - KNL_2}{LL_1 + LL_2 + L_1 L_2} ,$$

$$Q = \frac{RR_1 + RR_2 + R_1 R_2 - KR - KNR - KNR_2}{LL_1 + LL_2 + L_1 L_2} ,$$

and

$$S = \frac{R_2 v}{RR_1 + RR_2 + R_1 R_2 - KR - KNR - KNR_2} .$$

If N is made zero in the expression for P and Q the values for both short and long shunt couplings become the same and these are the values for a plain shunt machine. As in section 2, maintained oscillations are not possible.

In this case, as in the preceeding sections, the denominator of P is always positive. Considering the long shunt machine, (Figure 6,) and making R and L zero, (short circuiting the dynamo terminals,) the numerator of P becomes,

$$R_1 L_2 + R_2 L_1 - KNL_2$$

naturally a similar expression to those obtained in /

in sections 1 and 2, (pp10,16,) indicating that the problems are similar, and that maintained oscillations are also possible in this case.

An examination of the values of P and Q for both short and long shunts indicates, particularly in the latter case, that it would be difficult to make P zero or negative, without affecting Q similarly. It is not however, to be inferred from this that maintained oscillations are not possible, as the mathematics merely indicates that it is not possible to produce maintained oscillations in a generator with a level or rising volt-ampere characteristic. It is to be noted in this connection that only positive values of N, (cumulative winding,) will reduce the value of P to zero or less, which indicates that maintained oscillatory conditions can only appear in a generator having a falling characteristic.

This statement may be clarified if it is realised that under any vibratory conditions two stores of energy are essential, one of which is in a position to receive the energy given out by the other. In the case of dynamo circuits these two sources are clearly,

(1) the field magnetic system, and

(2) the load and armature circuits including their magnetic systems.

Under suitable conditions there can be an energy exchange between these in such a manner that when the field magnetism is falling, the armature, compensating, and other conductors are storing lines around them, thus absorbing the energy excess released from the field.

The necessary condition for oscillatory discharge in this case is a falling field magnetism, or generated e.m.f., accompanied by an increase in the armature /

armature current. To convert this discharge into a maintained oscillation a further condition is required, and this is, that a forcing frequency of the same period and approximately the same phase is necessary. Mathematical investigation shows that an impulse provided by a suitably disposed series winding is sufficient to maintain oscillations once started.

It may be of some interest at this stage to compare the proposed method with the usual electrical, or R-L-C, method of producing and maintaining oscillations. In the former both energy stores are magnetic and together with the maintaining mechanism contained within the generator itself may be termed, "resonance excitation." In the latter, a condenser, inductance and alternator are required, the alternator terminal voltage providing the forcing inpulse. The transformer method discussed in Sections 1 and 2 is also a form of resonance excitation, the only difference between the two being that the field obtains its impulse through the transformer secondary when correctly coupled. An example will serve to illustrate this point.

Suppose a dynamo, connected as in Figure 2, is running on open circuit and is suddenly short circuited. If the transformer secondary is coupled so that $\underline{\underline{M}}$ is negative, there will be an immediate positive impulse impressed on the field winding similar to that which would be due to an increasing load current in a cumulatively connected series winding. Immediately after the short circuiting switch is closed, the field magnetism is falling but the actual m.m.f. of the field winding is increasing --- exactly what happens in the case under discussion.

So far in this section the absence of the equations for a cumulatively wound drooping characteristic machine/

machine has prevented the working out of a numerical example. In Section 5 however, the equations for a separately excited welding generator are given, and it is clearly indicated there that, even when separately excited, such a machine can be arranged to start and maintain oscillations. In Section 5 the necessary conditions, (cumulative compound winding and falling characteristic,) are obtained by means of a negative e.m.f., proportional to the load current, injected into the separately excited field winding.

CHAPTER 2.

Section 4.

MATHEMATICS OF THE GENERAL CASE OF A COMPOUND MACHINE HAVING MUTUAL INDUCTANCE & SERIES IMPULSE.

The connection diagrams shown in Figures 5 and 6 apply in this case, but the circuit equations require modification to include the existance of mutual inductance between the shunt and series windings.

SHORT SHUNT CASE. Figure 5.

Using the symbols shown in Section 3, (p.19), the equations are :-

$$e = K(i_2 + Ni) + v = Z_1 i_1 + e_T \quad \ldots\ldots\ldots\ldots (1)$$

$$e_T = Z_2 i_2 + Mpi = Zi + Mpi_2 \quad \ldots\ldots\ldots\ldots (2)$$

$$i_2 = i_1 - i \quad \ldots\ldots\ldots\ldots (3)$$

From equations (2) and (3) eliminating i_2 we have,

$$i_1 = \left(\frac{Z - Mp}{Z_2 - Mp}\right) i + i \quad \ldots\ldots\ldots\ldots (4)$$

From equations (1) and (3) we have,

$$K(i_1 - i + Ni) + v = Z_1 i_1 + Z_2(i_1 - i) + Mpi \quad ..(5)$$

substituting the value of i_1 from (4) in (5) and reducing gives,

$$p^2 i + Ppi + Q(i - S) = 0 \quad \ldots\ldots\ldots\ldots (6)$$

where

$$P = \frac{RL_1 + R_1L + RL_2 + R_2L + R_1L_2 + R_2L_1 - 2R_1M - KL + KM - KNL_2 + KNM}{LL_1 + LL_2 + L_1L_2 - 2L_1M - M^2}$$

$$Q = \frac{RR_1 + RR_2 + R_1R_2 - KR - KNR_2}{LL_1 + LL_2 + L_1L_2 - 2L_1M - M^2},$$

and

$$S = \frac{R_2 v}{RR_1 + RR_2 \quad R_1R_2 - KR - KNR_2}.$$

LONG SHUNT CASE. Figure 6.

$$e = K(i_2 + Ni_1) + v = Z_1 i_1 + Mpi_2 + e_T \quad \ldots\ldots\ldots (1)$$

$$e_T = Z_2 i_2 + Mpi_1 = Zi \quad \ldots\ldots\ldots (2)$$

$$i_2 = i_1 - i \quad \ldots\ldots\ldots (3)$$

From equations (2) and (3) eliminating i_2 we have,

$$i_1 = \left(\frac{Z + Z_2}{Z_2 + Mp}\right) i \quad \ldots\ldots\ldots (4)$$

from (1) and (3) we have,

$$K(i_1 - i + Ni_1) + v = Z_1 i_1 + Mp(i_1 - i) + Zi \quad \ldots\ldots (5)$$

Substituting the value of i_1 from (4) in (5) and reducing gives,

$$p^2 i + Ppi + Q(i - S) = 0 \quad \ldots\ldots\ldots (6)$$

where

$$P = \frac{RL_1 + R_1 L + RL_2 + R_2 L + R_1 L_2 + R_2 L_1 + 2RM - KL + KM - KNL - KNL_2}{LL_1 + LL_2 + L_1 L_2 + 2LM - M^2},$$

$$Q = \frac{RR_1 + RR_2 + R_1 R_2 - KR - KNR - KNR_2}{LL_1 + LL_2 + L_1 L_2 + 2LM - M^2},$$

and

$$S = \frac{R_2 v}{RR_1 + RR_2 + R_1 R_2 - KR - KNR - KNR_2}.$$

This section is chiefly interesting because the results developed here contain the results of the three preceding sections.

The reasons for developing the argument in this way are :-

(1) To simplify it.

(2) To show and discuss separately the three different methods by which maintained oscillations can be produced.

An inspection of the values of P and Q in this /

this section for both shunt couplings show that, with cumulative series windings involving also positive mutual inductance, that it will be more difficult to produce oscillations than with the series impulse removed to a separate magnetic system, (see Figure 4,) where $\underline{\underline{M}}$ is absent.

It follows therefore that with compound wound machines as usually constructed, self-excitation on low frequency will not readily occur.

CHAPTER 2.

Section 5.

CONSIDERATION OF THE PRINCIPLES INVOLVED IN THE DESIGN OF DROOPING CHARACTERISTIC WELDING DYNAMOS FOR SUPPLYING INDIVIDUAL METAL ARCS, WITH A BRIEF DESCRIPTION OF SOME RECENT MACHINES.

EQUATIONS FOR ARMATURE AND FIELD CURRENTS BASED ON THE LINEAR THEORY.

EFFECTS OF SUDDEN LOAD CHANGES IN THE CIRCUITS OF A DYNAMO WITH LAMINATED FIELD SYSTEM AND COMPENSATING WINDINGS.

POSSIBILITY OF MAINTAINED OSCILLATIONS WITH SEPARATE EXCITATION AND DUE TO MUTUAL INDUCTANCE OR SERIES IMPULSE.

The drooping characteristic or direct current self regulating dynamo for supplying individual welding arcs is of recent introduction and is now almost universally employed where A.C. power supplies are not available and even in many cases where such supplies are to hand.

A reduction in the circuit voltage of this machine usually takes place through a reduction in the field magnetism and if the change takes place quickly, a sudden increase, beyond normal, of the load current is usually due to the magnetic energy discharge of the field. The discharge of such machines is analogous in many respects to the classical case of the Leyden jar, and may follow approximately,

(1) an exponential law,

(2) a damped oscillatory law,

(3) a damped oscillatory law on a displaced base.

If, in particular, mutual inductance between the primary and secondary circuits is present, the load current may be made to oscillate violently and continuously at a value and frequency depending on the load and other circuit conditions.

Low frequency current surging has been brought to the notice of welding operators by the mechanical /

mechanical impulse transferred to the hand controlling the electrode.

In welding with the metal arc it is essential that the machine characteristic must intersect the arc characteristic, otherwise the arc will be extinguished. Surging of the arc current is therefore undesirable. Further, the recovery from short to open circuit voltage must be reasonably fast in order to maintain a satisfactory arc. It has now been fairly well established that if the overshoot of the dynamo characteristic is not more than twice the steady short circuit value when switching from open circuit, this will be satisfactory, also an almost instantaneous recovery from short circuit to over 30 volts with a gradual rise to full open circuit voltage in about $\frac{1}{4}$th second thereafter represents satisfactory operation,[7]

([7] Willey, "Electric Arc Welding Machines" The Welding Industry, Vol. 4, No. 5, June, 1936.)

Modern types of drooping characteristic welding dynamos can be included under the following heads :-

(1) Separately excited, differentially wound,[8]

(2) Separately excited, split pole type,[8]

(3) Cross-field, or Rosenberg type,

(4) Self excited, compound, cumulatively wound.

([8] Third brush excitation is occasionally used in place of separate excitation.)

Type (1) is represented by the diagram of connections shown in Figure 7, the dotted lines showing the possible addition of an impulse transformer which is frequently added to reduce the mutual inductance of the differentially wound field windings of the dynamo.

The Rosenberg dynamo is described in many /

many publications[9] ,

([9] Elektrotechnishe Zeitshrift, Vol.26, p.393,(1905) and Vol.27, p.1035, (1906.) The Electrician, Vol.55, p.297, (1905,) and Vol.58 p.372, (1906.))

while the self excited compound dynamo is chiefly interesting because the mutual inductance of the field windings is helpful and tends to eliminate transient departure from the steady state characteristic without the use of an impulse transformer.

Referring again to type (1), (Figure 7,) and assuming the absence of magnetic saturation, the volt-ampere characteristic is approximately linear and adjustment of the current for various sizes of electrodes is usually obtained by diverting the series opposition winding and varying the resistance of the separately excited field.

Type (2) has also an approximately linear volt-ampere characteristic but the current adjustment in this case is usually obtained by movement of the dynamo brushes. The auxiliary poles of this machine are simply wide interpoles, and if the brushes are moved forward from the centre position the interpole flux creates a back e.m.f. in the armature conductors and at the same time a portion of the armature m.m.f. opposes the main pole m.m.f. Due to this double effect, the current value for a given voltage is sensitive to brush position.

In type (3) the shape of the volt-ampere characteristic, and the method of current adjustment are well known.[9]

In type (4) the drooping characteristic is usually obtained by a fairly high internal and a stabilising external resistance. The high internal resistance enables the shunt windings automatically to control the /

the terminal voltage to give at least the characteristic required for maximum current operation and the external resistance provides stability at low values of the field flux. Series, or partly series, and shunt field regulation give the necessary adjustment for smaller current values.

Figure 9 shows the coupling arrangement of the machine which it is now proposed to examine more particularly. The machine is provided with a laminated stator having compensating and field windings contained in slots. The compensating winding allows the generator to be designed with a strong armature, a weak field, and a small air-gap, and also the provision of a series opposition m.m.f. from the armature, if desired, by rocking the brushes forward of the neutral. The amount of brush movement from the neutral need only be small because,

(a) there is a back m.m.f. present,

(b) there is some flux from the compensating winding creating an opposition e.m.f.,

(c) the armature may be strong, and the field weak,

(d) it may be of the copper-type design, the internal IR drop of the machine is high at maximum short circuit current.

The field winding is supplied directly from a shunt wound exciter giving an approximately constant e.m.f., of much lower value than the main generator open circuit voltage [10] ,

([10] Figure 9 shows this exciter replaced by a battery.)

Examining Figure 9, when the regulating contact X is at O and the brushes suitably set, the welding generator will operate on its maximum volt-ampere /

volt-ampere characteristic. As the point X moves along the resistance OY, for every position in which it rests, there will be a new volt-ampere characteristic. Not only does the variable resistance OX provide a small amount of series control, but the drop across it provides a back e.m.f. in the main generator field itself, reducing the current in it to nearly zero on short circuit for a comparatively small drop in the series resistance.

If, for example, the exciter gives 10 volts at its terminals, and the open circuit e.m.f. of the generator is 60 volts, the regulator will only require to deal with 1/6th of the energy loss that would be necessary for pure series regulation alone between the voltage of the maximum characteristic and the point considered.

This method of control gives,

(a) A large range of current values with a single handle adjustment and low watt control,

(b) approximately the same open circuit voltage for all sizes of electrodes,

(c) efficient operation for all sizes of electrodes.

In the interests of power consumption it is better to obtain the maximum volt-ampere characteristic by giving the generator brushes sufficient forward lead, but the machine can be conveniently arranged to give a drooping characteristic with the brushes either at, or back from, the neutral with some loss in operating efficiency in each case. This is done by increasing the resistance OY, and preferably limiting the travel of X to some point O_1 , the resistance of OO_1 being sufficient to obtain the maximum desired volt-ampere characteristic.

Oscillograph records can be made for several brush/

brush positions equivalent to the mutual inductance between the field winding, the back armature m.m.f., being positive, zero, or negative. The equations representing these three conditions are given below.

CALCULATION BY MEANS OF THE LINEAR EQUATION OF ARMATURE AND FIELD CURRENTS IN A DROOPING CHARACTERISTIC WELDING GENERATOR OF THE COMPENSATED TYPE.

Let i, i_2 , be the currents in the armature and field circuits respectively,

Z, Z_2 , the impedances of the armature and field circuits respectively. Z_2 does not include the variable resistance OX.

r, the resistance of OX,

E_2, the constant exciter voltage,

n_2, the total number of turns on the generator field winding,

n, the equivalent effective turns of the armature winding produced by displacement of the brushes.

N, the ratio n/n_2 ,

e_T the terminal voltage of the generator,

e, the total generated e.m.f., and is proportional to the m.m.f., of each pole of the generator.

Then

$$e = K(i_2 + Ni)$$

where N may be positive (cumulative.)
negative (opposed.)
or zero.

The e.m.f., e is consumed by,

(1) the impedance of the main circuit,

(2) the mutual inductive reactance of the main field circuit on the armature, and

(3) by the IR drop over OX which is /

is

$$r(i + i_2), \text{ therefore,}$$

$$e = K(i_2 + Ni) = Zi + Mpi_2 + r(i + i_2) \quad \ldots\ldots (1)$$

$$E_2 = Z_2 i_2 + Mpi + ri \quad \ldots\ldots (2)$$

from (2) we have,

$$i_2 = \frac{E_2 - Mpi - ri}{Z_2} \quad \ldots\ldots (3)$$

Substituting the value of i_2 from (3) in (1) gives,

$$K(E_2 - Mpi - ri + Z_2 Ni) = ZZ_2 i - M^2 p^2 i - 2rMpi + Z_2 ri + rE_2 - r^2 i \quad \ldots.(4)$$

Replacing Z, Z_2, by their values and reducing gives,

$$p^2 i + Ppi + Q(i - S) = 0 \quad \ldots\ldots (5)$$

where

$$P = \frac{RL_2 + R_2 L + rL_2 + KM - KNL_2 - 2rM}{LL_2 - M^2},$$

$$Q = \frac{RR_2 + rR_2 + Kr - KNR_2 - r^2}{LL_2 - M^2},$$

and

$$S = \frac{E_2 (K - r)}{RR_2 + rR_2 + Kr - KNR_2 - r^2}.$$

$$i = S = \frac{E_2 (K - r)}{RR_2 + rR_2 + Kr - KNR_2 - r^2} \quad \ldots\ldots (6)$$

is a solution of equation (5) for static conditions.

To obtain the static volt-ampere characteristic, suppose the arc replaced by an external resistance $R_{Ext.}$ so that R becomes,

$$R = R_{Ext} + R_{Int}$$

Then

$$i = \frac{E_2 (K - r) - R_2 e_T}{R_2(R_{Int} + r - KN) + Kr - r^2} \quad \ldots\ldots (7)$$

from which $i = 0$ gives the light load, or open /

open circuit voltage.

$$e_T = \frac{E_2}{R_2}(K - r) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

and when $e_T = 0$, the short circuit current is given by,

$$i = \frac{E_2 \; (K - r)}{R_2 \; (R_{Int} + r - KN) + Kr - r^2} \quad \ldots\ldots\ldots\ldots \quad (9)$$

The expressions for the values of P, Q, and S, can be simplified for both neutral and forward brush positions. When the brushes are in the neutral, $\underline{N}$ and $\underline{M}$ are zero giving,

$$P = \frac{RL_2 + R_2L + rL_2}{LL_2},$$

$$Q = \frac{RR_2 + rR_2 + Kr}{LL_2},$$

$$S = \frac{E_2 \; (K - r)}{RR_2 + rR_2 + Kr}$$

When the brushes are forward $\underline{r}$ may be zero to give the maximum characteristic, and P, Q, and S become,

$$P = \frac{RL_2 + R_2L + KM - KNL_2}{LL_2 - M^2},$$

$$Q = \frac{RR_2 - KNR_2}{LL_2 - M^2},$$

and

$$S = \frac{KE_2}{RR_2 - KNR_2}.$$

It should be noted that when the brushes are back from the neutral the values for P, Q, and S, are unchanged and $\underline{N}$ and $\underline{M}$ are to be considered positive whereas for the forward brush positions, both $\underline{N}$ and $\underline{M}$ are negative.

$\underline{i_2}$ may be obtained in terms of $\underline{i}$ and $\underline{pi}$ by /

by eliminating pi_2 from equation (2), and is given by

$$i_2 = Upi + Vi + W \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where

$$U = \frac{LL_2 - M^2}{\phi},$$

$$V = \frac{RL_2 + rL_2 - rM - KNL_2}{\phi},$$

$$W = \frac{ME_2}{\phi},$$

and

$$\phi = R_2M + KL_2 - rL_2 .$$

The general solution of equation (5) for oscillatory conditions is

$$i = A\theta_1 + B\theta_{11} + S \quad \ldots\ldots\ldots\ldots (11)$$

where $\theta_1 = e^{bt} \sin\omega t$

and $\theta_{11} = e^{bt} \cos\omega t$,

also

$$i_2 = (AbU - B\omega U + AV)\theta_1 + (A\omega U + BbU + BV)\theta_{11} + (VS + W) \quad \ldots\ldots (12)$$

which is obtained by inserting the value of i and pi, equation (10).

The equations for this section have been worked out completely, as they will be freely used later.

Meanwhile the possibility of producing maintained oscillations with separate excitation due to

(1) Mutual Inductance between load and field circuits.

and (2) A forcing frequency due to the current in the load circuit,

will be investigated

(1) Consider again the dynamo of the welding generator unit A and use the figures for the /

the transformer already assumed and employed in previous sections. The connection diagram is again Figure 9, with the addition of the transformer between the load and field circuits.

The table below gives the circuit parameters including the transformer figures, and for the neutral brush position.

R	=	?	L	=	$\frac{2}{10^3}$
R_2	=	1.5	L_2	=	$\frac{4}{10}$
r	=	$\frac{2.6}{10^2}$	M	=	$-\frac{1.41}{10^2}$

$$K = 8$$

For $P = 0$

$$RL_2 + R_2L + rL_2 + KM - 2rM = 0$$

from which

$$R = \frac{2.5}{10} \text{ ohms.}$$

We have now,

P	=	0	Q	=	1040
$\sqrt{4Q}$	=	64.5	f	=	10.3 cycles/sec.

Regarding this frequency, the same reservations apply here as were applied to the result of the example in Section 2, (p. 19.)

(2) For this example consider generator A, again coupled as a separately excited machine, (Figure 9.) Table 33 provides the parameters for neutral brush position. It is assumed that a series impulse is imposed without the introduction of magnetic linkage with other field windings.

For these conditions,

$$P = \frac{RL_2 + R_2L + rL_2 - KNL_2}{LL_2},$$

/

$$Q = \frac{RR_2 + rR_2 + Kr - KNR_2 - r^2}{LL_2}.$$

For $P = 0$,

$$RL_2 + R_2L + rL_2 - KNL_2 = 0 ,$$

hence,

$$N = \frac{RL_2 + R_2L + rL_2}{KL_2} .$$

The value of N can be calculated from the circuit parameters of the generator for neutral brush position, assuming for convenience that it is operating without external load.

The parameters are :-

R	=	$\frac{3.5}{10^2}$	L	=	$\frac{1.3}{10^3}$
R_2	=	1	L_2	=	$\frac{2}{10}$
r	=	$\frac{2.6}{10^2}$	K	=	8

Turns in field winding are 120, hence :-

$$N = \frac{8.4}{10^3}$$

By definition N = number of series turns/number of field turns.

Therefore,

Series Turns = Unity (approximately.)

We have now,

P	=	0.	Q	=	775
$\sqrt{4Q}$	=	55.7	f	=	8.9 cycles/sec.

By the provision of the auxiliary core suggested in Section 3, Figure 4, to addomodate the series impulse turn, the R and L values used above would be materially altered, particularly if the second, or "booster", core is made of the same dimensions as the first. However, by making

$R = \frac{5}{10^2}$ ohms and $L = \frac{2.6}{10^3}$ henries a reasonable allowance would be provided for the proposed alteration. Using these figures, the new value of N and the frequency are respectively,

$$N = \frac{1.8}{10^2} \qquad f = 2.6 \text{ cycles/sec.}$$

In practice however, to provide for an impulse in this manner, the booster core need not be more than about 10% of the length of the main core, and therefore the new values of R and L need not be appreciably greater then the original values for this dynamo.

The linear theory indicates quite clearly that (2) is not only possible but probable where and when the essential conditions are fulfilled, namely

(a) where the generator discharge is naturally oscillatory,

(b) when the generator has a drooping volt-ampere characteristic, as in the case just discussed.

CHAPTER 2.

Section 6.

CONSIDERATION OF THE PRINCIPLES INVOLVED IN THE DESIGN OF CONSTANT CURRENT POWER DYNAMOS WITH SPECIAL REFERENCE TO THE METHODS OF EXCITATION EMPLOYED IN ORDER TO OBTAIN QUICK RESPONSE TO SUDDEN LOAD CHANGES.

EQUATIONS FOR THE ARMATURE, FIELD, AND ABUTMENT CURRENTS BASED ON THE LINEAR THEORY.

THE CAUSE AND CURE OF THE TENDENCY TO SELF-EXCITE AND PRODUCE LOW FREQUENCY OSCILLATIONS IN SOME CONSTANT CURRENT DYNAMOS.

Since the time of Thury's[11] early transmission system employing dynamos and motors with electro-mechanical

([11] Highfield - "Transmission of Energy")
(Journal I.E.E., Vol.38,1907 p. 471)

brush moving gears, constant current systems utilizing dynamos and motors (of more orthodox design have been introduced) for driving machines which require to be stalled frequently under limited torque and which also have to work through a considerable speed range.

Many thousands of horse power of electric motors are now working on constant current D.C. circuits, operating dock gates, capstans, caissons, diggers and ships' machinery on some of the largest liners afloat.

Of these systems the modern Thury, the Alsthom, (French Thomson-Houston Company,) and the Austin have had considerable application.

The Austin dynamo is a simplification of the Thury and assuming a source of constant voltage supply, consists of a main dynamo the field of which is supplied from a differentially wound exciter of special design. Figure 10 shows the skeleton connection diagram for the Austin system, while Figure 11 gives that for the Thury. Inspection of these diagrams shows that the Austin is merely the Thury without the impulse transformer /

transformer, T, and compound winding C. The absence of these two units is made up in the Austin system by the special exciter design.

Regarding the Alsthom system, this consists of a special convertor on Metadyne, (not a dynamo,) used to convert a constant voltage supply to one of [redacted] constant current. Since this apparatus is of limited application it is not proposed to deal with it here.

SOME DESIGN CONDITIONS AFFECTING QUICK RESPONSE UNDER SUDDEN LOAD CHANGES.

In large constant current power dynamos the energy stored in the magnetic field is considerable and its release may cause considerable damage if proper steps are not taken for it's control. To obtain quick response it is desirable that :-

(a) The field system of the main generator, at least, should be completely laminated,

(b) the armature cross field should be eliminated by means of compensating windings, and

(c) the design should follow generally that of single phase A.C. commutator motors where applicable.

When suitable compensating windings are used copper-type designs are possible, and this leads to the following advantages :-

(1) For a given number of poles, the flux per pole and air gap length can be reduced and the inductance, stored energy, and time of building up the field will then vary rapidly with variations in these quantities.

(2) Although the introduction of the compensating winding reduces the inductance of the armature /

armature winding, the added inductance due to the increased armature strength, along with the leakage of the compensating winding itself, together compensate for the loss of the cross field.

(3) The reduced commutator section voltage due to the absence of field distortion is an important improvement in large constant current power dynamos.

(4) The extra iron loss due to distortion in uncompensated machines is absent.

(5) By using distributed field and compensating windings, and skewing the stator slots one slot pitch, the amplitude of the polar flux pulsation is reduced to a minimum.

As (1) is of some considerable importance it may be of interest to indicate, by means of an example, the rate of variation of the quantities mentioned. These can be expressed in designer's terms thus :-

$$L \text{ (henry)} = \frac{\phi \times ATs}{i^2 \times 10}$$

$$P = \text{Energy/pole, (watt seconds)} = \frac{\phi \times ATs}{2 \times 10^8}$$

Time to build up field to 90% of full value

$$= t = \frac{2.3 \times \phi \times ATs}{w \times 10^8}$$

where ϕ = flux per pole, (c.g.s. lines)

ATs = ampere turns/pole

i = current in winding, (amps)

w = energy loss in each field coil

= $i^2 r$ watts.

Assume that by the assistance of a compensating /

compensating winding the armature strength is doubled, the air gap length is halved, and by using a ballast resistance in the field circuit, the current $\underline{\underline{i}}$ and the watts w are increased by 100%. The new values become,

$$L_1 = L \times \frac{1}{2} \times \frac{1}{4} \times \frac{1}{4} = \frac{1}{32} L$$

energy, $$P_1 = P \times \frac{1}{2} \times \frac{1}{4} = \frac{1}{8} P$$

and $$t_1 = t \times \frac{1}{2} \times \frac{1}{4} \times \frac{1}{2} = \frac{1}{16} t$$

COMPARISON WITH A.C. DESIGN PRACTICE.

A comparison with A.C. practice is useful when considering the design of these dynamos, for they work under conditions in which the field flux is, or may be, changing rapidly. Thus with A.C. commutator motors it is usual to keep the flux per pole as low as possible by increasing the armature strength and the number of poles. It is also usual to provide the armature with :-

(a) an odd number of coils per slot,

(b) a winding pitch other than a multiple of the number of slots,

(c) a fractional pitch winding sufficiently short to reduce to a minimum the mutual inductive effect of the coils under commutation.

These minimize the perturbing effects of the commutation phenomena when the flux is changing.

In a constant current power circuit it is usual to switch the motor from full power in one direction to full power in the opposite direction/

direction and this is not a condition which affects the generator or circuit seriously because the motor field strength and therefore its back e.m.f. cannot change instantaneously. If, however, the generator terminals, when on full load, are short circuited, or the constant current circuit opened by accident and closed again, the field energy released in either case, is considerable, and the more nearly the design of the generator follows A.C. practice the better will be its performance under these severe conditions.

COMPARISON WITH A.C. EXCITATION VALUES.

In a 50 cycle A.C. system the crest voltage changes from positive to negative values in 1/100th second and from maximum positive to zero in 1/200th part of a second with corresponding changes in the generator flux. An illustration of the amount of power required for these rapid changes can be acquired from the knowledge that an induction motor having a power factor of 71% requires the same amount of power for magnetising as it gives in useful power, that is, if it were separately excited the exciter would require to be of the same size and rating as the main motor.

If a constant current generator were short circuited when working at full load no damage would be likely to occur if the current were to swing up to, say, 5 times full load value for a fraction of a second and from this point of view alone, satisfactory operation would be obtained with an exciter of 1/5th the continuous capacity of the main generator.

/

FIELD AND COMPENSATING WINDINGS FOR CONSTANT CURRENT GENERATORS.

By arranging the armature winding correctly and fixing the air gap length in compensated D.C. dynamos, complete armature compensation can be provided and good commutation obtained without the addition of local interpole coils. In recent designs, the compensating winding has been arranged as one phase of a two-phase, double layer, half span winding, the other phase being used for field excitation. By arranging the armature winding with a short span, it has been possible completely to compensate the armature m.m.f. at all points, leaving sufficient flux at the neutral point only to ensure satisfactory commutation at all loads. The field winding is usually excited with a comparatively high current from a low voltage source, thus enabling the main generator to have duplicate windings for field and compensating purposes.

A generator of this design is not only more suitable from the point of view of operation, but is smaller, cheaper, and more efficient, then the non-compensated salient pole type.

ARRANGEMENT AND CAPACITY OF EXCITER.

With constant current power dynamos the regulating features are included within the exciter and this requires a separate source of supply for the abutment excitation, (A, Figure 10.) The chief features of the Austin exciter are :-

(a) its large transient capacity or high ceiling voltage /

(b) the low inductance of each of its field windings, and

(c) a ballast resistance in the abutment field.

Its mode of action is best illustrated by examples.

Example 1.

Assume the main generator field required 100 amperes at 10 volts to give full load on the generator, and that the exciter can give 100 volts before magnetic saturation of its field begins, that is, its ceiling voltage is over 100. Assume also that the abutment winding has a strength of 3000 ATs and that 100 ATs are sufficient to produce 10 volts, (or full field,) at the exciter terminals. The strength of the series opposition is therefore 2900 ATs at full load and, compounding neglected, the full load current is 29/30 of the no load value. As the current has fallen by $3\frac{1}{3}$%, the percentage regulation or current rigidity is here $3\frac{1}{3}$%.

An exciter with about 5900 ATs total on each of its poles would require a lot of space for field copper and the mutual inductance between the windings would be large, but a transient reduction of the line current to 2/3rds. of its value or a transient increase to 4/3rds. of its value would cause a sudden alteration of the impressed e.m.f. over the main generator field to 100 volts, thus producing an increased main field speed of operation of approximately 10 times its normal value.

Example 2.

In order to show the effect of increasing the size of the exciter, let it be assumed that its core length and all parts of the magnetic sections of the exciter are doubled, then 50 ATs will now be sufficient to produce 10 volts at its terminals for the same number of armature /

armature conductors and the same speed of rotation. The abutment field can now be reduced to 1500 ATs with a series opposition giving 1450 ATs at full load. Let it be assumed also that the opportunity has been taken to include a ballast resistance in the abutment circuit and so alter the conditions that the current flowing in this circuit is doubled. The following conditions are now evident :-

(a) the regulation or rigidity percentage is unaltered,

(b) the ceiling e.m.f. is now raised to 200 volts for the same alteration of the line current,

(c) the initial inductances of the exciter field windings are reduced to $\frac{1}{4}$ of their previous values because the turns in the abutment coil are reduced to $\frac{1}{4}$.

It is obvious that this process could be carried further with corresponding improvement in (b) and (c) or alternatively, advantage could be taken of the increased size to improve the percentage regulation.

An increase in the magnetic sections of the exciter does not mean either a proportionate increase in the weight or cost of the machine for not only is the weight of the field copper rapidly reduced with falling m.m.f., but the space occupied by it is also less, and this latter may mean overall reduction in the diameter of the magnet frame, further, the brushgear, commutator, and several mechanical parts will not be altered. Hence the Austin arrangement permits of reasonably economic design, and gives not only a very fast exciter but very good automatic regulation of the line current under static conditions, and because the natural regulation of the set is good, complete or overcompounding can be /

be obtained by rocking the exciter brushes backward a small amount from the neutral.

CALCULATION BY MEANS OF LINEAR EQUATIONS OF THE ARMATURE, FIELD, & ABUTMENT CURRENTY IN THURY & AUSTIN CONSTANT CURRENT DYNAMO CIRCUITS UNDER SUDDEN CHANGES OF LOAD.

Let i, i_1, i_2, be the armature, abutment, and field currents respectively.

Z, Z_1, Z_2, be the corresponding inpedances with corresponding R's and L's.

E_1, the constant exciter voltage.

The following assumptions are made :-

(1) The excitation of the exciter, (abutment,) field is at constant voltage, i.e., E_1 = constant.

(2) As the field structures of both exciter and main dynamo are assumed laminated, the eddy current effects in both machines may be neglected.

(3) Except at maximum load, (voltage,) the saturation of the main dynamo field is negligible and the exciter field has no saturation within its working range.

(4) As the speed of the set is constant, and magnetic saturation absent, the e.m.f., e developed by the main dynamo armature is strictly proportional to i_2, i.e.

$$e = K_2 i_2$$

(5) As the series winding, S, (Figure 10,) is magnetically opposed to the abutment winding, A, the e.m.f., e_2 generated in the exciter armature is proportional to $(i_1 - i)$, i.e.

$$e_2 = K_1 (i_1 - i)$$

(6) In order to simplify the calculations the turns of the abutment coil A are assumed equal to those of the series opposition S and E_1 can be adjusted to suit if this circuit power loss is varied.

(7) The reactions of the coils undergoing commutation in both main generator and exciter are neglected.

The following relations apply :-

$$e = K_2 i_2 = Zi + Mpi_1 \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$E_1 = \text{Constant} = Z_1 i_1 + Mpi \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$e_2 = K_1(i_1 - i) = Z_2 i_2 \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where M is the coefficient of mutual induction between coils A and S and $Z = R + Lp$,

$$Z_1 = R_1 + L_1 p, \text{ etc.}$$

These equations are those for the Austin constant current dyanmo circuit and, if the compounding coil is omitted, they are also the equations for the Thury dynamo circuit.

In equations (1) and (2), M is negative, but by the insertion of an impulse transformer, M may be increased to a zero or positive value. If M is zero, $\underline{i_1}$ becomes constant, and the e.m.f.'s are simplified becoming,

$$e = K_2 i_2 = Zi \quad \ldots\ldots\ldots\ldots \quad (A)$$

$$E_1 = \text{Constant} = R_1 I_1 \quad \ldots\ldots \quad (B)$$

$$e_2 = K_1(i_1 - i) = Z_2 i_2 \quad \ldots \quad (C)$$

If M becomes positive, the change of the exciter e.m.f. $\underline{e_2}$ will lead the change of the line current $\underline{i}$ and will therefore anticipate to some extent the /-

the consequent change of i_2 and by the use of the Thury transformer the overshoot of the characteristic is considerably reduced, provided the exciter is suitably designed.

In the Austin system the exciter is made of large transient capacity which enables a considerable inherent reduction of M to be made, also since the abutment circuit has a relatively high power loss, these effects combined reduce the variation of i_1 under load fluctuations.

Eliminating i_1 and i_2 from equation (1) and giving Z, Z_1, Z_2 their values and reducing we have,

$$p^3 i + Pp^2 i + Qpi + Q'(i - S) = 0 \quad \ldots\ldots (4)$$

where

$$P = \frac{RL_1L_2 + R_1LL_2 + R_2LL_1 - M^2R_2}{LL_1L_2 - M^2L_2},$$

$$Q = \frac{RR_1L_2 + RR_2L_1 + R_1R_2L + K_1K_2L_1 + K_1K_2M}{LL_1L_2 - M^2L_2},$$

$$Q' = \frac{R_1 \ (RR_2 + K_1K_2)}{LL_1L_2 - M^2L_2},$$

and

$$S = \frac{K_1K_2 \ E_1}{R_1(RR_2 + K_1K_2)}$$

Equation (4) may be completely solved by means of the Heaviside expansion formula but as the work involved is not appreciably less than the orthodox method, this latter is used.

From (2)

$$pi_1 = \frac{1}{L_1}(E_1 - R_1i_1 - Mpi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

From (3)

$$pi_2 = \frac{1}{L_2}\left\{ K_1(i_1 - i) - R_2i_2 \right\} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

Substitute (5) in (1) giving

$$K_2i_2 = Ri + Lpi + \frac{M}{L_1}(E_1 - R_1i_1 - Mpi) \quad \ldots\ldots (7)$$

Differentiate (7) and replace pi_1, i_2, and pi_2 by their values from (5), (1) and (6) and the result becomes/

becomes

$$i_1 = Tp^2 i + Upi + Vi + W \quad \ldots\ldots\ldots\ldots (8)$$

where

$$T = \frac{L_1 (LL_1 L_2 - L_2 M^2)}{\phi},$$

$$U = \frac{L_1^2 (RL_2 + R_2 L) - M^2 (R_2 L_1 - R_1 L_2)}{\phi},$$

$$V = \frac{L_1^2 (RR_2 + K_1 K_2)}{\phi}$$

$$W = \frac{ME_1 (R_2 L_1 - R_1 L_2)}{\phi}, \quad \text{and}$$

$$\phi = K_1 K_2 L_1^2 + R_1 M (R_2 L_1 - R_1 L_2).$$

From (1) $i_2 = \frac{1}{K_2}(Ri + Lpi + Mpi_1)$

$$= \frac{1}{K_2}\left\{Ri + Lpi + M(Tp^3 i + Up^2 i + Vpi)\right\}$$

$$= \frac{MT}{K_2}p^3 i + \frac{MU}{K_2}p^2 i + \left(\frac{MV + L}{K_2}\right)pi + \frac{R}{K_2}i \quad \ldots (9)$$

Assuming the motion to be oscillatory, the solution of (4) is

$$i = A\theta' + B\theta'' + C\theta''' + S \quad \ldots\ldots\ldots\ldots\ldots (10)$$

where A,B,C are the terminal constants and $\theta' = e^{at}$, $\theta'' = e^{bt}\sin\omega t$, $\theta''' = e^{bt}\cos\omega t$.

Differentiating equation (10) 3 times gives

$$pi = aA\theta' + D\theta'' + F\theta'''$$

$$p^2 i = a^2 A\theta' + G\theta'' + H\theta'''$$

$$p^3 i = a^3 A\theta' + J\theta'' + N\theta'''$$

where $D = (Bb - C\omega)$, $F = (B\omega + Cb)$,

$G = (Db - F\omega)$, $H = (D\omega + Fb)$,

$J = (Gb - H\omega)$, and $N = (G\omega + Hb)$.

Inserting these values in (8) and (9) and reducing we have

$$i_1 = A_1\theta' + B_1\theta'' + C_1\theta''' + VS + W \quad \ldots\ldots\ldots (11)$$

$$i_2 = A_{11}\theta' + B_{11}\theta'' + C_{11}\theta''' + \frac{R}{K_2}S \quad \ldots\ldots\ldots\ldots\ldots (12)$$

where/

where

$$A_{,} = A(V + aU + a^2T),$$

$$B_{,} = VB + UD + TG,$$

$$C_{,} = VC + UF + TH,$$

$$A_{,,} = \frac{A}{K_2}\left\{R + (MV + L)a + MUa^2 + MTa^3\right\}$$

$$B_{,,} = \frac{1}{K_2}\left\{RB + (MV + L)D + MUG + MTJ\right\}$$

$$C_{,,} = \frac{1}{K_2}\left\{RC + (MV + L)F + MUH + MTN\right\}$$

Reverting to equations (A), (B) and (C), the solution for $M = 0$ becomes

$$p^2i + Ppi + Q(i - S) = 0 \quad \ldots\ldots\ldots\ldots \text{(D)}$$

where

$$P = \frac{RL_2 + R_2L}{LL_2},$$

$$Q = \frac{RR_2 + K_1K_2}{LL_2},$$

$$S = \frac{K_1K_2E_1}{R_1(RR_2 + K_1K_2)}$$

$\underline{i_2}$ is obtained in terms of $\underline{i}$ and $\underline{pi}$ directly from equation (A) and is given by

$$i_2 = Upi + Vi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(E)}$$

where $U = \frac{L}{K_2}$

and $V = \frac{R}{K_2}$

Assuming the motion to be oscillatory, the general solution of (D) is

$$i = A\,\theta_{,} + B\,\theta_{,,} + S \quad \ldots\ldots\ldots\ldots\ldots \text{(F)}$$

where $\theta_{,} = e^{bt}\sin\omega t$

and $\theta_{,,} = e^{bt}\cos\omega t$

also $i_2 = A_{,,}\,\theta_{,} + B_{,,}\theta_{,,} + C \quad \ldots\ldots\ldots\ldots\ldots \text{(G)}$

where $A_{,,} = AbU - B\omega U + AV$

$B_{,,} = A\omega U + BbU + BV$

$C_{,,} = VS,$

obtained by inserting the values of $\underline{i}$ and $\underline{pi}$ in equation/

equation (E).

NUMERICAL EXAMPLE:

The following numerical circuit parameters have been obtained from an Austin constant current generator (Reference letter E) of 250 amperes, 160 K.w. capacity.

The method of measurement and leading design data for the generator are given in Chapter 5 together with open circuit characteristics for both main generator and exciter. An approximate estimate of the current values i, i_1, and i_2 can now be made when switching from full (or any) load to say, light load (or short circuit) condition.

Circuit Data for Austin Constant Current Generator No.11839.

$R = \frac{9}{10^2}$ ohm. $\quad L = \frac{4}{10^3}$ henry $\quad K_1 = \frac{1}{4}$

$R_1 = \frac{1}{10^2}$ " $\quad L_1 = \frac{7}{10^4}$ " $\quad K_2 = 4.6$

$R_2 = \frac{8}{10^2}$ " $\quad L_2 = \frac{1.5}{10^2}$ " $\quad K_1K_2 = 1.15$

$M = -\frac{7}{10^4}$ henry.

Loss in abutment winding 625 watts.

Since the ratio of abutment to series opposition turns is 1, i_1 will have a constant steady value of 250 amperes, whatever the load, also

$i = i_1$ under ideal short circuit conditions.

Further, $\quad E_1 = i_1R_1$

and $\quad E_1 i_1 = 625$

therefore $\quad E_1 = 2.5$ volts.

From (4) $\quad i = S$

$$= \frac{K_1K_2\ E_1}{R_1(RR_2 + K_1K_2)} = \frac{E_1}{R_1} - \frac{R_2 e}{K_1K_2} \quad .... (13)$$

(13) is obtained by replacing R_1 now taken to be the/

the total circuit resistance (i.e., load plus internal), with $\frac{e}{I}$, where e is the total generated e.m.f.

If the generator is working at 90% full load (generating $e = 605$ volts) and is suddenly short circuited, then from (13)

$$i = 208 \text{ amperes}$$

and from the open circuit characteristic,

$$i_2 = 132 \text{ amperes.}$$

Although the natural regulation (non-compounded) of this machine is over 16%, in practice the static value current was maintained within .03% of 250 amps., from zero to 640 volts with only a slight displacement of the exciter brushes. As the equations are formed on the basis of no compounding, the terminal conditions for

will be taken as

$$t = 0$$
$$i = 208 \text{ amperes}$$
$$i_1 = 250 \text{ amperes}$$
$$i_2 = 132 \text{ amperes.}$$

The table given below is used for the numerical evaluation of various necessary constants for 3 values of M. The values of M are,

(1) $M = -\frac{7}{10^4}$ henry,

(2) $M = 0$ " ,

(3) $M = +\frac{7}{10^4}$ " ,

corresponding to the Austin, Thury with complete compensation and Thury with over compensation respectively.

	$M = -\frac{7}{10^4}$	$M = 0$	$M = +\frac{7}{10^4}$
P	50	27.8	50
Q	628	19300	47000
Q'	334000	--	334000
S	248.5	248.5	248.5

	$M = -\frac{7}{10^4}$	$M = 0$	$M = +\frac{7}{10^4}$
a	-87	--	-7.2
b	18.5	-13.9	-21.4
ω	60	138	215
Freq.	9.55	22	34.3
ϕ	$5.64/10^7$	--	$5.62/10^7$
T	$4.31/10^5$	--	$4.31/10^5$
U	$1.54/10^3$	$8.7/10^4$	$1.54/10^3$
V	1.005	$1.95/10^2$	1.01
W	.3	--	-.3
D	(18.5B-60C)	--	(-21.4B-215C)
F	(60B+18.5C)	--	(215B - 21.4C)
G	(-3260B-2220C)	--	(-45740B+9200C)
H	(2220B - 3260C)	--	(-9200B-45740C)
J	(-193400B+154400C)	--	(2955000B+9643000C)
N	(-154400B-193400C)	--	(-9643000B+29550000C)
UD	$\frac{1}{10^2}(2.85B - 9.23C)$	--	$\frac{1}{10^2}(-3.29B - 33.1C)$
UF	$\frac{1}{10^2}(9.23B + 2.85C)$	--	$\frac{1}{10^2}(33.1B - 3.29C)$
TG	$\frac{1}{10^2}(-14.05B - 9.566)$	--	(-1.97B + .396C)
TH	$\frac{1}{10^2}(9.56B - 14.05C)$	--	(-.396B - 1.97C)
MV+L	$\frac{3.3}{10^3}$	--	$4.7/10^3$ ~~[illegible]~~
(MV+L)D	$\frac{1}{10^2}(6.1B - 19.8C)$	--	$\frac{1}{10}(-1.005B - 10.1C)$
(MV+L)F	$\frac{1}{10^2}(19.8B + 6.1C)$	--	$\frac{1}{10}(10.1B - 1.005C)$
MUG	$\frac{1}{10^2}(-.355B + 2.42C)$	--	$\frac{1}{10^2}(-4.93B + .992C)$
MUH	$\frac{1}{10^2}(-.242B + .355C)$	--	$\frac{1}{10^2}(-.992B - 4.93C)$

	$M = \frac{-7}{10^4}$	$M = 0$	$M = \frac{+7}{10^4}$
MTJ	$\frac{1}{10^2}$(528B .465C)	--	$\frac{1}{10^2}$(8.9B + 29C)
MTN	$\frac{1}{10^2}$(.465B + .528C)	--	$\frac{1}{10^2}$(-29B + 8.9C)
A_1	1.197A	$\frac{1}{10^2}$(.74A-12B)	A
B_1	$\frac{1}{10^2}$(89.3B-18.89C)	$\frac{1}{10^2}$(12A+.74B)	$\frac{1}{10^2}$(-99.29B+6.5C)
C_1	$\frac{1}{10^2}$(18.89B-89.3C)	4.85	$\frac{1}{10^2}$(6.5B + 99.29C)
VS+W	250	--	250
A_{11}	$-\frac{4.03}{10^2}$ A	--	$\frac{1.22A}{10^2}$
B_{11}	$\frac{1}{10^2}$(3.48B-4.36C)	--	$\frac{1}{10^2}$(.635B -15.4C)
~~C~~	~~$\frac{1}{10}$(4.36B - 4.36C)~~	~~--~~	~~$\frac{1}{10}$(.635B - 15.4C)~~
C_{11}	$\frac{1}{10^2}$(4.36B + 3.48C)	--	$\frac{1}{10^2}$(15.4B +.635C)
$\frac{R}{K_2}$S	22.3	--	22.3

NUMERICAL VALUES

A	-710	1060	3.1
B	1335	-40.5	714
C	669.5	248.5	-43.6
A_1	-850		3.1
B_1	1067		-712.8
C_1	850		-3.1
A_{11}	28.6	12.7	$\frac{3.78}{10^2}$
B_{11}	17.3	127.2	11.25
C_{11}	81.6	4.85	109.8

It is now possible to write equation (4) with numerical co-efficients.

Equation (4) is, for $M = -\frac{7}{10^4}$,

$$p^3 i + 50p^2 i + 628pi + 334000(i - 248.5) = 0$$

and its roots are, as already indicated in the table, approximately

$$-87 \text{ and } 18.5 \pm 60j.$$

The table also allows the values of $\underline{i}$, $\underline{i}_1$ and $\underline{i}_2$ from equations (10), (11) and (12) to be stated, thus

$$i = -710\,\theta' + 1335\,\theta'' + 669.5\,\theta''' + 248.5 \quad \ldots\ldots\ldots\ldots (14)$$

$$i_1 = -850\,\theta' + 1067\,\theta'' + 850\,\theta''' + 250 \quad \ldots\ldots\ldots\ldots (15)$$

$$i_2 = 28.6\,\theta' + 17.3\,\theta'' + 81.6\,\theta''' + 22.3 \quad \ldots\ldots\ldots\ldots (16)$$

Equation (D) for M = 0 is now

$$p^2 i + 27.8pi + 19300(i - 248.5) = 0,$$

and its roots are approximately,

$$-13.9 \pm 138j.$$

$\underline{i}$ and $\underline{i}_2$ for this case are given by equation (F) and (G) are now

$$i = 1060\,\theta_1 - 40.5\,\theta_{11} + 248.5 \quad \ldots\ldots\ldots\ldots (H)$$

$$i_2 = 12.7\,\theta_1 + 127.2\,\theta_{11} + 4.85 \quad \ldots\ldots\ldots\ldots (K)$$

Equation (4) for $M = +\frac{7}{10^4}$ becomes

$$p^3 i + 50p^2 i + 47{,}000pi + 334000(i - 248.5) = 0,$$

and its roots are approximately,

$$-7.2, \quad -21.4 \pm 215j.$$

$\underline{i}$, $\underline{i}_1$ and $\underline{i}_2$ for this are given by equations (10), (11) and (12) and are now,

$$i = 3.1\,\theta' + 714\,\theta'' - 43.6\,\theta''' + 248.5 \quad \ldots\ldots (17)$$

$$i_1 = 3.1\,\theta' - 712.8\,\theta'' - 3.1\,\theta''' + 250 \quad \ldots\ldots (18)$$

$$i_2 = \frac{3.78}{10^2}\,\theta' + 11.25\,\theta'' + 109.8\,\theta''' + 22.3 \quad \ldots (19)$$

The main, abutment and field currents calculated by the tabular method (Tables 17, 18 and 19) from equations (14), (15), (16) for M negative, from equations (H), (K)/

(K) for M zero, and from equations (17), (18), (19) for M positive, are plotted in figures 12, 13 and 14 respectively.

Inspection of these figures clearly shows that when the transformer is absent (M negative, figure 12) the current, unless otherwise controlled, rises indefinitely. The curves shown in figure 12 (M zero and positive) demonstrate that the addition of a correctly coupled transformer cures this tendency, and further, reduces considerably the initial peak value of the current. For the 3 cases considered the peak value ratios are

$$1 : .47 : .34$$

CHAPTER 2.

Section 7.

BRIEF CONSIDERATION OF A METHOD OF EXCITATION FOR ALTERNATORS, SIMILAR TO THAT ADOPTED FOR CONSTANT CURRENT GENERATORS, TO LIMIT THE TRANSIENT OVERSHOOT OF THE LINE CURRENT DURING SUDDEN SHORT CIRCUITS WHEN POWER LIMITING REACTORS ARE ABSENT.

Improvements in circuit rupturing methods by means of fast circuit breakers have solved many problems and have enabled the design limits of large alternators, rotary convertors and other dynamo-electric machines to be widened. Nevertheless new aspects of old problems are sometimes useful and the proposal to limit, in an alternator, the overshoot of the load current by a method similar to that adopted for some recently designed constant current generators may prove of some interest.

A sudden change of the alternator load current due to any cause whatever is reflected on the field circuit, especially if the poles are built up of laminations. In the event of a current increase being due to a short circuiting of all the alternator phases at one time the corresponding field current rise will be such as almost completely to prevent the armature reaction m.m.f. from sufficiently de-magnetising the field before the short circuit current reaches a value many times that of its stable value. If, however, the exciter is provided with an abutment and series opposition winding (the latter coupled in series with the main alternator field) and is capable of generating a high ceiling voltage, any sudden increase in the alternator field current will usually reduce the exciter voltage to a negative value numerically many times that of nominal full load voltage.

Figure 15a shows the proposed arrangement, the diagram being self explanatory. The adoption of an excitation scheme of this nature would not only tend to keep the field current constant and to limit the transient short circuit armature current but it would also be readily adaptable for the maintenance of good alternator regulation. The speed of operation of the arrangement would be enhanced by the inclusion of an injection transformer between the armature circuit and the abutment field circuit of the exciter, but this has not been shown in figure 15a.

A method of compounding alternators was proposed by Rudenberg and collaborators.[12]

([12] U.S. Patent No. 1,572,959, 16th Jan. 1923 "Rapid Regulation of the Voltage in Conductor Systems.")

in which a difference of voltage V (provided by a rectifier fed from a transformer coupled across the A.C. mains, the D.C. side of the rectifier being coupled in opposition with a battery or other constant voltage D.C. source) is used to excite a stabilising coil on a series wound exciter field. In figure 15b a similar arrangement is shown but in this case an auxiliary shunt wound exciter Ea is proposed, this carrying an additional field winding excited by the voltage difference V.

The mode of action is as follows:-

If the line voltage falls, the corresponding increase of V increases the terminal voltage of the auxiliary exciter Ea and in turn strengthens the abutment field A of the main exciter. In order to limit the transient it would be necessary in practice with this device to limit the auxiliary exciter e.m.f. and this could be effected by introducing saturation into its magnetic circuit when a definite alternator overload was reached, thus limiting the voltage V and/

and enabling the series opposition winding to reach and overcome the abutment m.m.f. for a definite value of the transient line current.

The problems of excitation and rapid response in alternators and constant current dynamos are, to some extent, analogous and may therefore be studied together with advantage.

CHAPTER 3.

PREPARATION OF INSTRUMENTS & APPARATUS USED DURING THE TESTS, WITH A BRIEF ACCOUNT OF THE WORK PERFORMED.

Arrangements were first made so that any suitable machine for test could be placed in the laboratory and means for driving considered. Unfortunately a public supply of 3 phase A.C. was not available but several alternators were to hand. After a few preliminary trials a 30 kVA. alternator driven by a D.C. motor was selected to provide the supply and this machine was connected through the main distribution board and various available circuits to the test machine, the measuring instruments on the supply side being a part of the alternator panel.

Generator A (see Table 1) was then installed and trials for power, regulation, etc., were made, after which attention was turned to the preparation of other apparatus required.

DETAILS OF 30 kVA. ALTERNATOR SET:

Alternator:- 30 kVA., 440 volts, 83 amperes, 750 r.p.m., 8 poles. Excitation, 125 or 250 volts. Serial No. 58085, Lab. No. 9.

Motor:- 45 H.P. 500 volts D.C. to drive above alternator through a flexible coupling.
750 r.p.m. Serial No. 65526.
Lab. No. 10.

Chapter 3.

PRELIMINARY TRIALS.

Since a large part of this research consisted of switching a generator from one load condition to another, a heavy current switch was constructed of parts acquired from an old centrifugal motor oil break switch.

The arrangement consisted of 2 heavy copper knives swinging on suitable fulcrums and engaging with massive phosphor bronze contacts, the whole being mounted on a slab of 3/4" ebonite and provided with terminals. The construction was so arranged that the knives could be operated together or separately and to this end were provided with wooden file handles, one painted red and the other yellow, to facilitate identification.

The generator was now connected as in figure 22, circuit 1, with the field excitation provided by a 10 volt, 2000 ampere-hour submarine battery, through a carbon resistance and ammeter and then supplied by the alternator. When running conditions had stabilized the generator was short-circuited and immediately stalled, bringing out the line fuses. Heavier fuses were installed and the alternator excitation increased to 250 volts, while the field control resistance was brought up to the welding generator for ease of control. With these alterations and having control of the alternator output to hand, it was found possible to maintain the generator speed under changing load conditions.

The welding of the generator was next tested using 1/4" Ironex electrodes and was found to be excellent although some difficulty was experienced in obtaining accurate readings of the arc current and voltage owing to the rapid fluctuations in these quantities. A dead beat combined volt and ammeter (VA1) was therefore obtained and included in the circuit with conspicuous/

conspicuous success, this instrument being employed thereafter throughout all the tests.

In order that the switching tests could be performed without actually welding, a heavy E.M.B. resistance of .11 ohm to carry 300 amperes was provided to form an artificial load approximately the same as a welding load and it was found necessary to connect a small Ferry coil in parallel with this to obtain the desired value, namely .075 ohms.

It was noted during the above series of tests that the generator shunt voltage, required constant, varied considerably and to ensure constancy the carbon resistance was removed and 9 - 2 volt cells of 150 amp-hour capacity connected directly to the machine through an existing 300 ampere cable line, while to protect the field when breaking this circuit, a 125 volt lamp was employed as a discharge resistance. The arrangement when tested gave satisfaction and attention was next turned to the oscillograph necessitated by the investigation.

THE DUDDELL OSCILLOGRAPH.

The oscillograph available at this stage of the investigation was a Double Projection Duddell instrument made by the Cambridge Scientific Instrument Co. Ltd., in 1903 and is illustrated in figure 16. The apparatus consists essentially of a modified D'Arsonval galvanometer combined with a rotating or vibrating mirror. The following description of its mode of operation is based on a Cambridge pamphlet.

Figure 17 is a diagrammatic view of the galvanometer. In the narrow gap between the poles N, S, of a powerful magnet are stretched two parallel conductors S, S, formed by bending a strip of phosphor bronze back/

back upon itself over the pulley P which is attached to a small spring balance. At the bottom ends the strips are clamped to a block K, while at the top they are held in position by a bridge piece L. Alteration of the strip tension by means of the spring balance permits variation of the element's natural periodicity at will.

Each strip passes through a separate gap in the magnetic circuit (not shown in figure 17) and the clearance is made very small, so that when the ribbons are surrounded by damping oil their movements are dead beat. A small mirror M is affixed to the phosphor bronze strips by means of shellac.

The effect of passing a current through the strips is to cause one leg to advance while the other retreats, thus imparting to the mirror M a rotary movement about a vertical axis. A beam of light reflected from the mirror M is received on a screen or photographic apparatus, the instantaneous value of the current passing being proportional to the linear deflection of the spot of light so formed. When traversed by an alternating current the strips cause the light spot to oscillate as the current varies and would thus trace a straight line, hence to obtain an image of the wave form, a second mirror is interposed between M and the screen.

This second mirror is made to rotate and the light spot now traces on the stationary screen a curve of current on a time base. If the current variations are periodic, as in alternating currents, the second mirror may be synchronized and a stationary wave produced on the screen.

In the apparatus available the oscillograph itself/

itself was mounted on a wooden table which also carried an arc lantern, tracing desk, rotating mirror and synchronous motor gear, together with the necessary shunts, resistance boxes, switches, etc. The general arrangement is shown in figure 18.

Since the work in this research is of a low frequency and transient nature the available vibrating mirror and synchronous motor gear was valueless, for the motor range was from 25 to 100 cycles per second, and other means of providing the time base were considered.

A continuously rotating mirror of small but uniform speed was indicated and the unit shown in figure 19 was accordingly designed and made. This consists of a small gramophone motor driving, by means of a round rubber belt, a brass carrier on which a strip of mirror was fastened, this mirror being placed at such a height above the steel base plate that it would receive the beams reflected from the oscillograph mirrors. Immediately above the rotating mirror a cylindrical lens of 5½" focal length was mounted in a Vee-shaped projection attached to the lower side of the tracing desk, as shown in figure 20. The reflected beams, on passing through this lens, were brought to a focus on the upper side of a curved piece of plate glass upon which a sheet of tracing paper formed a screen. A film box, having a dark slide (figure 21) and into which photographic film or paper of post card size could be inserted, was arranged to clamp over the tracing desk and thus a permanent record obtained.

Since the maximum current with which the existing apparatus could deal was 100 amperes and as currents exceeding 500 amperes will frequently be encountered/

encountered during this work, a specially designed shunt was made to provide the drop for the current element, while the maximum deflection of the light spot was controlled by an additional resistance in the ribbon circuit (figure 23). The existing voltage resistance box was suitable for 500 volts and this was therefore retained.

PRELIMINARY TESTS WITH THE OSCILLOGRAPH.

Several preliminary tests were made with the oscillograph using A.C. waves and it was found immediately that films were being fogged by light leaking through the lens casing and the lens itself. Black velvet covers were therefore made and affixed so that all light was excluded from the rotating mirror chamber. These covers may be seen in figure 20.

When thoroughly accustomed to the use of the oscillograph, the generator was again coupled as in figure 22 (circuit 1) and the heavy current switch affixed to the oscillograph table (seen in figure 18a).

Several trials were made with this arrangement but great difficulty was experienced in closing the switch at the correct time to ensure the appearance of a record on the film. In order to overcome this difficulty the rotating mirror shaft was extended to pass through the velvet cover on the tracing box side and a small brass pointer mounted on the extended shaft outside the box. A cocoa tin lid was next mounted on a suitable support and provided with 3 holes, A, B and C. The gear was then arranged so that just after the pointer appeared at A, the light spots were entering their traverse across the film.

Similarly, hole C indicated the end of the traverse while hole B gave the position at which the/

the switch should be closed. This scheme worked very successfully and it is of interest to note in passing that 3 different operators were employed from time to time to close the machine switch as the pointer appeared at hole B, and it was found that 3 different positions of the hole relative to the support were required to ensure that the record appeared at the appointed place on the film, this "angle of advance" having a bearing on the operator's reaction period. These angles were found and tabulated so that the aperture could be immediately placed in the correct position to suit the operator for the time being employed.

It was originally intended that the time base for the records should be measured by the speed of the gramophone motor and to this end the governor lever was provided with definite stops. On calibrating the motor, however, it was found that the speeds corresponding to the stops were not constant owing to wear on the felt governor pad of the motor. Alternative means of fixing the time base for the records had therefore to be found. As the oscillograph had but two elements and these were both required, it did not appear possible to add a timing wave to the oscillograms by means of an A.C. wave of known frequency. Further experiment showed, however, that the motor speed was reliable for about 2 minutes after a rewind and if this was performed before each record was taken the light spots could be allowed to travel twice across the film without appreciable error in the resulting record. The voltage ribbon circuit was therefore provided with a change-over switch so that the element could record either the voltage over the test generator/

generator or that from a small 25 cycle alternator. At this time, too, the ppportunity was taken to remove entirely the zero mirror from the oscillograph since this did not give such a good image as the ribbon mirrors, the zero line now being provided by the current mirror when on the timing wave traverse of the film. The oscillograph was thus made able to perform the functions of a 3-element unit and was found to work satisfactorily.

The sequence of events when taking a record was now thus:-

(1) Load the film box and place in position.

(2) Rewind motor and set in motion.

(3) Set change-over switch to give the timing wave and open film box slide.

(4) Allow mirror to pass once across the film as shown by the pointer.

(5) Set change-over switch to pass test generator voltage and close current element switch.

(6) When pointer indicates the correct position (hole B) close the load switch.

(7) After pointer has passed hole C, close film box slide and open all switches.

Each revolution of the rotating mirror occupied a time which may vary between 3 and 6 seconds and this cycle of operations had to be carried out during the time of two revolutions.

After this cycle of events had been practised, reasonable records were obtained and the tests were commenced. When only 3 records had been made an earth developed in the oscillograph field windings and it was necessary to dismantle, repair and re-build the instrument. On being replaced in position it was found/

found impossible to focus the light spots on the tracing desk screen and a lengthy series of discouraging experiments commenced. It transpired that the oscillograph had been frequently altered during its career and the good focus obtained originally had been largely by luck. It was therefore expedient to strip the entire apparatus and alter parts where necessary.

The optical system, shown diagrammatically in figure 24, was first attacked. This had been altered from time to time, each alteration apparently carrying the addition of a lens. Each lens was therefore measured for focal length and power, the correct positions calculated and the system re-assembled with conspicuous absence of success so far as the spots were concerned. Their appearance indicated that the present slit (shown in figure 24) was too wide and another narrower one was made and fitted, with some improvement. The tension of the element ribbons was next examined and it was noted that a slight movement of these produced disastrous results. The mirrors affixed to the elements were fairly large, about 4 x 2.5 m.m. and of very thin glass, so that alteration of the ribbon tension produced a distortion of the originally plane mirror surface.

The oscillograph was accordingly dismantled again, and the mirrors removed and replaced after the ribbons had been stretched to their working tension. On re-erection the spots were again worse and a new scheme had to be found.

So far a parallel light beam, as indicated in figure 24, had been the criterion but this policy was now abandoned and trials were made of focussing the/

the image of the projection arc on the oscillograph mirrors. To facilitate this work the cylindrical lens was temporarily removed and an improvised tracing cloth screen used in place of the tracing desk. This scheme proved immediately successful but also brought to light the fact that the tracing desk was not in the correct position. The entire tracing desk structure was therefore removed and re-constructed, after which good results were obtained.

A few records were now taken using film of 2000 H. and D. nominal speed, but fine definition was not a feature of these, as will be seen from a print of one of them appearing in figure 25. It will be noted from this figure, too, that the current rise is very rapid, the line being practically invisible. As this current rise is of considerable importance during this investigation a means of increasing the available light was sought. Trials were made with a Point-o-Lite lamp, special projector lamp, motor car head lamp and ordinary 100 watt house bulb, without appreciable improvement and attention was again directed to the arc lamp, several experiments being carried out on this. Finally, small diameter cored carbons were obtained from a cinema operator and tried with varying currents, and when used with a current about 15% in excess of their rated value, gave good results.

Due to the greatly increased light now available and to the presence of unavoidable stray reflections from the rotating mirror, trouble was now experienced with the fogging of the record film. In order to overcome this difficulty, a camera shutter was obtained and mounted on the rotating mirror unit as shown in figure 26, this shutter being operated from outside the tracing/

tracing desk chamber through a long cable release, which was interconnected with the generator load switch and [redacted] arranged to open an instant before the load switch was closed. It was intended that the current and voltage transients should now be recorded before the zero and timing wave (see p.66) but the long cable release proved unequal to the work. Several forms were tried, including a Bowden cable and piano wire, but all were eventually discarded in favour of separate manual operation, which had the advantage that the shutter could be closed between the 1st and 2nd revolutions required of the rotating mirror, with further improvements in the quality of the finished oscillogram. While improving the records the manual operation of the shutter further complicated the cycle of events necessary for the production of the records, the complete cycle for making a single record being now:-

(1) Load the film box and place in position.

(2) Rewind motor and set in motion.

(3) Strike arc in lantern and check its position.

(4) Close oscillograph field switch.

(5) Set change-over switch to record the timing wave and zero line and close voltage element switch.

(6) Withdraw film box dark slide.

(7) When pointer is at hole A (see p.65) open shutter.

(8) When pointer reaches hole C close shutter.

(9) Swing change-over switch to record generator voltage and close current element switch.

(10) When pointer is again at hole A, open shutter.

(11) When pointer is at hole B, assistant closes load switch.

(12) When pointer is at hole C, close shutter.

(13) Replace dark slide in film box, stop gramophone motor, open all switches and remove film box.

(14) Take film box to dark room, remove film and develop.

As before the operations (7) to (12) must be performed during $1\frac{1}{4}$ revolutions of the rotating mirror, that is during about $4\frac{1}{2}$ seconds, and since the pointer gear was necessarily on the opposite side of the oscillograph from the controls, the pointer had to be viewed in a mirror. A certain amount of drill was found imperative before this cycle of operations was mastered, but when proficiency had been attained good records were obtained.

Several records were then taken with disappointing results, since serious deviation from the expected curve shape was immediately noticed, an extreme case being reproduced in figure 27. This shows great irregularity.

Investigation into this phenomenon demonstrated that mechanical vibration of the oscillograph table was the cause, this being due to the shock of closing the load switch, which was of heavy construction and required rapid closing. The switch was therefore removed entirely from the oscillograph table and no further trouble of this nature experienced.

About this time samples of photographic recorder paper were obtained, the emulsion having a nominal speed of 600 H. and D. This material was tested with such satisfactory results that it was found desirable to scrap all previous records obtained on the film so far used, and to start again with the paper as the/

the recording material for a considerable time saving could be thus effected, since the paper could be processed and dry for examination within 20 minutes of being exposed, compared with about 4 hours for the film.

EXPERIMENTAL WORK.

Switching Tests: Generator A (Table 1) was again connected as in figure 22 and a series of switching tests commenced. These tests were carried out in the cycle enumerated below:-

(1) Switching from open to short circuit.
(2) " " short " open " .
(3) " " open circuit to load.
(4) " " load to open circuit.
(5) " " " " short " .
(6) " " short circuit to load,

and were performed with the oscillograph recording firstly, the main circuit currents and voltages and secondly, the corresponding shunt values, for each of three brush positions, namely:-

(a) Brushes forward.
(b) Brushes neutral.
and (c) Brushes back.

It is of interest to note here that in the case of the shunt values, the voltage drop required to excite the oscillograph current ribbon was obtained over two ammeters in series.

Throughout the tests all timing waves used were of 25 cycle frequency and no attempt was made to calculate the oscillograph sensitivity since a record was kept of the steady state currents and voltages as read/

read, during the tests, from the instruments included in the circuit, thus permitting the calibration of each individual record.

Minor annoyances were experienced during the switching test series, such as sticking bearings in the rotating mirror system and frequent breakage of the cable release but these were duly overcome as encountered.

A complete record of the oscillograms taken appears in Tables 2 to 6 inclusive but only representative examples are reproduced in Volume 2 (figures Nos. 33 to 40).

FIRST OSCILLATION TESTS. On completion of the switching tests noted above, Generator A was now connected as in figure 28, and since this machine was designed with a low voltage field (now connected across the brushes) alterations were made to the alternator switchboard to obtain a 25 cycle supply in order that the generator could be run at 1500 r.p.m. The injection transformer shown in figure 28 was a temporary arrangement, formerly part of a rectifier equipment, consisting of 3 laminated cores with coils wound directly upon them, the transformation ratio being about 15.

Much time was then spent in trying various combinations of connections between the transformer, shunt and load circuit, with variations of circuit impedance before oscillation was finally obtained. Several records were now taken and four of these are reproduced in figures 29 to 32 while the details are given in Table 11. These records are not examined in this thesis but are merely shown to demonstrate the work of the DUDDELL Oscillograph on oscillation phenomena/

phenomena. They also demonstrated convincingly that a new form of oscillograph was necessary in order to obtain suitable records for the continuance of this investigation.

To conclude this section of the work a list of instruments used to date was compiled (Table 7) to facilitate correction of the readings obtained by means of existing calibrations for the instruments.

THE PERMANENT MAGNET OSCILLOGRAPH.

As suggested above the continuance of this investigation necessitated a new form of oscillograph and it was noted that the laboratory possessed a Two Element Modified Duddell type permanent magnet oscillograph.

This instrument had no equipment whatever and, being of a suitable type, it was decided to construct the necessary auxiliaries and erect the whole as a unit on a small portable table. To this end several experiments were carried out to determine its leading design data and these were afterwards confirmed by the makers, again the Cambridge Instrument Co.Ltd.

The experience gained with the original Duddell outfit now proved invaluable and recalling the many difficulties encountered, it was at once decided to keep the design as simple and compact as possible, and to employ only one D.C. supply of 250 volts to operate all auxiliaries. Particular attention was first paid to the projector lamp system and experiments were made using an ordinary gas filled 250 volt lamp as the source of light, the optical system being provided from an optician's box of spectacle test lens. When a suitable system was found and verified, the trials were repeated using several sources of light, these/

these including:-

2 forms of D.C. arc,

Low voltage projector lamp,

Point-o-Lite Arc,

Various Cinema Projector Lamps,

but the first scheme of the 100 watt gas filled bulb gave the best all round results.

A rotating mirror arrangement was next extemporised and a visual inspection made of a 50 cycle A.C. wave after erecting the apparatus in a photometry room. These experiments conclusively showed the vast superiority of the permanent magnet instrument over its predecessor and designs were accordingly commenced for the final layout. Before completing the designs, however, the opportunity was taken to visit Cambridge once again and a similar permanent magnet instrument was seen in action there. This erection had a somewhat complicated optical system with an arc as the source of light, and further confirmed the suggestion made above of using the ordinary gas filled bulb. Nevertheless the visit was fruitful in information which was later turned to good account.

The problem of the design was to provide,

(1) a suitable table with castors,

(2) convenient Shunts,

(3) convenient Voltage control,

(4) a time marking system,

(5) a projector lamp and optical system,

(6) photographic recording apparatus,

and (7) a rotating mirror system for visual inspection, and to keep all the above to the minimum space compatible with efficiency. Since the instrument would be employed finally for general laboratory use, it was/

was further decided to arrange for a higher voltage range than immediately necessary and to add a tracing desk to be employed instead of the photographic apparatus when investigating periodic phenomena.

The ranges selected were:-

2, 6, 20, 60, 200 and 600 amperes.

20, 100, 200, 300, 400, 500 and 600 volts.

The current side of the apparatus was first tackled and the Universal, or Galvanometer, shunt principle adopted. The shunts, the four larger of which were designed to dissipate approximately 4 watts per square inch, were cut from 21 S.W.G. Eureka sheet and varied in width from 6" to 1/4", while the smaller pair, to carry 6 and 2 amperes, consisted of a double and single strand of 18 S.W.G. Eureka wire respectively. All the shunts were provided with massive copper end pieces, rivetted and sweated together and carrying suitable terminals and potential screws. The shunts were then mounted as a unit on hardwood blocks, the complete unit being mounted under a plain deal table in such a manner as to be readily detachable should replacements be necessary.

A heavy current commutator switch was next designed and constructed from a sectional brass ring anchored by terminals to a slab of 1" slate, recessed to provide a register. The brushgear connecting the segments consisted of a pair of laminated copper brushes (taken from a two speed centrifugal motor controller) clamped in a cast brass mount which in turn was carried on a central operating spindle. To the upper end of the spindle was affixed an adjusting handle and pointer while the lower end was spring loaded/

loaded to provide an adjustable brush tension. The complete switch was mounted under the oscillograph table with its spindle projecting above and its pointer arranged to pass over an ivorine scale indicating the shunt presently in circuit. Connections were then made by leads varying from single 7/20 cables to double $1\frac{1}{4}$" x $\frac{1}{8}$" copper conductors between the controller and the appropriate shunts according to the diagram shown in figure 42. The current supply was brought to the shunts by a pair of dual terminals, $\frac{5}{8}$" diameter, ebonite mounted on the table top and arranged to take heavy cables by means of shell clamps, or light cables up to about 7/20 by means of holes and pinching screws.

The completed oscillograph unit is shown in figures 43 and 44 and the shunt units and its controller may be specially noted in figure 43.

The voltage side of the circuit now came in for attention and the resistance steps were made from 36 S.W.G. nickel-chrome wire wound non-inductively on mica plates originally intended as commutator plate separators and locally acquired. The elements, when wound, were dipped in shellac and later mounted side by side on a red fibre strip, also shellaced, and attached to one of the table legs. Any desired number of steps could be included in the circuit at will by means of a plug board arrangement mounted on the oscillograph table top and placed on the opposite side to the current control. The supply to the voltage circuit was achieved through a pair of ebonite mounted 4 B.A. terminals affixed to the table top.

It was later considered that the forms of current and voltage control just described might prove rather coarse in practice having regard to the limited recorder/

recorder film width likely to be available and a pair of small resistance tubes of about $\frac{1}{2}$ ampere, 300 ohms capacity were consequently acquired, provided with $\frac{1}{8}$" pitch lead screws and sliders and mounted vertically below the table at the control end. The ends of the lead screws were arranged to project above the table and were equipped with small engraved handles showing the directions of rotation necessary to increase the resistance. These two resistances were then included in the current and voltage ribbon circuits as shown in figure 45, to act as vernier adjustments on the amplitude of deflection of the light spots.

It will be seen from figure 46, which shows the layout of the oscillograph table, that all the most frequently used controls have been kept to one end, while the coarse adjustments and live terminals were arranged at the other.

The permanent magnet oscillograph instrument was designed for a lens centre height of approximately $5\frac{1}{2}$" and the preliminary experiments showed this to be insufficient when the provision of a lamp house and a rotating mirror was considered. An increased centre height of $7\frac{1}{2}$" was therefore adopted and the oscillograph, which was provided with 3 pointed levelling screws (see figure 41), finally mounted on 3 small brass pillars screwed to a wooden packing piece. One of these pillars was given a dimple to take the point of a levelling screw while the remaining pair were arranged to have a 45 degree groove and a plane top respectively. This device, originally due to Lord Kelvin, ensured that the instrument would invariably return to the same position in the event of its removal. A small steel stay and knurled locating screw/

screw was employed to prevent the instrument toppling over should the table receive a shock. Small terminals on ebonite blocks attached to the packing piece and flexible leads to the ribbons completed the arrangement.

Attention was then focussed on the provision of a projection box to contain a part of the optical system, support the camera and house the rotating mirror gear. This box was made from suitably stiffened 5-ply wood and supplied with an easily detachable lid which also carried the tracing desk and stationary film box. The box was mounted on the table and secured by small thumb screws (to facilitate rapid removal) and a brass slide affixed to one end. The slide was provided with a slit to pass the projected light spots and was capable of supporting alternatively a Cambridge 64 m.m. continuous film camera (later described) or a special screen when the former was not in use. The screen could be moved until either a ground glass or an opaque white surface was presented to the light spots, the former arrangement allowing the light spots to be seen from outside the projection box when focussing, while the latter provided a screen for viewing by means of a rotating mirror and suitable visor. The face of the observer was projected from the sheet brass of the visor by a length of motor car windscreen wiper tubing suitably moulded to exclude stray light when making an observation and small shutter closed the visor completely when using the camera or tracing desk.

The cylindrical lens shown in the skeleton optical system (figure 47) was supported on an L-shaped hardwood mount secured in guides to the table top and a 4-sided rotating mirror in brass bearings was driven by a 200 volt variable speed D.C. motor through a spring belt/

belt and Vee pulleys, these units being arranged as indicated in figure 46. The rotating mirror motor was controlled by a "Zenith" lead screw type wire resistance mounted vertically below the table and conveniently placed to the hand. A second L-shaped erection was also constructed this to carry a hexagonal, surface silvered mirror with a cylindrical lens above it, the entire arrangement being intended to replace the single cylindrical lens, previously mentioned, when employing the tracing desk. The hexagonal mirror could be driven either by the existing 200 volt motor or by an additional gramophone motor when very low speeds were required. The projection box also carried the 2D focussing lens (figure 47a) in a suitable mount, this lens being a standard spectacle one locally obtained.

On completion of the projection box and its equipment, the problem of the projector lamp was clearly of the next importance and it will be recalled that a 100-watt gas filled bulb was to be the source of light. Consideration suggested that while this would give every satisfaction for the low tracing pencil speed here employed it might not provide sufficient intensity of light when high frequencies and high film speeds were encountered. It was therefore deemed desirable to use a 200 volt, 100 watt lamp whose circuit was loaded with a resistance to drop 50 volts, a portion of this resistance, dropping approximately 46 volts, having connected across it a bell push so that it could be short circuited at will, the remaining 4 volts being kept to excite the windings of a time-marking device described later. In this manner the amount of light available for projection could be greatly increased when required.

The lamp house was constructed from beaten sheet/

sheet brass with soldered joints and ventilating holes, and carried the lamp on a sliding base (to provide vernier focussing adjustment), the whole being supported on a vertical column itself capable of 3 dimensional adjustment. A pair of + 7 D plano-convex spectacle lenses were next mounted as a unit on the front of the lamp house so that they could be moved vertically or horizontally in guides and a brass aperture slide placed in front of them. This slide was perforated with 4 slits varying from .01" to .04" wide by .3" high, the slit presently in front of the condenser system being the actual source of light from the oscillograph mirror viewpoint. For easy removal of the complete lamp house unit, with or without its columns, the lamp received its power supply through a 5 amp plug screwed to the table top while the lamp itself could be removed or replaced through a detachable ventilated lamp house cover.

The time marker device referred to above was simply provided by means of a small additional adjustable mirror secured beside the oscillograph face (see figure 41) and in the beam of the projector lamp, so adjusted as to reflect an image of the projector slit through the projection box and its attendant lens system to the film or screen.[13]

([13] This arrangement is shown diagrammatically in figure 47b.)

A Deprez Time Marker, a small electro-magnet attracting an armature which carries an aluminium lamina, was next fixed to a vertical column providing 3-dimensional adjustment so as to intercept the auxiliary beam when the lamina was raised by the armature and the electro-magnet coils excited from the 4 volt (lamp resistance) supply previously noted. The marker/

marker circuit, which appears in figure 45b, included a switch and a make and break gear, the latter consisting of a clockwork driven contactor arranged to break the current supply every tenth part of a second, omitting every tenth interruption, thus marking seconds and tenths on the film or screen.

Consideration was then turned towards photographic recording apparatus and after several schemes had been examined and rejected a Cambridge continuous film camera, using 64 m.m. film or fast bromide paper, was finally selected and purchased. The sensitive material eventually used was a fast bromide paper provided with Edison gauge perforations to suit the camera driving sprocket and carried on dismountable flange reels each capable of accommodating 100 foot lengths. The camera was equipped with an ingenious film tensioning device, a film gate and integral exposure shutter and was intended to be driven by means of a rapid release coupling. The coupling proved unsuitable to the existing oscillograph gear and was therefore scrapped, the simple arrangement sketched in figure 48 being adopted in its place. In place of the coupling plate, a steel pulley with flanges was mounted on the camera driving shaft and the drive provided from a 1/4" H.P. motor by means of an endless cotton belt passing over a jockey pulley, the jockey pulley being fixed to the swinging arm shown. The link was also interconnected with the camera shutter through the intermediate drag link, column and lever shown in figure 48. The mode of action is as follows:-

(1) The camera motor is started and its speed regulated by means of the two resistances (shunt and series) provided, the belt merely slipping over the motor shaft.

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(2) The swinging arm is pressed forward, putting a tension on the belt by means of the jockey pulley, thus driving the camera. At the same time the linkage gear opens the camera shutter, permitting the light beams from the oscillograph to act on the sensitive paper now passing the camera aperture.

(3) When a sufficient length of record has been thus exposed, the swinging arm is released and its controlling spring returns it to the original position, at the same time applying a brake to the driving pulley surface, thus stopping the film.

This method of camera drive was found remarkably successful in actual use, and very economical in film, the time for acceleration and braking being of the order of one tenth of a second, while the constancy of the film speed was well within the desired range.

It has been noted above that the camera driving motor was of 1/4 H.P., but the actual power required was only about 1/10th H.P. The larger motor was employed in order to reduce, as far as possible, the speed variation when the camera load was suddenly applied. The motor actually used was obtained from a Power Supply Company's change-over department and was originally the motive power of a Hobart coffee grinder.

The oscillograph and its auxiliary gear were now largely complete with the exception of the fitting of ivorine nameplates, staining, varnishing, lacquering, etc., and the final tests as a unit, each individual part having been tested as far as possible, immediately on its completion. During these tests all resistance values were measured on a Wolff Precision Bridge while/

while the larger shunts were tried for voltage drop by short circuiting a welding generator through them in series with an ammeter and having a low reading accurate voltmeter across them.

Reference to figures 43 and 44 will demonstrate that the completed apparatus gave the appearance of a compact, workmanlike job, the overall dimensions being only 20" wide, 34" long and 43" high for a maximum capacity of 360 Kw.

The design and construction briefly described here occupied rather more than four months and with the exception of the gear specially mentioned as purchased, was entirely constructed in the laboratory. When considering the vastly improved records finally obtained, the 4 months' delay proved a sound investment.

PRELIMINARY TESTS WITH THE NEW OSCILLOGRAPH.

Immediately the new oscillograph[14]

([14] This term has been used rather loosely, it should really refer to the oscillograph instrument alone, but for convenience, it will now be used to indicate the entire oscillograph and its auxiliaries.)

was available a few trials were carried out with it using various A.C. waves and the results gave every satisfaction, the camera and its driving gear being particularly commended. As has been noted previously the acceleration and braking of the film could each be achieved within about a tenth of a second and since a film speed of approximately 1¼ feet per second was eventually adopted, the film wastage was only a few inches per record.

During these preliminary tests only one real trouble was discovered and this was that the red window in the camera was insufficiently dark and several/

several records were fogged in consequence. This window was therefore temporarily sealed and the desired results immediately obtained. Later, during a test, this temporary seal was accidentally dislodged and several records partly fogged (see figures 63 and 64) but a permanent seal finally removed the trouble.

The question of film development caused slight inconvenience throughout the remainder of this investigation since the available apparatus could not deal with more than about 6 feet of film at a time. This difficulty was finally removed by the discovery that the camera shutter could be opened long enough to mark the film with a pencil without fogging more than ½" at a time and this was accordingly done after each record was exposed. This method had the dual advantage of pointing clearly where the film had to be cut prior to development and of assuring the operator that the film was still passing the camera aperture without resort to the red window previously sealed.

The oscillograph was next connected with Generator A according to Circuit No.3 (figure 28), and the generator made to oscillate. Trials were then made to determine a suitable film speed, the 1¼ feet per second above mentioned being ultimately adopted.

This concluded the preliminary trials.

EXPERIMENTAL WORK.

The day upon which the above described trials were completed, the opportunity was offered by Messrs. The Macfarlane Engineering Co.Ltd., to test several welding and constant current generators of a larger capacity than was possible to supply with power in the laboratory and arrangements were made with Messrs. Gilbert Austin

Austin Ltd., Cathcart, for the use of their test bed which was equipped for about 400 KVA. The oscillograph was therefore taken to Cathcart and connected to Generator B according to Circuit NO. 4 (figure 49) and the series of switching tests detailed in Table No. 8 carried out.

Generators G and H were also tested in a similar manner and their records are described in Tables No. 8 and 9.

Generator D then came in for attention and its records are given in Tables No. 9 and 10.

It would serve no useful purpose to give here a detailed list of the many tests carried out since those of particular interest are selected and dealt with in Chapter 4. The scope of the tests may be gathered from an inspection of Tables No. 8 to 16 inclusive particularly when the following reference scheme is noted. Suffice it to say that, where possible, switching and oscillation tests were carried out on all the available machines.

As the number of records produced by these tests became larger, a scheme of rapid reference became increasingly desirable. The main information required at a glance was obviously:-

(a) Record serial number,

(b) Generator reference letter,

(c) From which part of generator (e.g. Main, field or abutment), and

(d) On what external circuit.

A composite reference number could easily give these requirements and this was made of the type:-

Serial No./Reference Letter./Current No./Circuit No., the generator letter being obtained from Table 1, while the current numbers were:-

Chapter 3.

0 .... Main Current,

1 .... Abutment Current,

2 .... Field Current,

these numbers corresponding to the suffices used in Chapter 2. The circuit number was taken from the connection diagram actually in use and may be referred to through Table 22.

As an example of the above scheme,

106/B/0/4

means Record Serial No. 106, taken from Generator B and showing the main current. Diagram of connections is Circuit No. 4 and (from Table 22) is given in figure 49.

For the sake of uniformity this reference scheme was ante-dated to include all the records previously taken with the Duddell oscillograph.

When the tests at Messrs Austin's works were completed, the oscillograph was returned to the laboratory and an extensive series of tests carried out on Generator C, a plain shunt machine without interpoles or compensating windings and not so far employed during this investigation, the results being given in Tables 11 and 12. Later, attention was returned to Generator A and a new series of tests started, these being with various combinations of the circuit inductance and other parameters, and included a series of tests with specially narrow brushes. These results are detailed in Tables 12 to 16 inclusive.

FINAL NOTES.

Throughout the tests in which oscillation occurs, the scale values for the records were later measured by arranging a definite deflection on the camera screen by means of a direct current and voltage, supplied by/

by a battery, before alteration of any of the oscillograph controls were made, and a short length of film exposed. All load and circuit resistances were measured by means of accurate volt-and ammeters.

During the tests made with the new oscillograph more than 500 feet of film or paper was exposed and of this total, less than 10 feet was wasted due to the oscillograph. Throughout no trouble was experienced and the 200 volt projector bulb has been supplied at 250 volts for rather more than a total of 4 hours and is as yet in good condition. The Deprez time marker performed faultlessly and, compared to the original Duddell outfit, the entire unit was a pleasure to operate.

CHAPTER 4.

EXPERIMENTAL RESULTS & COMPARISONS WITH THEORY.

This Chapter is divided into 7 Sections and each may be regarded as a continuation and conclusion of the equivalent Section of Chapter 2.

CHAPTER 4.

Section 1.

MAINTAINED OSCILLATIONS PRODUCED BY THREE WELDING GENERATORS, A, B and C, WITH TRANSFORMER FIELD EXCITATION ONLY (FIGURE 1).

---

(1) EXPLANATORY INTRODUCTION.

To prove that the indications of the linear theory outlined in Chapter 2, Section 1 are reasonable, three dynamos of different designs and capacities have been tested, coupled generally as in figure 1, and in each case were caused to self-excite and produce low frequency oscillations without difficulty, except that if the circuit was broken at zero current it was usually necessary to re-establish the residual magnetism by temporary separate excitation from a battery.

Before recording or discussing the results obtained, it is useful to enumerate here some of the variables and interpret some of the methods used in making the records.

(a) Tests were made on almost short circuit conditions and also with some resistance in the external circuit.

(b) The resistance of the field circuits was not altered in this series of tests (except in the case of Record No. 107 (figure 71) which had an added resistance of 1.4 ohms) and the total circuit resistance included that of the transformer secondary and oscillograph shunt, the latter being maintained at .1 ohm throughout.

(c) The load voltages recorded in the various tables and shown on each of the records is the dynamo terminal value and includes the transformer primary drop, the oscillograph/

oscillograph shunt and that due to any added external resistance.

(d) The total resistances given in Table 20 includes the internal values of the machine (i.e. the armature, compensating windings if any, and allowance for the brush drop).

(e) The field voltages recorded in the tables and shown on the corresponding records is that appearing at the ends of the field winding alone.

By varying the experiments a slight attempt has been made to find the effect of the following on the wave-shape, amplitude and frequency of the oscillation:-

(1) The value of M (obtained by varying the transformer airgap and number of coils in use),

(2) The brush position,

(3) The brush width,

(4) Load resistance,

but no definite conclusions have been drawn.

In recording the results each record used is given a separate figure and record number as described in Chapter 3 (p. 86). Scales are also given which enable the maximum currents and voltages reached during the oscillation to be stated within 10% and 20% respectively.

In order to recognise instantly the current line on an oscillogram, the voltage element of the instrument was tilted forward slightly so that only one half of its reflected light spot reached the screen. This gave the current record as a heavy black line while the voltage line appeared light. In some cases too, where conditions compelled the two lines to be close/

close together on the record, the voltage element was reversed with respect to the current.

In Table 20 all necessary test information is gathered together and, in addition to the details taken from the oscillograms, the actual circuit resistances are given. The letters B and N denote the brush position as back and neutral respectively, O.L., that only one limb of the transformer T is in use, and w, that the circumferential width of the brushes was temporarily reduced to about $^1/_8$".

The dynamo resistances used in the following calculations are taken from Table 33, modified as under to include stray losses, the inductances being the machine and transformer values added together. The values of P and Q are those given in Chapter 2, Section 1, and for convenience are repeated here:-

$$P = \frac{RL_2 + R_2L + KM}{LL_2 - M^2},$$

$$Q = \frac{RR_2}{LL_2 - M^2}.$$

---

(2) EFFECTIVE RESISTANCE.

In Table 20 the actual resistances of the load circuits are recorded but for the purpose of frequency calculations by means of the linear theory allowance must be made to cover stray losses, particularly those occurring in the coils under commutation. These, and other losses which can be represented by an additional resistance, will be large, and in making the calculations for Generators A and C the armature circuit resistances have been taken at approximately 3 times their measured value and for Generator B, at approximately twice the measured value, the reason for the latter/

latter being that this machine was slightly over-compensated particularly with the brushes neutral. To the load circuit resistances given in Table 20, the above additional allowances have been made and included in the table of calculations below.

(3) VALUES OF K, L AND M.

In order to calculate the frequency it is not only necessary to assume modifications of the circuit resistances to include stray losses but to arrive at the actual value of K which should be used in the calculations is a matter of some difficulty owing to the presence of saturation in the magnetic circuit of all the generators tested. The method which has been adopted here to evaluate K is to find its minimum value from the appropriate open circuit characteristic for the tabulated maximum field current taken from each record. A value between the unsaturated (or maximum) and the saturated (or minimum) has been chosen.

Where the brushes are displaced a corresponding modification has been made in the values of L and M, that is, as the brushes are in each case placed back from the neutral, the numerical value of the transformer M has been reduced.

(4) CALCULATIONS.

For simplicity these are in tabular form.

Fig.No. & Ref.No.	96 151/A	98 153/A	100 154/A	71 107/B	87 138/C	88 137/C
R	$\frac{1.0}{10}$	$\frac{1.25}{10}$	$\frac{1.8}{10}$	$\frac{2.2}{10}$	$\frac{1.2}{10}$	$\frac{1.8}{10}$
R_2	1.45	1.45	1.45	2.2	25.5	25.5
L	$\frac{3.2}{10^3}$	$\frac{2.25}{10^3}$	$\frac{2.25}{10^3}$	$\frac{1.6}{10^3}$	$\frac{9.5}{10^3}$	$\frac{9.5}{10^3}$

Fig.No. Ref.No.	96 151/A	98 153/A	100 154/A	71 107/B	87 138/C	88 137/C
L_2	$\frac{5.8}{10}$	$\frac{4.8}{10}$	$\frac{4.8}{10}$	$\frac{2.4}{10}$	11	11
$-M$	$\frac{2.7}{10^2}$	$\frac{1.85}{10^2}$	$\frac{1.28}{10^2}$	$\frac{1}{10^2}$	$\frac{7}{10^2}$	$\frac{7}{10^2}$
Average K	5	4	7	4.2	30	62
LL_2-M^2	$\frac{1.13}{10^3}$	$\frac{7.37}{10^4}$	$\frac{9.24}{10^4}$	$\frac{2}{10^4}$	$\frac{1}{10}$	$\frac{1}{10}$
P	-17.7	-15	-.3	+72	-5.3	-21
Q	244	246	281	2400	31	46
$\frac{P^2}{4} - Q$	-165	-190	-280	--	-24	+64
ω	12.8	13.8	16.7	--	4.9	--
freq.	2.05	2.2	2.7	0	.78	0
Observed Frequency	3.2	3	4.5	4.6	2.2	1.5
Maximum Output Kw.	11	9	10	--	9.5	2.2

The results of these calculations show that so many adverse conditions exist in practical generators that it is nearly impossible to obtain reliable results by calculation during a state of oscillation and this applies not only to the linear theory but to Tensor Analysis, recently applied to dynamo-electric machinery by Kron and others.[15]

([15] "The Application of Tensors to the Analysis of Rotating Electrical Machinery", Kron, General Electric Review, Vol.38, April 1935.)

Tensor analysis, although a powerful method when applied to ideal machines, is subject to similar limitations to the linear theory in actual practice.

---

(5) COMMENTS ON THE ABOVE RESULTS.

According to the linear theory and the assumptions made, two of the calculated results indicate no oscillation, although the actual oscillograms taken under these conditions (107/B/0/7 and 137/C/0/13) are good examples of maintained vibrations. In the first case P appears positive while in the second P is negative.

Generator B is known to be over-compensated in the neutral brush position (see above) and it is more than likely that the oscillation is here maintained by the presence of a series impulse communicated to the field by the coils under commutation.

In the case of Generator C, because P is numerically large and negative,

$$\frac{P^2}{4} - Q \text{ is positive}$$

An examination of the constituents of P indicates that this large negative value can only be affected by a modification in the values of K or M. K is not likely to be greatly different from the chosen figure and therefore the value of M is suspect. Since this machine has no interpoles, the reaction of the coils under commutation will undoubtedly affect the practical value of M.

Chapter 4.

Section 2.

MAINTAINED OSCILLATIONS PRODUCED BY TWO SHUNT WOUND WELDING GENERATORS WITH MUTUAL INDUCTANCE BETWEEN THE ARMATURE OR LOAD CIRCUIT AND THE FIELD WINDING (FIGURE 2).

---

(1) EXPLANATORY INTRODUCTION.

To prove that the indications of the linear theory outlined in Chapter 2, Section 2, are reasonable, two dynamos of different capacities and designs were tested, coupled generally as in figure 2, and in each case were caused to self-excite and produce low frequency oscillations without difficulty.

The variables were as follows:-

(a) Tests were made on almost short circuit and also with some resistance in the external circuit.

(b) The resistance of the field circuits was kept constant for both machines.

(c) Inspection of the circuits 15 and 16 (figures 60 and 61) will show where the currents and voltages were measured.

(d) The resistances given in Table 21 are the load, R, the armature circuit, R_1, and the field circuit, R_2.

(e) The field voltage recorded in the tables and shown on the corresponding records is that appearing at the ends of the field winding alone.

(f) Scales are given which enable the maximum current and voltage reached during an oscillation to be stated within 10% and 20% respectively.

In Table 21 all the necessary test information is gathered together and, in addition to the details taken

taken from the oscillograms, the actual circuit resistances are given. The armature circuit resistances used in the following calculations are modified as under to include an approximate allowance for stray losses, the inductance being the machine and transformer values added together. The values of P and Q are those obtained in Chapter 2, Section 2, for the short shunt case and for convenience are repeated here:-

$$P = \frac{RL_1 + R_1L + RL_2 + R_2L + R_1L_2 + R_2L_1 - 2R_1M - KL + KM}{LL_1 + LL_2 + L_1L_2 - 2L_1M - M^2},$$

$$Q = \frac{RR_1 + RR_2 + R_1R_2 - KR}{LL_1 + LL_2 + L_1L_2 - 2L_1M - M^2}.$$

---

(2) EFFECTIVE RESISTANCE.

For the purpose of calculating the frequency by means of the linear theory the same allowance has been made to the armature circuit resistances to cover stray losses as was made in Section 1 of this chapter.

---

(3) VALUES OF K, L AND M.

It might appear in this case that the value of K should be numerically the same as R_2 and this would be true for zero frequency but is not the case when the machine is maintaining oscillations and, as before, an average value of K has been chosen.

Again, as in Section 1, modifications have been made in the values of L and M to take account of different brush positions.

---

(4) CALCULATIONS.

For simplicity these are again in tabular form.

Fig.No. Ref.No.	102 166/A	106 169/A	110 185/A	90 141/C	92 142/C
R	$\frac{3.8}{10^2}$	$\frac{9}{10^2}$	$\frac{3.8}{10^2}$	$\frac{7.8}{10^2}$	$\frac{7.8}{10^2}$

Fig.No. Ref.No.	102 166/A	106 169/A	110 185/A	90 141/C	92 142/C
R_1	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$
R_2	1.45	1.45	1.45	1.45	1.45
L	$\frac{1.22}{10^3}$	$\frac{1.9}{10^3}$	$\frac{1.22}{10^3}$	$\frac{5}{10^3}$	$\frac{5}{10^3}$
L_1	$\frac{1.15}{10^3}$	$\frac{1.3}{10^3}$	$\frac{1.15}{10^3}$	$\frac{4.5}{10^3}$	$\frac{4.5}{10^3}$
L_2	$\frac{4.8}{10}$	$\frac{5.8}{10}$	$\frac{4.8}{10}$	11	11
$-M$	$\frac{1.85}{10^2}$	$\frac{2.1}{10^2}$	$\frac{1.85}{10^2}$	$\frac{7}{10^2}$	$\frac{7}{10^2}$
K	4	5	4	62	30
ϕ	$\frac{8.38}{10^4}$	$\frac{1.49}{10^3}$	$\frac{8.38}{10^4}$	$\frac{1}{10}$	$\frac{1}{10}$
P	-6.2	4	-6.2	-21	-.3
Q	60	-114	60	-3	22.2
$\frac{P^2}{4} - Q$	-50.4	118	-50.4	113	-22
ω	7.3	--	7.3	--	4.7
frequency	1.16	0	1.16	0	.75
Observed Frequency	4.6	7.5	4.5	2.5	2.5
Maximum Output Kw.	9.5	13.2	10	1.5	8.5

(5) COMMENTS ON THE ABOVE RESULTS.

The results of these calculations again show great discrepancies between the indications of the linear theory (during vibration) and the actual tests. The calculations are, of course, sensitive to the values of the circuit parameters, particularly to the value of K, M and the load, and these are in turn dependent on so many variables that only by exhaustive tests on one machine for one condition only are close approximations to be obtained.

Since/

Since this enquiry is more concerned with the principles and existence of maintained vibrations than with the calculated frequencies and wave shapes, it is not proposed to go further into these discrepancies.

It is of interest to note, however, from the above table, that the maximum outputs during oscillation are high, in one instance being in excess of 13 Kw. When this power, with the addition of that required for internal losses and the driving of the generator unit, was demanded from the supply alternator, the regulation of which was poor, the generator speed dropped considerably and this in turn affected the wave shape of the oscillation. It is also of interest to note that the injector transformer raised the field terminal voltage to quite high values in some cases.

Record Nos.168, 169 and 171 (figures 104, 106 and 108) show nearer approach to the sinusoidal shape than any of the others and an inspection of the corresponding field values, Record Nos. 177, 175 and 173 (figures 105, 107, 109) will demonstrate one of the reasons for this. The latter records show that the maximum value of the field current is situated more nearly at one quarter period from the start of a wave than in any other experiment recorded, and the maximum value of the load current and voltage must therefore be placed in an equivalent relative position. The greatest values of the field currents shown on Records 177, 175 and 173 are 14, 16 and 6.7 amps. respectively and a reference to the open circuit characteristic for Generator A (figure 126) shows that a field saturation condition exists well beyond the knee of the curve for all these current values. This constitutes a second reason for the sinusoidal shape. The relative widths of the top/

top portions of the e.m.f. waves on Records 168, 169 and 171 are in reasonable proportion to the field current values of 14, 16 and 6.7 amperes.

CHAPTER 4.

Section 3.

EVIDENCE COLLECTED IN FAVOUR OF PRODUCING & MAINTAINING OSCILLATIONS IN A DYNAMO CONTAINING NO MUTUAL INDUCTANCE AND HAVING A FORCING FREQUENCY APPLIED TO ITS FIELD IN PHASE WITH THE FREE FREQUENCY OF THE CIRCUIT.

No direct evidence has been obtained on the above method of producing and maintaining oscillations but the indirect evidence is fairly conclusive.

The indirect evidence may be summed thus:-

(1) In Section 1 of this Chapter, it was shown that although the linear theory indicated no oscillation by means of mutual inductance, good oscillations were shown on Record No. 107/B/0/7, (figure 71) and can only be accounted for on the basis of the series impulse which undoubtedly exists in this machine on account of its over-compensation.

(2) In Section 5 of this Chapter the same machine shows exactly the same results. (Record No. 106/B/0/6, figure 70).

(3) In Section 6 of this Chapter it is shown that Generator D (70 Kw. constant current):-

(a) Produces and maintains oscillations without the injector in circuit (111/D/0/4, figure 76) and these can only be eliminated by a forward lead of the main generator brushes, that is, by a negative series impulse.

(b) When a correctly coupled injector is utilised both theory and practice show that with the brushes neutral maintained oscillations are not possible. Record 121/D/1/9 (figure 80) shows the abutment field variation almost eliminated and in fact slightly reversed. Record number 113/D/0/8 (figure 79) shows/

shows the resulting damping of the oscillatory discharge in the main dynamo circuit.

(c) Although the theory shows that there should be no tendency to generate and maintain oscillations with a suitable injector and particularly with the brushes back (M positive), the corresponding series impulse does, in practice, produce and maintain oscillations as indicated in Record number 119/D/O/8 (figure 82).

(d) The Generator F could only be stopped from oscillating in practice by diverting its interpoles thus introducing a transient negative series impulse through the coils under commutation.

Paragraphs (b), (c) and (d) are dealt with at greater length in the proper Sections and will therefore be noted again.

CHAPTER 4.

Section 4.

MATHEMATICS OF THE GENERAL CASE.

Since this Section in Chapter 2 dealt almost entirely with the mathematics of the general case, little further need be said in this connection, except that the conclusions noted in Section 3 of this Chapter apply here with equal force.

CHAPTER 4.

Section 5.

TESTS ON WELDING GENERATORS.

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(1) EXPLANATORY INTRODUCTION.

Using the Duddell Oscillograph a large number of oscillograms of armature and field circuit currents were taken from Generator A, coupled generally as shown in figure 9, with the brushes in the three different positions forward, neutral and back.

As outlined in Chapter 3 many difficulties had to be overcome before reasonably satisfactory oscillograms were produced.

A resistance of about .11 ohm capacity was utilised to replace the arc and to represent load conditions when the load to short circuit switching records were taken. Most of the oscillograms taken with the Duddell instrument show a high frequency ripple which may be caused by a variation of the polar reluctance since it was not practicable (due to the short core length) during manufacture to skew the stator slots of this generator a complete slot pitch, and as the magnetic circuit is completely laminated, there exist only the coils under commutation to act as dampers.

The oscillograms for the backward brush position are, in most cases, not representative owing to the large speed variation which occurred during the taking of the records and therefore, in making a comparison between calculation and experiment, only those for the forward and neutral brush positions are chosen.

(2) SWITCHING FROM FULL LOAD TO SHORT CIRCUIT, GENERATOR A.

Table 23 gives the terminal details taken from the oscillograms and it will be noticed that there are/

are discrepancies between the details for the load and field circuit records, due to these being taken at different times and therefore under different temperature and other conditions. Three further points should be noted:-

(1) An inspection of the open circuit characteristic (figure 126) shows that between zero and 25 volts the machine operates almost entirely outwith the magnetic saturation zone and therefore the assumption of non-saturation of the magnetic circuit is reasonable in this case.

(2) The value of S for the neutral brush position has been calculated from equation (6) (Chapter 2, Section 5) and when using the value of r for this test ($\frac{2.6}{10^2}$ ohms) the calculated figure is less than the short circuit current from the record, which is 510 amperes (figure 67). This difference may have been due to the brushes being slightly displaced from the neutral, errors of observation, etc.

(3) For the forward brush position the value of N cannot be directly known but once the short circuit current has been determined it can be calculated from equation (6) (Chapter 2, Section 5).

In carrying out the calculations to compare the calculated and recorded curves the tabular method was adopted and the table below gives the equation constants. Although the records give slightly different readings, the constants of the following equations are based on terminal figures for

$$t = 0$$

of $i = 315$ amperes, $i_2 = 15$ amperes } Brushes forward, Calculations Table 24.

$i = 340$ amperes
$i_2 = 6.1$ amperes } Brushes neutral, Calculations Table 25.

Brush Position	Forward	Neutral
Record Number	5/A/0/1	67/A/0/1
Load Volts	25	27.5
Load Amperes	315	340
SC. Amperes	405	505
Record Number	11/A/2/2	73/A/2/2
Field Volts	15.8	15
Field Amperes	15.5	15.5
Field Amperes (taken as)	15	15
Load Speed (r.p.m.) ..	2842	2670
Light " (") ..	--	3100
S.C. " (") ..	2912	2532
r ohms	0	$\frac{2.6}{10^2}$
CIRCUIT PARAMETERS.		
R ohms	$\frac{3.5}{10^2}$	$\frac{3.5}{10^2}$
R_2 "	1	1
L henries	$\frac{13}{10^4}$	$\frac{11.5}{10^4}$
L_2 "	$\frac{2}{10}$	$\frac{2}{10}$
M "	$-\frac{6}{10^3}$	0
N "	$-\frac{3.3}{10^2}$	0
r ohms	0	$\frac{2.6}{10^2}$
E_2 (assumed) volts..	15	15
K	8	8
EQUATION CONSTANTS.		
P	58.5	58

Brush Position	Forward	Neutral
Q	1330	1165
S	405	440
b	-29.3	-29
ω	21.8	18
Freq.	3.47	2.87
ϕ	1.594	1.594
U	$\frac{1.4}{10^4}$	$\frac{1.44}{10^4}$
V	$\frac{3.76}{10^2}$	$\frac{7.65}{10^3}$
W	$-\frac{5.65}{10^2}$	0
A	990	1070
B	-90	-100
C = S	405	440
A_1	33.4	8.012
B_1	0	-2.5
C_1	15	3.6

The equations may now be written with numerical coefficients.

Forward Brush Position:-

$$i = 990\,\theta_1 - 90\,\theta_{11} + 405$$

$$i_2 = 33.4\,\theta_1 + 15$$

Neutral Brush Position:-

$$i = 1070\,\theta_1 - 100\,\theta_{11} + 440$$

$$i_2 = 8\,\theta_1 - 2.5\,\theta_{11} + 3.6$$

where $\theta_1 = e^{bt}\sin\omega t$, Forward, and $\theta_{11} = e^{bt}\cos\omega t$.
and $\theta_1 = e^{bt}\sin\omega t$, Neutral, and $\theta_{11} = e^{bt}\cos\omega t$.

Figures 114 and 115 for the forward brush position and figures 116 and 117 for the neutral position, plotted on the basis that the final static values of the short circuit and field currents from the records are altered/

altered to correspond with the calculated values, show the results of calculation and experiment together, and fairly good agreement will be observed between these particularly in regard to the amplitude of the overshoot.

The experimental curves, however, are all displaced relatively towards the left and this is almost certainly due to the mutual inductive reaction of the coils under commutation. It is well known that the presence of a short circuited secondary coil in a magnetic circuit causes the primary current (when a voltage is applied to the primary) to rise faster and fall slower during the earlier and later parts of the change respectively and this condition appears to be clearly indicated in the figures.

In a recent paper,[16]

([16] "Transients in Arc Welding Generators" Miller, Trans. A.I.E.E., Vol.52, Mar. 1933.)

a much closer agreement between calculated and test results is indicated in similar circumstances but the writer is inclined to the opinion that this closer agreement has been obtained by modifying the circuit parameters to suit the observed results.

(3) SWITCHING FROM OPEN CIRCUIT TO SHORT CIRCUIT, GENERATOR A.

Table 26 gives the terminal details taken from the appropriate oscillograms when switching from open to short circuit and to make a comparison the calculations for Generator A in this instance have been based strictly on the designed parameters for forward and neutral brush positions with r adjusted to give approximately the same volt-ampere characteristic and short circuit current for brushes neutral as for brushes/

brushes forward. The values of r are,

$$r = 0 \text{ ohms, brushes forward.}$$

$$r = \frac{2.6}{10^x} \text{ ohms, " neutral.}$$

It was also intended to make the calculation for the backward brush position, but as the preliminary calculation showed non-oscillatory conditions and as the oscillograms taken were not sufficiently representative, this plan was discarded.

The chief object of this part of the enquiry is to indicate how magnetic saturation affects the results when the value of K has been taken from the straight part of the open circuit characteristic. If the value of K is correspondingly reduced, a much nearer approximation could, of course, be obtained.

As before, in carrying out the calculations the tabular method was adopted, the table below giving the equation constants, while the calculated terminal conditions for

$$t = 0$$

are

$$\left.\begin{array}{l} i = 0 \text{ amperes} \\ i_2 = 15 \text{ amperes} \end{array}\right\} \text{Brushes forward, Calculations table 27.}$$

$$\left.\begin{array}{l} i = 0 \text{ amperes} \\ i_2 = 15 \text{ amperes} \end{array}\right\} \text{Brushes neutral, Calculations Table 28.}$$

Brush Position	Forward	Neutral
Record Number	1/A/0/1	63/A/0/1
S.C. Amperes	405	520
Record Number	7/A/2/2	69/A/2/2
Field Volts	15.8	14.8
Field Amperes	16	16.2
r ohms	0	$\frac{2.6}{10^x}$

Brush Position		Forward	Neutral
CIRCUIT PARAMETERS.			
R	ohms	$\frac{3.5}{10^2}$	$\frac{3.5}{10^2}$
R_2	"	1	1
r	"	0	$\frac{2.6}{10^2}$
L	henries	$\frac{13}{10^4}$	$\frac{11.5}{10^4}$
L_2	"	$\frac{2}{10}$	$\frac{2}{10}$
M	"	$-\frac{6}{10^3}$	0
N	"	$-\frac{3}{10^2}$	0
E_2	volts	8	8
K		15	15
EQUATION CONSTANTS.			
P		36	58
Q		1230	1165
S		440	440
b		-18	-29
ω		30.1	18
Freq.	Cycles/Sec.	4.28	2.87
ϕ		1.594	1.594
U		$\frac{1.4}{10^4}$	$\frac{1.44}{10^4}$
V		$\frac{3.45}{10^2}$	$\frac{7.65}{10^3}$
W		$-\frac{5.65}{10^2}$	0
A		3300	5060
B		-440	-440
C		440	440
A_1		107.3	17.62
B_1		0	11.58
C_1		15	3.42

The equations may now be written with numerical coefficients.

Forward Brush Position:-

$$i = 3300\,\theta_{,} - 440\,\theta_{,,} + 440$$

$$i_2 = 107.3\,\theta_{,} + 15$$

Neutral Brush Position:-

$$i = 5060\,\theta_{,} - 440\,\theta_{,,} + 440$$

$$i_2 = 17.62\,\theta_{,} + 11.58\,\theta_{,,} + 3.42$$

where $\theta_{,} = e^{bt}\sin\omega t, \quad \theta_{,,} = e^{bt}\cos\omega t$, forward.

$\theta_{,} = e^{bt}\sin\omega t, \quad \theta_{,,} = e^{bt}\cos\omega t$, neutral.

Figures 118 and 119 for the forward brush position and figures 120 and 121 for the neutral brush position show the result of experiment and calculation together and, as to be expected, the calculated results greatly exceed those obtained by experiment, chiefly on account of magnetic saturation as previously indicated.

From the chosen value of K the light load voltage would be at least twice the actual value obtained in each experiment, involving twice the field energy discharge.

(4) MAINTAINED OSCILLATIONS WITH SEPARATE EXCITATION.

The oscillograms which illustrate the maintenance of oscillations from a separately excited generator are:-

103/B/0/6, 104/B/0/6, 105/B/0/6, and 106/B/0/6

and the corresponding figures are:-

68, 72, 69, and 70

Table 29 gives the details taken from these records.

All these results were obtained from Generator B with the brushes approximately neutral and the injector transformer airgap set at 1/8". Records of the load current and voltage only were taken and Table 29 gives/

the values of the circuit resistance from which the total resistances, including the transformer, were obtained. Record Nos. 103/B/0/6 and 104/B/0/6 show oscillations of quite abnormal shape, the observed frequencies from 103/B/0/6 being 1.9 cycles/second and from 104/B/0/6, 1.2 cycles per second. The frequency calculation for Record Nos. 105/B/0/6 and 106/B/0/6 is shown below.

GENERATOR B.

Record No.	105/B/0/6	106/B/0/6
Figure No.	69	70
Observed Freq.cycles/Sec.	4.5	7
R ohms	.17	.29
R_2 "	1.7	1.7
r "	0	.12
L henries	$\frac{2.9}{10^3}$	$\frac{2.9}{10^3}$
L_2 "	$\frac{4.8}{10}$	$\frac{4.8}{10}$
M "	$-\frac{2.7}{10^2}$	$-\frac{2.7}{10^2}$
K	4.2	4.2
E_2 Volts	1.95	11.55
P	-39.5	-
Q	440	-
$\frac{P^2}{4} - Q$	-2500	-
ω	7.1	-
Calc. Freq.	1.13	0

The values of P and Q above are calculated from the expressions given in Chapter 2, Section 5 and, for convenience of reference, are repeated here,

$$P = \frac{RL_2 + R_2L + rL_2 + KM - KNL_2 - 2rM}{LL_2 - M^2},$$

$$Q = \frac{RR_2 + rR_2 + Kr - KNR_2 - r^2}{LL_2 - M^2}$$

In this case, since the brushes are neutral, N is zero.

According to the linear theory the calculations show P to be positive (i.e. no vibrations) in the case of Record No. 106/B/O/6, while the actual record shows a very good oscillation. The observations on over-compensation made on p. 94 in this connection apply here also.

Concluding, records of maintained oscillations with separate excitation have been obrained from Generator A and all the constant current units D, E and F have been known to produce and maintain similar oscillations.

(5) SWITCHING TESTS ON GENERATORS B, G and H. COMPARISON WITH PUBLISHED CRITERIA.

The tests made on these generators consisted of switching from open to short circuit and back again to open circuit.

The method of current regulation used with Generator B has already been described fully (figure 9). In the cumulative compound Generator G, shunt field regulation is employed between the limits of full load (200 amperes) and approximately half load (100 amperes) when a new welding terminal is available which introduces a series resistance to the arc circuit, thereby enabling the open circuit voltage to return to its original value and allowing the shunt regulator to be used throughout its range again. Oscillogram No. 88/G/O/4 (figure 67) shows the result with the 100 ampere terminal in use.

For the series opposition generator H, similar/

similar performance to that of Generator G is obtained on smaller electrodes by the use of a shunt regulator and a series field tapping switch, the opposition m.m.f. being increased in definite steps for smaller current values allowing the restoration of the open circuit voltage for each step and a new shunt control effected.

Oscillograms No. 82/B/0/4, 85/G/0/4 and 91/H/0/4 (figures 62, 63 and 64 respectively) show the short circuit currents and terminal voltages for the appropriate generators, the fields being set for maximum output in each case. Record No. 98/G/0/4 (figure 66) shows the short circuit current with the dynamo field regulated to give approximately 100 amperes load current and 88/G/0/4 shows the corresponding result using the 100 ampere terminal and full field. A further record was taken (99/B/0/5, figure 65) to show the effect of using the injector transformer (with an 1/8" air gap) to increase the speed of response of Generator B. The open circuit voltage in this case was reduced from 66 to 49 by the additional resistance of the transformer secondary in the field circuit of the machine.

SWITCHING FROM OPEN CIRCUIT TO SHORT CIRCUIT AND BACK TO OPEN CIRCUIT - GENERATORS B, G AND H.

Figure No.	Reference No.	Open Circuit Volts	Short Circuit Volts	Short Circuit Amps.	Remarks.
62	82/B	66	3	330	Maximum Output.
63	85/G	70.5	3	325	Maximum Output.
64	91/H	73	3	295	Maximum Output.
66	98/G	49	3	285	Regulated Down.
67	88/G	72.5	1.5	165	100 amp. Terminal.
65	99/B	49	2.5	182	Injector used.

In making these switching tests fast circuit breakers were not available and the time taken completely to rupture the circuit by hand operated switch is clearly indicated on all the records, and was of the order of 1/20th of a second. This condition masks the transient voltage rise which would appear due to the discharge of the armature circuit stored energy.

The table below shows:-

(1) The values of the current overshoot taken as a percentage of the steady short circuit current.

(2) The reserve voltage measured approximately 1/20th of a second after rupture.

(3) The approximate time taken to recover to within 5% of the normal open circuit voltage.

(4) The ratio of the reserve to open circuit voltage.

Figure No.	Ref. No.	O.C. Volts	Overshoot %	Reserve Voltage	Reserve Volts / O.C.Volts	Recovery Time, Secs.
62	82/B	66	70	44	.67	.125
63	85/G	70.5	37	44	.62	.2
64	91/H	73	30	46	.63	.23
66	98/G	49	5	39	.8	.06
67	88/G	72.5	5	59	.82	.1
65	99/B	49	0	49	1	Approx. 0

The details given in the above table demonstrate that all these generators are well up to the requirements of good welding, at least with regard to speed of action. It is interesting to note that:-

(1) Generator G gives quite good results when regulated by field resistance only and that the ratio $\frac{\text{Reserve Volts}}{\text{O.C.Volts}}$ is actually greater than for the full load condition. This im-/

improvement is undoubtedly due to the introduction of resistance into the field circuit with consequent reduction of its stored energy.

(2) The introduction of resistance into the arc circuit raises the open circuit voltage for a given arc current and this has the effect of increasing the ratio $\frac{\text{Reserve Volts}}{\text{O.C.Volts}}$.

(3) The introduction of the injector has made the performance of Generator B almost perfect on all the three criteria.

The injector, however, is a large piece of apparatus and further, introduces inductance into the arc circuit and this is not always desirable.

CHAPTER 4.

Section 6.

TESTS ON A CONSTANT CURRENT GENERATOR SWITCHING FROM LOAD TO SHORT CIRCUIT.

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(1) COMPARISON OF CALCULATION AND TEST FOR ABUTMENT VARIATION COMPLETELY DAMPED OUT BY THE INJECTOR.

Details from the Record:-

Figure Number	85
Reference Number	129/D/0/8
Short Circuit Amperes	250
Short Circuit Volts	2.4
Load Amperes	250
Load Volts	250
Field Amperes S.C.	15
Field Amperes Load	195
Brushes	Neutral
Transformer	1/8" Airgap.

The following preliminary calculations and assumptions are required in order to comply with the conditions upon which the equations are based.

(a) Since compounding is neglected, the value of i for t = 0 should be calculated from equation (13) of Chapter 2, Section 6.

This equation is:-

$$i = \frac{E_1}{R_1} - \frac{R_2 e}{K_1 K_2} = 224.$$

The natural regulation is therefore 10%.

(b) It is assumed that the ratio - $\frac{\text{Abutment Turns}}{\text{Series Opposition Turns}}$ is unity.

(c) Due to the action of the injector the abutment current becomes almost constant and is assumed to be so, therefore, ■/

i_1 = constant = I_1 = 250 amps.

(d) The power loss in the abutment circuit is 400 watts, therefore,

$$E_1 = 1.6 \text{ volts.}$$

As, however, no great error will be introduced by using the steady state values from the record, these will be employed in the calculations, thus, for

t = 0,

i = 250 amperes

i_1 = 250 amperes

i_2 = 195 amperes on load

i_2 = 15 amperes on short circuit.

In forming the complete circuit parameters, those for the primary of the transformer must be included in the load circuit. As the m.m.f's of the primary and secondary are cumulative when used as an injector, the yokes and cores of the transformer will be well saturated, at least while the high impulse current remains. An allowance for the primary self-inductance of one half normal value should be sufficient to cover this condition, that is $\frac{8}{10^4}$ henries while $\frac{4}{10^2}$ ohms will be taken for the additional resistance. The tables below gives the circuit parameters and equation constants.

CIRCUIT PARAMETERS		
R	$\frac{4.4}{10^2}$	$\frac{4}{10^2} + \frac{4}{10^3}$
R_1	$\frac{6.4}{10^3}$	
R_2	$\frac{5}{10^2}$	
L	$\frac{3.3}{10^3}$	$\frac{2.5}{10^3} + \frac{8}{10^4}$
L_2	$\frac{7.5}{10^3}$	
E_1	1.6	

K_1	.3	From O.C. Char.
K_2	2.	" " "
$K_1 K_2$	.6	

EQUATION CONSTANTS.

P	20	$\frac{RL_2 + R_2 L}{LL_2}$
Q	24,400	$\frac{RR_2 + K_1 K_2}{LL_2}$
S	249	$\frac{K_1 K_2 E_1}{R_1 (RR_2 + K_1 K_2)}$
b	-10	
ω	156	
Freq.	25	
U	$\frac{1.65}{10^3}$	$\frac{L}{K_2}$
V	$\frac{2.2}{10^2}$	$\frac{R}{K_2}$
A	700	
B	0	
C	249	
A_1	4	$AbU - B\omega U + AV$
B_1	180	$A\omega U + BbU + BV$
C_1	15	V S

The equations may now be written with numerical coefficients and are

$$i = 700e^{-10t} \sin 156t + 250$$

$$i_2 = 4e^{-10t} \sin 156t + 180e^{-10t} \cos 156t + 15$$

The equation for the load current for a time equivalent to one quarter of the first period gives i = 850 amperes approximately, whereas the maximum value taken from Record No. 129/D/0/8 (figure 85) is about 20% greater than this, further, the calculation shows the

the decrement to be small and the record indicates a fairly large decrement. The frequency measured from the oscillogram is 27 cycles per second. Figure 122 gives a comparison of calculated and experimental curves.

The chief difference between test and calculation is again undoubtedly due to the mutual inductance of the coils under commutation. Further inspection of figure 122 shows a rapid current rise to peak value and the experimental curve is again displaced towards the origin when compared with the calculation. This indicates that the field flux is retained for a longer period at a higher value than would otherwise be the case if negative mutual inductance were not present, and although the peak value attained in the first half period is greater than the linear theory indicates, this must ultimately result in a quick dissipation of the field energy with consequent increase of the decrement.

While measuring the inductance values for Generator D (figure 132), the necessary readings were taken at 25 cycles per second and were made with the main brushes in place and also raised from the commutator. The great difference observed in the inductance values of the field circuit under these conditions further emphasises the effect of the coils undergoing commutation.

(2) EFFECTS OF THE INJECTOR.

(a) On the current overshoot.

The oscillograms used to compare the current overshoots are detailed in Table 30 and are Nos. 110/D/0/4 and 113/D/0/8 (figures 73 and 79 respectively). Both these records were taken in switching from 126 volts load to short circuit, the first with the main generator brushes 1/4 " forward and without the injector, the second/

second including the injector (1/8" airgap) in circuit and with the brushes neutral.

These records demonstrate that the effect of the injector has been to reduce the overshoot by 35% in addition to allowing the machine to operate successfully with the brushes in the neutral position.

(b) On the tendency to oscillate.

The value of P in the equation for M = 0 (Equation (D), Chapter 2, Section 6) must always be positive, indicating that the addition of an injector of sufficient capacity completely to stabilise the abutment current during sudden load changes, will eliminate all possibility of low frequency self excitation in such generators.

Inspection of Record 113/D/0/8 (figure 79) shows that although oscillatory discharge is present, the decrement is great and the fluctuations are quickly damped out.

(c) On the abutment and field currents.

Record 121/D/1/9 (figure 80) shows clearly that the abutment circuit fluctuation is almost eliminated and the e.m.f. generated in the transformer to bring this about is also shown. The peak value of the injected e.m.f. is about 6 times the steady abutment value (8.45 volts). Record 126/D/2/12 (figure 81) shows the corresponding field current and it may be observed that the main field current dies quickly to zero, and that the voltage peak value required to reverse it is at least 5 times that of the steady state value. Comparing these records (121 and 126) with Records 123/D/1/10 and 124/D/2/11 (no injector) it will be observed from Record 123/D/1/10 that the abutment

abutment current rises to 2.5 times its steady state value and it is interesting to note that the main field current actually rises at the moment of switching. This is due to the main brushes being forward, thus providing direct negative mutual inductance between the armature and field circuits.

(d) On the Frequency.

Adding the injector to the circuit has the effect of raising the frequency of the discharge from about 10 to 27 cycles per second. The calculations made in Chapter 2, Section 6 indicated that this was likely to be the case but when comparing Records 110/D/0/4 and 113/D/0/8 it must be noted that the brush positions are not the same and this may have a considerable effect on the actual value of the frequency obtained.

(3) EFFECTS OF BRUSH POSITION.

Comparison of the line current Records 111/D/0/4 and 119/D/0/8 (figures 76 and 82) and the corresponding abutment and field records, details of which are given in Table 31, will show that maintained oscillations with forward and backward brush positions and separate excitation are possible. Record 111/D/0/4 demonstrates the production of maintained oscillations with the brushes 1/8" forward and no injector while Record 119/D/0/8 shows a similar condition with the brushes 1/4" back and having the injector in circuit (airgap 1/4"). The frequency of the oscillation is twice as fast in the latter case as in the former, the approximate values being 22 and 11 cycles per second respectively.

(4) EVIDENCE ON SERIES IMPULSE.

The indications of the mathematical analysis applied to constant current generators are to the effect/

effect that maintained oscillations are not possible when an injector of sufficient capacity is coupled in circuit generally as figure 11. By giving the main generator brushes lead or lag, negative or positive mutual inductance and series impulse is introduced between the armature and field circuits and fluxes. If magnetic linkage is present between these circuits it must be assumed that series impulse effects in the form of extra magnetism must exist, and therefore that this effect must preponderate over the corresponding additional M between the circuits. Giving the brushes a forward lead introduces a negative M and, in accordance with previous calculations and experimental results, should increase the tendency to oscillate, but does not. On the other hand, giving the brushes a negative lead introduces positive M and should eliminate the tendency to oscillate, but does not, as demonstrated by Record No. 119/D/O/8. These conditions provide strong evidence that the differential series impulse on the main field, in the first case, tends to and does eliminate and overcome the effect of negative mutual inductance and actually prevents self excitation, the opposite being true in the latter case.

In further support of the above, three generators of 320 Kw capacity (the details of which are given under the reference letter F in Table 34) when first tested gave a considerable amount of trouble with low frequency self excitation. It was found that the usual expedient of giving the main brushes a forward lead was not completely effective and other methods were tried. Past experience clearly indicated that the opposition impulse was, in this case, too small, and to increase this, the possibilities of using the coils under com-/

commutation were considered and employed with success. The method finally adopted was to increase the interpolar air gap and to divert a portion of the current from the interpole coils.

Under steady state conditions the commutation was unaffected, but, if the load changed suddenly, the divertor temporarily took more than its share of the current, thereby introducing to the main field a negative (demagnetising) impulse through the agency of the coils under commutation. This expedient was sufficiently successful to enable the main brushes to be restored to their neutral position without recurrence of the trouble.

(5) IMPORTANCE OF THE $\frac{\text{ARMATURE}}{\text{FIELD}}$ STRENGTH RATIO.

This matter has been considered previously, but from the point of view of fast operation, the larger the dynamo the greater is the necessity for providing relatively strong armatures. In all the constant currents units discussed here the armature strengths have not been very different to those adopted in ordinary D.C. practice, reliance for rapid operation being placed on the high exciter ceiling voltage rather than on the armature m.m.f./field m.m.f. ratio. Considerable improvement in speed of operation could certainly have been made in the cases of the larger generators (E and F) had a stronger armature been adopted.

CHAPTER 4.

Section 7.

EXCITATION OF ALTERNATORS.

As mentioned in Chapter 1 (p.6), it was not proposed to carry out any research on the above subject but it is worthy of mention in passing that if it were possible in practice to employ higher ratios of armature m.m.f./field m.m.f. in alternators, better performance and cheaper units would result. The design tendencies for these machines should therefore incline towards the higher ratio, more reliance being placed on improved excitation methods than has hitherto been customary.

Since switching transients in alternator circuits may be considered as direct current phenomena on a sinusoidal base, the calculations of these could proceed on similar lines to those performed for constant current generators, the seat of the mutual inductance being between the armature and field circuits as for the constant current generators described here.

CHAPTER 5.

LEADING DESIGN FEATURES OF THE MACHINES TESTED INCLUDING METHODS OF OBTAINING CHARACTERISTIC CURVES AND CIRCUIT PARAMETERS.

In this chapter details are given in tabular form which enables the electrical design of all the machinery used in the production of this thesis to be visualised.

The methods by which the approximate circuit parameters are obtained for each unit are outlined and the leading figures for the inductances corresponding to various airgap lengths of the transformer T are also given.

A large number of oscillograms were taken and many scrapped. For record purposes, however, tables giving details of those preserved appear in Volume II while those of particular interest to the investigation have been given figure numbers, reproduced in Volume II., and referred to throughout this text.

The two classes of generator tested were:-

(1) Welding Generators driven by suitable motors,

(2) Constant Current Generators driven by suitable motors,

and the design details are given in separate tables (Tables 32 and 34) under the machine reference letters of Table 1. Table 32 gives all design details for the welding units A, B and C, while Table 34 provides for the Constant Current Plant.

Two further welding units, G and H, were submitted to switching tests but it is unnecessary to give complete design details for these.

The circuit parameters for each of the welding/

welding units are given in Table 33, those for Generator A being divided into parts corresponding to the three brush positions, forward, neutral and back.

The circuit resistances are obtained by adding the resistance of each of the constituent elements of the circuit and an allowance is made for the contact resistance of the brushes where these appear. The inductances are calculated from the voltage and current values given in figures 123, 124 and 125 on the assumption that the resistance side of the e.m.f. triangle is negligible in each instance. For example,

$$L = \frac{E}{2\pi f I} = \frac{6.37}{10^3} \times \frac{E}{I},$$

$$M = \frac{E}{2\pi f I} = \frac{6.37}{10^3} \times \frac{E_2}{I},$$

where E and E_2 are the e.m.f.'s appearing at the terminals of the circuit through which the current I passes and the linked circuit respectively.

Where brushes appear the resistance is not strictly constant but is a function of the current and the inductance is modified by the reaction of the coils under commutation where these appear. Average allowances have been made in the above values to cover this condition.

The field circuit inductances were measured under two conditions to bring out the effect of the coils short circuited by the brushes and these were (a) brushes raised, (b) brushes in place.

The wide variations of the field circuit inductances due to the reactions in the coils short circuited are shown in figures 132 and 133, where an average increase of current of approximately 50% for the same applied voltage is shown for the main brushes in place condition.

The/

Chapter 5.

The values given for the constant current generators in Table 35 include both generator and exciter, that is, the generator and exciter are treated as one unit. The resistances and inductances respectively are added together for those generator and exciter circuits which are in series. If a transformer is used, this is indicated in the text and suitable adjustments made to obtain the circuit parameters. The values of K are measured from the respective open circuit characteristics, while the abutment voltage E is reduced to correspond with that of the series opposition winding and is obtained by dividing the abutment circuit power loss (watts) by the line (or constant) current of the dynamo.

Each dynamo tested was further subjected to an open circuit test to give its characteristic and in the case of the welding dynamos, its volt-ampere characteristic also. These are reproduced in Volume II under the figure numbers given in the design tables.

The modern welding units G and H were tested to indicate the conditions required for good welding performance. G is an example of the cumulative compound type and H represents the separately excited, differentially wound type. Both units are of 6 Kw capacity their maximum output being 30 volts, 200 amps., obtained when running at 1500 r.p.m. The light load e.m.f. of each is approximately 70 volts and both generators are fitted with salient laminated poles and solid yokes.

THE INJECTOR TRANSFORMER, (Ref. T).

Figure 139 shows the leading dimensions of the core and sections of the windings. The primary winding consists of 7 turns of flat copper strip 2.5" x .03", the resistance cold being $\frac{3.8}{10^3}$ ohms.

The/

Chapter 5.

The secondary winding has 100 turns of .124" diameter copper wire wound on top of the primary and its cold resistance is $\frac{3.5}{10}$ ohms.

Table 36 shows the results of tests on A.C. of 25 cycles/second with different air gaps, the resulting values of the inductances for these being obtained by calculation from the recorded voltages and currents, these results being based on the assumption that the resistance side of the voltage triangle is small enough to be neglected. The values of L and M have been calculated for all the test figures given and plotted in figure 138, and the curve value taken for each airgap. L_2 has been estimated on the assumption that perfect linkage exists between the primary and secondary coils, and therefore,

$$L_2 = \frac{M^2}{L}$$

In every case, throughout this text, where the transformer has been used and where it has been necessary to apply these inductance figures, the curve values have been adopted.

CHAPTER 6.

CONCLUSION AND SUMMARY.

To a large extent the problems considered in this thesis relate to what happens when a circulation of energy takes place between the field and armature circuits of commutator dynamo-electric machines.

When switching from the open to short circuit condition the energy stored in the field system (if the dynamo is excited) is discharged and consumed as follows:-

(1) It is dissipated by the effective resistance of the field, armature and associated circuits, such as the coils under commutation and the eddy current paths in the iron and copper.

(2) Any remaining energy is temporarily stored in the armature circuit by a temporary increase of the armature or load current beyond its steady state value.

(a) If the effective resistances are great, the load current may only rise to its steady state value without overshoot. This may be compared with a displaced pendulum, the bearing friction of which is so great, that when released it cannot swing beyond the vertical.

(b) If the effective resistances are less than in (a) the load current may overshoot and fall back exactly to the steady state value; in this case the equivalent of a pendulum which, in its swing, passes the vertical position once and returns there without again re-passing.

(c) If the effective resistances are again less than in (b) a state of damped oscillatory motion is reached.

(d)/

Chapter 6.

(d) If at maximum amplitude and beginning to fall, an external impulse is communicated to the swing, maintained oscillations are to be expected.

WELDING GENERATORS.

Consider now the action of a self-regulating welding generator in practice. When contact between the electrode and the metal is made, the dynamo terminals are short circuited and the short circuit current may rise to a value much larger than that indicated by the static volt-ampere characteristic. During this operation nearly all the field energy is liberated and a considerable amount of it wasted in the armature coils undergoing commutation. Later, when contact is completely broken, the energy stored in the armature circuit is liberated, appearing for a very short period as high voltage and small current at the dynamo terminals and finally disappearing in heat in the form of an arc at the electrode point. Good welding depends chiefly on the ability of the generator to maintain the arc and this in turn depends on its ability to reproduce its steady open circuit voltage very rapidly after a rupture. Although, due to the discharge of the load circuit magnetic energy, a very high striking voltage may temporarily be obtained, this will usually die away in less than 1/200th part of a second and the arc will be extinguished if a further reserve voltage is not instantly available. For metal arc welding a reserve of not less than 30 volts is considered necessary which means that the generator field must rise sufficiently to provide this value within the period mentioned.

To increase this reserve and limit the current/

current overshoot it is still prevalent practice to load up the arc circuit with inductance or provide a transformer injector between the load and field circuits.

Neither of these expedients is desirable for the following reasons:-

(1) Both involve the use of an extra piece of apparatus increasing the cost, weight and maintenance of the unit.

(2) It has been found in practice that large arc circuit inertias tend to produce arc spread and the burning away of the protective coating at the electrode point, thereby increasing the danger of harmful inclusions in the weld metal.

(3) The large energy discharge possible on sudden rupture of the arc circuit causes piercing when welding thin metals.

(4) Holding a long arc is very easy and, with inexpert operators, produces bad results.

All four objections apply in a varying degree to both expedients, for an injector is not really effective unless designed for high self inductance in its primary.

These arguments lead to the following criteria for good welding dynamo design.

(1) The electrical inertia of the load and field circuits should be as small as possible.

(2) The capacity for magnetic energy storage in each circuit should be of the same dimensional order, that is, the armature circuit should be able at least to absorb the residue of the field energy discharge under rapid load changes without the armature current fluctuating seriously from the prescribed static value.

Both/

Chapter 6.

Both criteria point to the employment of compensating windings, for these allow the armature m.m.f. to be increased without involving an increase in its circuit inertia over that of the non-compensated machine and, other things being equal, lead to a reduction of the field circuit inertia.

As an illustrative example of the latter, suppose the armature m.m.f. doubled, thus involving a reduction of the field energy to one quarter for the same terminal voltage.

The arguments and example quoted show the importance of compensating windings and armature strength and if the former is used and the correct armature strength chosen, excellent welding generators can be constructed without the use of external aids.

CONSTANT CURRENT POWER DYNAMOS.

In larger dynamos, such as the constant current generators described earlier in this thesis, the handling of the field energy becomes more difficult and a resort to separate excitation generally becomes necessary. When employed it enables the application of high ceiling voltages (for rapidly altering the main field energy under sudden load changes) to be economically employed in two ways. These are:-

(1) By means of a special exciter design.

(2) By means of an injector transformer.

The objections raised to the employment of an auxiliary transformer in welding generators are not applicable to constant current machines because the transformers here are relatively small and light in comparison with the dynamos, since they operate on relay/

relay (exciter abutment) fields.

Under transient conditions both exciter and transformer perform the same functions, that is, provide a high ceiling voltage, but under static conditions the high terminal voltage which the exciter is capable of producing increases the rigidity of the volt-ampere characteristic and allows compounding or over-compounding to be easily effected.

GENERAL NOTES.

A. From the foregoing remarks it is apparent that all types of dynamos subject to sudden load variations should be of the laminated, compensated field type and that further, for the larger sizes, the use of a high ceiling voltage exciter is imperative for good performance.

B. In alternating current generators compensating windings are not commercially possible because, due to the absence of the commutator, the axis of the armature m.m.f. is not fixed in space, and it would be difficult therefore to provide compensating windings supplied with current at zero frequency. It is possible however that exciters employing high ceiling voltages have not been fully explored as an alternative to fast circuit-breakers and power limiting reactors.

C. As the following summary will indicate the scope of this enquiry has been large but it has not been possible, with the available apparatus, to investigate in detail, questions such as the following:-

(1) The influence of design on the frequency, wave shape and amplitude of the maintained oscillations obtained.

(2)/

Chapter 6.

(2) The effects of the reaction of the coils under commutation, brush position, width of brushes, and the interpole strength on the frequency, wave shape and amplitude of the maintained oscillations.

(3) The effect of varying the mutual inductance M on these.

(4) The direct proof that oscillations may be maintained by impulse from series windings only.

It would be possible to clear up most of these questions by research on a specially designed unit such as the following:-

A dynamo of the laminated, compensated field type having 8 terminals for a 4 pole field winding, an additional localized 8 terminal interpole winding (so that the effect of the compensating winding could be modified locally in small increments) would be a suitable machine especially if it were also provided with an auxiliary core having an 8 terminal series impulse winding. To obtain high ceiling voltage effects an exciter of the constant current type and a variable airgap injector would also be necessary, the whole being mounted on a single bedplate and driven by a suitable motor of sufficient power.

CHAPTER 6.

SUMMARY.

It has been indicated by mathematical analysis and proved, in some cases, by experiment that:-

(1) A dynamo, the field of which is excited through a transformer, will produce and maintain low frequency oscillations of controllable magnitude and frequency.

(2) A shunt wound dynamo, having a mutual inductive link between the load and field circuits will self-excite, produce, and maintain low frequency oscillations of controllable amplitude and frequency.

(3) A plain shunt dynamo, although capable of oscillatory discharge, will not maintain oscillations without external aid.

(4) A plain series dynamo can neither produce an oscillatory discharge nor maintain oscillations without external aid.

(5) In a compound dynamo the fields of which are mutually linked, the tendency to maintain oscillations through the presence of mutual inductance is balanced, or partially balanced, by the impulse from the series winding.

(6) In a compound dynamo the fields of which are not mutually linked, the tendency to produce and maintain oscillations is present due to the impulse from the series winding. Analysis indicates that this impulse must be positive, that is, obtained from cumulative series coils, and it would/

would appear that a further condition is necessary for the maintenance of oscillations. This is that although the dynamo is cumulatively wound, the field must fall with increase of load current.

(7) A separately excited dynamo can produce and maintain oscillations if either the transformer or series impulse method is correctly applied.

In testing the above statements 6 generators of various types and sizes were examined, some of these having completely laminated field structures and compensating windings, others with salient poles and solid yokes, and one having neither compensating nor interpole windings. These generators varied in output from 6 to 320 Kw, in speed from 1000 to 3000 r.p.m. and all have been known or caused (for the purpose of this investigation) to self-excite, produce and maintain low frequency oscillations under various conditions of excitation. These results indicate that any shunt dynamo-electric machine may self-excite under suitable conditions and that there exists a value of M which can be inserted between the load and field circuits to cause this condition. For the compound wound dynamo it will not be so easy to arrange for an oscillatory condition because of the difficulty of providing a series winding without interfering with the shunt winding and at the same time assuring that the dynamo is naturally capable of oscillatory discharge.

It has been further indicated by theory and proved in some cases, by experiment, that:-

(a) The linear theory, under the quoted assumptions, gives reasonably good results for the transient/

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transient values of current and voltage during switching.

(b) The linear equation, although giving a good indication that maintained oscillations may be expected under certain conditions, does not correctly predict either the wave shape or the frequency of the resulting oscillation.

(c) To obtain rapid response to sudden changes of load it is necessary that the magnetic energy stored in the armature and field circuits must be kept as low, and that in the load circuit relatively as high as possible.

(d) For extreme rapidity of response in larger dynamos, the use of high ceiling voltage exciters and injector transformers are indicated.

Concluding, the oscillograms taken from the three welding dynamos of recent but quite different design, indicate that the criteria evolved for good welding performance are reasonable.

ACKNOWLEDGMENTS.

The writer desires to acknowledge his indebtedness to:-

Professor G.W.O. Howe, D.Sc., Wh.Sc., M.I.E.E., the supervisor under whom this work was carried out, for generous provision of apparatus and ever-ready advice and assistance.

J.C. Macfarlane, O.B.E., Wh.Sc., M.I.E.E., of Messrs. The Macfarlane Engineering Co. Ltd., for the loan of the Generators and valuable advice,

Messrs. Gilbert Austin, Ltd., for the use of their test bed and a supply of power,

Messrs. W. McHutchison and A. Spence for their aid in tracing many of the figures and tables of Volume II,

And to numerous Members of the Engineering Department Staff for their tolerance and assistance.

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OSCILLATORY and TRANSIENT

PHENOMENA

in

DYNAMO CIRCUITS

by

James W. Macfarlane, Wh. Sc., Dipl. R.T.C.

VOLUME II

A Thesis presented for the degree of Ph. D.,

in the Faculty of Engineering,

of the University of Glasgow,

APRIL, 1937.

N O T E

This copy of Volume II contains reproductions of the oscillograms referred to in the text of Volume I, the originals appearing in another copy.

A sample of the records taken from each of the Oscillographs used during the enquiry is, however, shown in Figures A and B.

LIST OF FIGURES.

LIST OF FIGURES. (Cont'd.)

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LIST OF FIGURES. (Cont'd.)

LIST OF FIGURES. (Cont'd.)

LIST OF TABLES.

LIST OF TABLES. (Cont'd.)

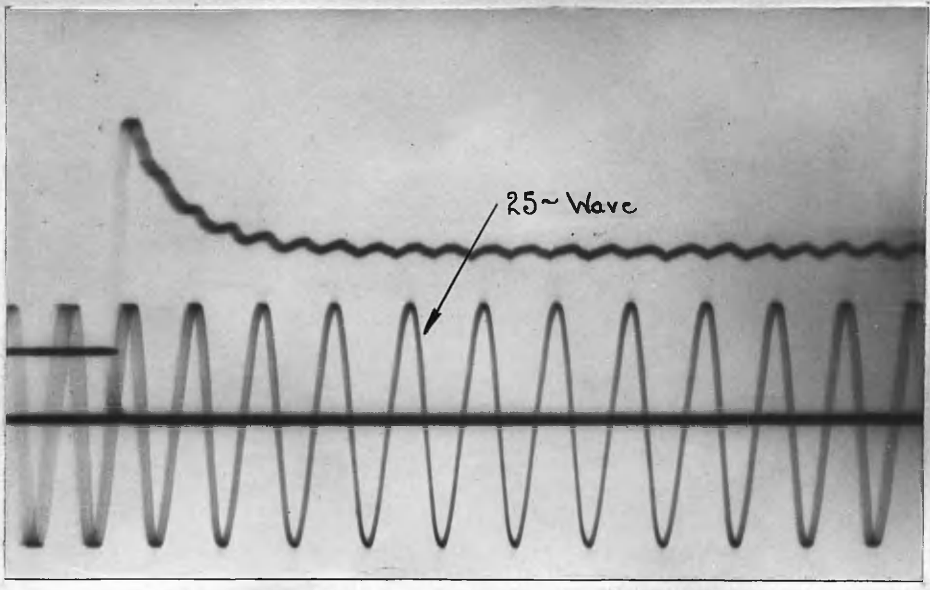


FIG. A.

SAMPLE OSCILLOGRAM FROM

THE DUDDELL OSCILLOGRAPH.

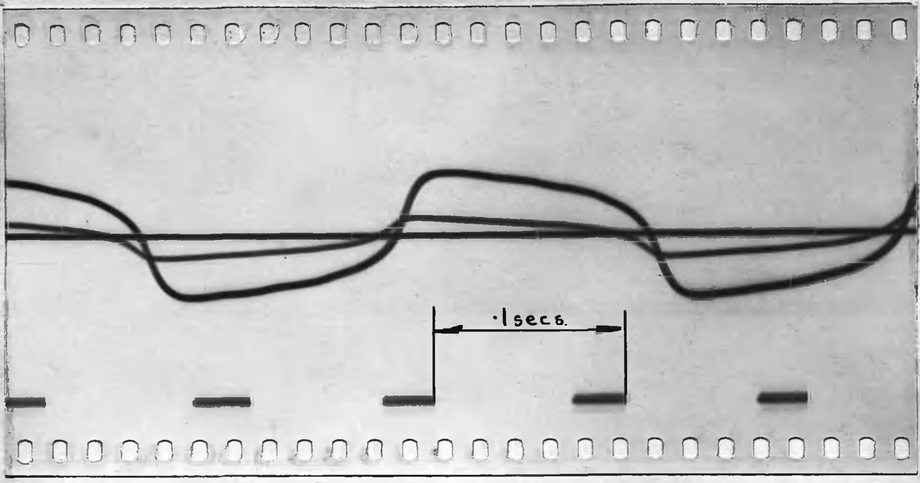


FIG. B.

SAMPLE OSCILLOGRAM FROM

THE PERMANENT MAGNET OSCILLOGRAPH.

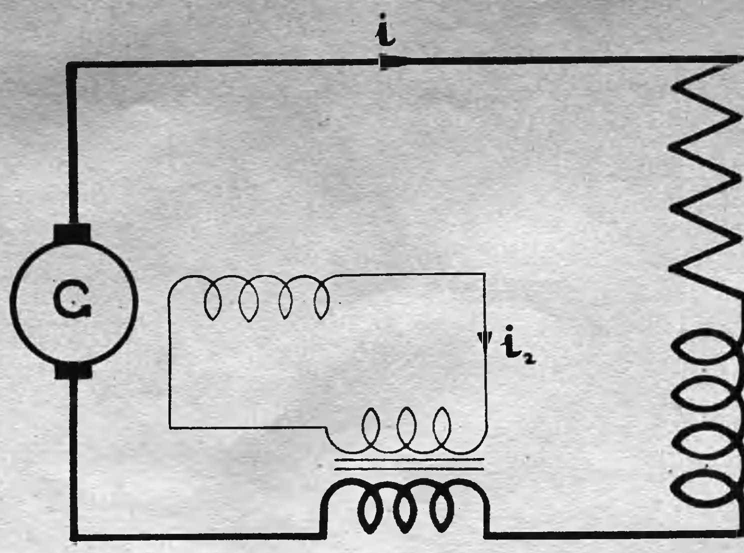


FIG. 1

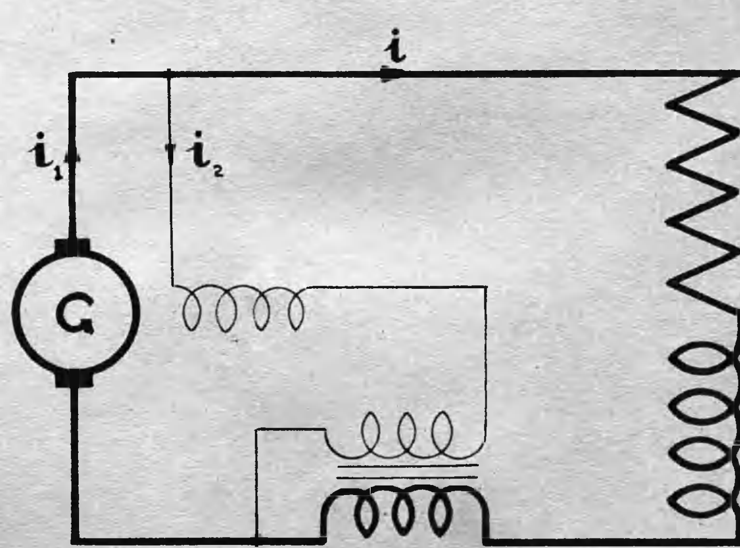


FIG. 2

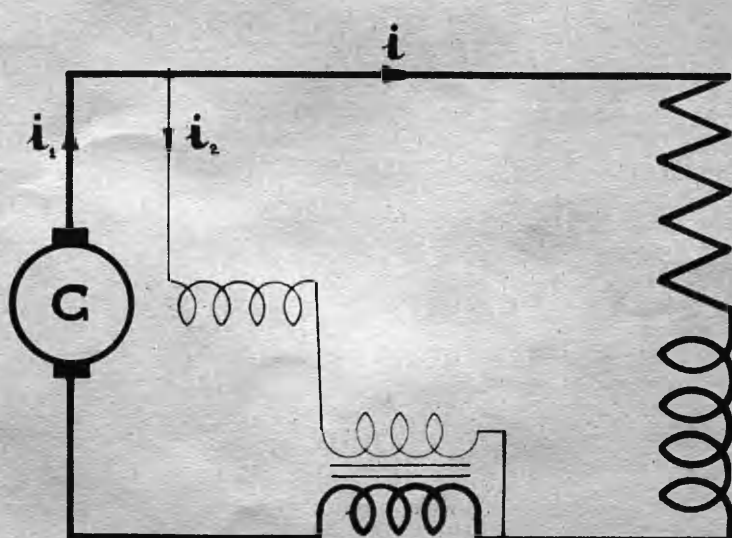


FIG. 3

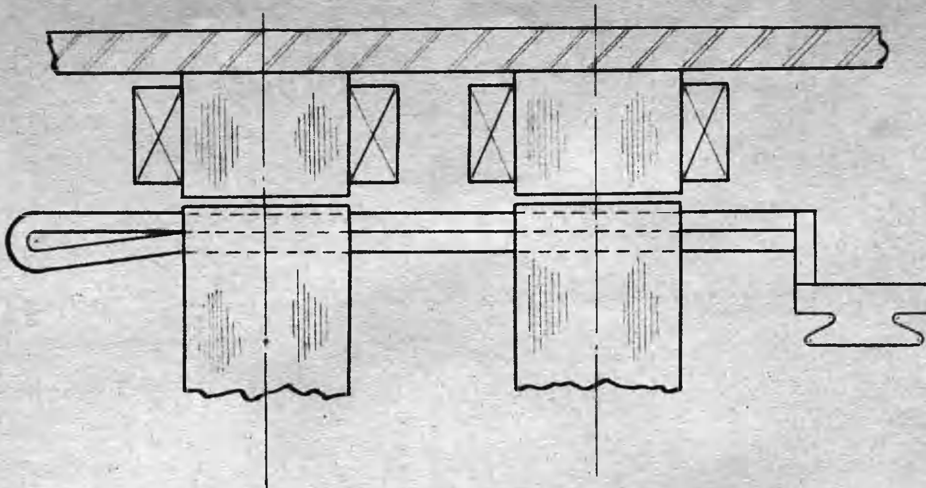


FIG. 4.

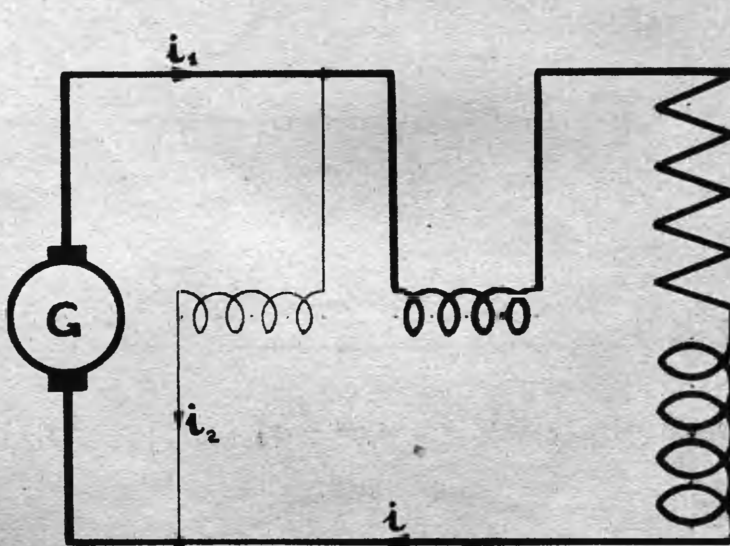


FIG 5

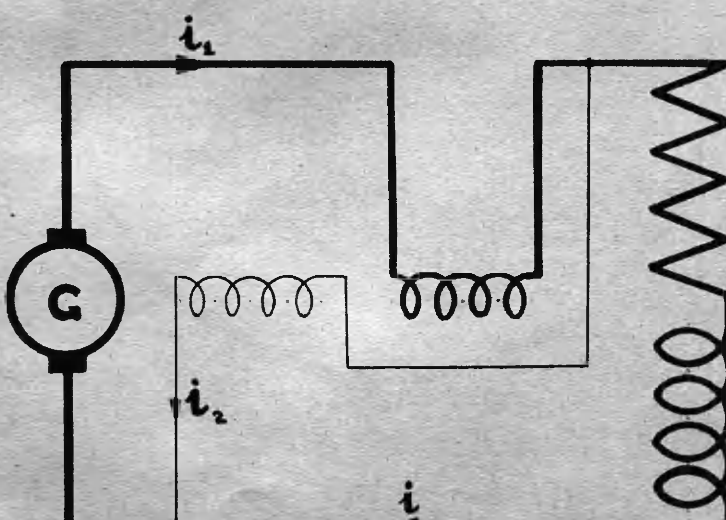


FIG 6

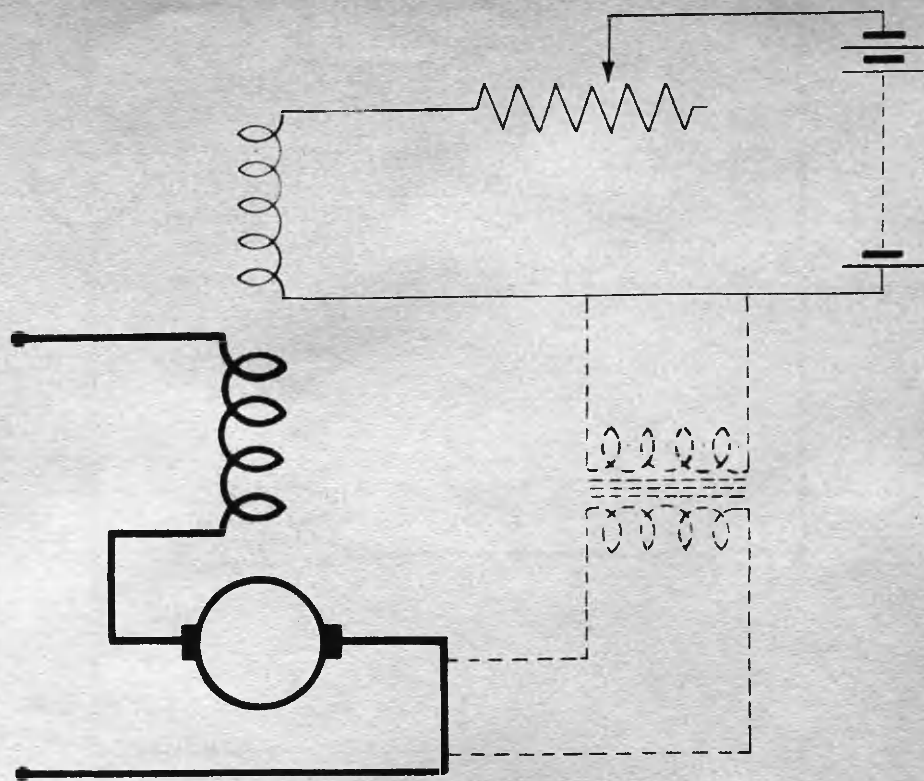


FIG. 7

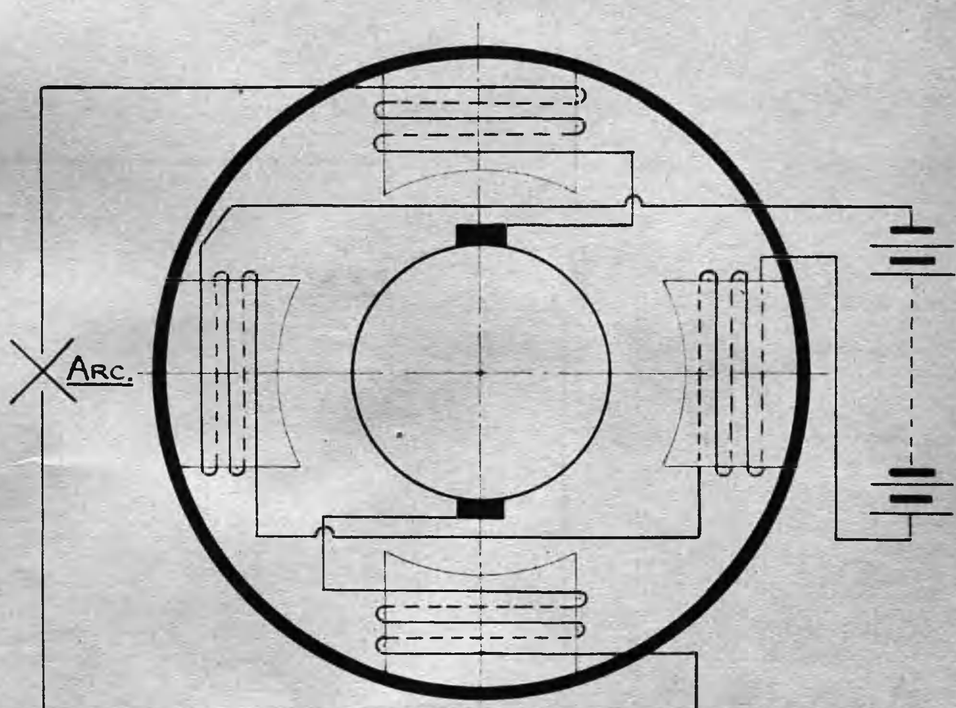


FIG. 8

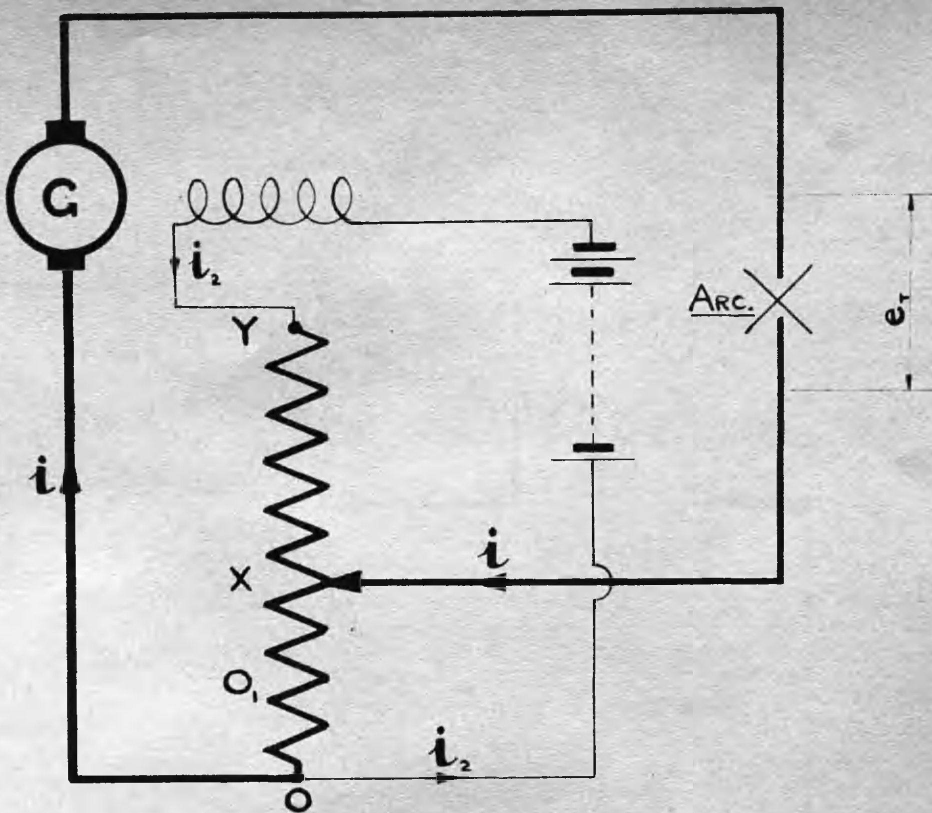
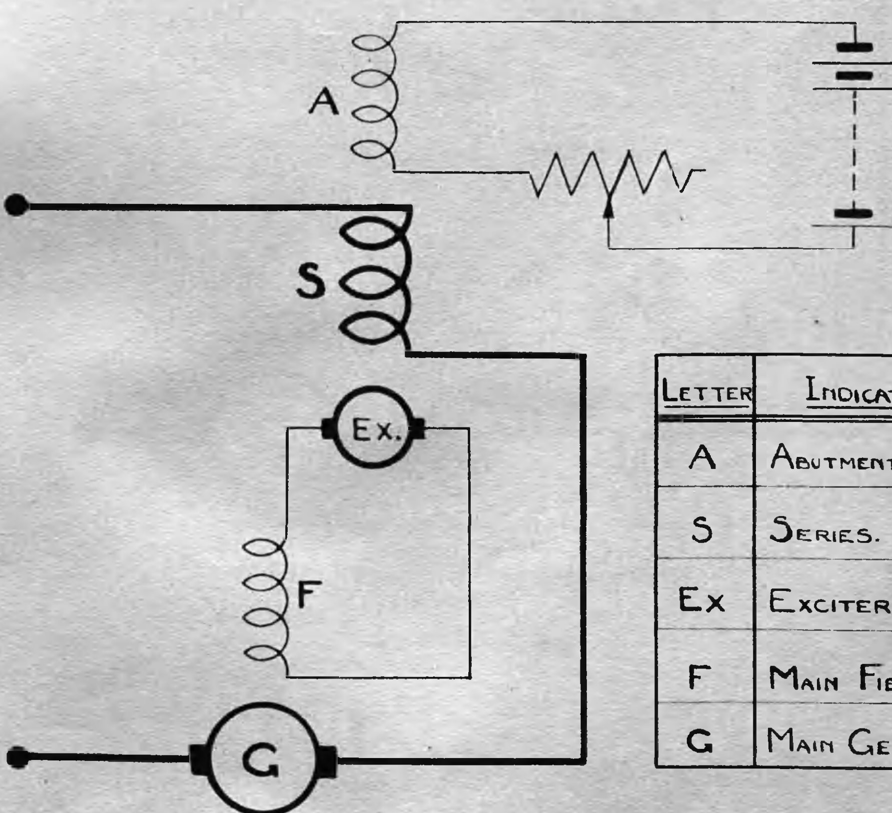
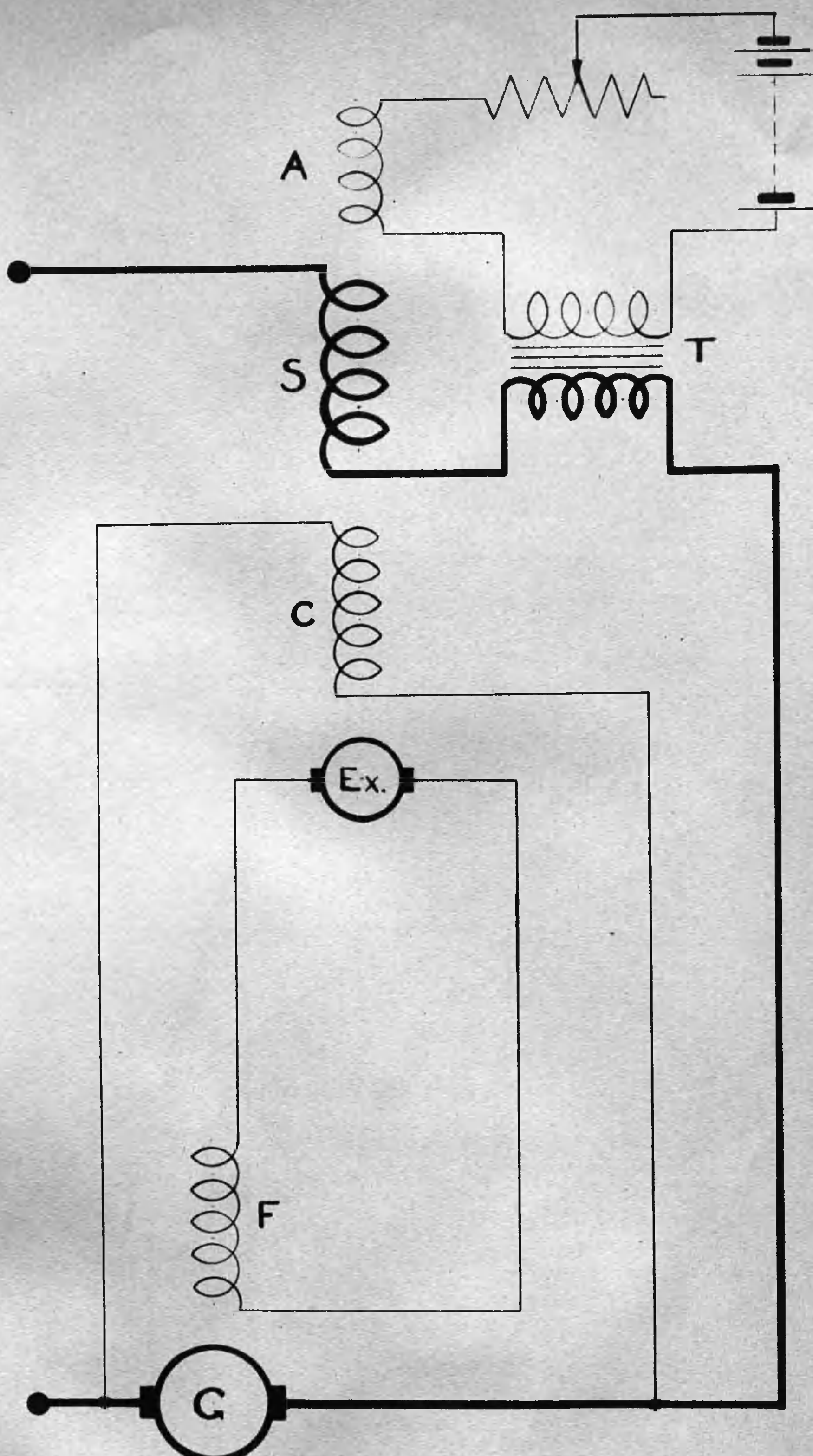


Fig. 9



Letter	Indicates
A	Abutment.
S	Series.
Ex	Exciter
F	Main Field
G	Main Generator.

Fig. 10



Letter	Indicates
A	Abutment
S	Series
C	Compound
T	Transformers
Ex	Exciter
F	Main Field
G	Generator

Fig 11

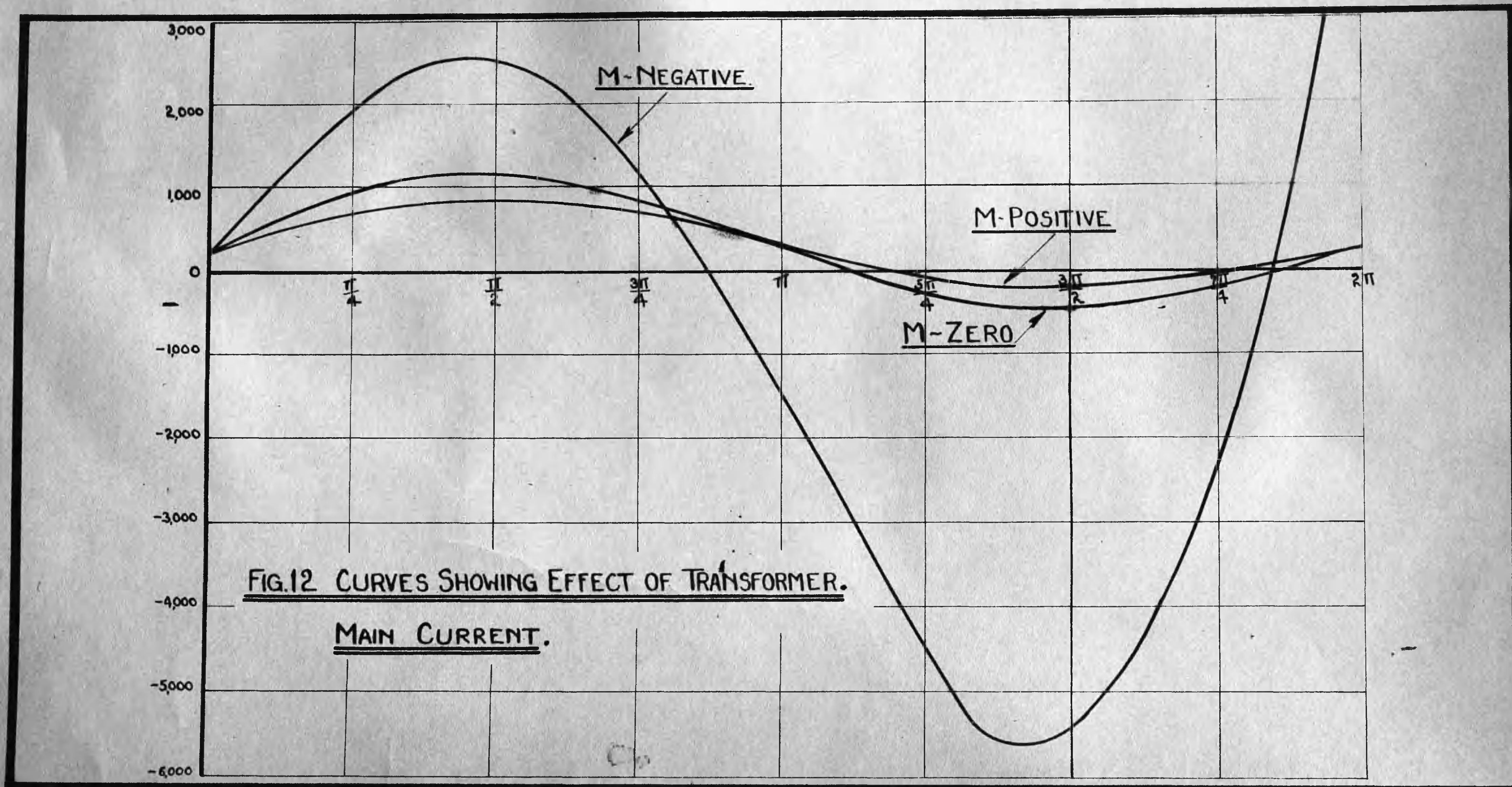


FIG.12 CURVES SHOWING EFFECT OF TRANSFORMER.

MAIN CURRENT.

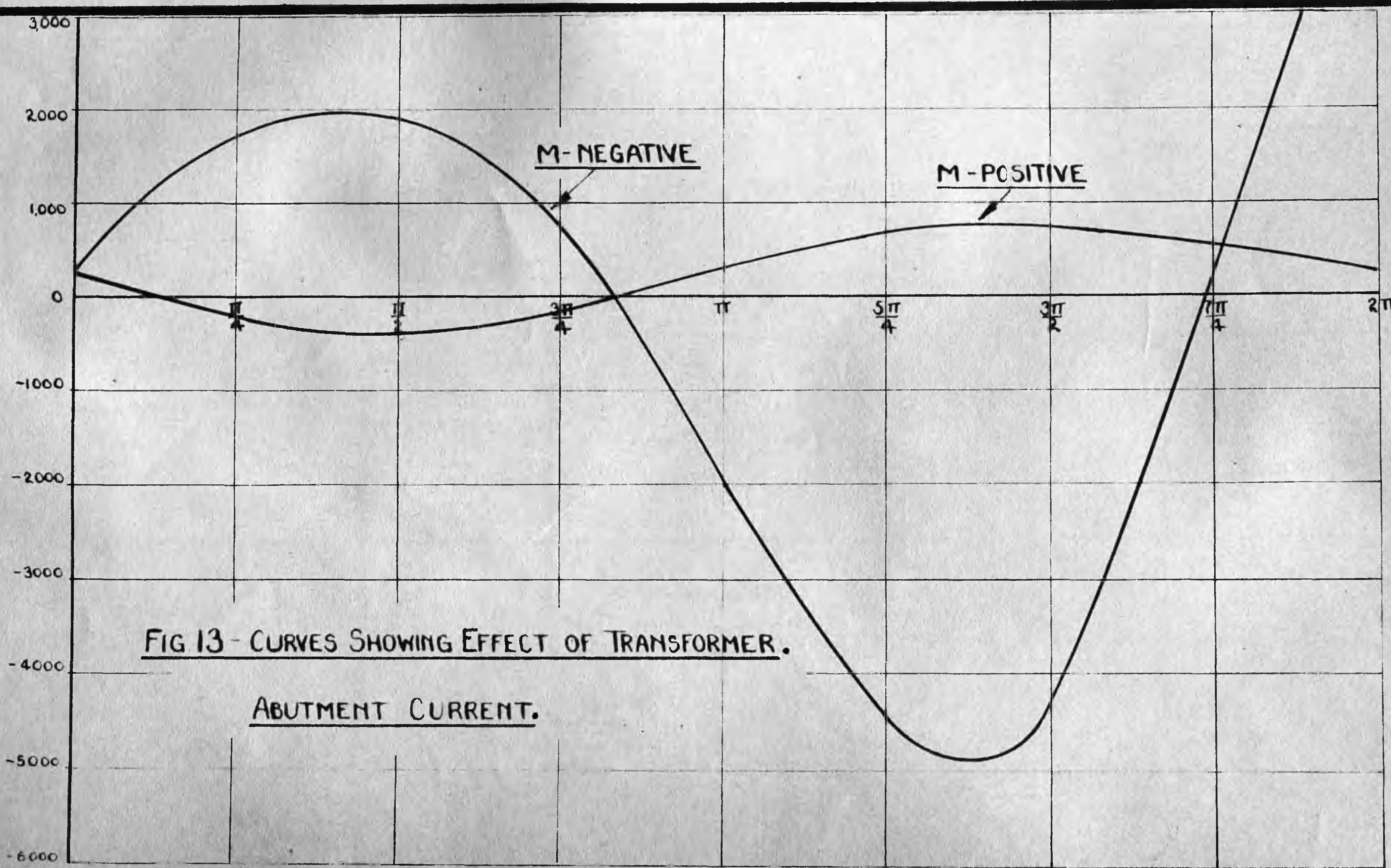


FIG 13 - CURVES SHOWING EFFECT OF TRANSFORMER.

ABUTMENT CURRENT.

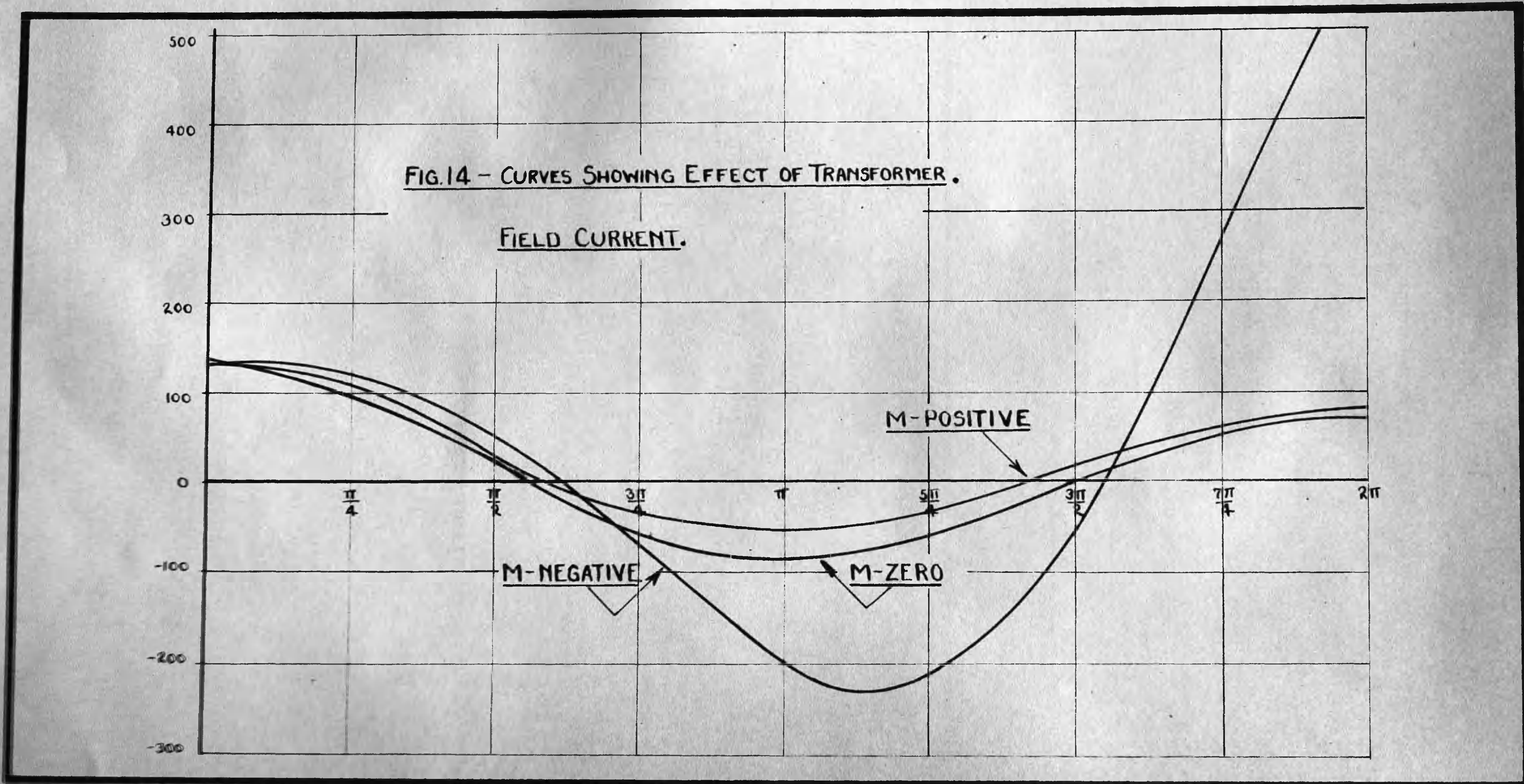


FIG. 14 - CURVES SHOWING EFFECT OF TRANSFORMER.
FIELD CURRENT.
500
400
300
200
100
0
-100
-200
-300
π/4
π/2
3π/4
π
5π/4
3π/2
7π/4
2π
M-POSITIVE
M-NEGATIVE
M-ZERO

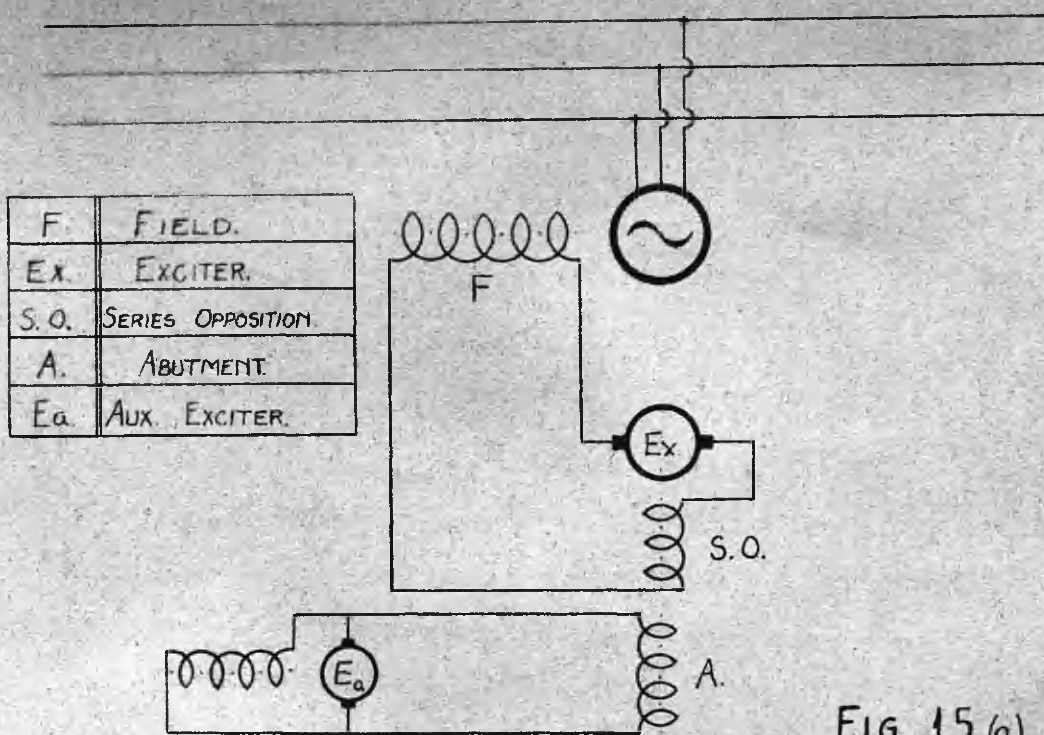


FIG. 15 (a.)

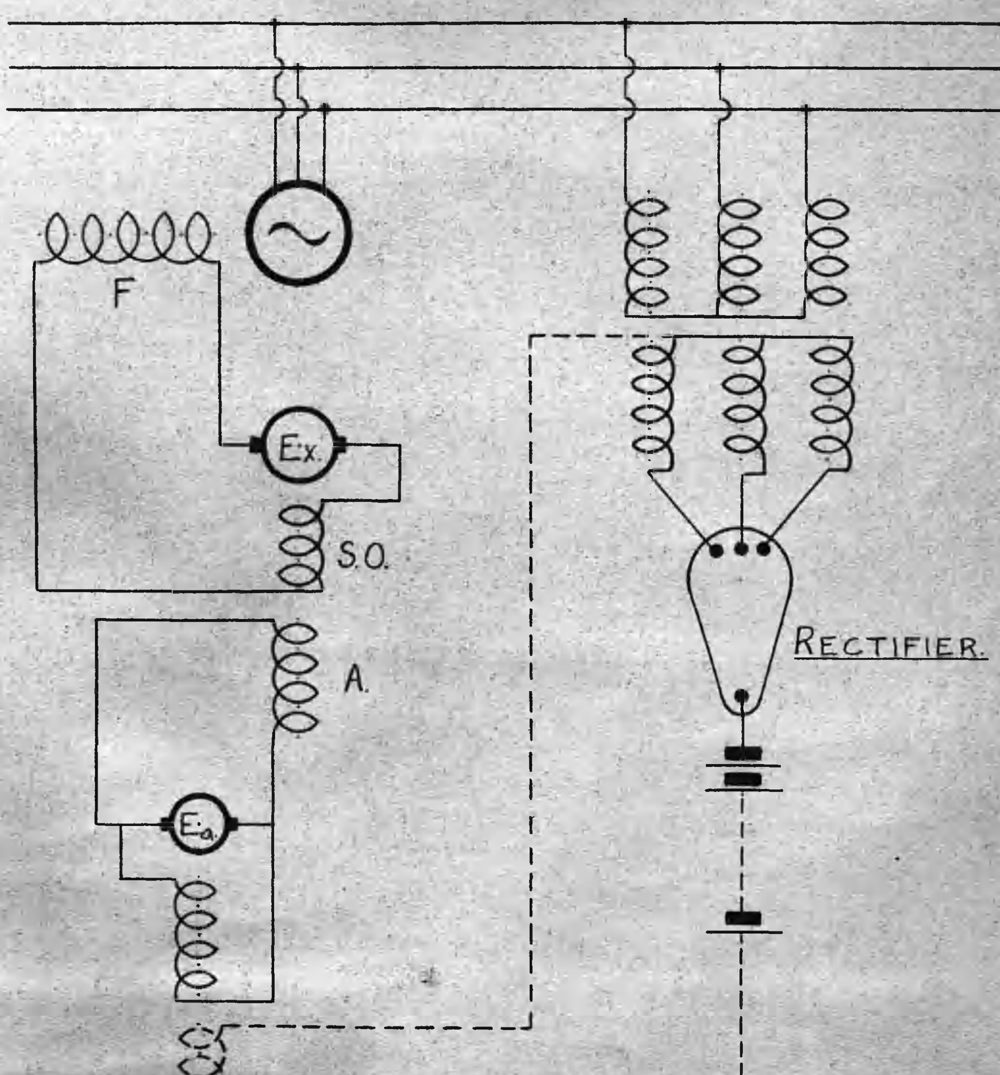
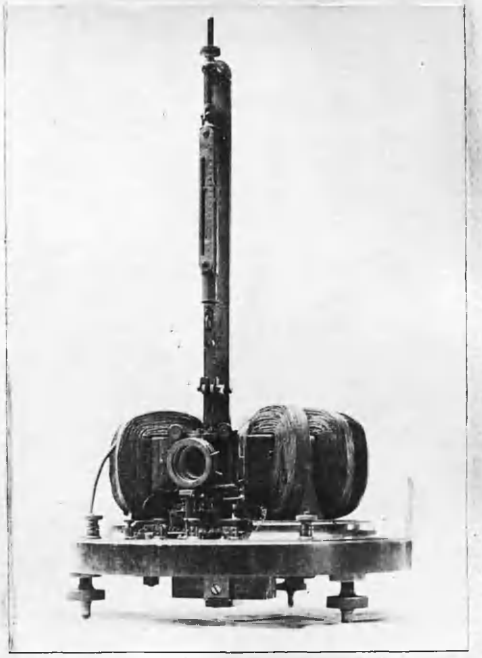
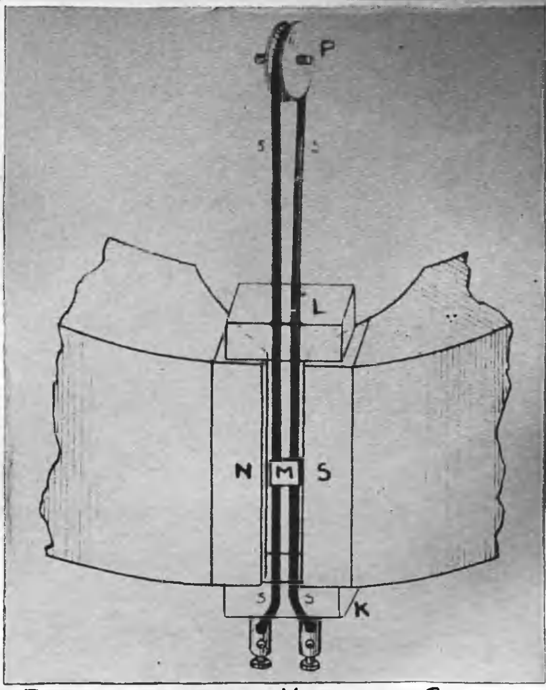


FIG. 15 (b).



Duddell Oscillograph.
Fig. 16.



Essentials of the Vibrating System.
Fig. 17.

Fig. 18a. – Oscillograph Table, Control Side.

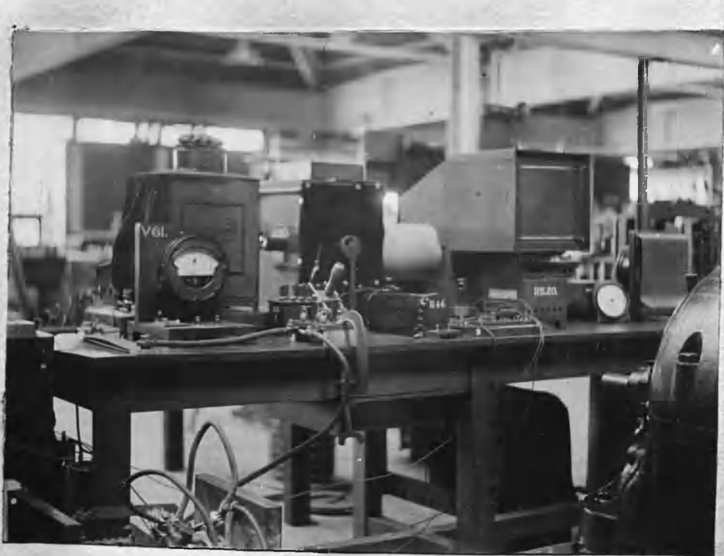


Fig. 18b. – Oscillograph Table, Reverse Side.

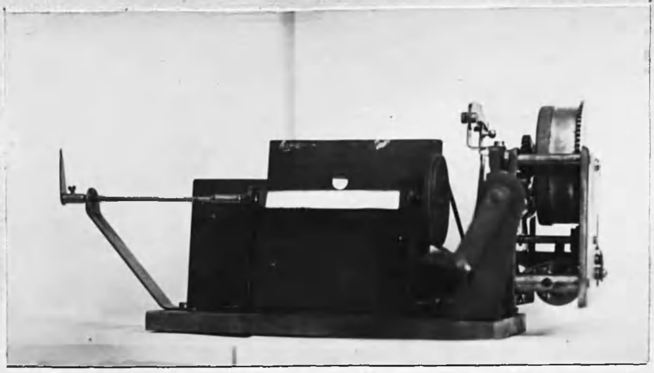


Fig. 19. – Motor Unit with Rotating Mirror.

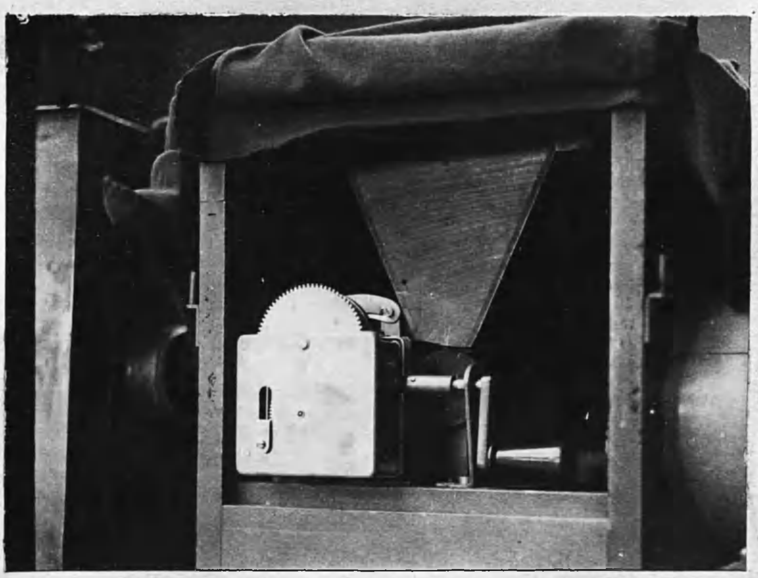
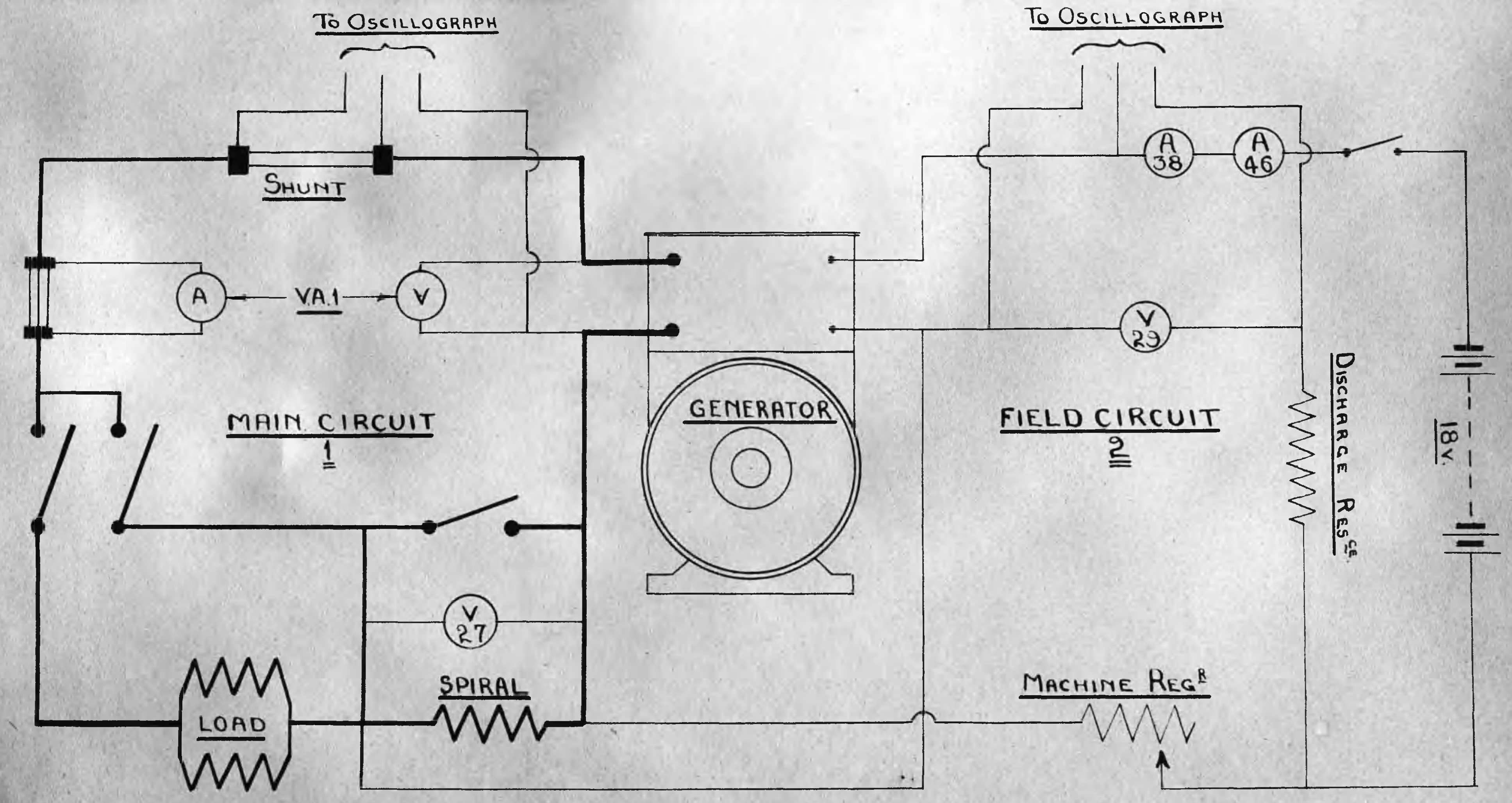


Fig. 20. – Motor Unit in Place Showing Covers.

Fig. 21. – Film Box.



— Fig. 22 — Practical Connection Diagram —

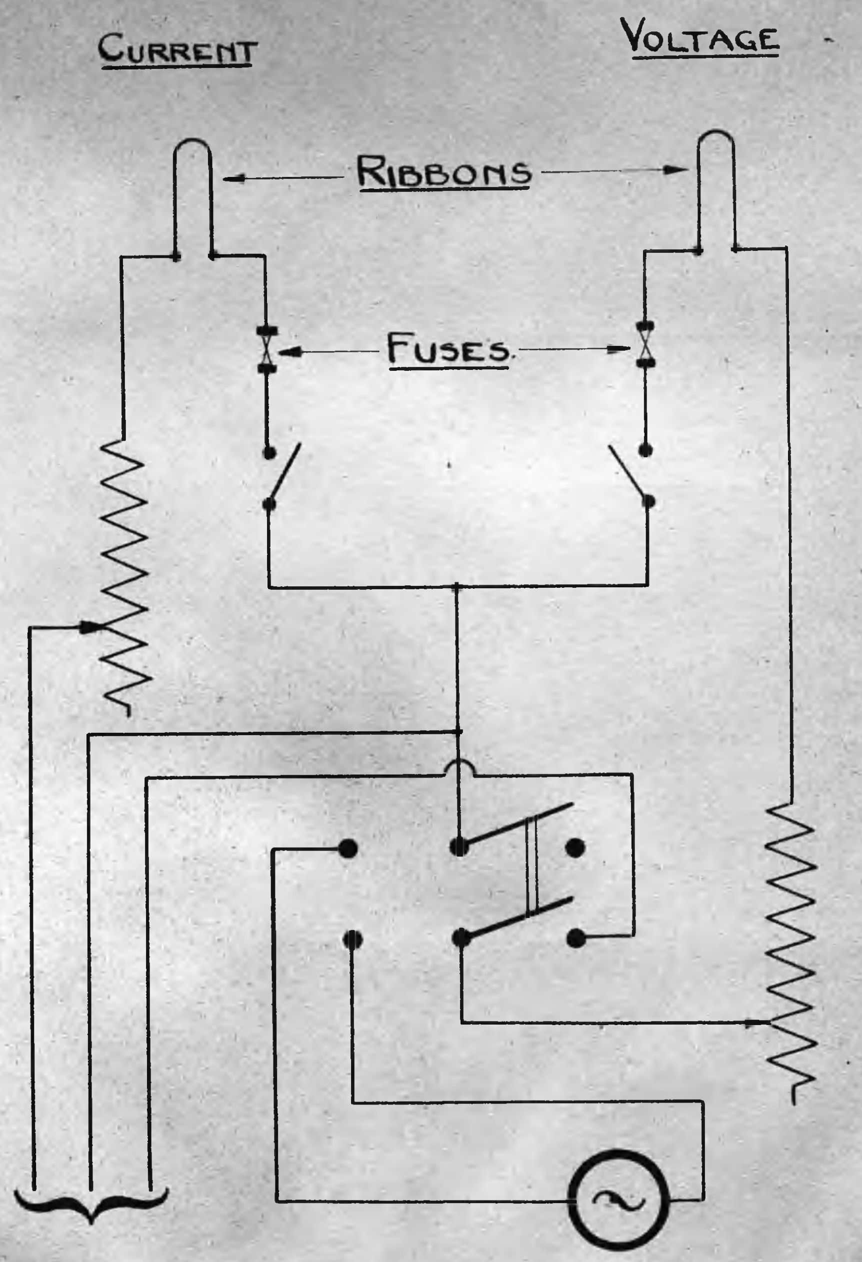


FIG. 23.- OSCILLOGRAPH TIMING ARRG^{T}

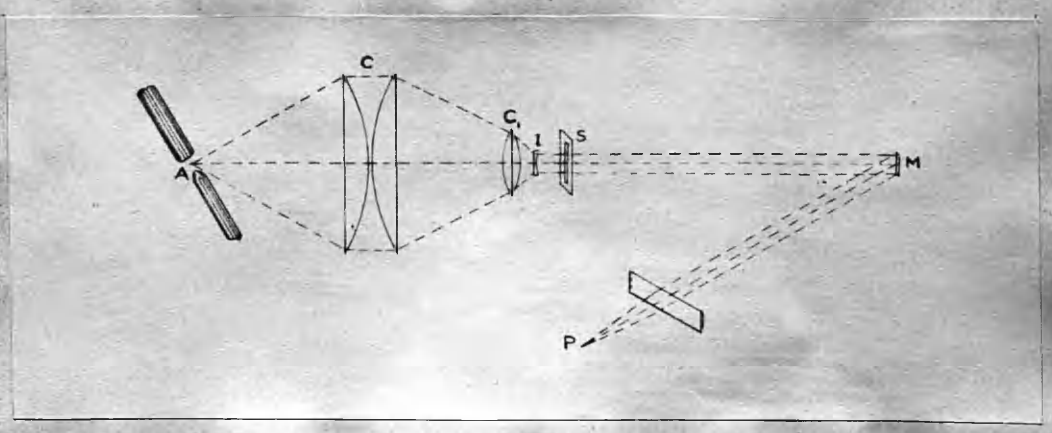


FIG. 24- DIAGRAM OF OPTICAL SYSTEM.

Fig. 25 - Print from Original Film Record.

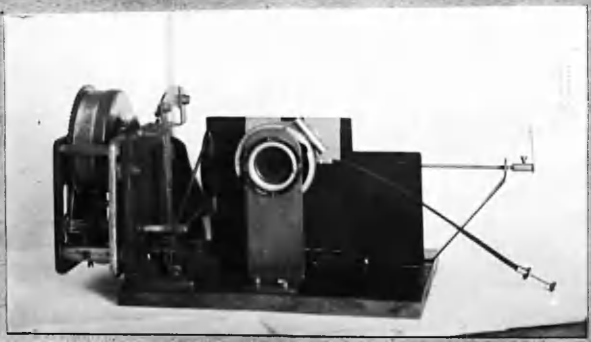


Fig. 26. - Motor Unit with Shutter.

Fig. 27. - Print Showing Oscill$^{PH.}$ Table Vib$^{NS.}$

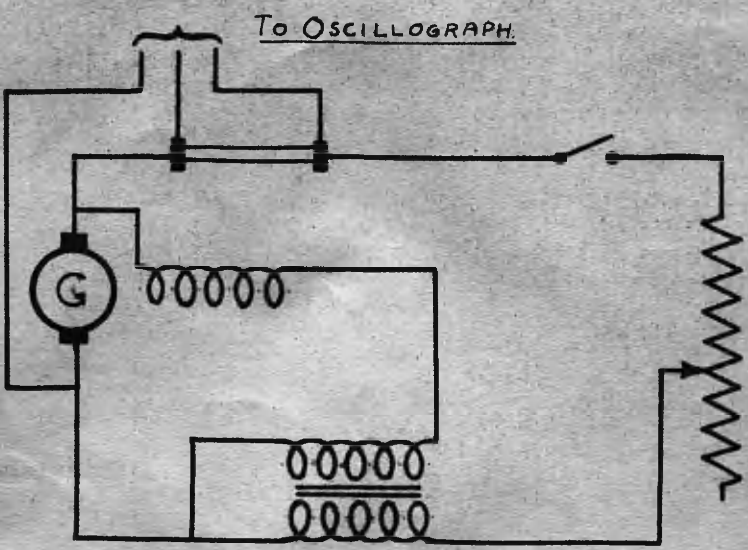
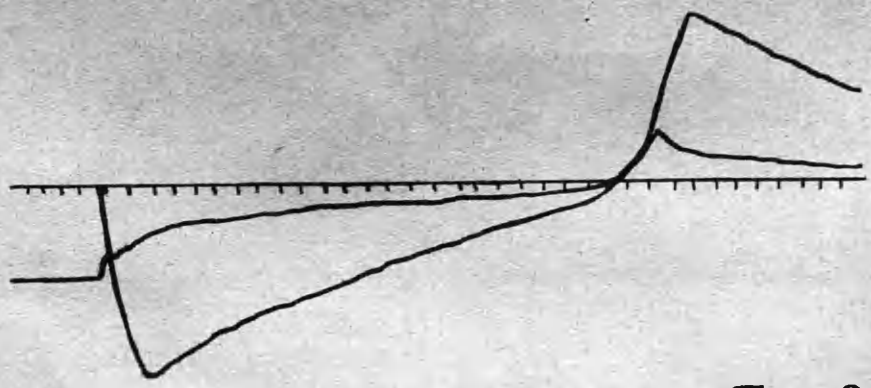
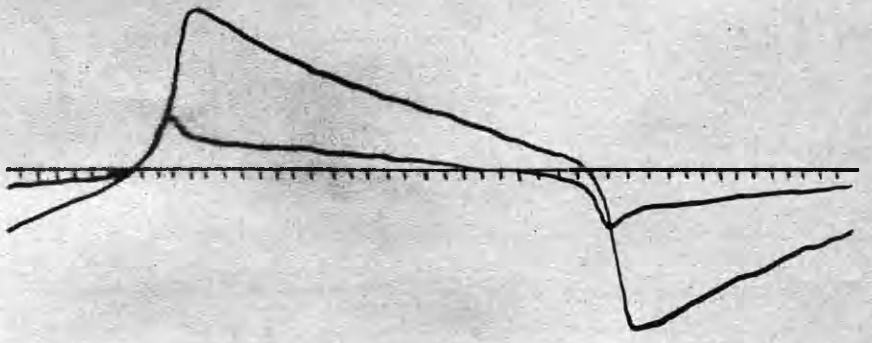


Fig. 28 - Circuit Nº 3.



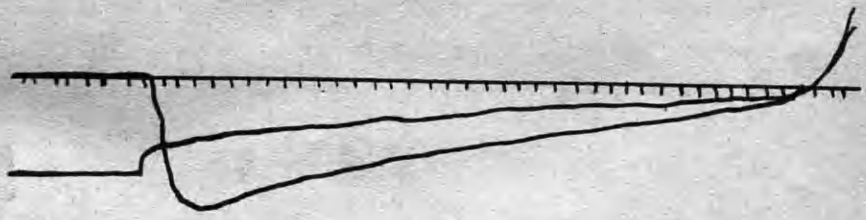
REF. Nº 78|A|0|3

FIG. 29



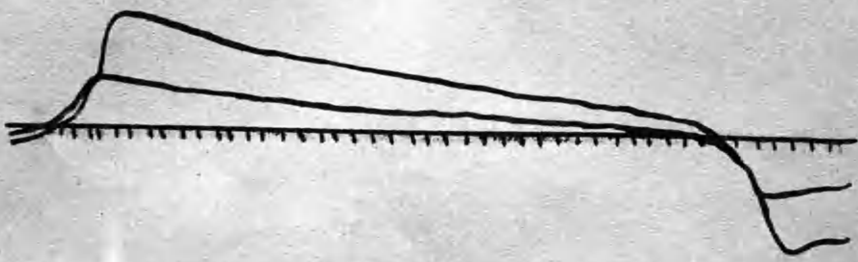
REF Nº 79|A|0|3

FIG. 30



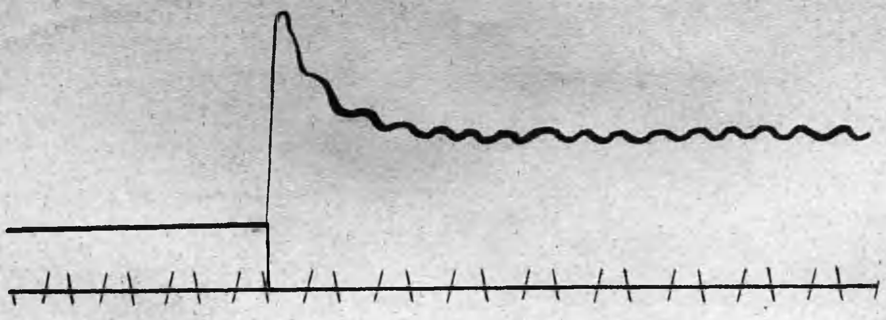
REF. Nº 80|A|0|3

FIG. 31



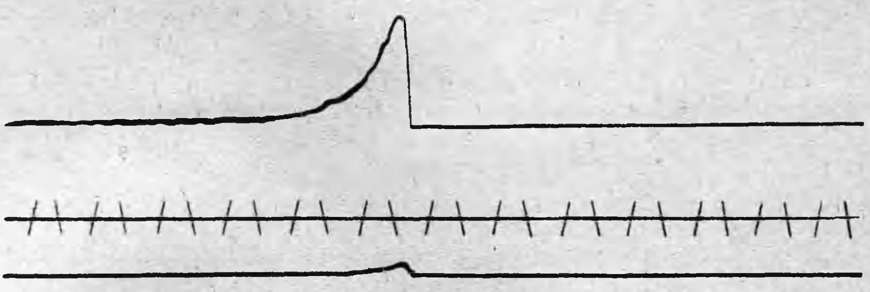
REF. Nº 81|A|0|3

FIG. 32



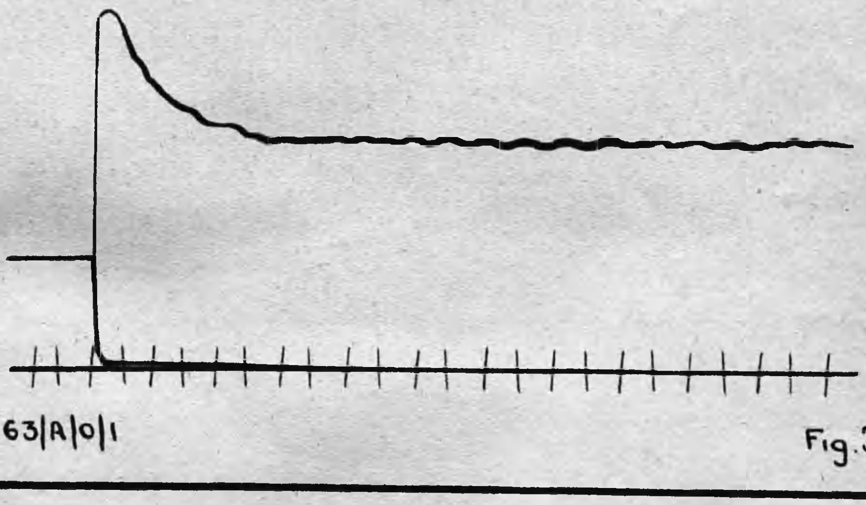
REF. Nº 1/A/0/1

Fig. 33



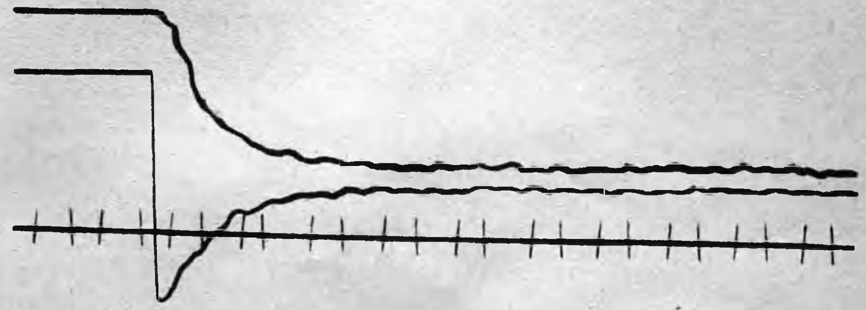
REF. Nº 7/A/2/2

Fig. 34



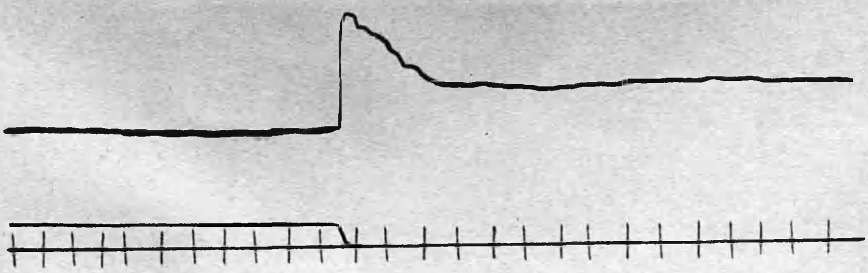
REF. Nº 63/A/0/1

Fig. 35



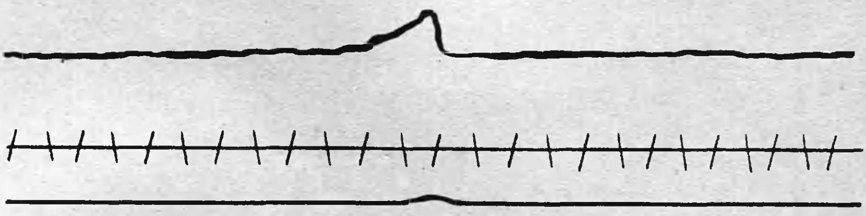
REF. Nº 69/A/2/2

Fig. 36



REF. Nº 5|A|0|1

Fig. 37



REF. Nº 11|A|2|2

Fig. 38

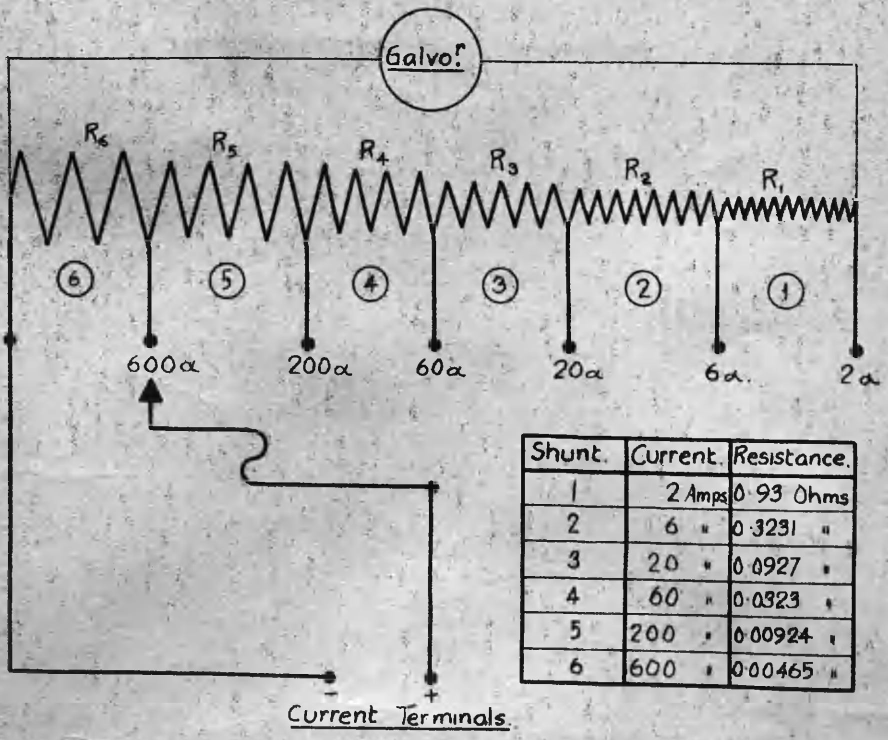
REF. Nº 67|A|0|1

Fig. 39

REF. Nº 73|A|2|2

Fig. 40

FIG. 41 – THE PERMANENT MAGNET OSCILLOGRAPH



Shunt.	Current.	Resistance.
1	2 Amps	0·93 Ohms
2	6 "	0·3231 "
3	20 "	0·0927 "
4	60 "	0·0323 "
5	200 "	0·00924 "
6	600 "	0·00465 "

FIG. 42 – CONNECTIONS FOR UNIVERSAL SHUNT.

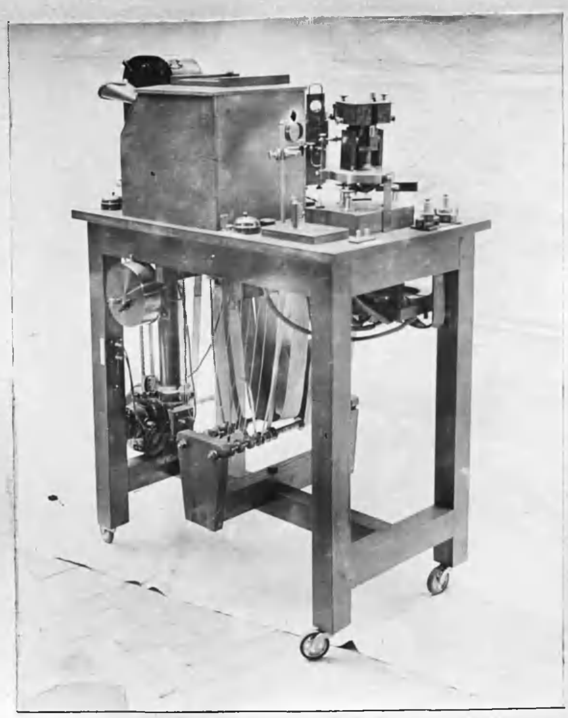


Fig. 43.
The New Oscillograph Unit, Supply End.

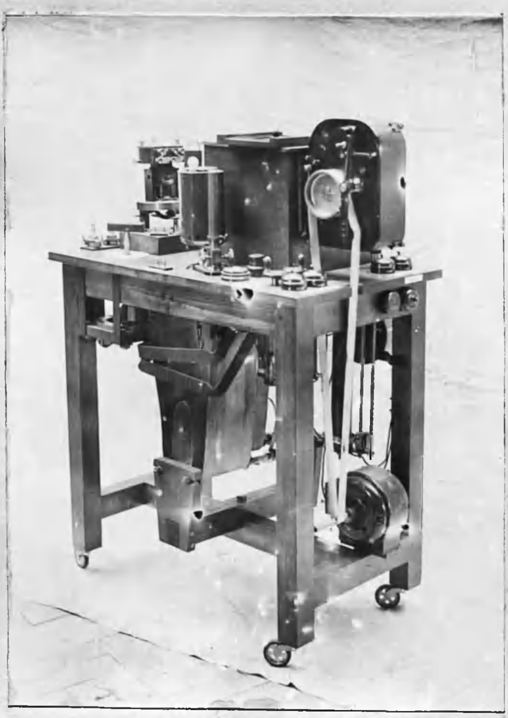


Fig. 44.
The New Oscillograph Unit, Control End.

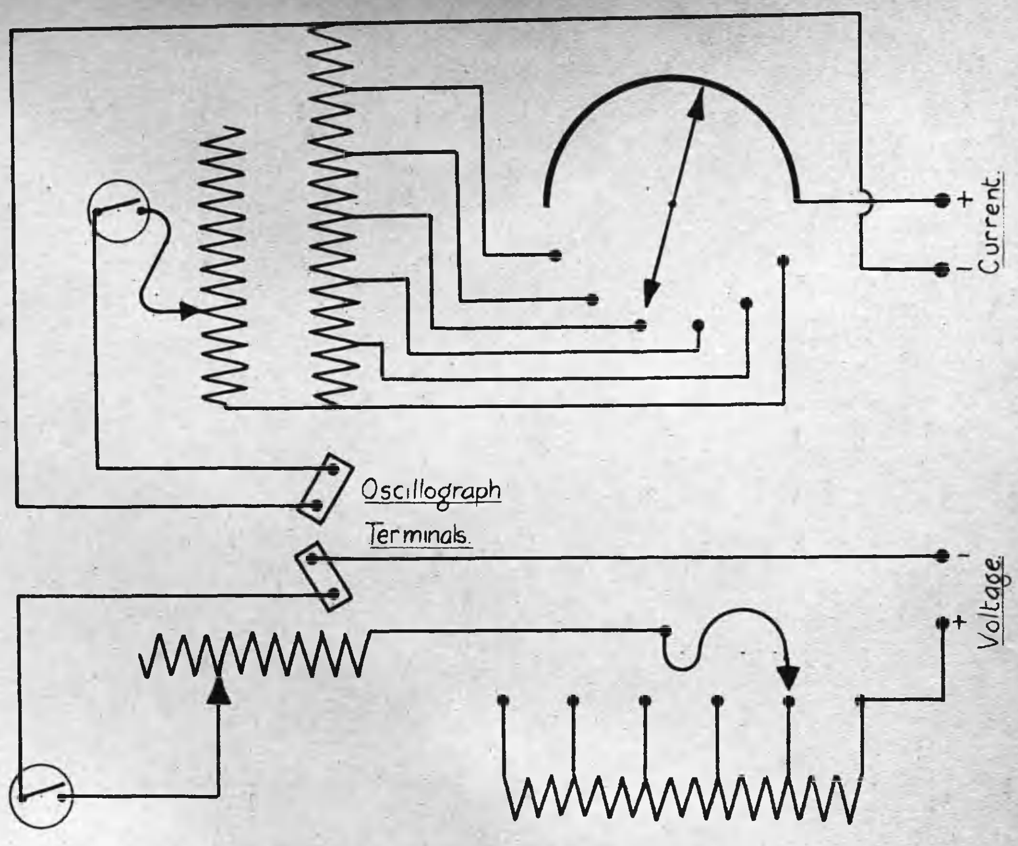


FIG. 45A. —OSCILLOGRAPH ELEMENT CIRCUITS.

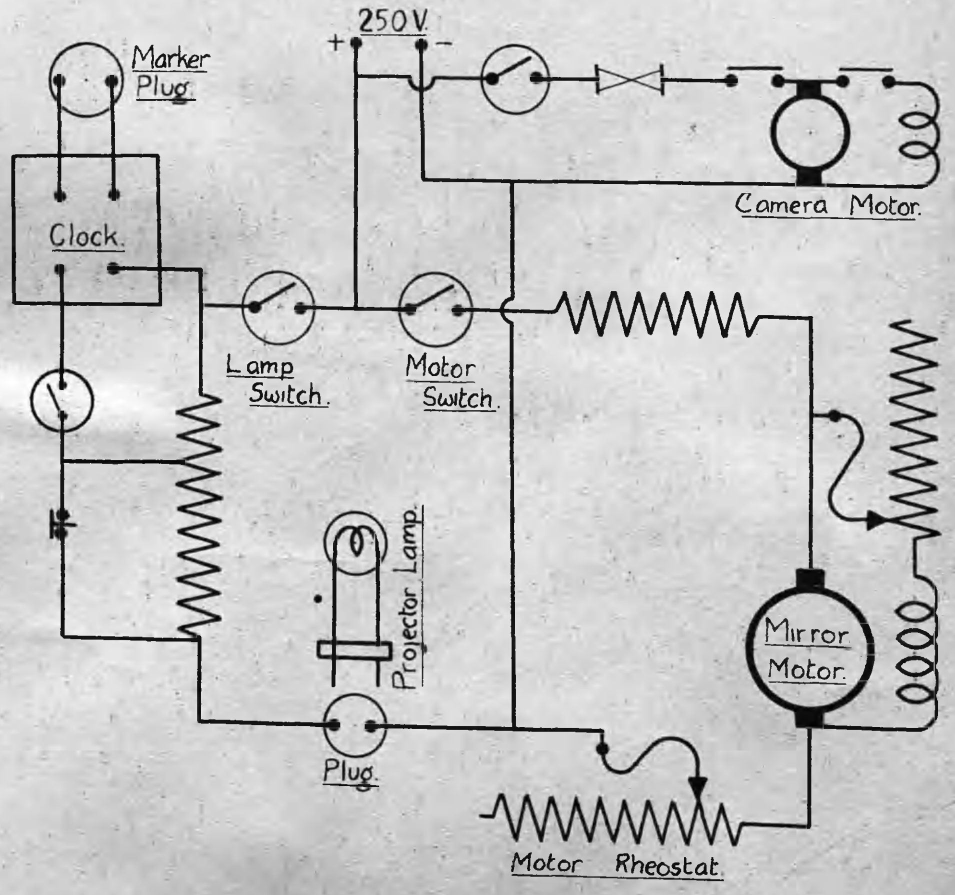


FIG. 45 B. — OSCILLOGRAPH AUXILIARY CIRCUITS.

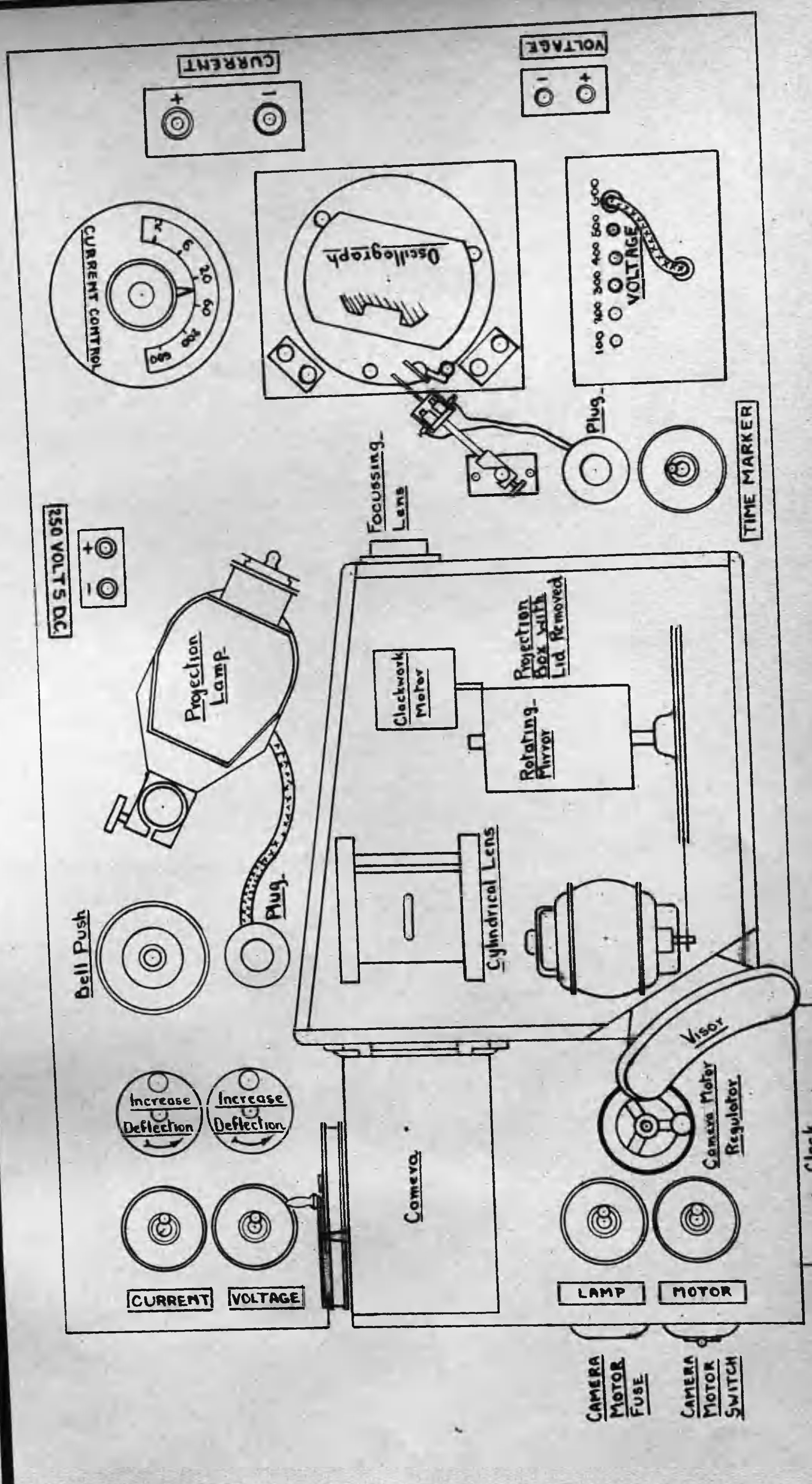


FIG. 46 —OSCILLOGRAPH TABLE LAYOUT

Projection Box Cover Removed

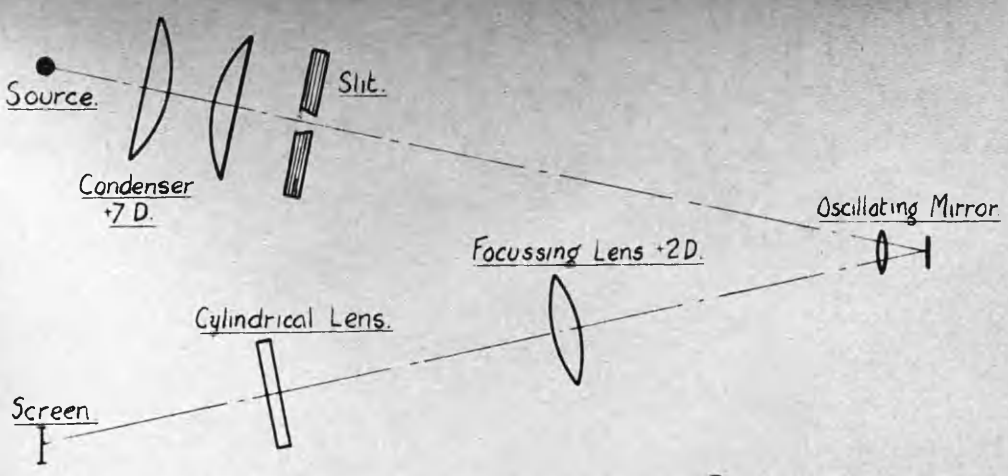


FIG. 47A - OPTICAL SYSTEM FOR MAIN BEAM.

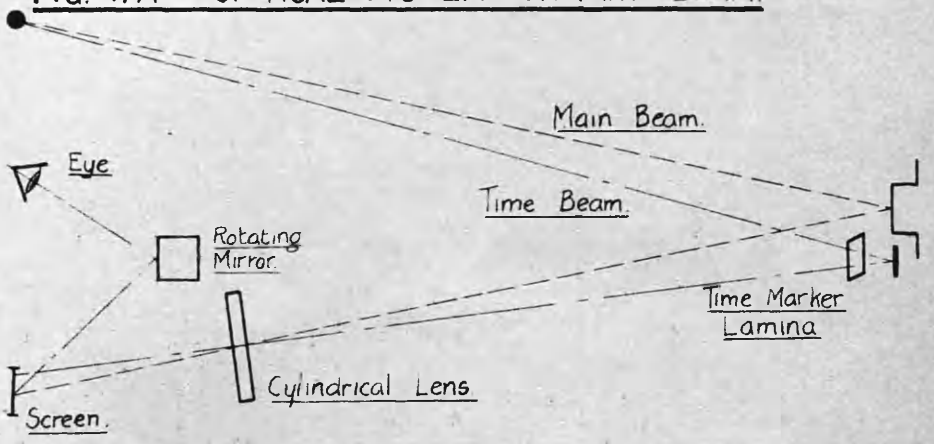


FIG. 47B. - OPTICAL SYSTEM FOR TIME MARKER BEAM.

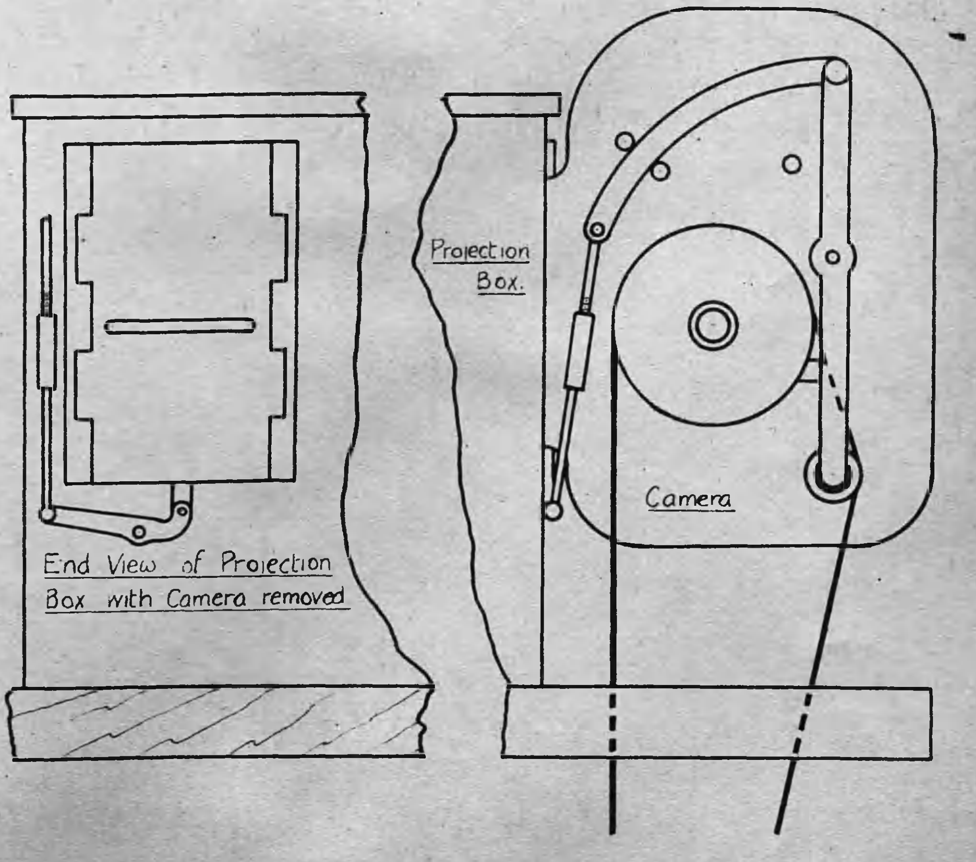


FIG. 48 - CAMERA DRIVE ARRANGEMENT.

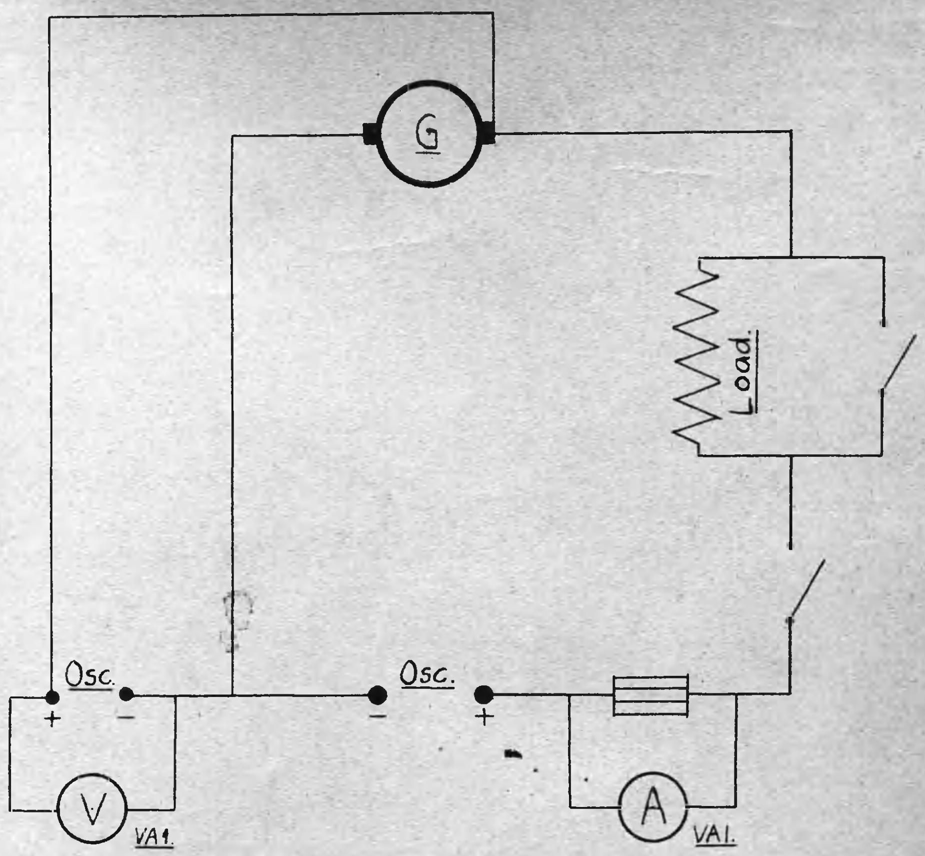


FIG. 49. — CIRCUIT Nº 4.

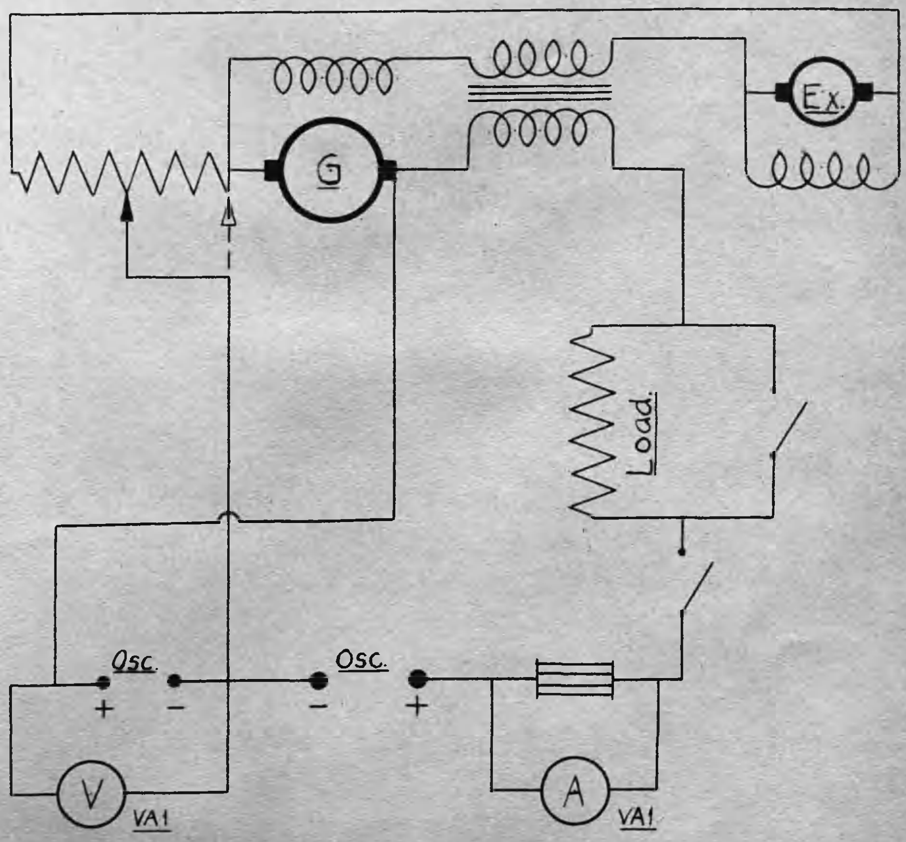


FIG. 50 — CIRCUIT Nº 5.

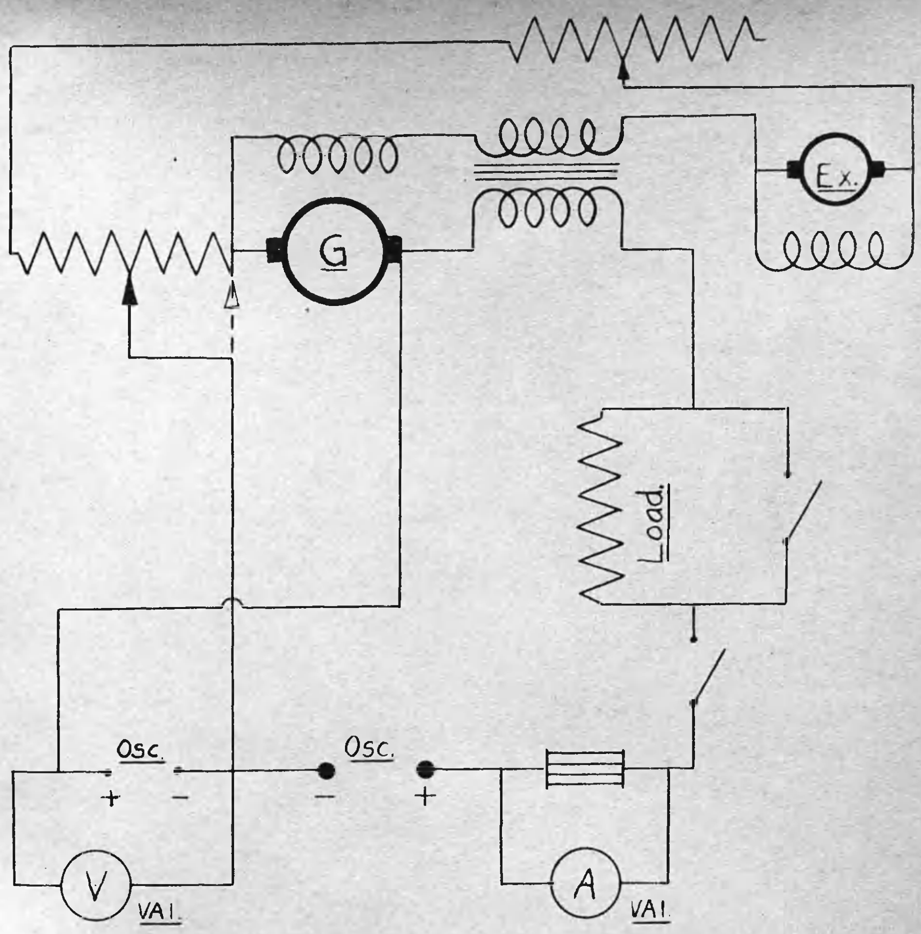


FIG. 51 – CIRCUIT Nº 6.

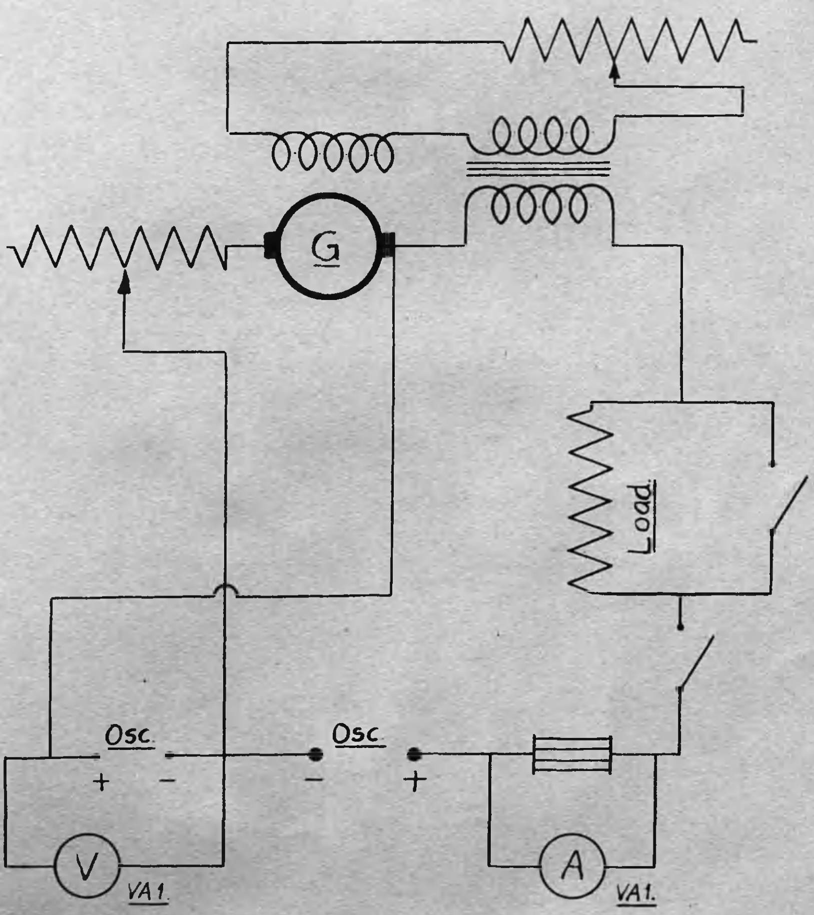


FIG. 52 – CIRCUIT Nº 7.

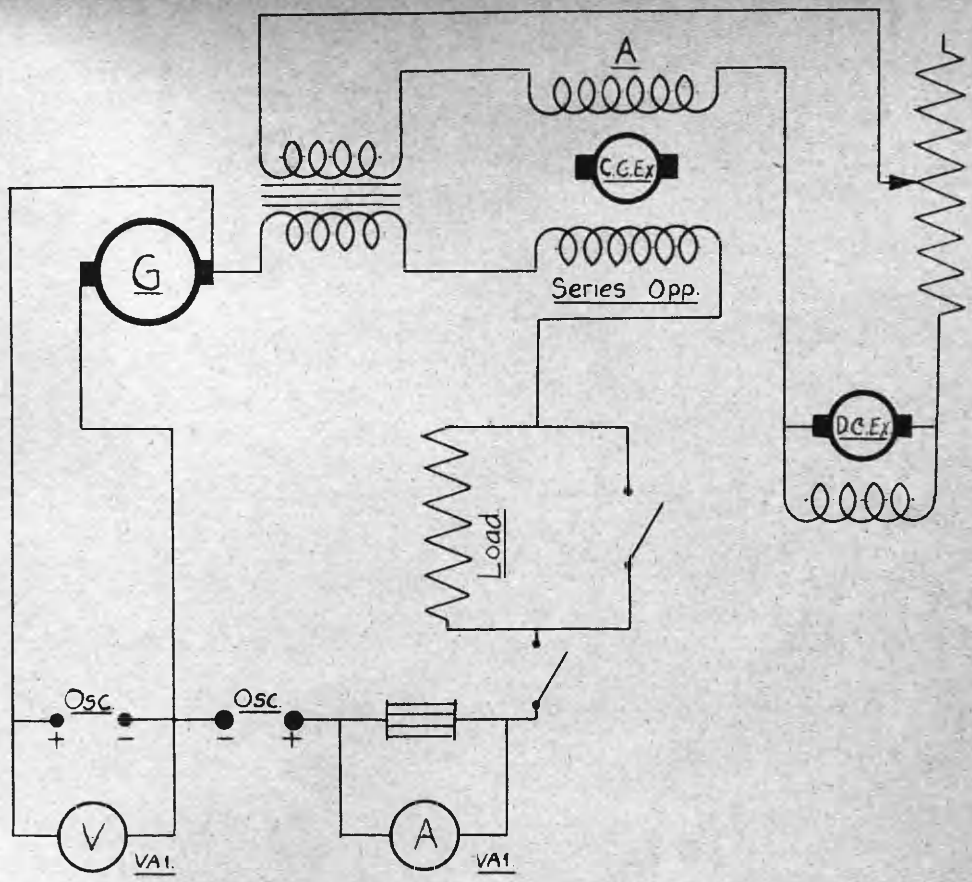


FIG. 53. — CIRCUIT Nº 8.

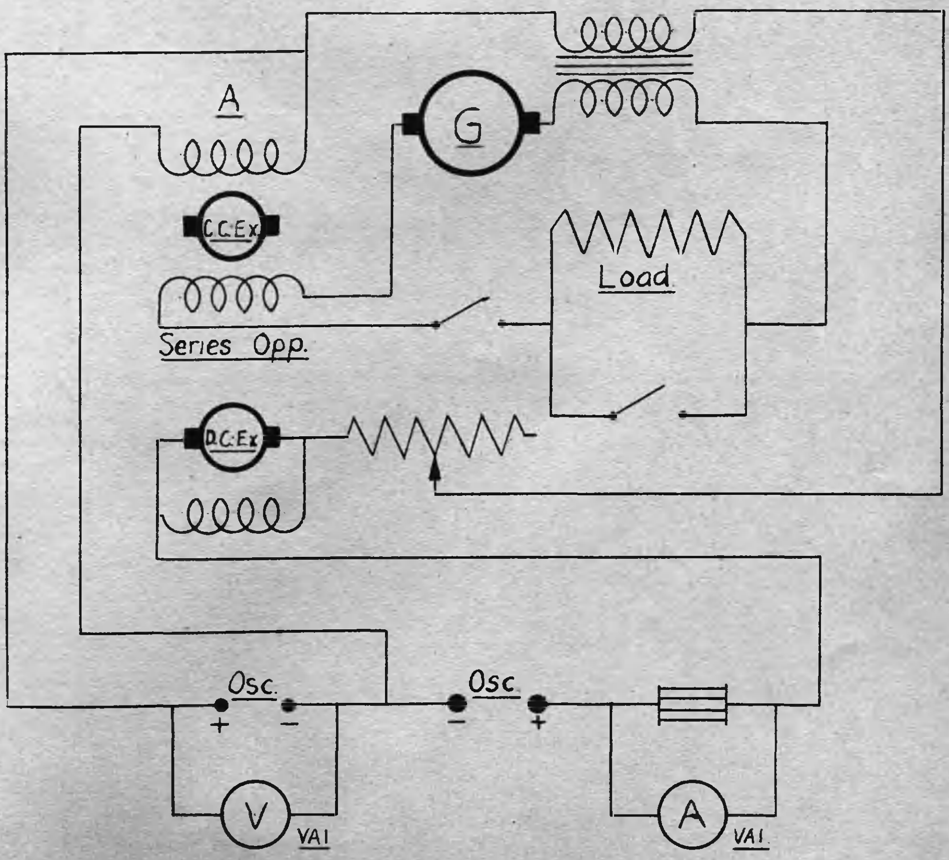


FIG. 54. — CIRCUIT Nº 9.

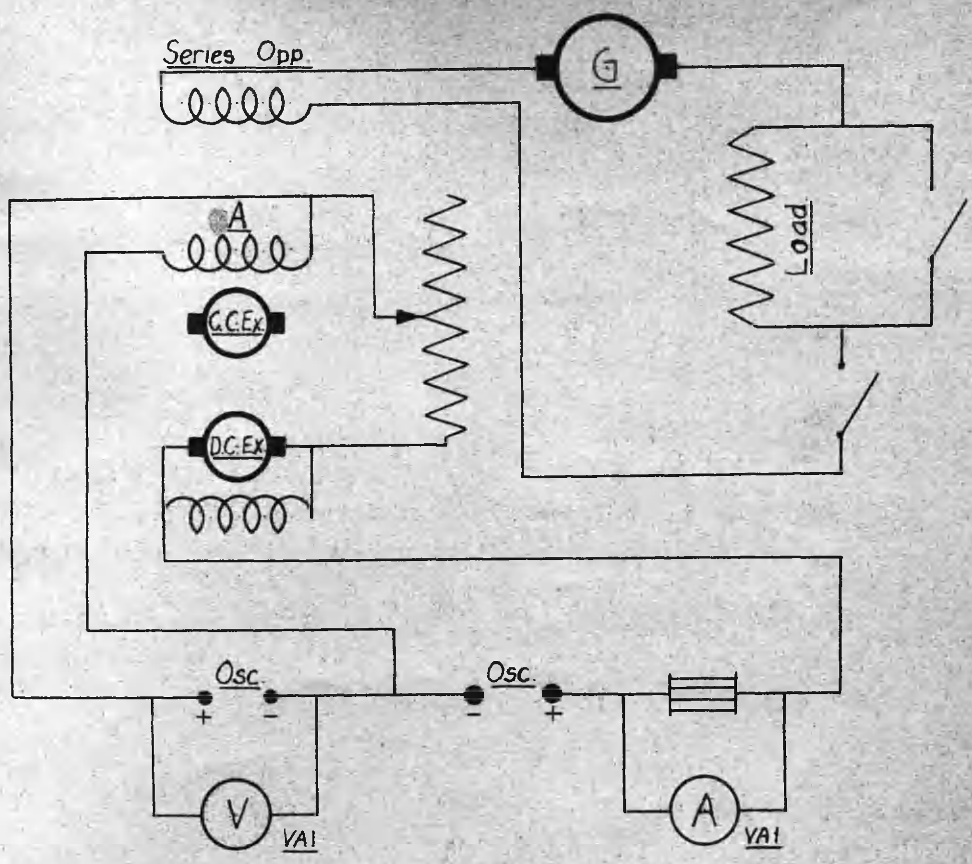


FIG. 55 — CIRCUIT Nº 10.

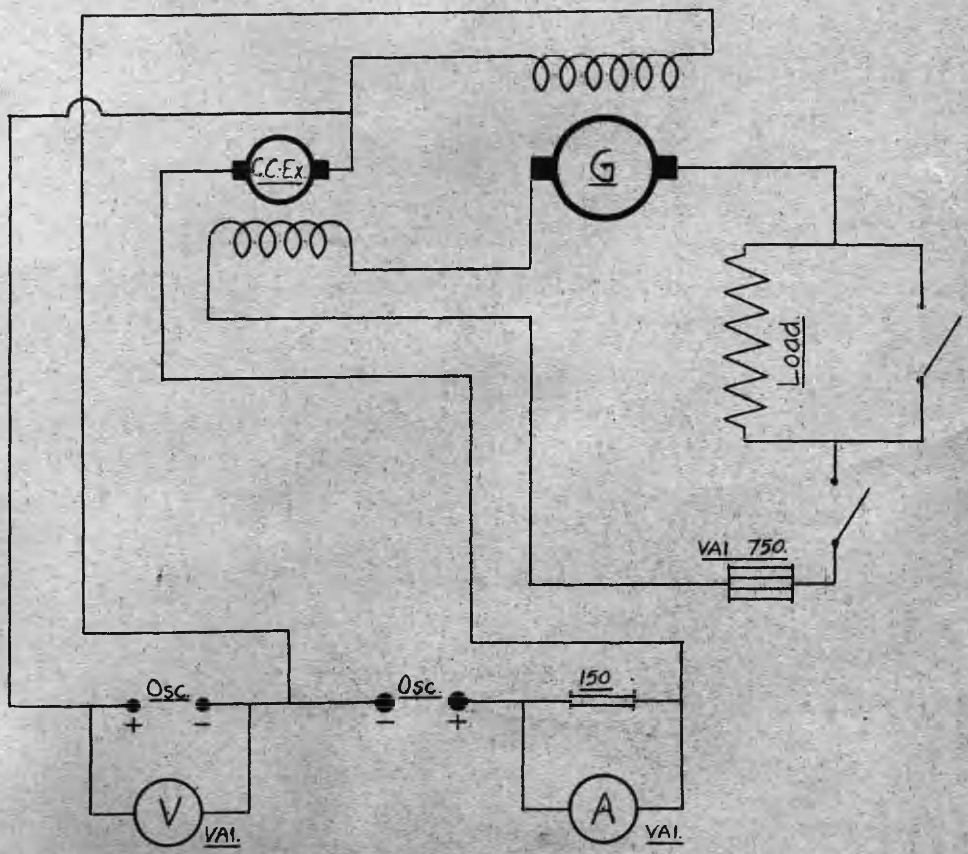


FIG. 56 — CIRCUIT Nº 11.

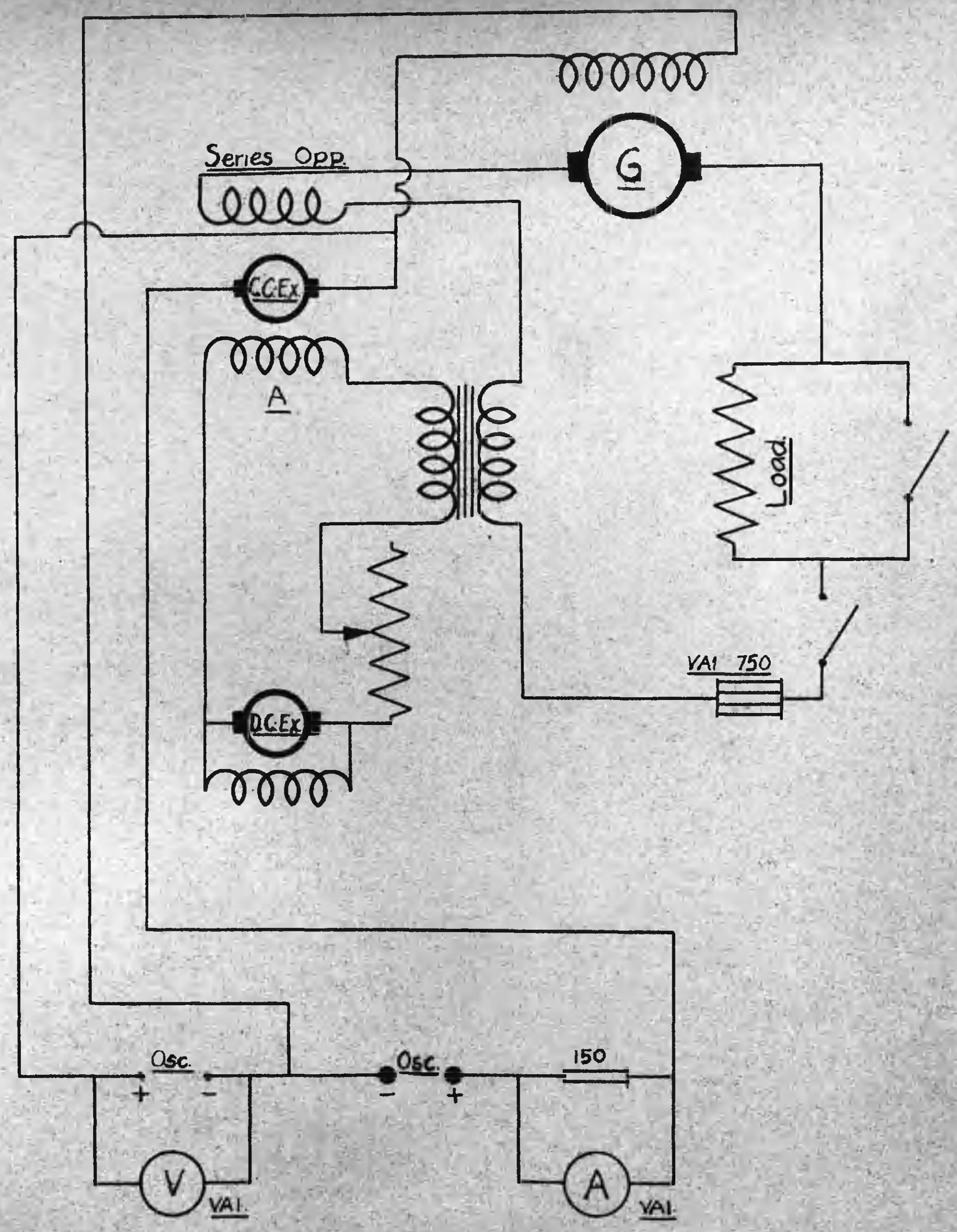


FIG. 57. CIRCUIT No 12.

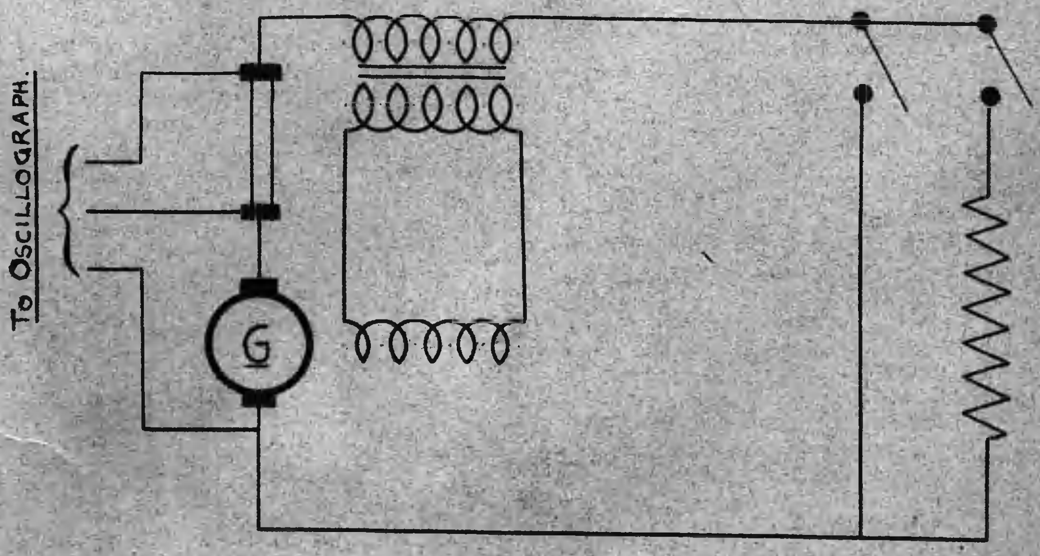


FIG. 58 – CIRCUIT No 13.

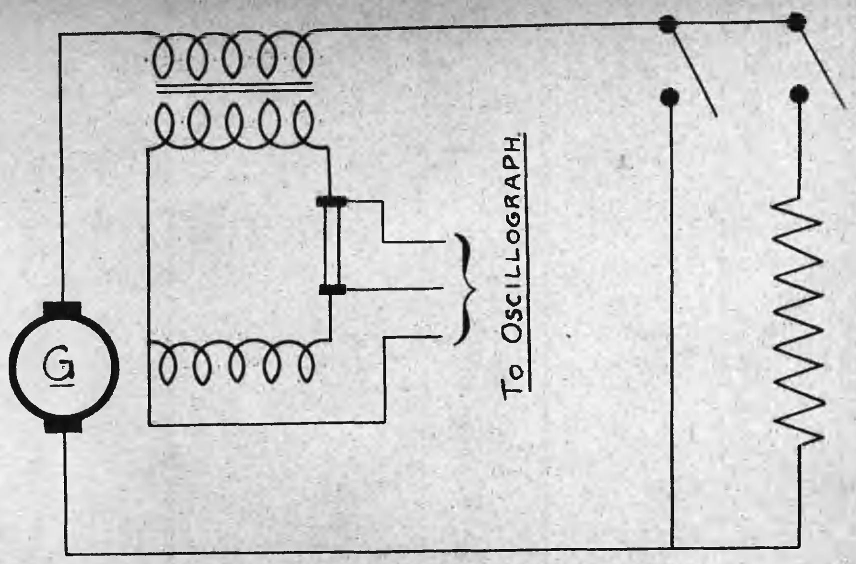


Fig. 59. – Circuit No. 14.

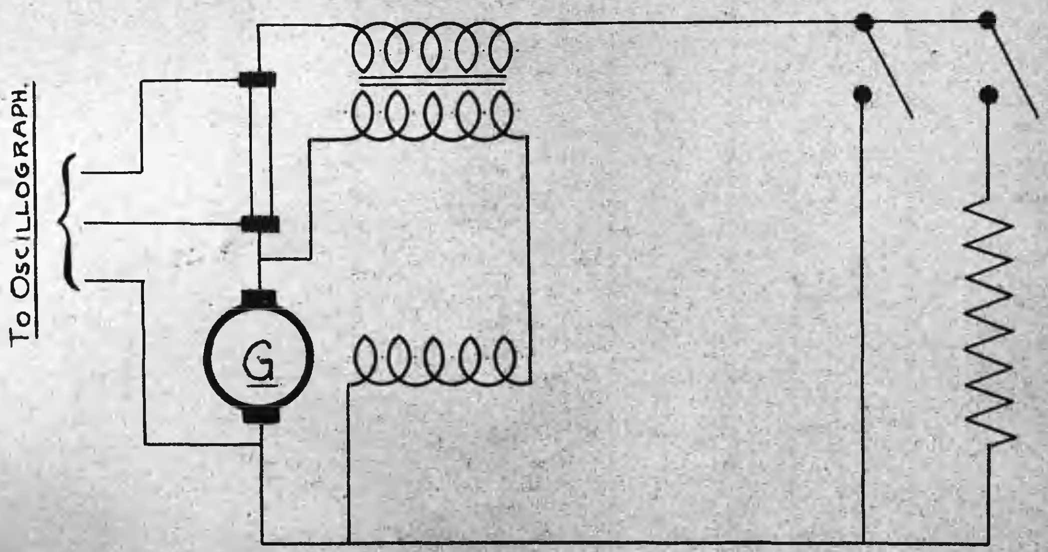


Fig. 60 – Circuit No. 15.

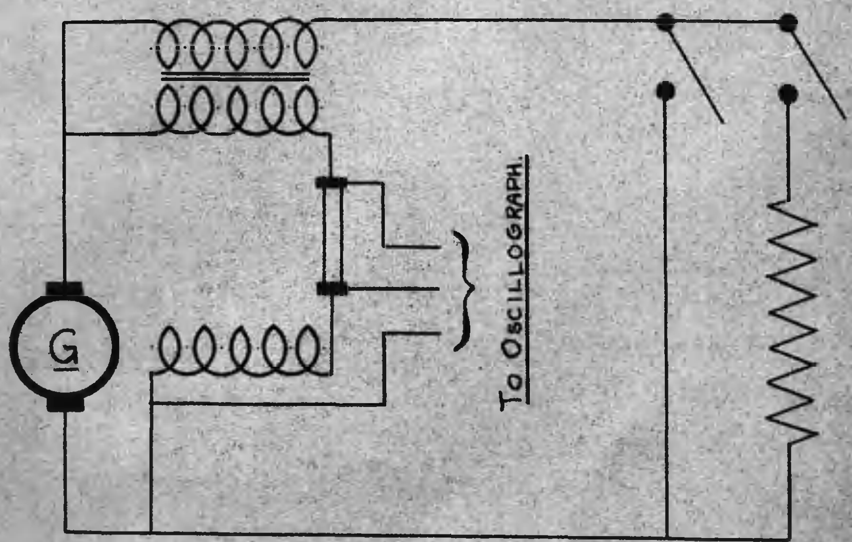
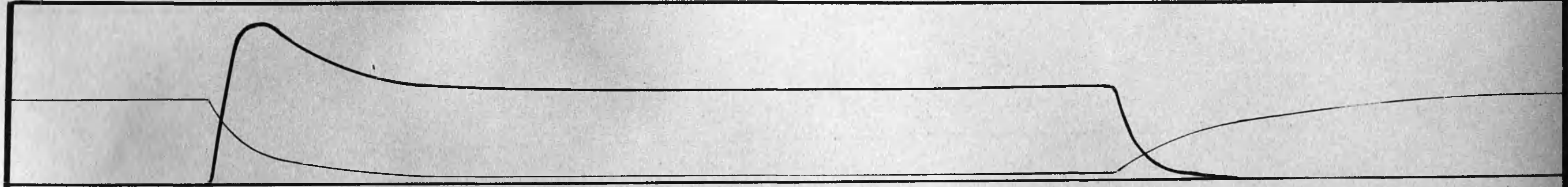
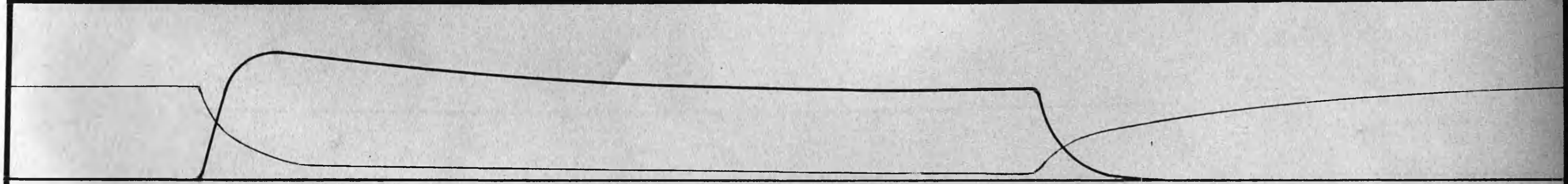


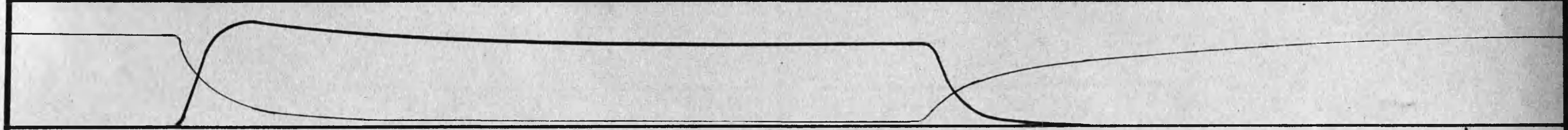
Fig. 61 – Circuit No. 16.



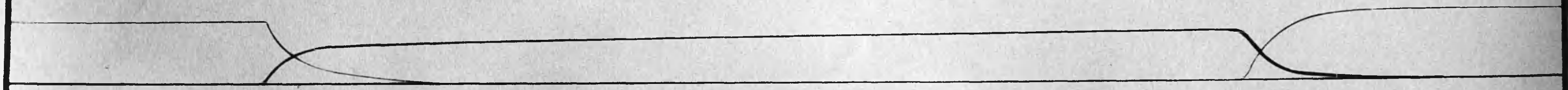
Ref. Nº 82|B|0|4 Fig. 62



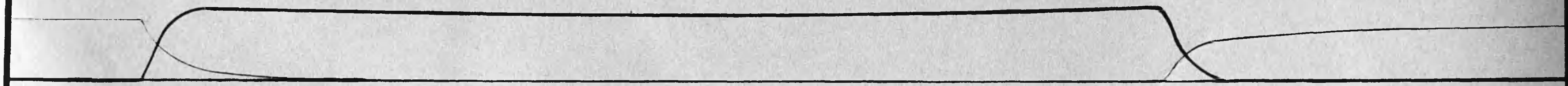
Ref. Nº 85|G|0|4 Fig. 63



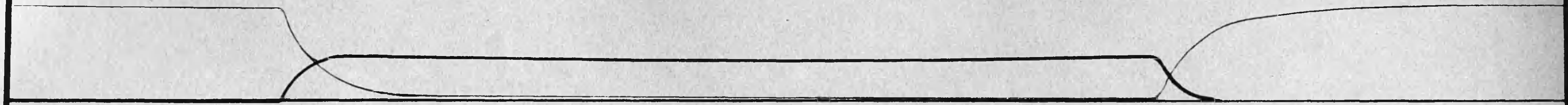
Ref. Nº 91|H|0|4 Fig. 64



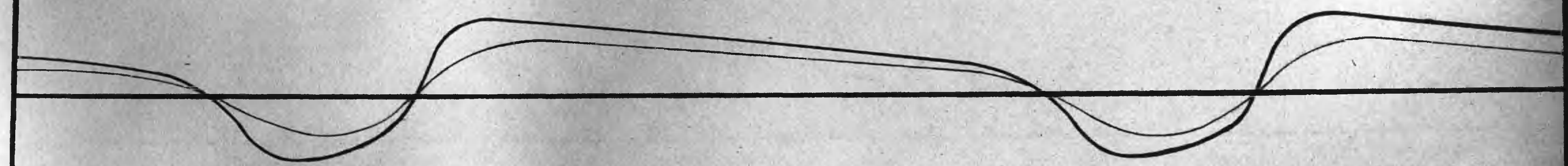
Ref. Nº 99|B|0|5 Fig. 65



Ref. Nº 98|G|0|4 Fig. 66

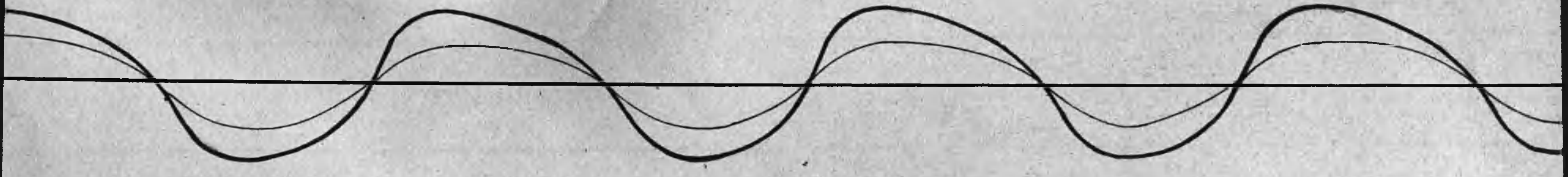


Ref. Nº 88|G|0|4 Fig. 67



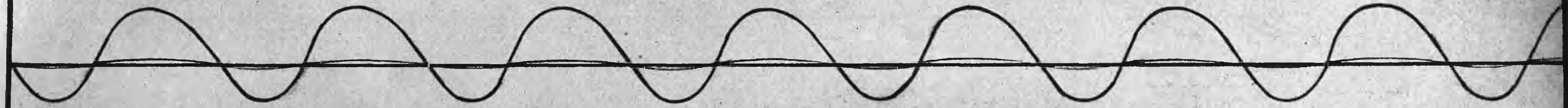
Ref. N° 103|B|0|6

Fig. 68



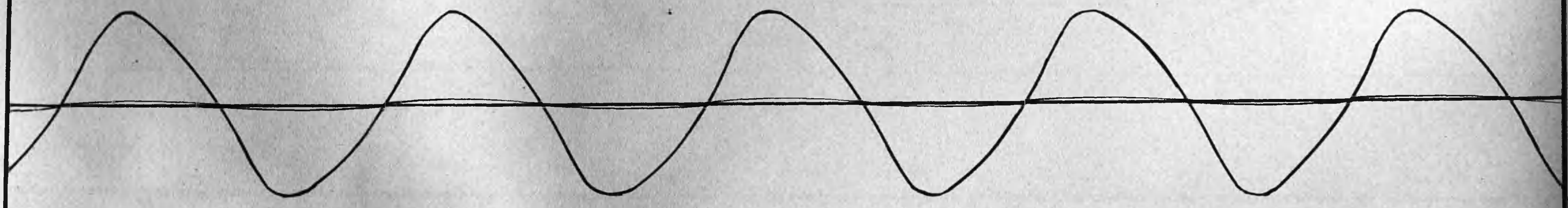
Ref. N° 105|B|0|6

Fig. 69



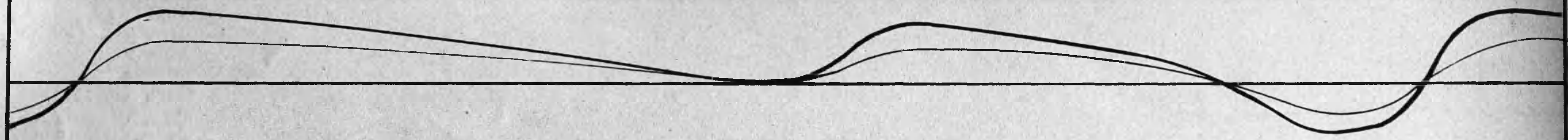
Ref. N° 106|B|0|6

Fig. 70



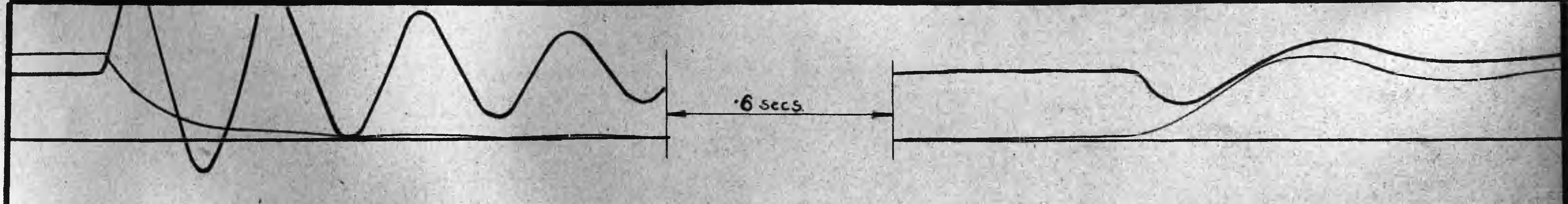
Ref. N° 107/B/0/7

Fig. 71



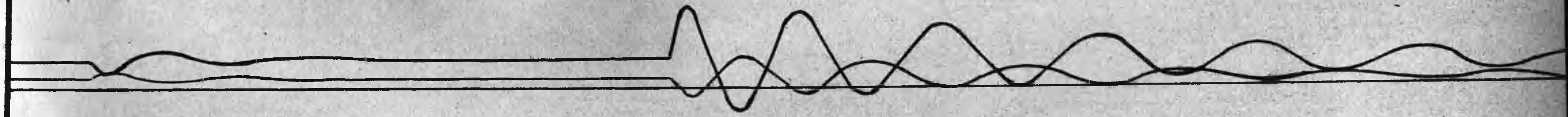
Ref. N° 104/B/0/6

Fig. 72



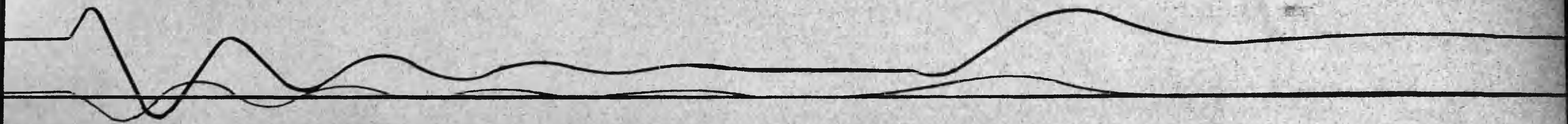
Ref. Nº 110|D|0|4

Fig. 73



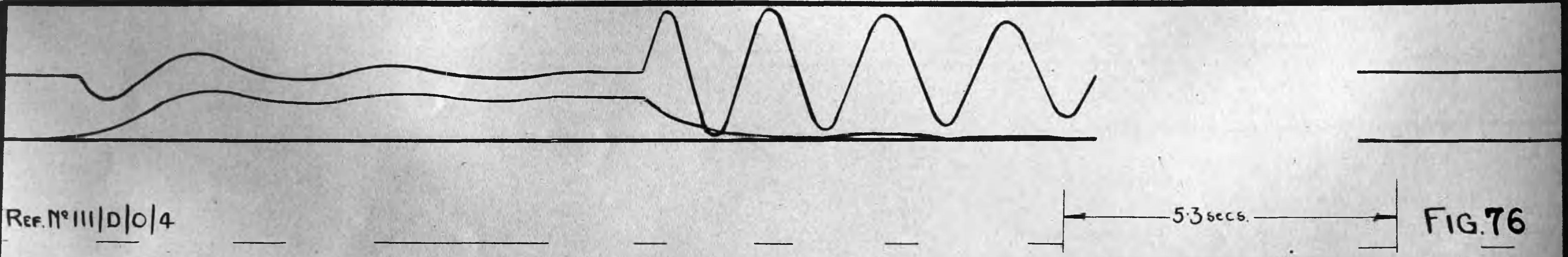
Ref. Nº 123|D|1|10

Fig. 74



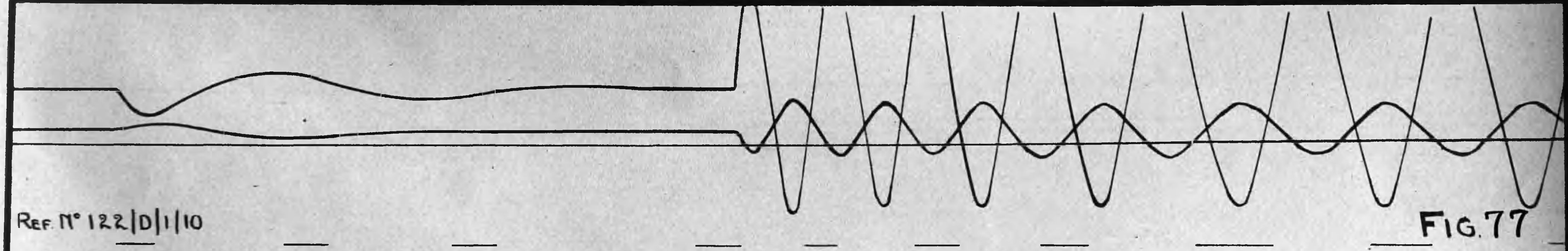
Ref. Nº 124|D|2|11

Fig. 75



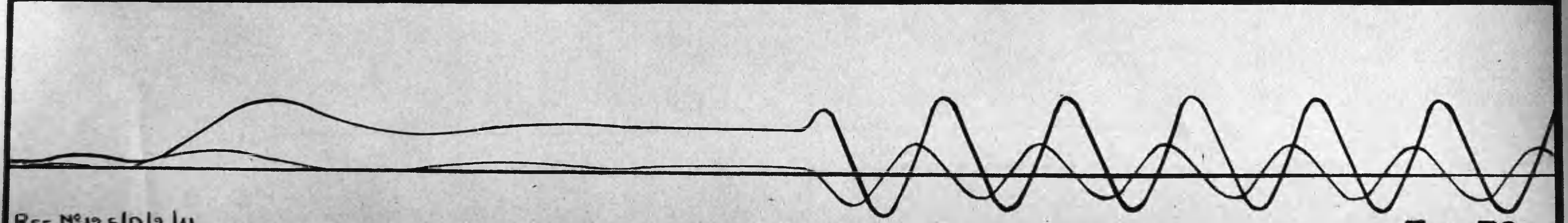
Ref. No 111|D|0|4

Fig. 76



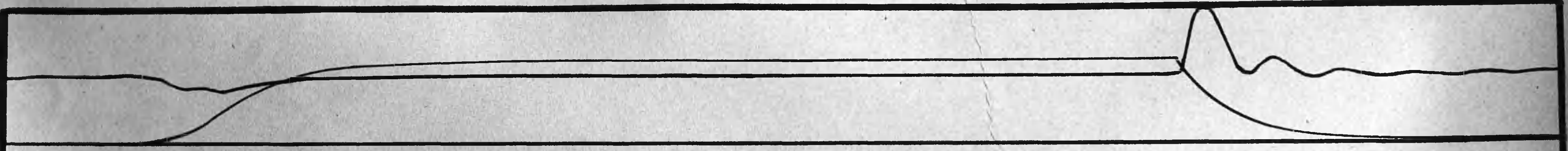
Ref. No 122|D|1|10

Fig. 77

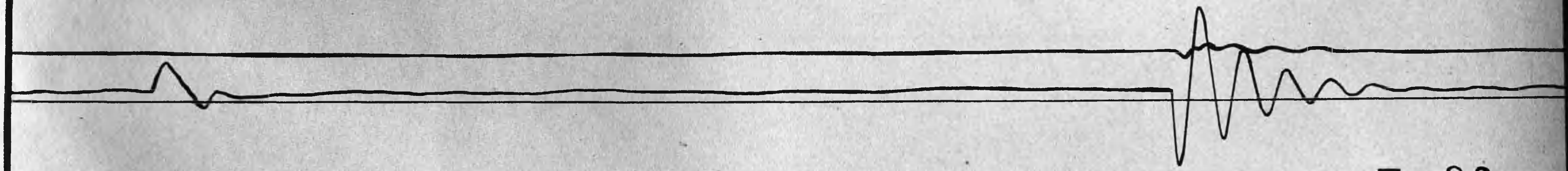


Ref. No 125|D|2|11

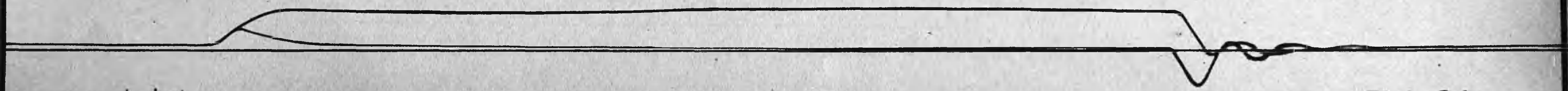
Fig. 78



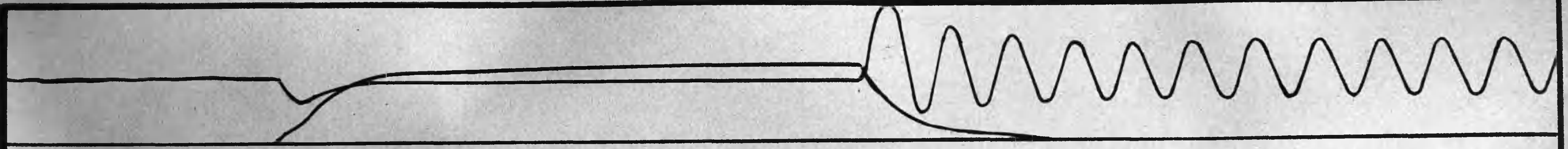
Ref. Nº 113|D|0|8 Fig. 79



Ref. Nº 121|D|1|9 Fig. 80

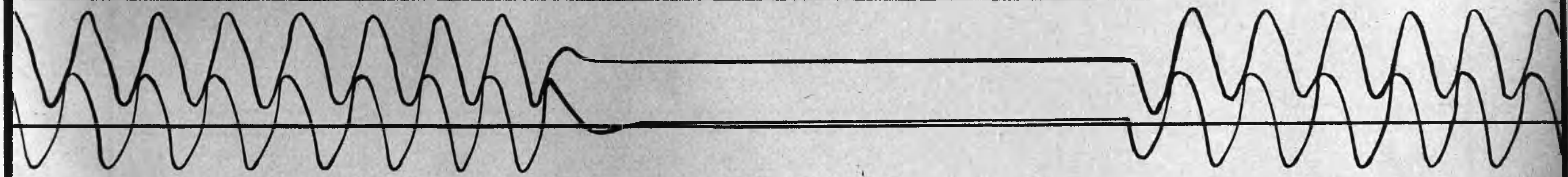


Ref. Nº 126|D|2|12 Fig. 81



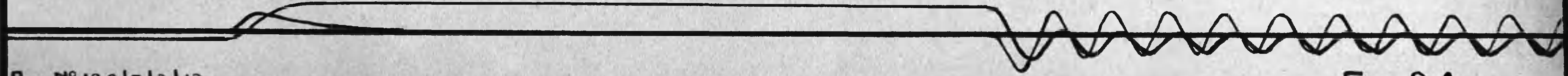
REF. Nº 119|D|0|8

FIG. 82



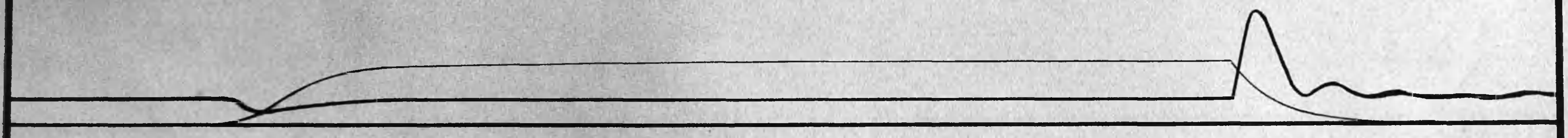
REF. Nº 120|D|1|9

FIG. 83



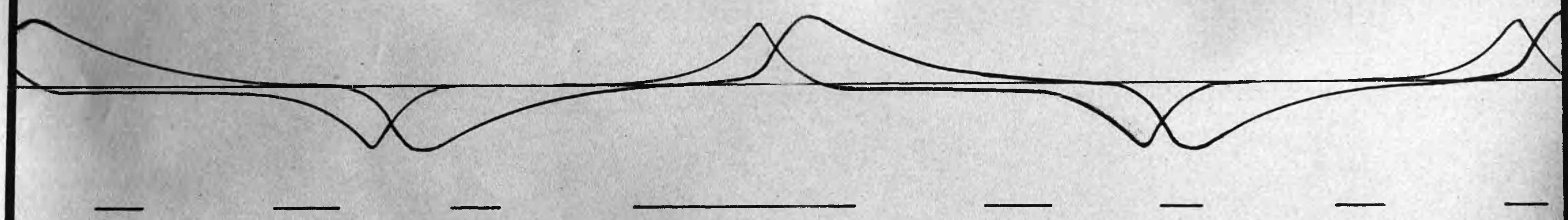
REF. Nº 128|D|2|12

FIG. 84



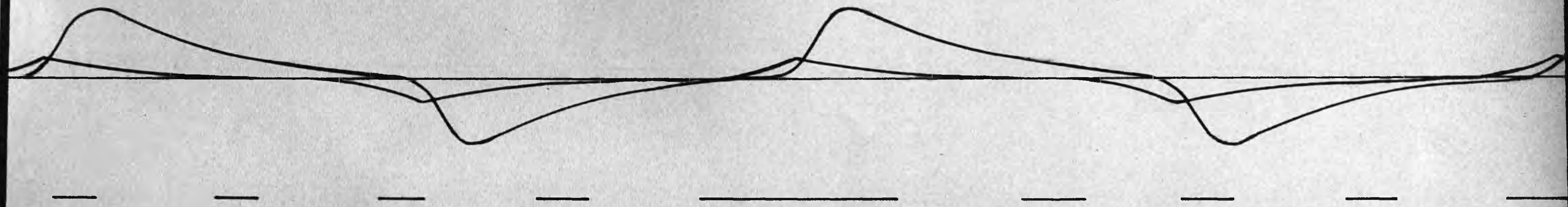
REF. Nº 129|D|0|8

FIG. 85



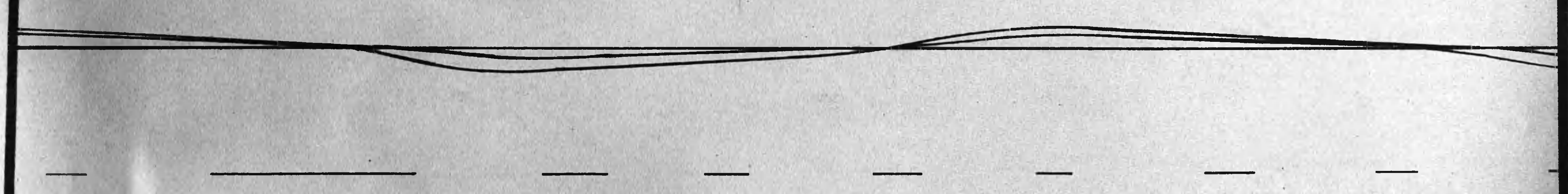
REF. Nº 133|C|2|14

FIG. 86



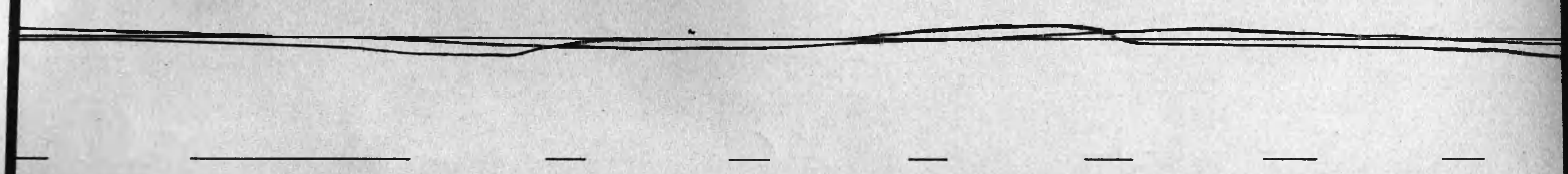
REF. Nº 138|C|0|13

FIG. 87



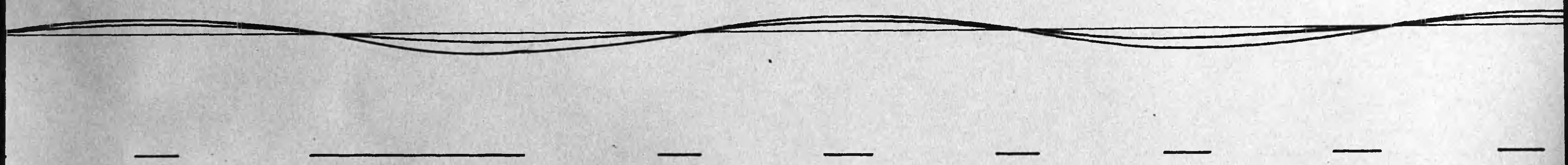
REF. Nº 137|C|0|13

FIG. 88



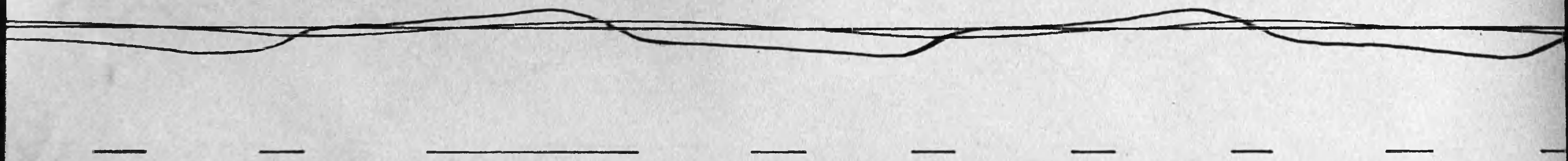
REF. Nº 132|C|2|14

FIG. 89



Ref No 141|C|0|15

Fig. 90



Ref No 143|C|2|16

Fig. 91

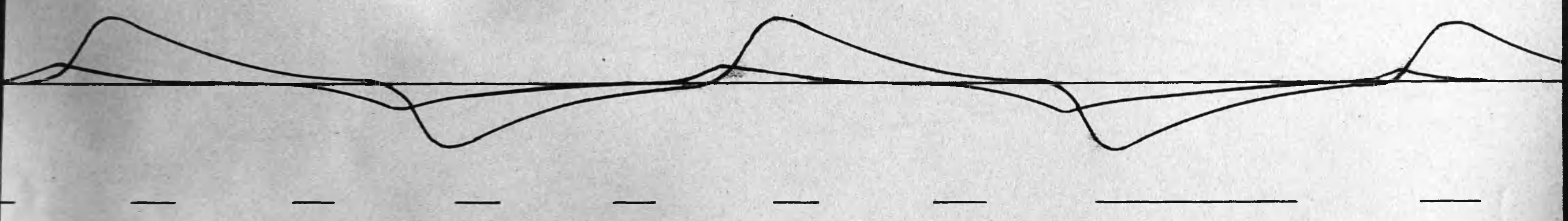


FIG. 92

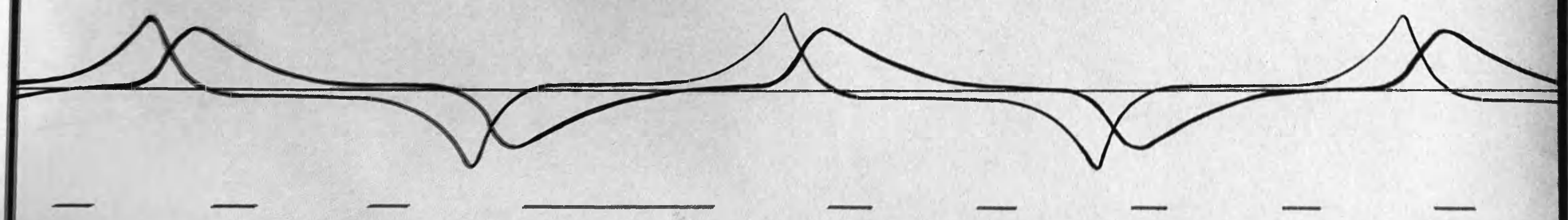


FIG. 93

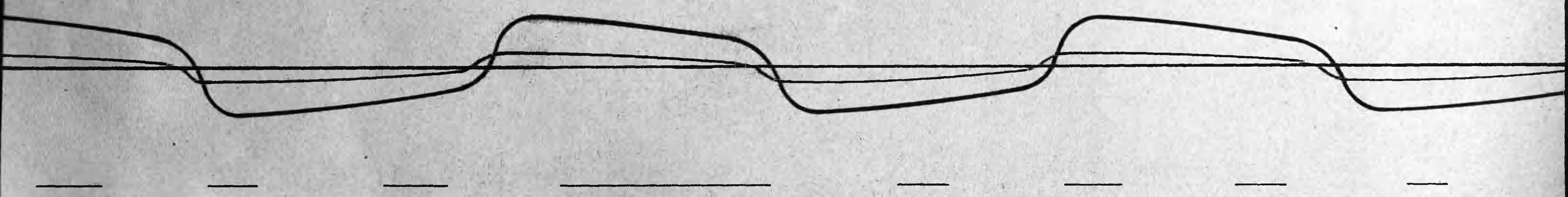


FIG. 94

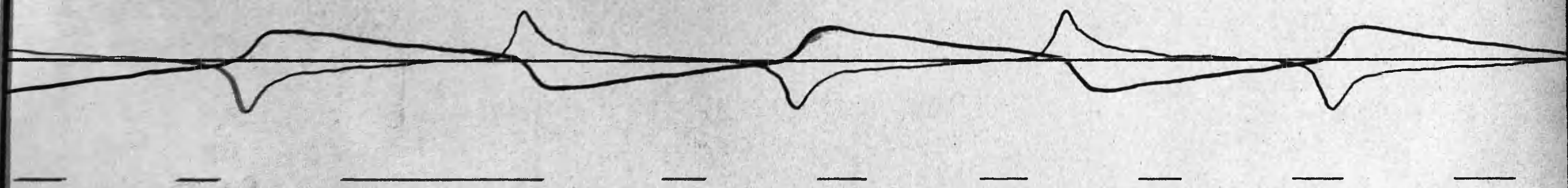


FIG. 95

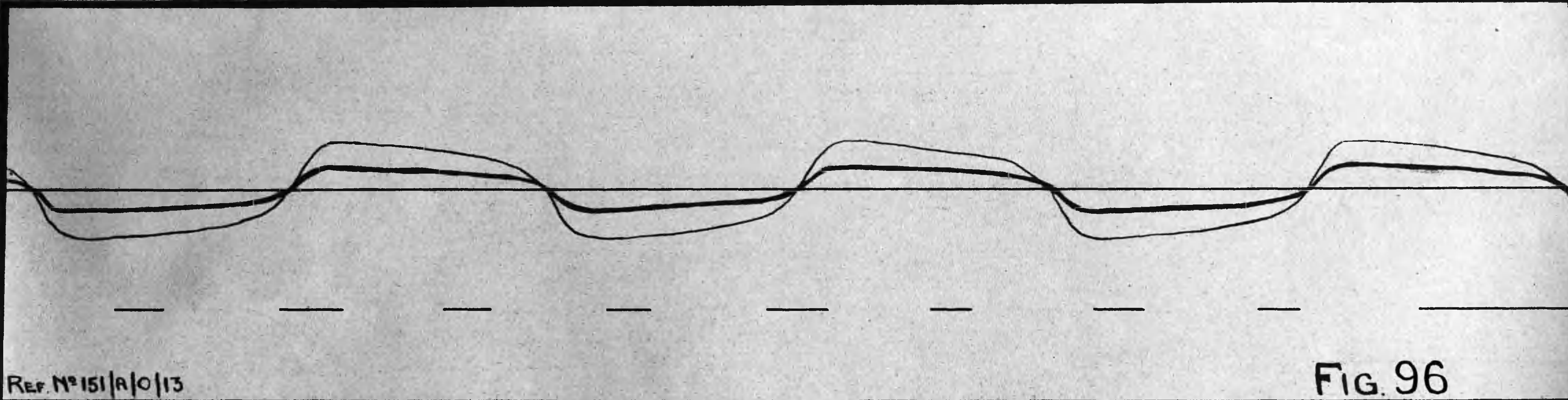


Fig. 96

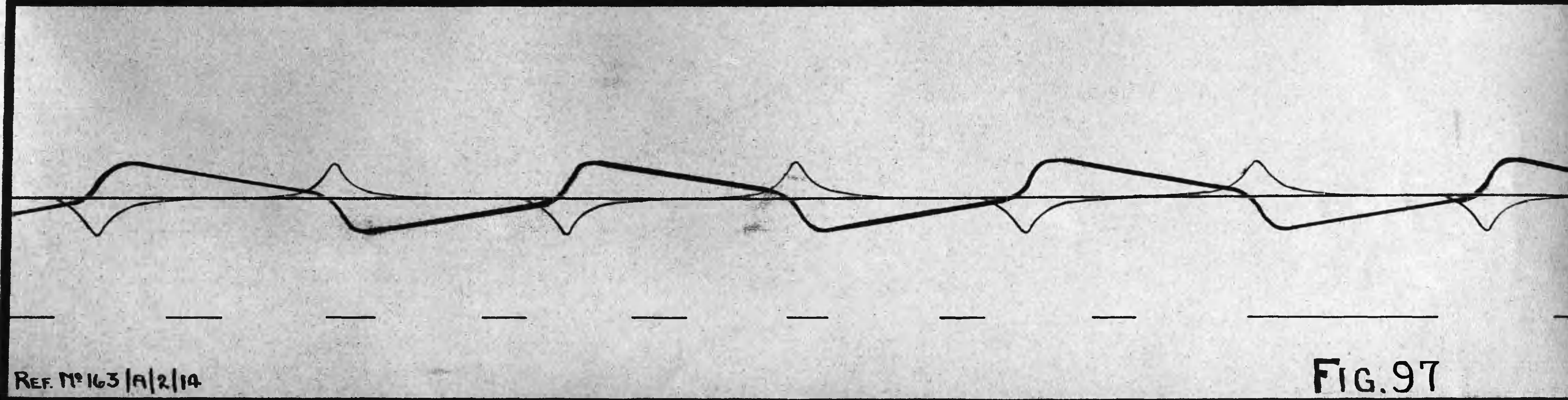
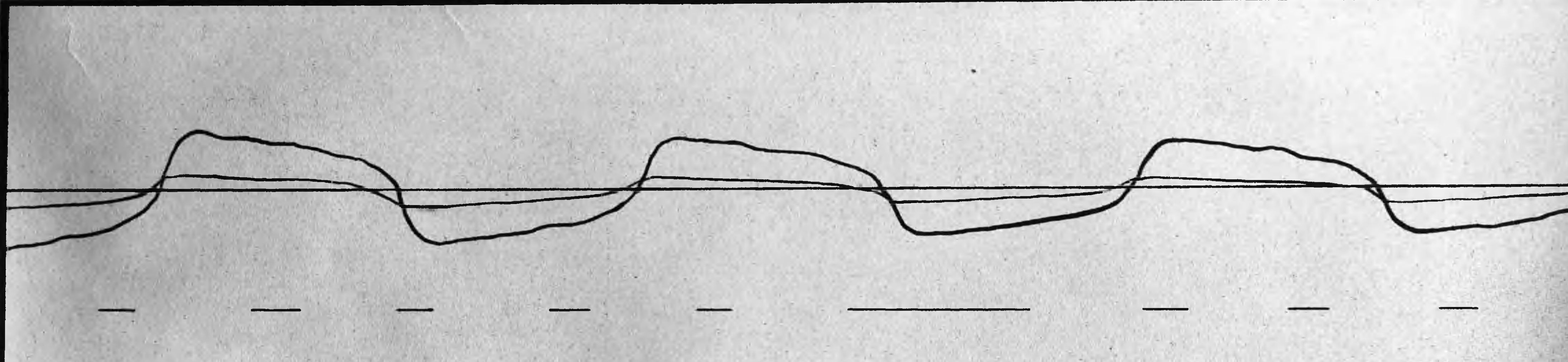
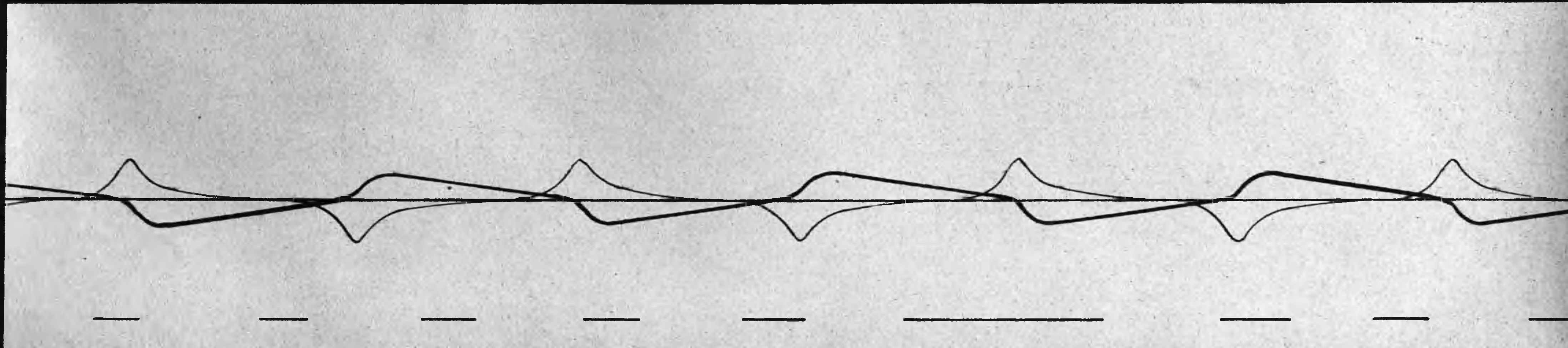


Fig. 97



REF. Nº 153|A|0|13

FIG. 98



REF. Nº 162|A|2|14

FIG. 99

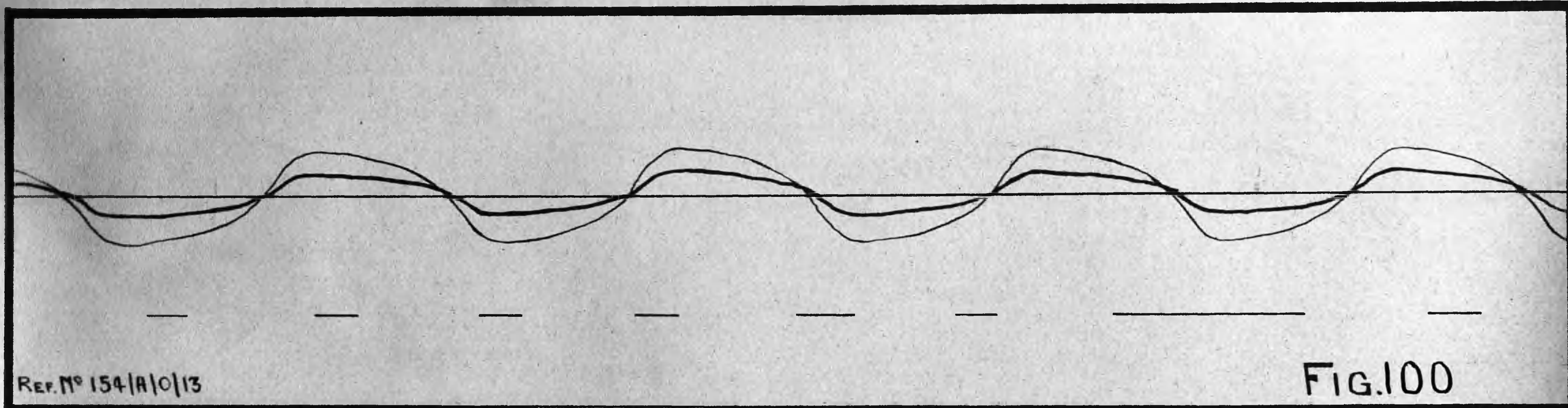


FIG. 100

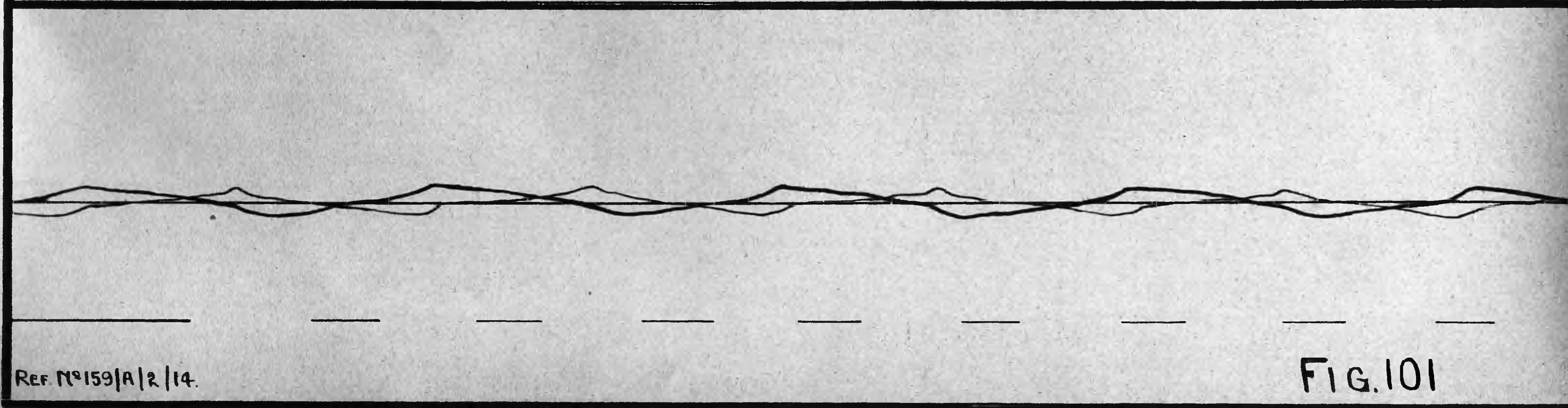
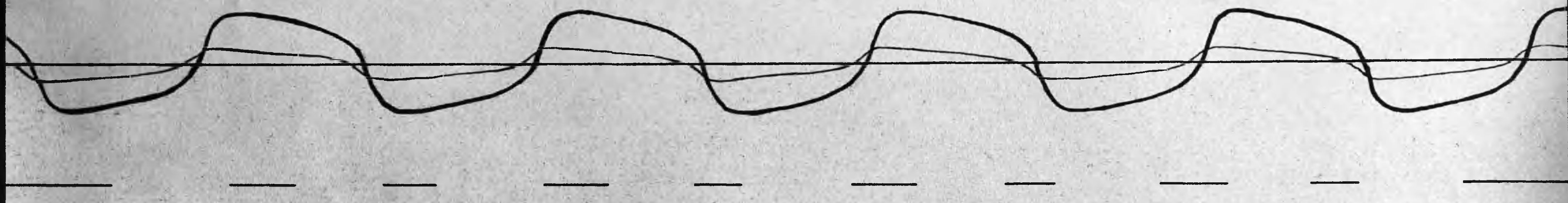
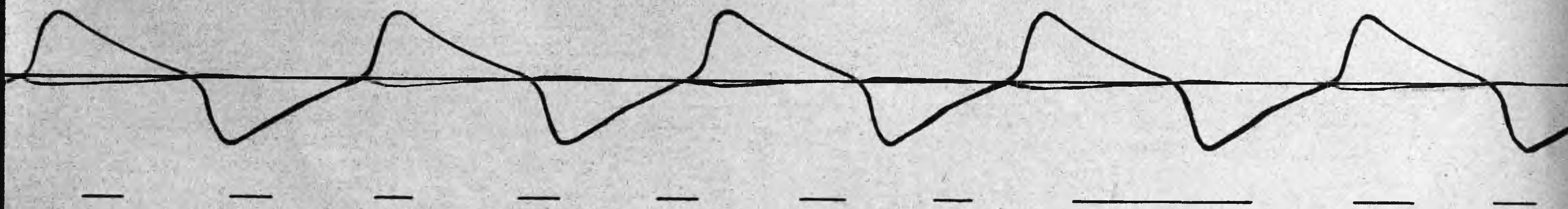


FIG. 101



REF. Nº 166/A/0/15

FIG. 102



REF. Nº 180/A/2/16

FIG. 103

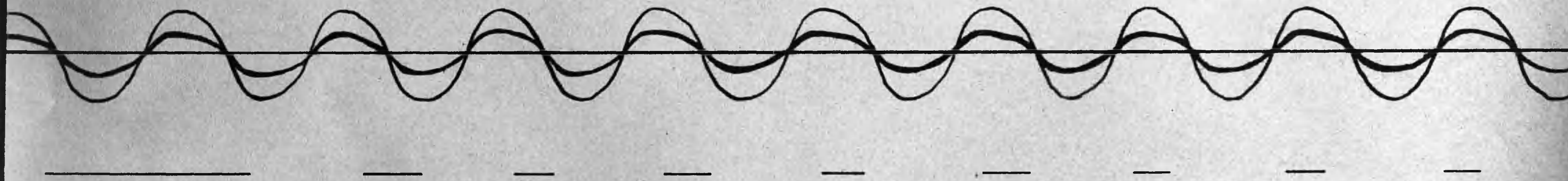


FIG. 104

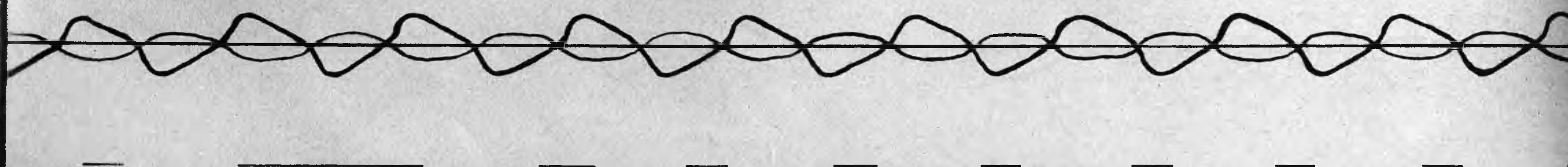
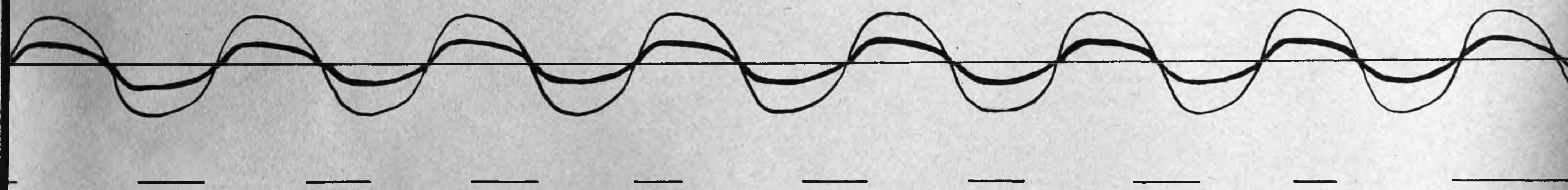
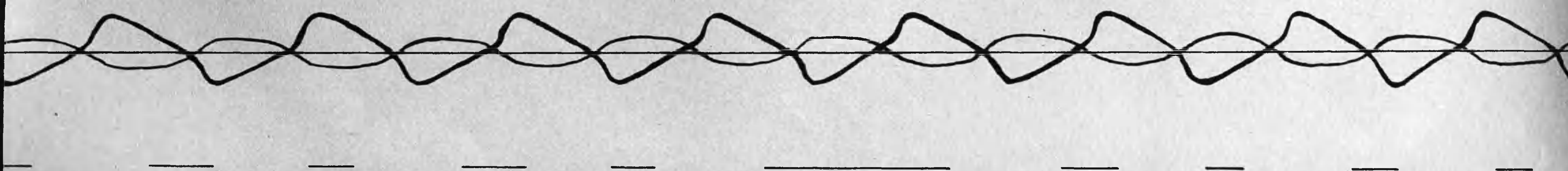


FIG. 105



REF Nº 169/A/0/15

FIG. 106



REF Nº 175/A/2/16

FIG. 107

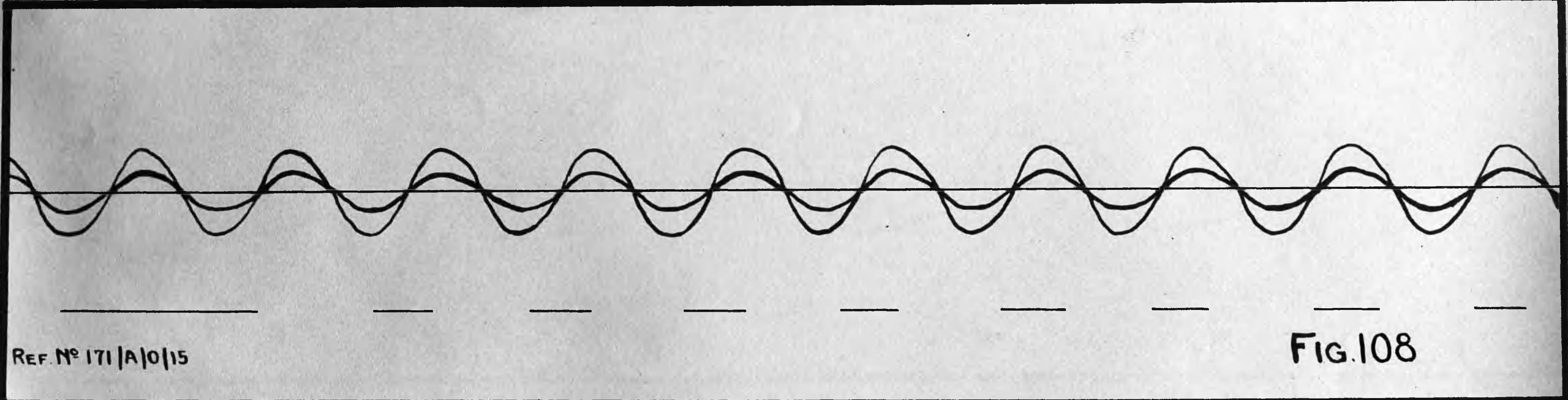


FIG. 108

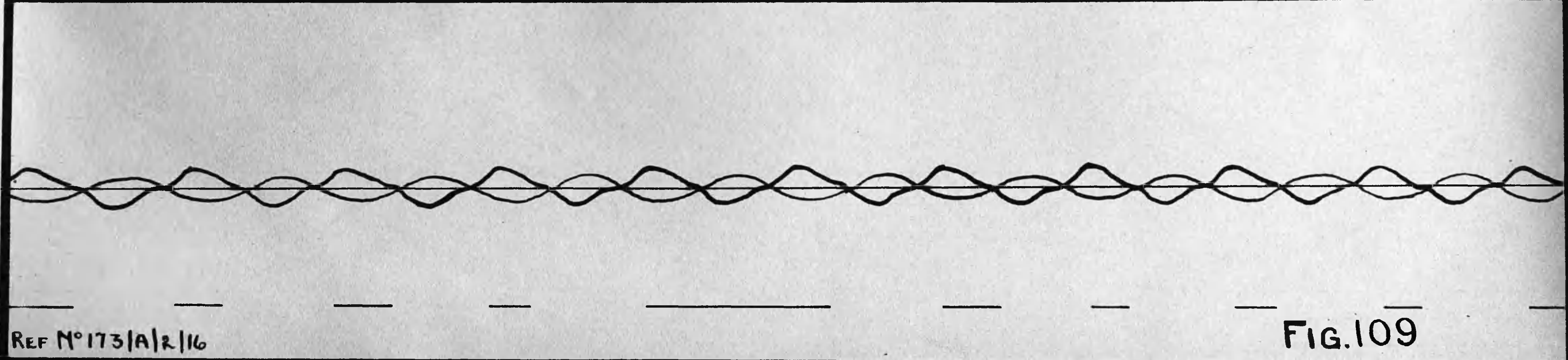
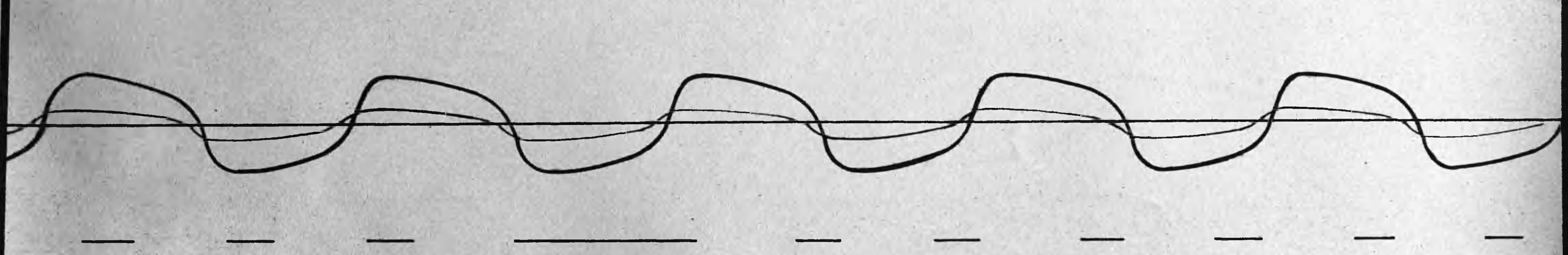
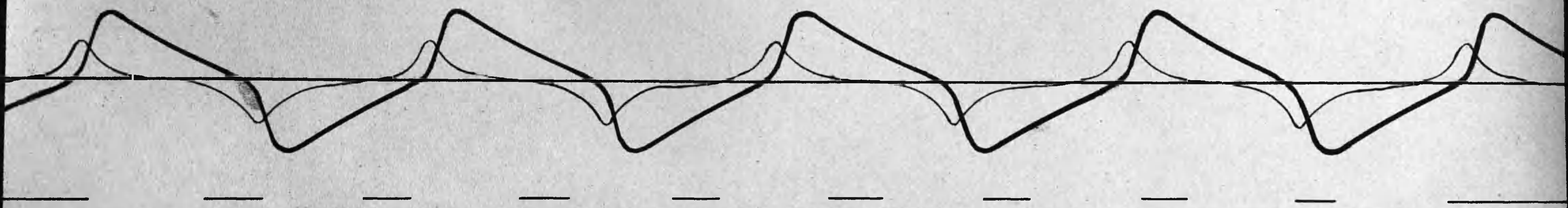


FIG. 109



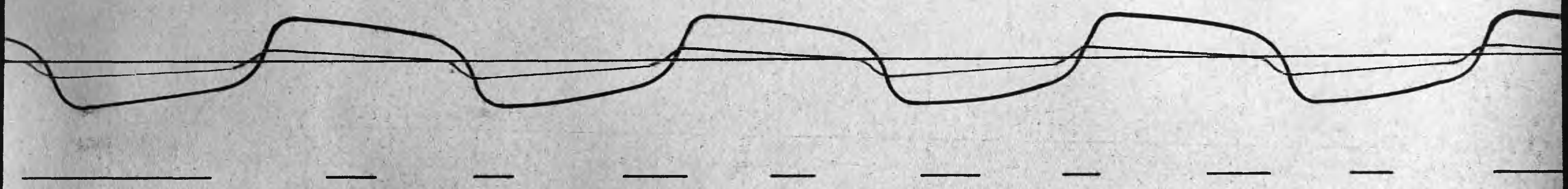
Ref. Nº 185/A/0/15

Fig. 110



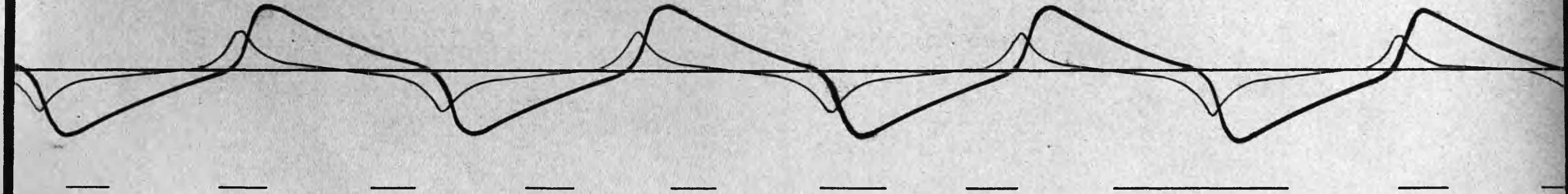
Ref. Nº 190/A/2/16

Fig. 111



Ref. Nº 198/A/0/13

Fig. 112



Ref. Nº 193/A/2/14

Fig 113

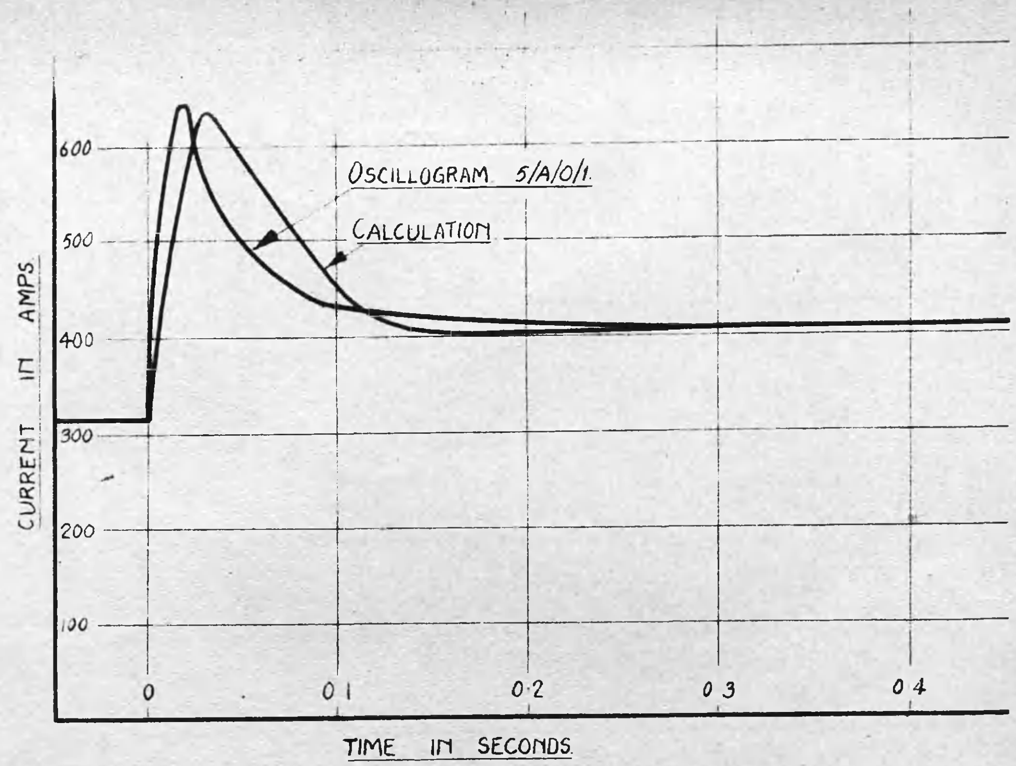


FIG. 114. - COMPARISON OF CURVES.
MAIN CIRCUIT, BRUSHES FORWARD.
CALCULATIONS TABLE - 24.

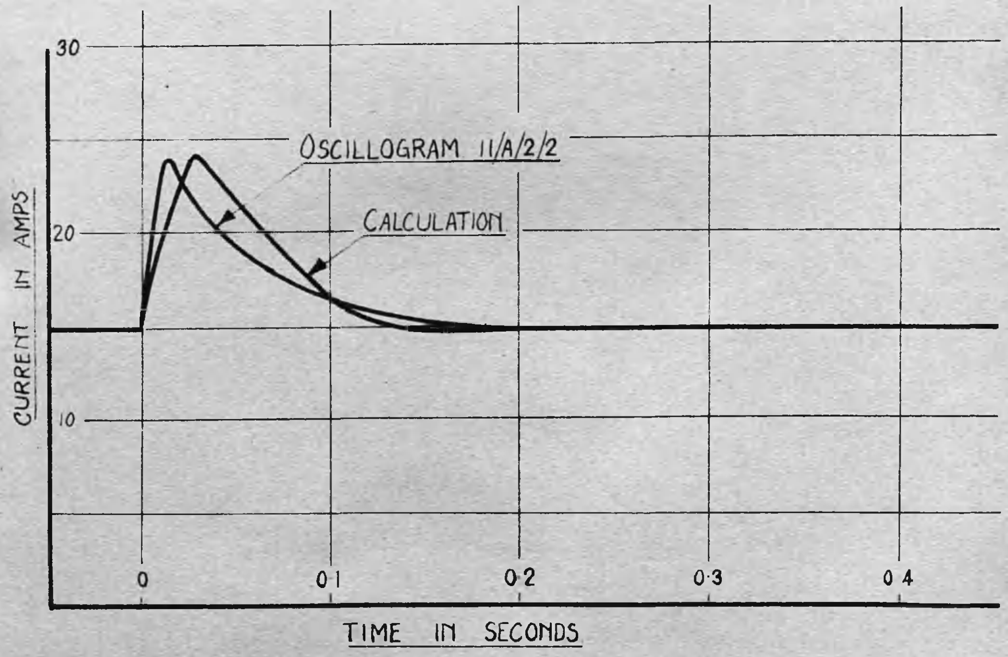


FIG. 115 - COMPARISON OF CURVES.
SHUNT CIRCUIT, BRUSHES FORWARD.
CALCULATIONS TABLE 24.

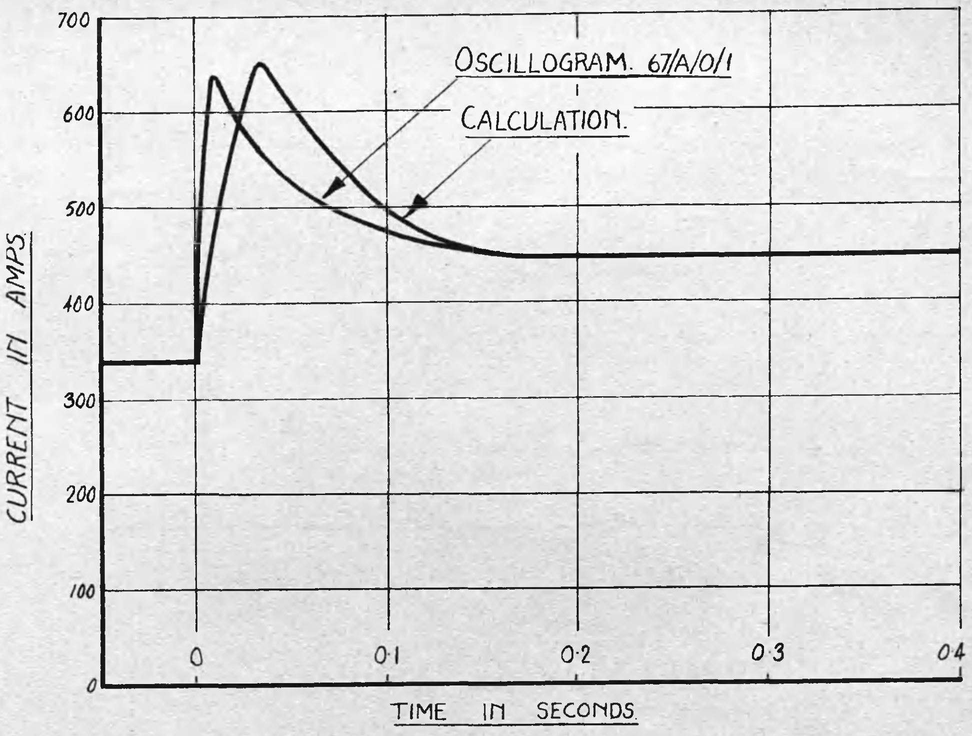


FIG. 116 - COMPARISON OF CURVES.

MAIN CIRCUIT, BRUSHES NEUTRAL.

CALCULATIONS TABLE - 25.

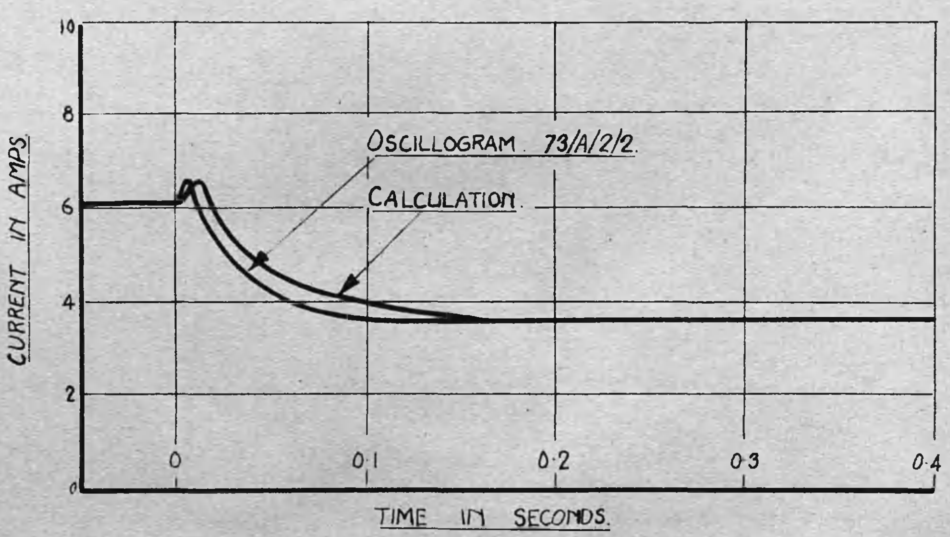


FIG. 117 - COMPARISON OF CURVES.

SHUNT CIRCUIT, BRUSHES NEUTRAL.

CALCULATIONS TABLE - 25.

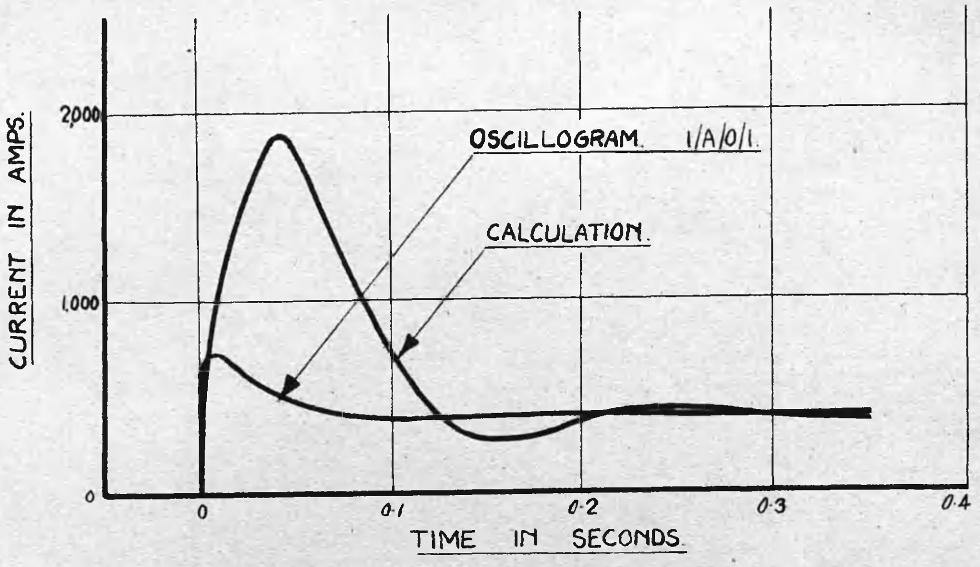


FIG. 118 - COMPARISON OF CURVES.

MAIN CIRCUIT. BRUSHES FORWARD.

CALCULATIONS TABLE - 27.

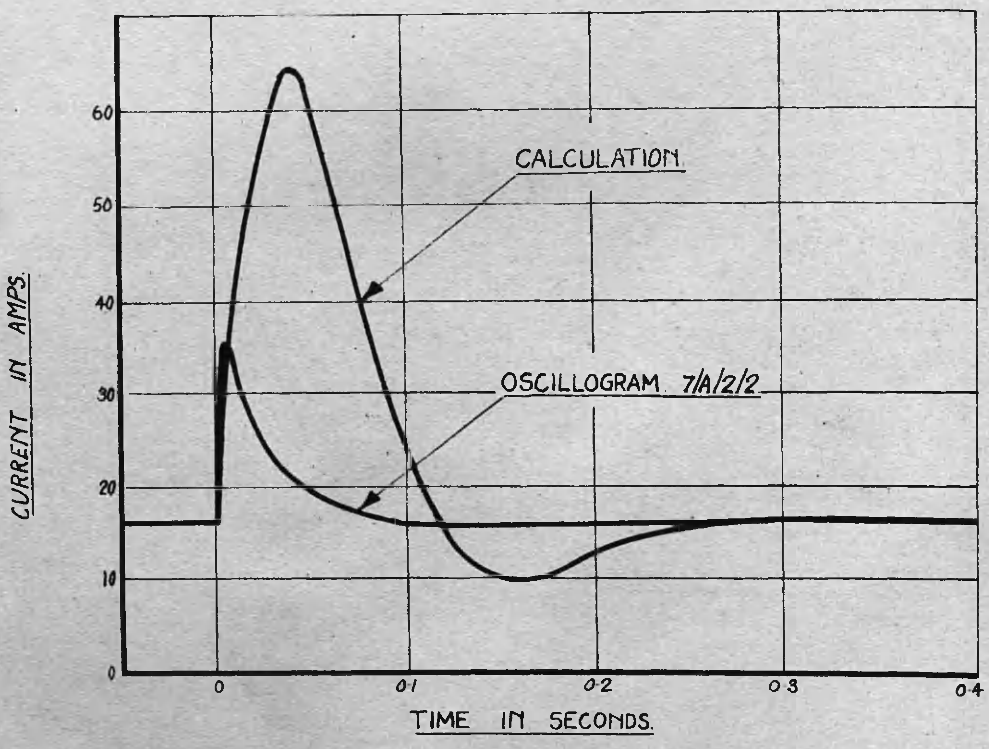


FIG. 119 - COMPARISON OF CURVES.

SHUNT CIRCUIT, BRUSHES FORWARD.

CALCULATIONS TABLE - 27.

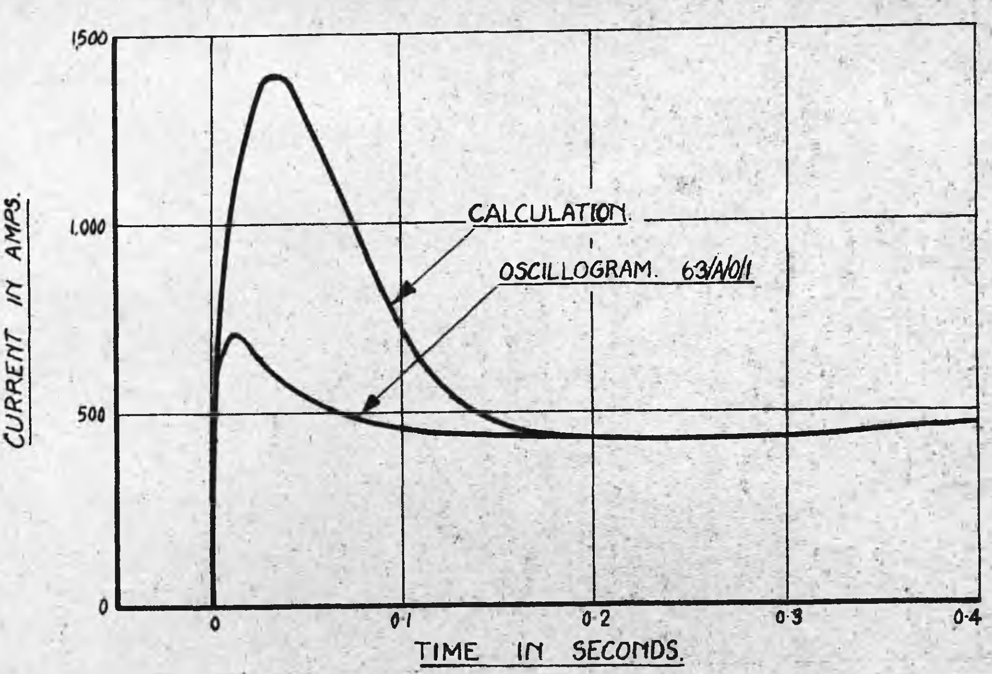


FIG. 120 - COMPARISON OF CURVES.
MAIN CIRCUIT. BRUSHES NEUTRAL.
CALCULATIONS TABLE - 28.

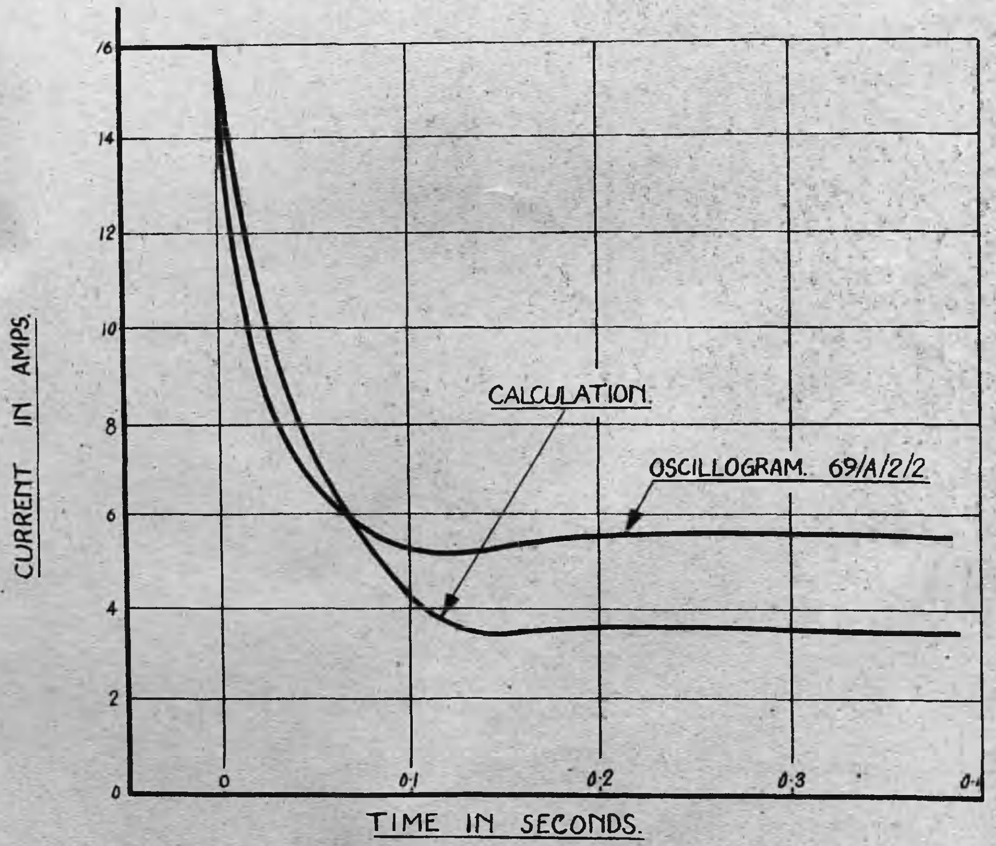


FIG. 121 - COMPARISON OF CURVES.
SHUNT CIRCUIT. BRUSHES NEUTRAL.
CALCULATIONS TABLE - 28.

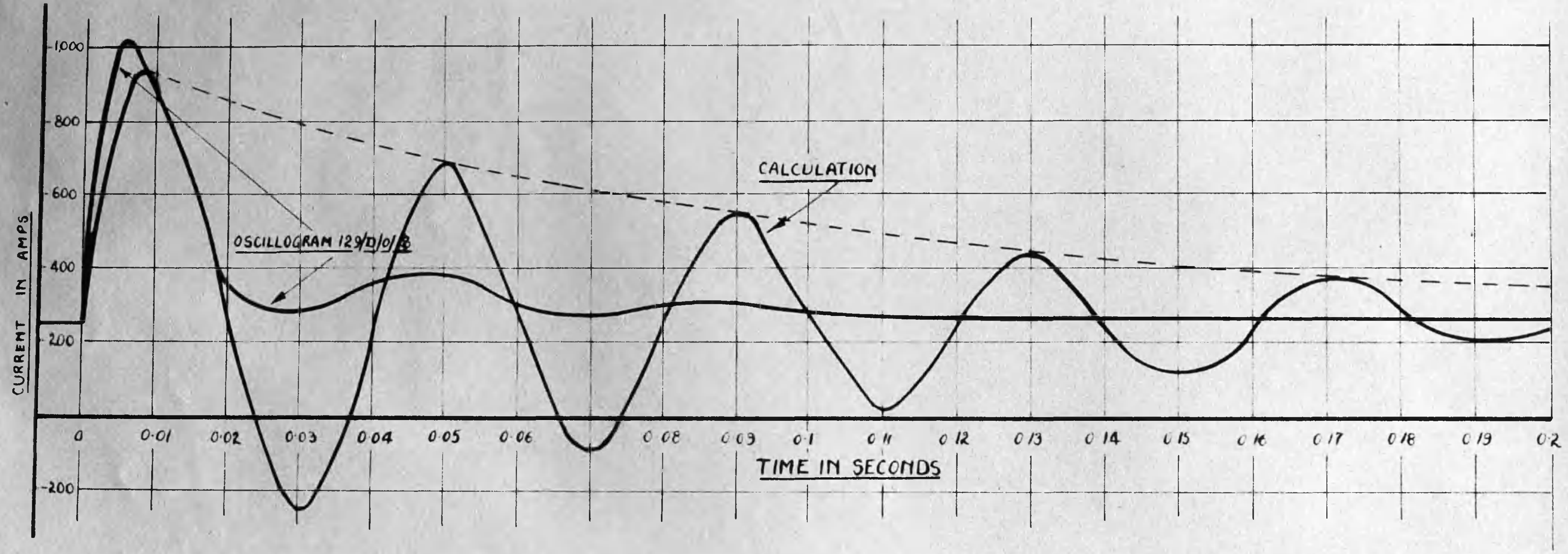


FIG. 122. - COMPARISON OF CURVES

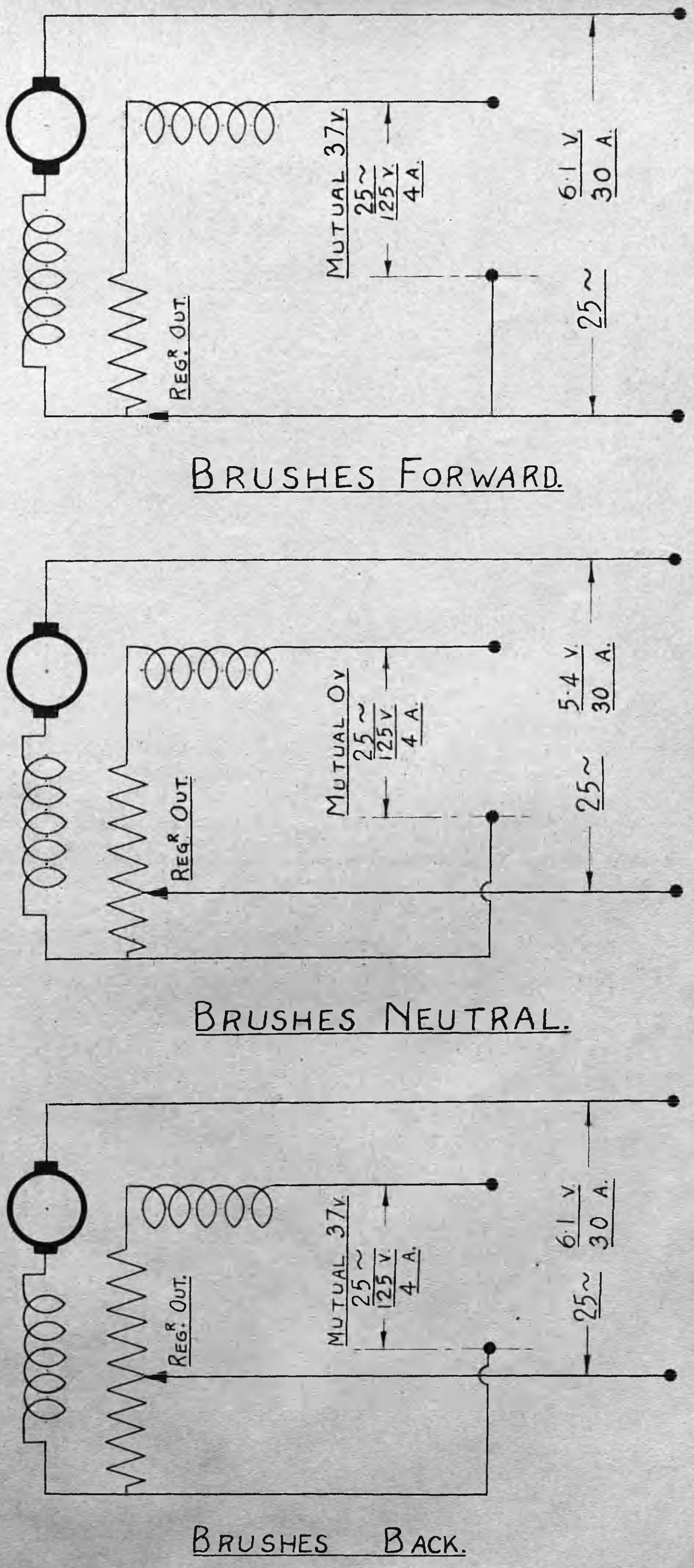


Fig. 123 – Inductance Measurements. Genr. A.

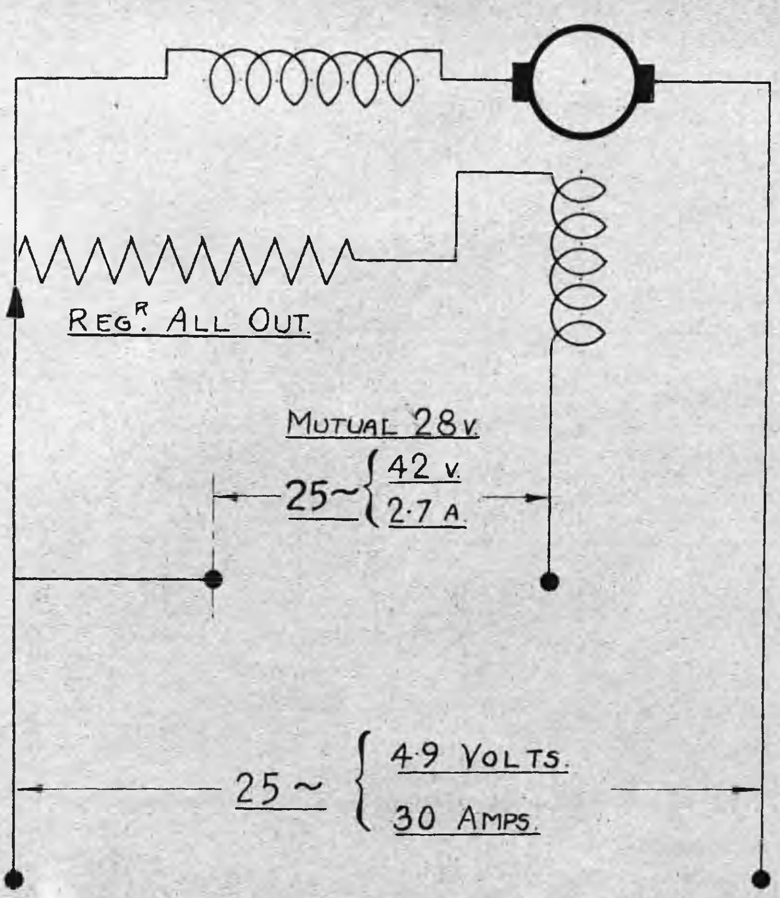


Fig. 124 - Inductance Measurements. Gen^R. B.

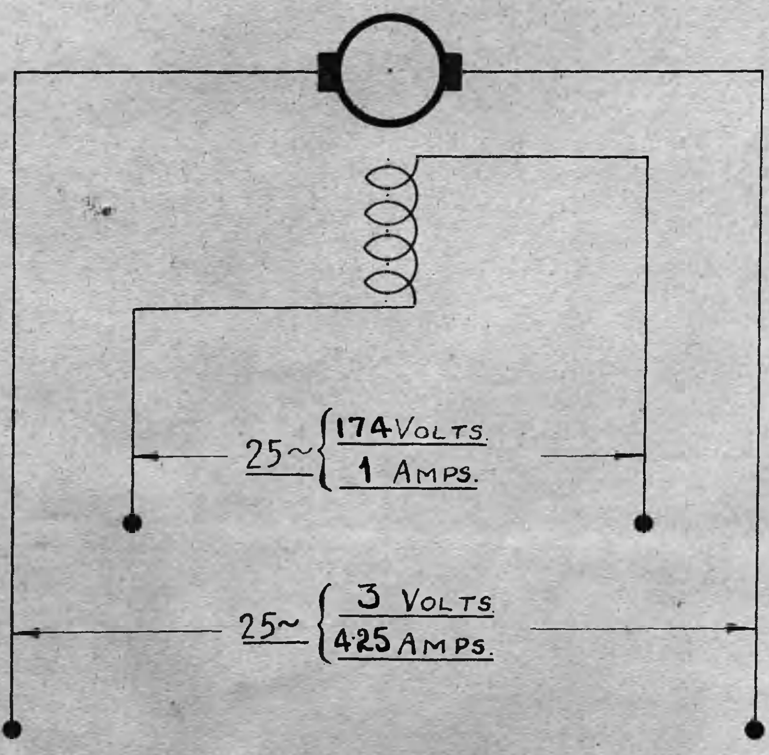


Fig. 125 - Inductance Measurements. Gen^R C.

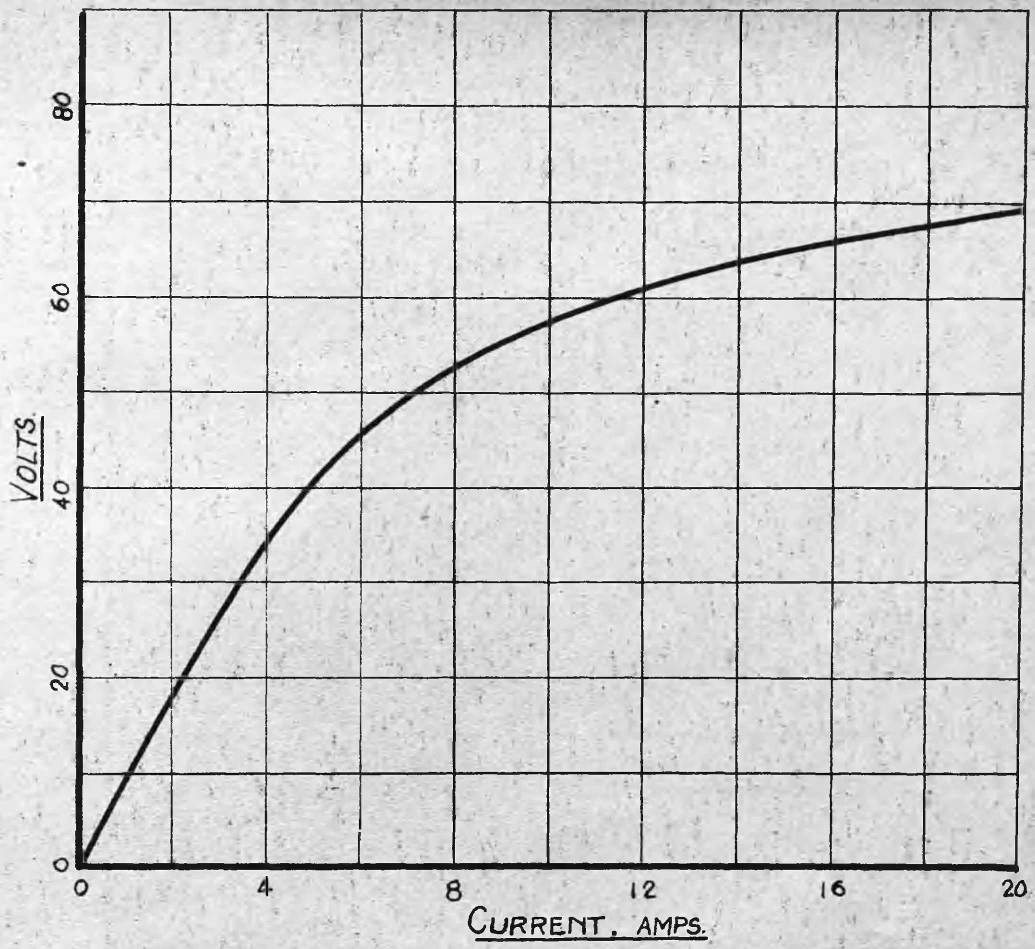


FIG. 126 - O.C. CHARACTERISTIC. GEN^R A.

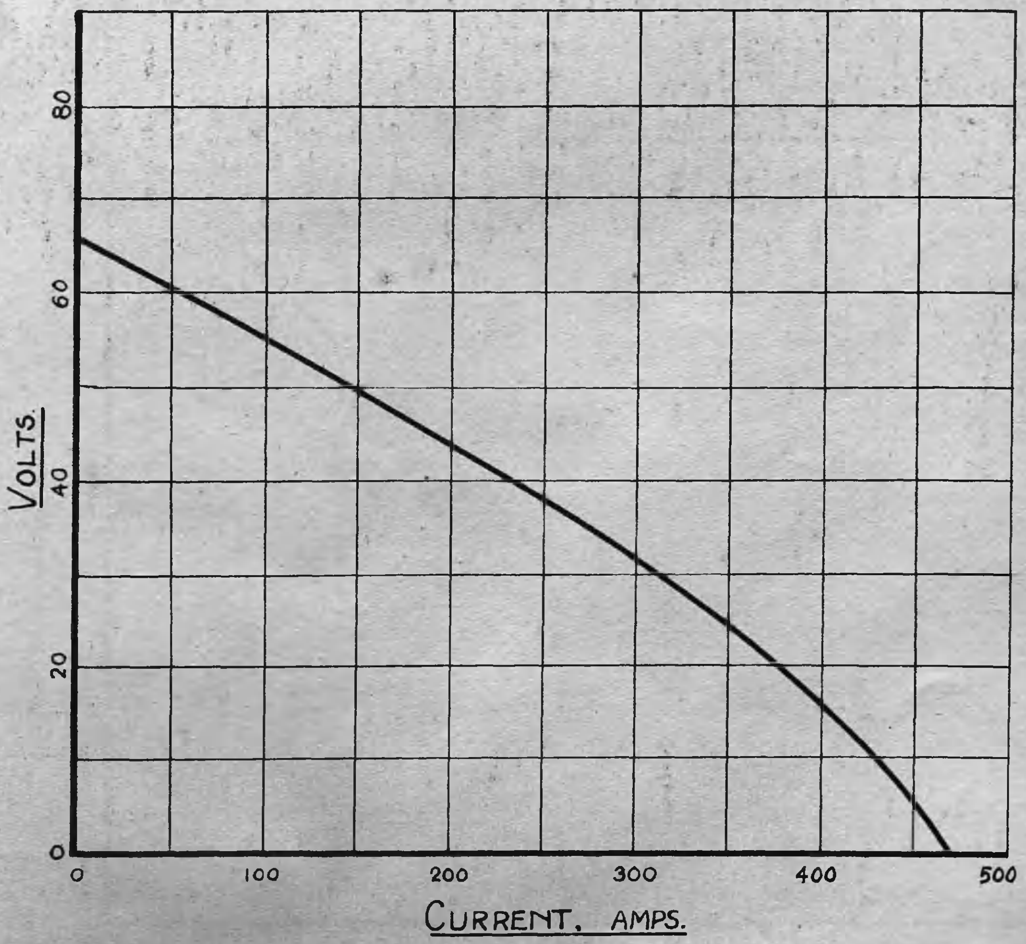


FIG. 127 - VOLT-AMP. CHARACTERISTIC. GEN^R A.

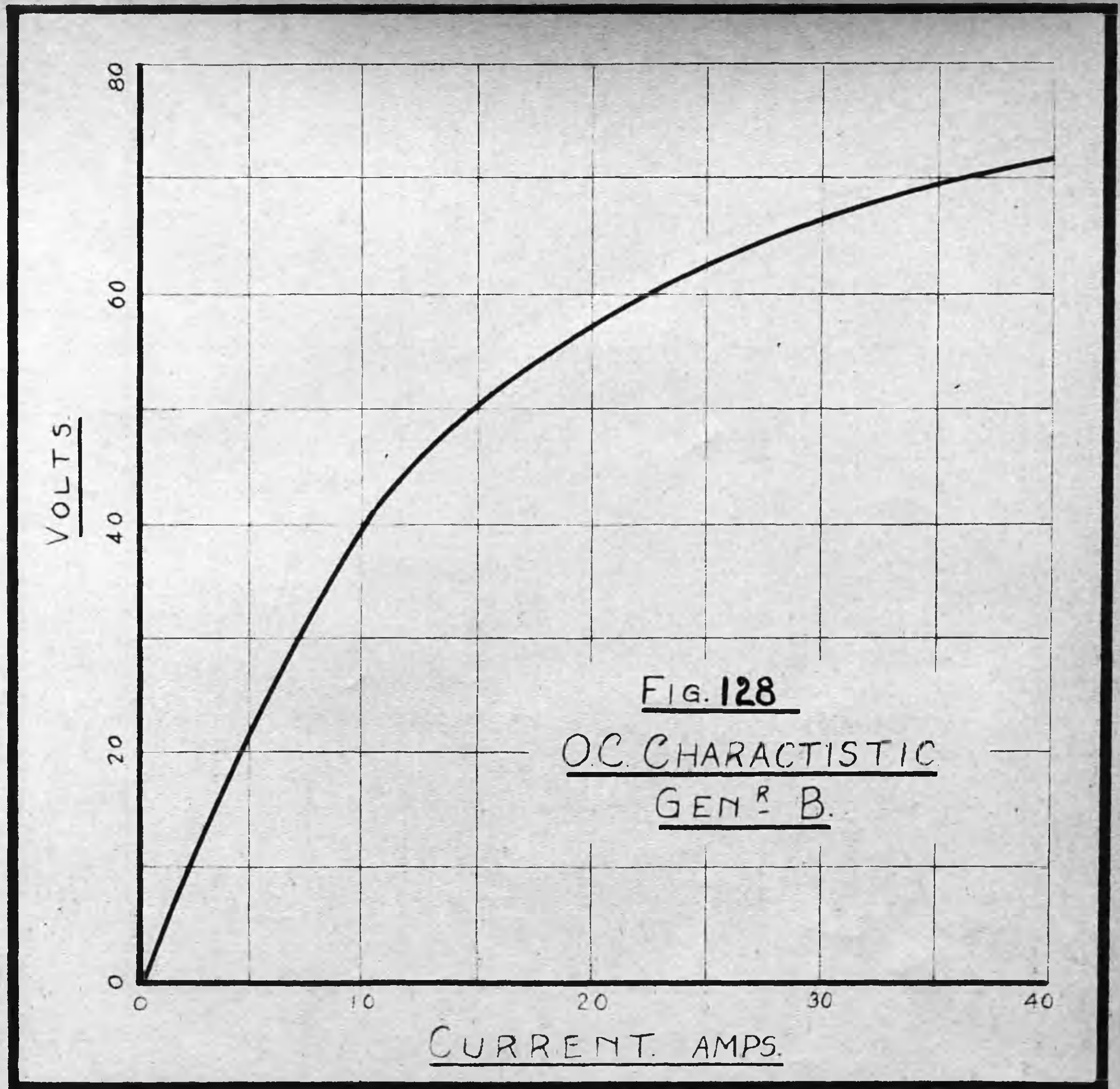


Fig. 128
O.C. Charactistic
Gen^r B.

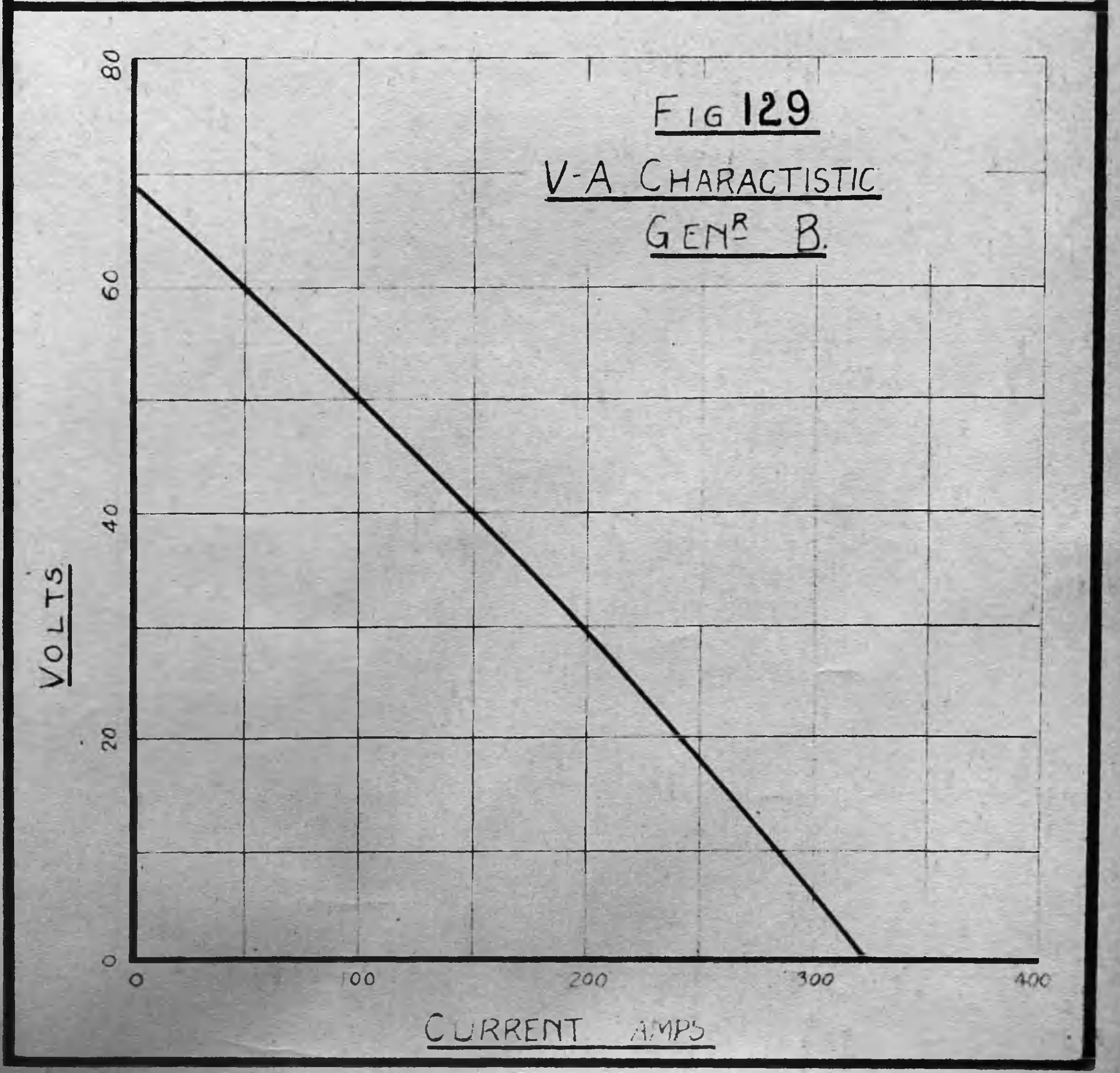


Fig 129
V-A Charactistic
Gen^r B.

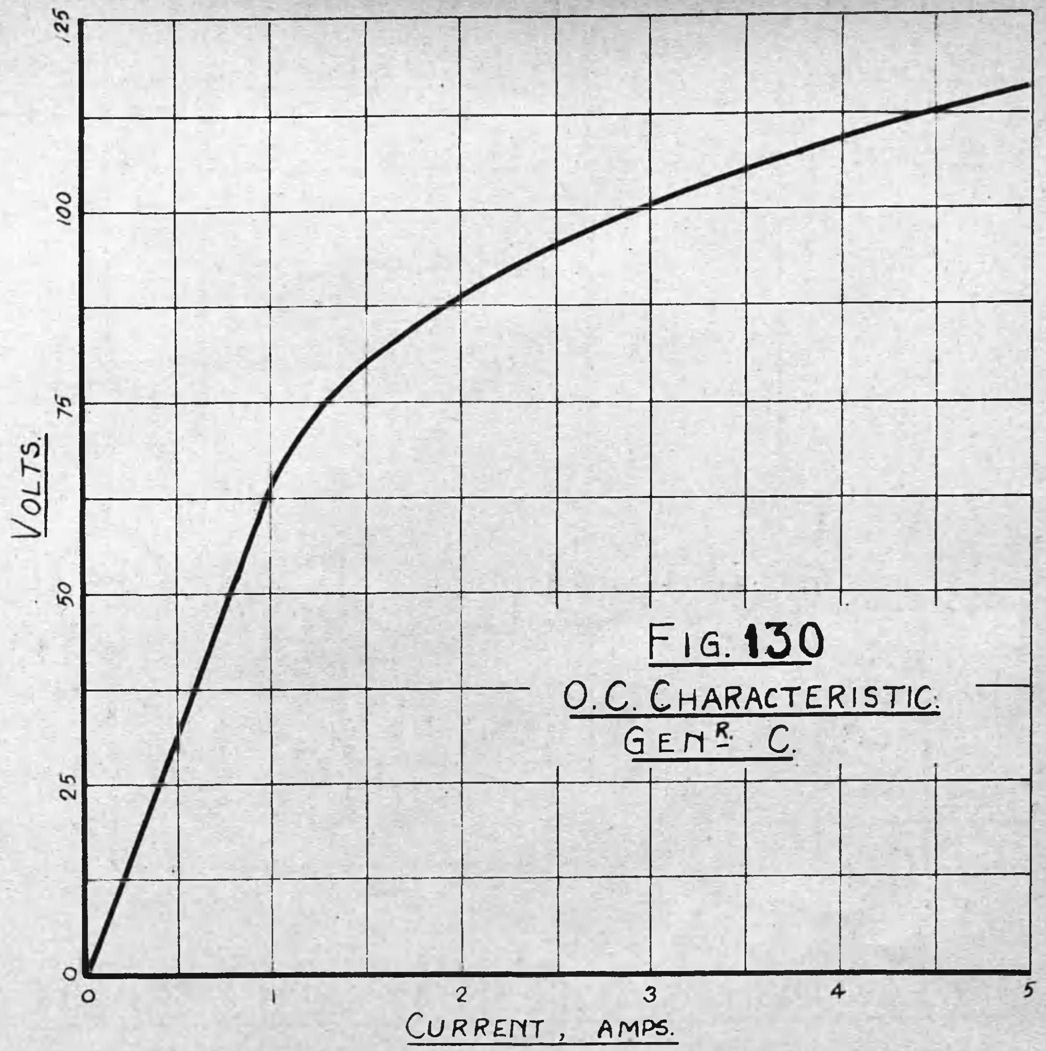


FIG. 130
O.C. CHARACTERISTIC.
GEN^R. C.

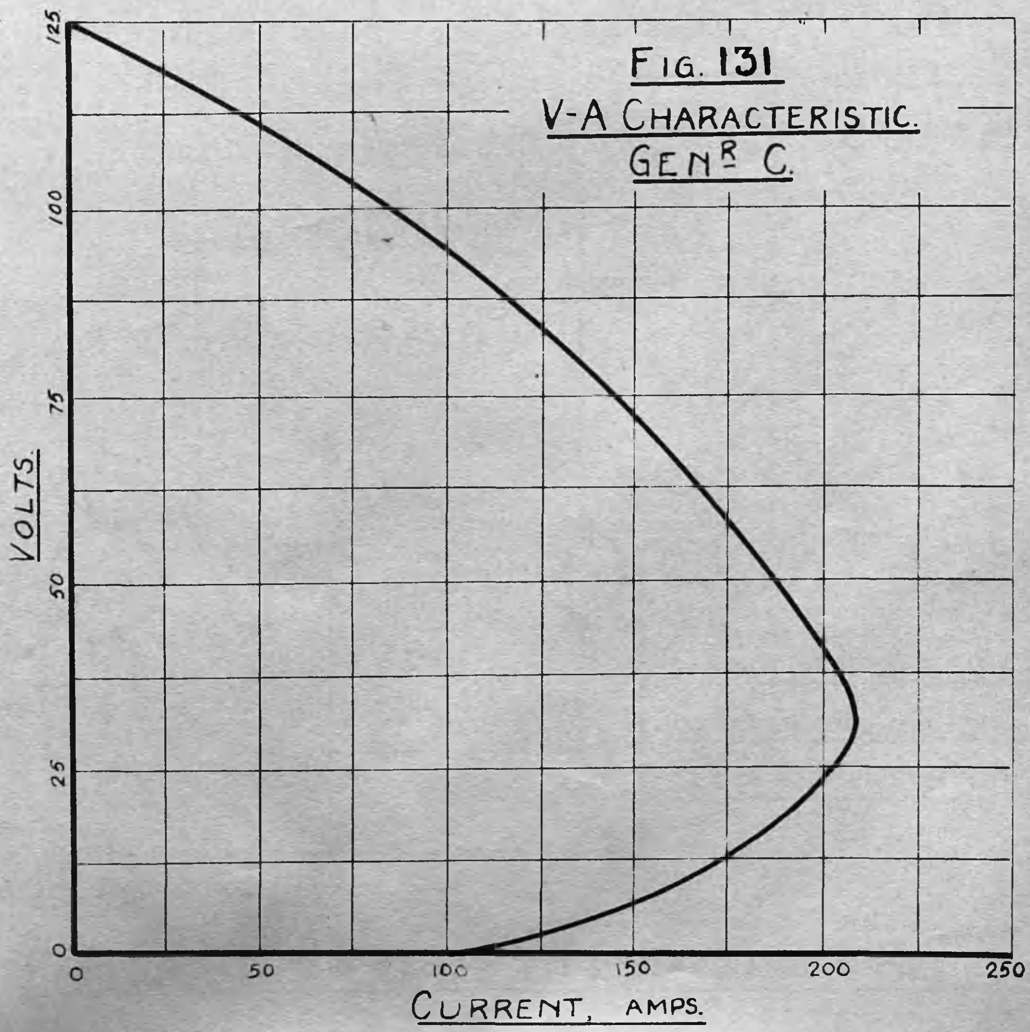


FIG. 131
V-A CHARACTERISTIC.
GEN^R. C.

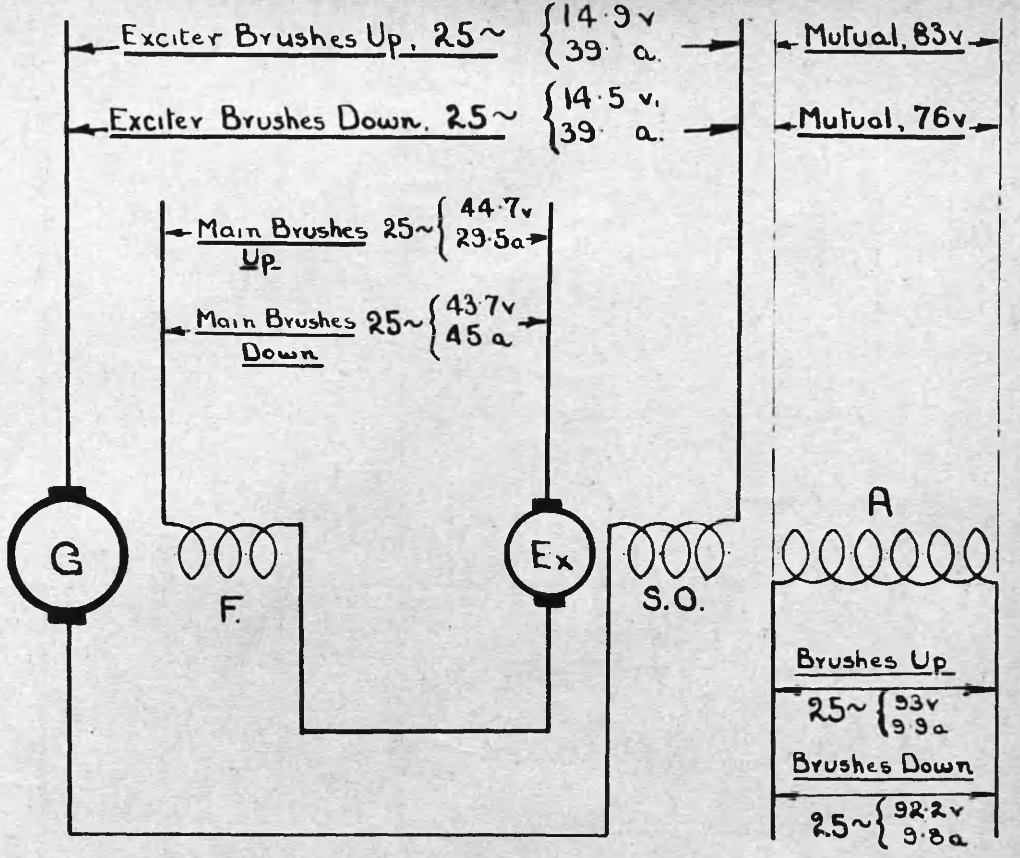


FIG. 132 - INDUCTANCE MEASUREMENTS, GENR D

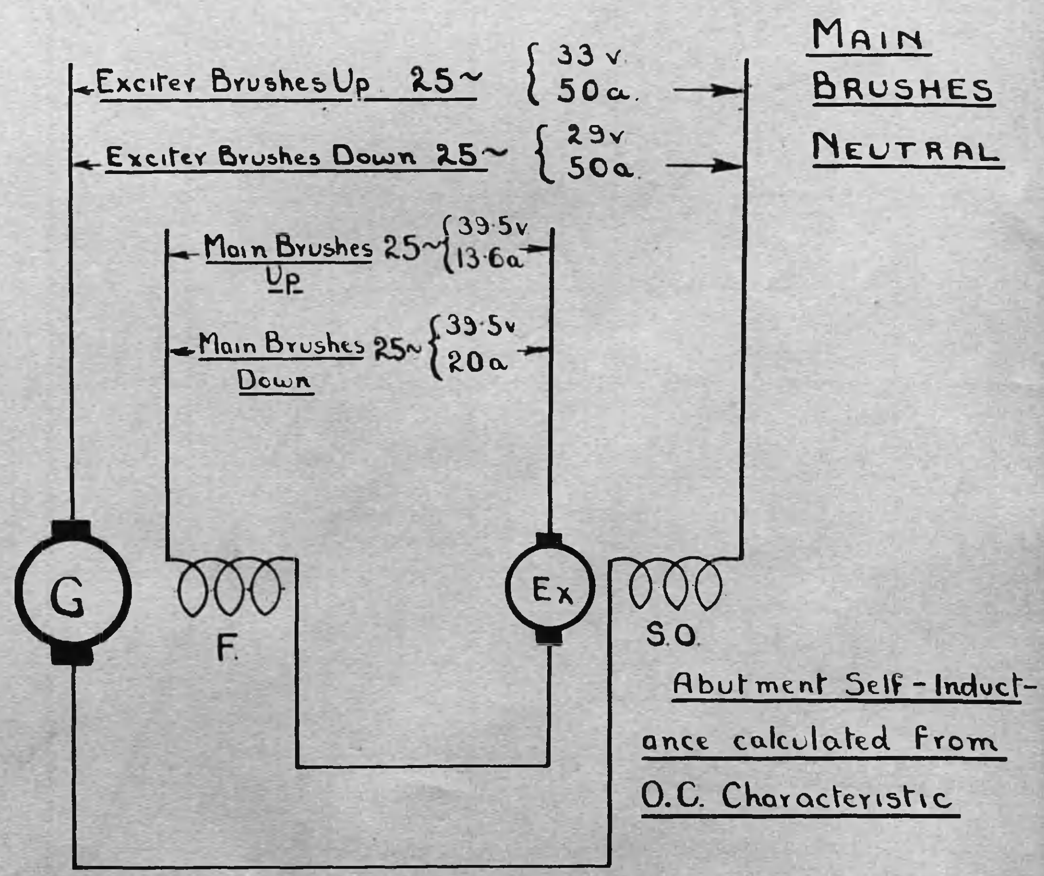


FIG 133 - INDUCTANCE MEASUREMENTS, GENR E.

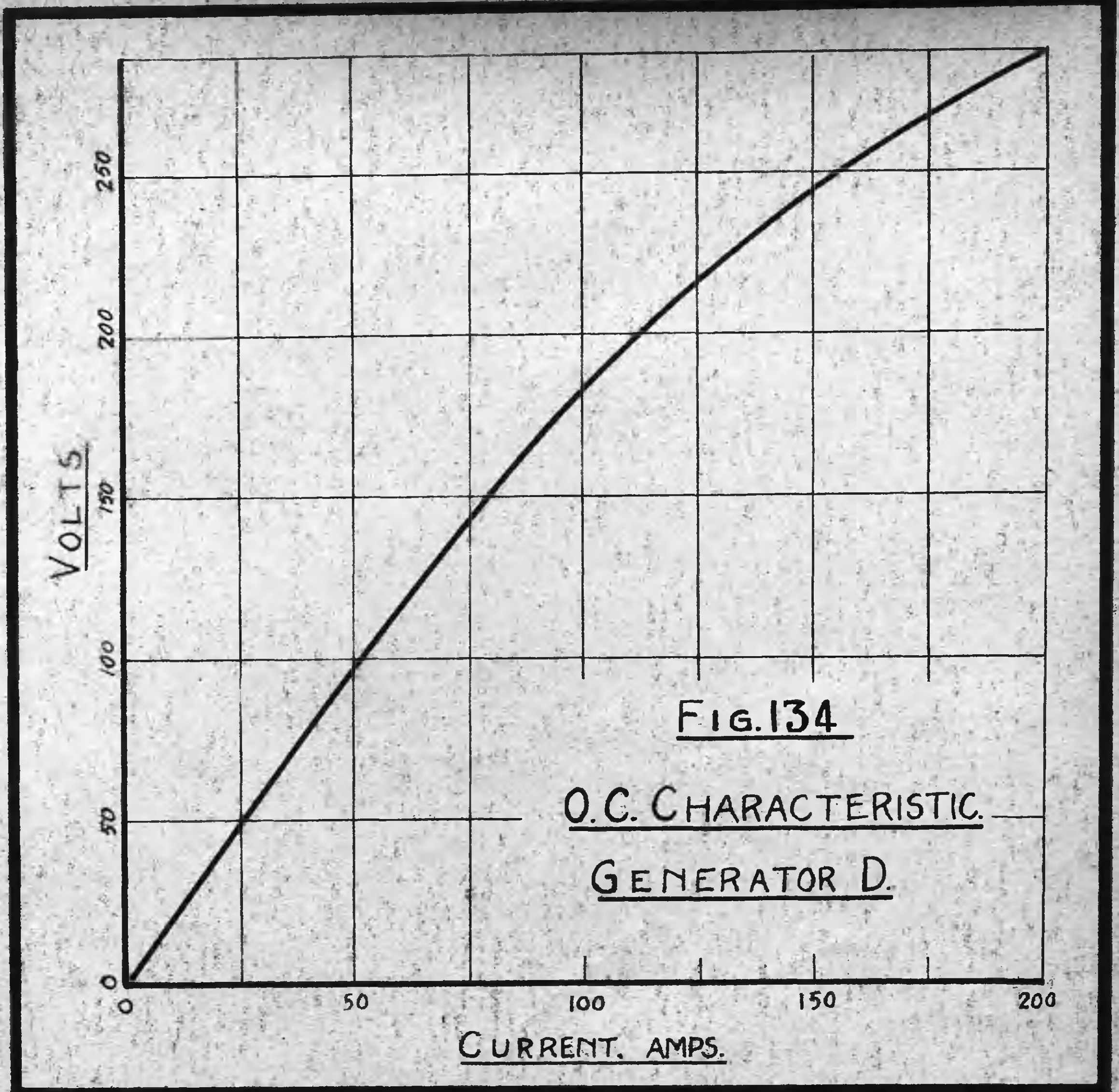


FIG. 134

O.C. CHARACTERISTIC.

GENERATOR D.

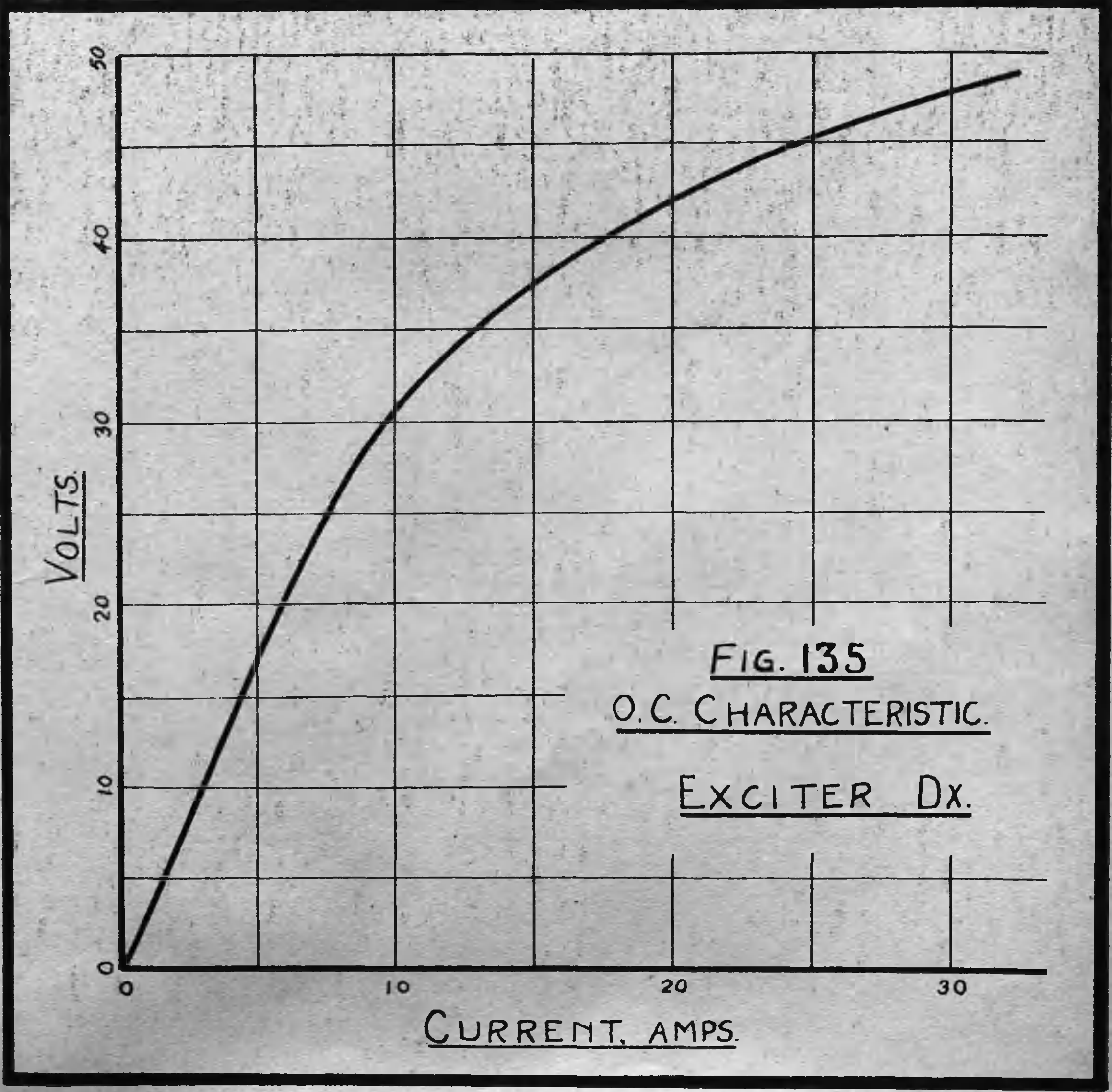


FIG. 135

O.C. CHARACTERISTIC.

EXCITER DX.

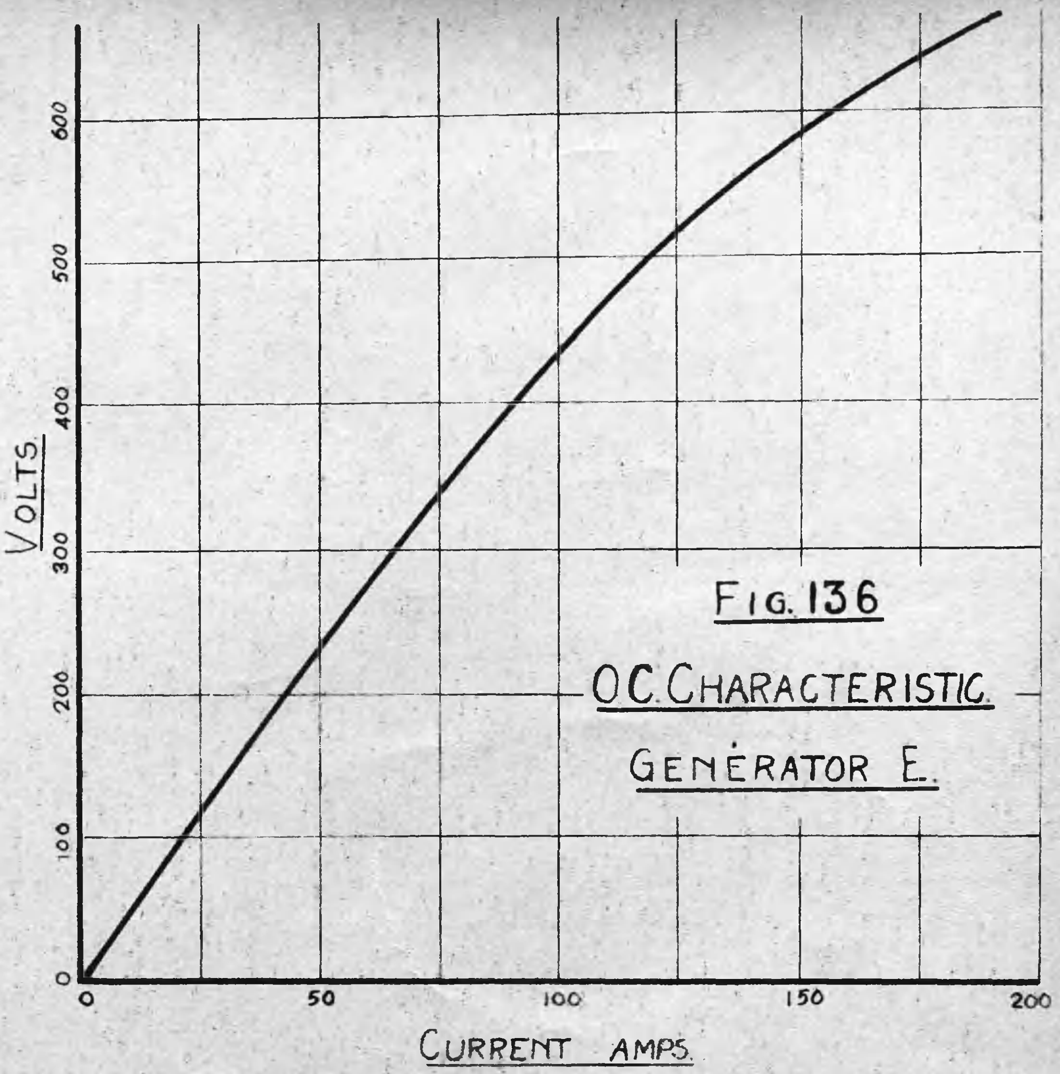


FIG. 136
O.C. CHARACTERISTIC.
GENERATOR E.

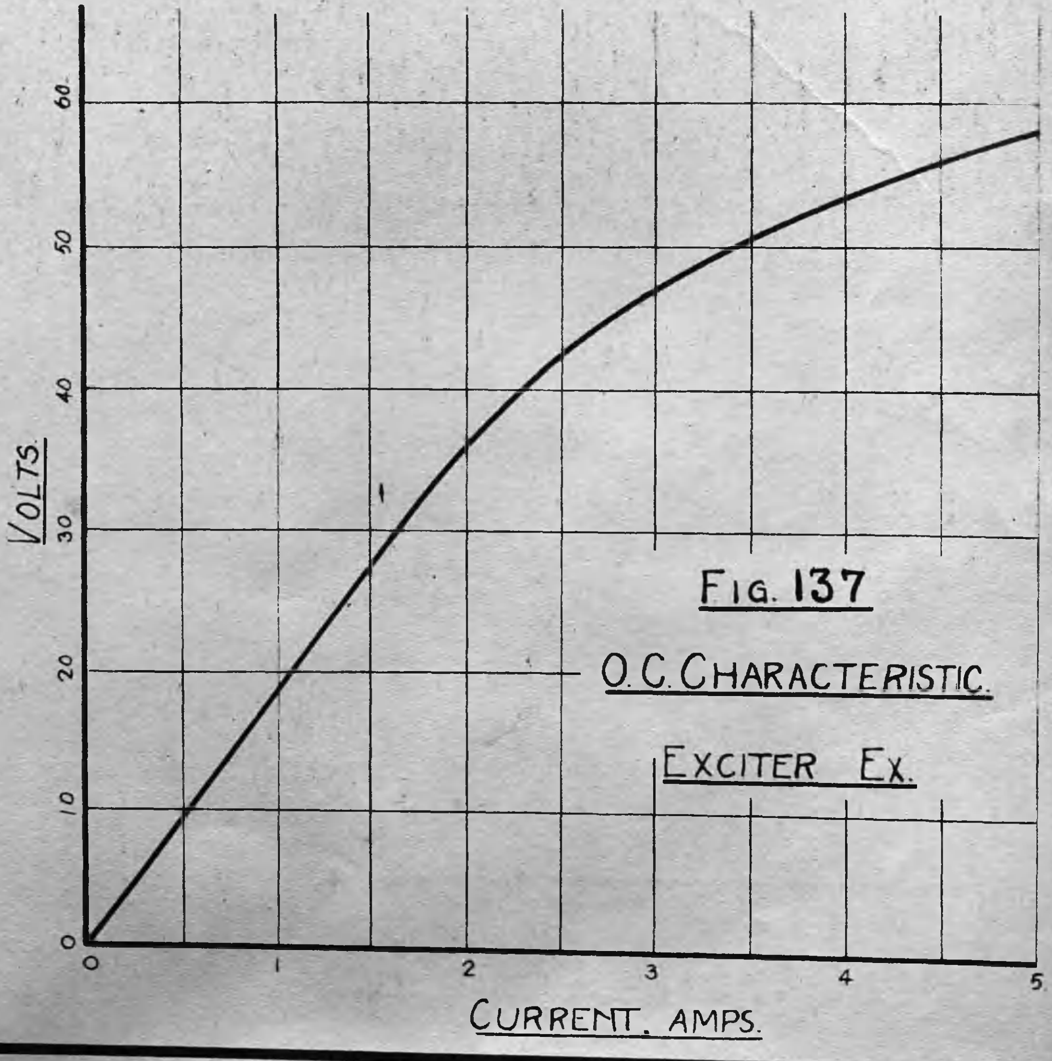
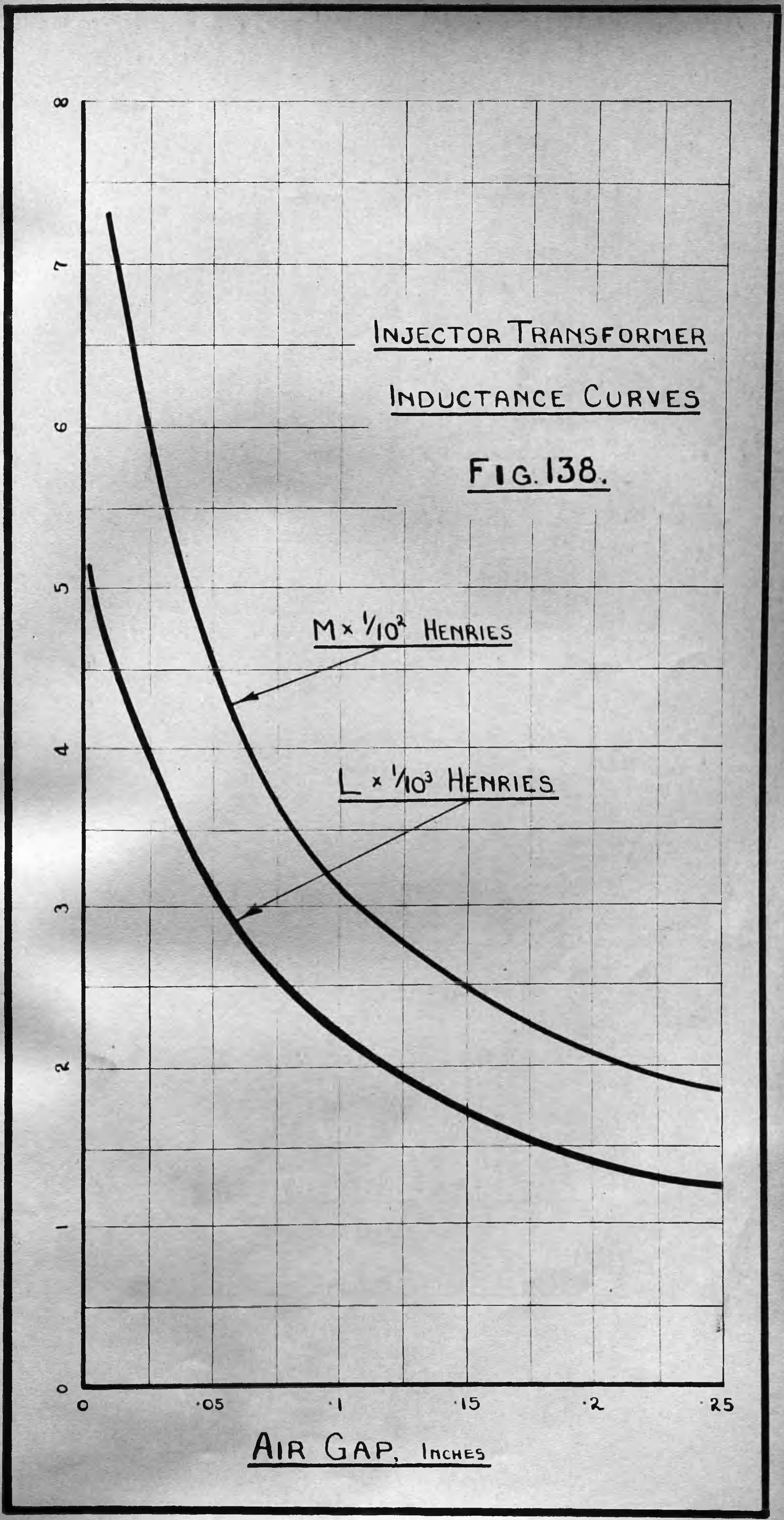
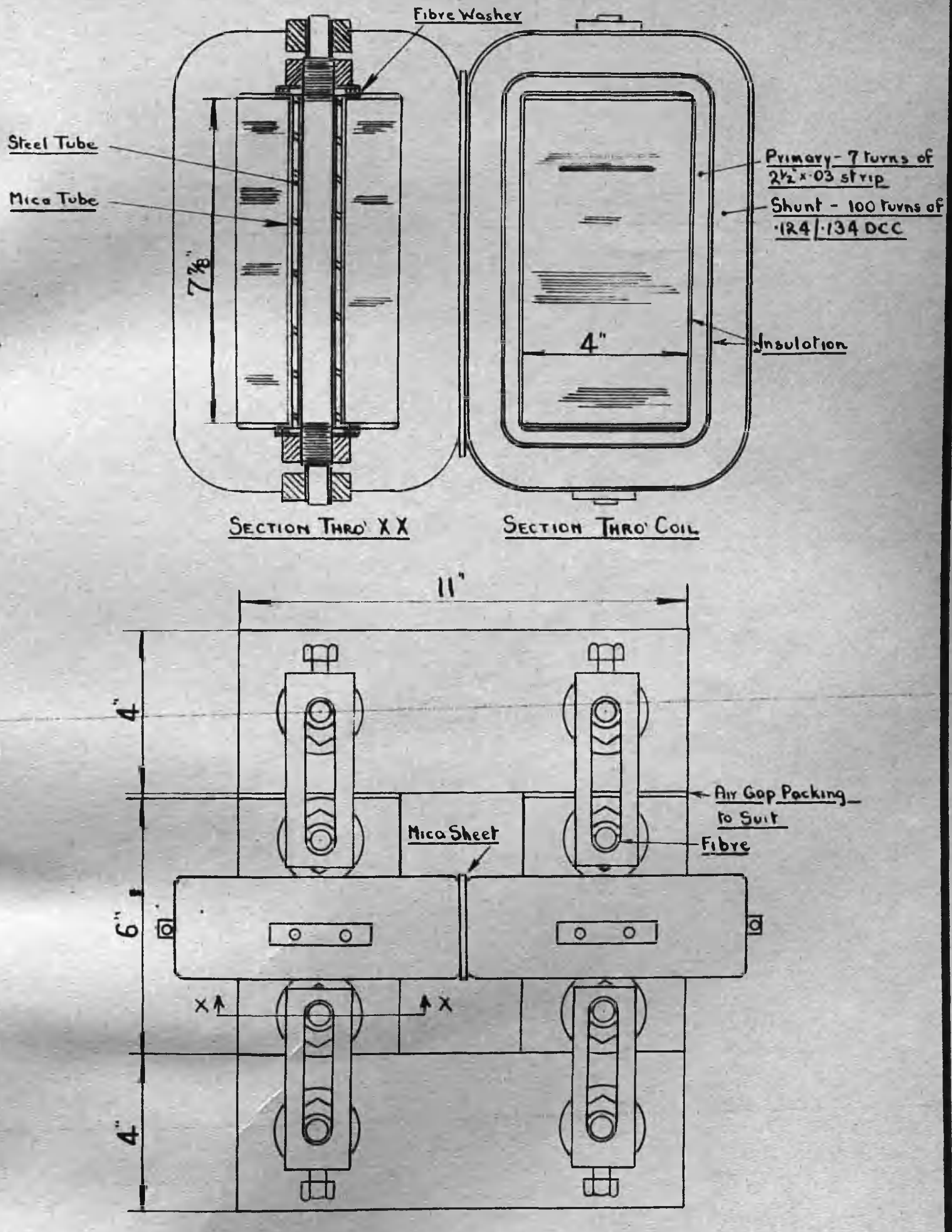


FIG. 137
O.C. CHARACTERISTIC.
EXCITER EX.



Injector Transformer Inductance Curves

Fig. 138.



General Arrangement of Injection Transformer

Fig. 139

LIST OF TABLE 1. MACHINES

Reference Letter	Generator.							
	Power, Kw.	Speed, R.P.M.	Poles	Field System	Yoke	Notes	Purpose	Design Table No
A	9	3000	Distributed	Laminated	—	Compensating Winding	Welding	32
B	6	1500	"	"	—	" "	"	"
C	6	1200	Salient	"	Laminated	No Compensating Winding No Interpoles	"	"
D	70	1500	Distributed	"	—	Compensating Winding Separate Excitation	Const. Current	34
D_{ex}	—	1500	"	"	—	Compensating Winding.	Exciter for D	"
E	160	1000	"	"	—	" "	Const. Current	"
E_{ex}	—	1000	Salient	—	Solid	Interpoles	Exciter for E.	"
F	320	1000	"	—	"	No Compensating Winding Interpoles	Const. Current	"
F_{ex}	—	1000	"	—	Solid	Interpoles.	Exciter for F.	"
G	6	1500	"	—	"	Cumulative Compound with Interpoles	Welding	—
H	6	1500	"	—	"	Differential Compound with Interpoles	"	—
T	—	—	—	Laminated	—	Injection Transformer with Variable Air Gap.	—	Figure 139

1st. Series — **TABLE - 2** — 2 - 9 - 36

Brushes Forward

Load Resistance .075 ohms

Record Shows ---- Current	Record No.	Switching From	Switching To	Main O.C. Volts	Main S.C. Volts	Main S.C. Amps	Main Load Volts	Main Load Amps	Shunt O.C. Volts	Shunt O.C. Amps	Shunt S.C. Volts	Shunt S.C. Amps	Shunt Load Volts	Shunt Load Amps	Supply 50~ 3ph. O.C. Volts	Supply O.C. Amps/ph	Supply S.C. Volts	Supply S.C. Amps/ph	Supply Load Volts	Supply Load Amps/ph	Gen^R Speed R.P.M. O.C.	Gen^R Speed S.C.	Gen^R Speed Load	Spiral Res^ce Value, Ω	Notes
Main.	1/A/0/1 2/A/0/1	O.C. S.C.	S.C. O.C.	66	2	405	–	–	15·8	15·5	–	–	–	–	500	3	440	15	–	–	3,080	2,972	–	–	Fig. 33 –
Main.	3/A/0/1 4/A/0/1	O.C. L	L O.C.	65	–	–	25	315	15·8	15·5	–	–	–	–	500	3	–	–	440	22·5	3,080	–	2,842	–	
Main.	5/A/0/1 6/A/0/1	L S.C.	S.C. L	–	2·5	405	25	315	–	–	–	–	–	–	–	–	440	15	440	22·5	–	2,972	2842	–	Fig. 37 –
Shunt.	7/A/2/2 8/A/2/2	O.C. S.C.	S.C. O.C.	66	2·5	405	–	–	15·8	16	15·8	16	–	–	500	3	440	16	–	–	3,040	2,900	–	–	Fig. 34 –
Shunt.	9/A/2/2 10/A/2/2	O.C. L	L O.C.	66	–	–	25	315	15·8	16	–	–	15·8	16	500	3	–	–	440	24	3,040	–	2,820	–	
Shunt.	11/A/2/2 12/A/2/2	L S.C.	S.C. L	–	2·5	405	25	315	–	–	15·8	16	15·8	16	–	–	440	16	440	24	–	2,900	2,820	–	Fig. 38 –
Welding	13/A/0/3 14/A/0/3	Welding.		–	–	–	28	285	–	–	–	–	15·8	16	–	–	–	–	440	20	–	–	–	–	Murex 1/4" Rod.
Welding	15/A/0/3 16/A/0/3	Welding.		–	–	–	34	270	–	–	–	–	15·8	16	–	–	–	–	440	20	–	–	–	–	Lincoln. 1/4" Rod.

2nd. Series

Table - 3

9 - 9 - 36

Brushes ... Neutral ...
Load Resistance ·075 ohms

Record Shows ... Current	Record No.	Switching From	Switching To	Main O.C. Volts	Main S.C. Volts	Main S.C. Amps	Main Load Volts	Main Load Amps	Shunt O.C. Volts	Shunt O.C. Amps	Shunt S.C. Volts	Shunt S.C. Amps	Shunt Load Volts	Shunt Load Amps	Supply 50~ 3ph. O.C. Volts	Supply O.C. Amps/ph	Supply S.C. Volts	Supply S.C. Amps/ph	Supply Load Volts	Supply Load Amps/ph	Genr. Speed r.p.m. O.C.	Genr. Speed S.C.	Genr. Speed Load	Spiral Res. & Value, Ω	Notes
Main.	17/A/0/1	O.C.	S.C.	65	2·5	435	–	–	13·6	15·2	5·2	6	–	–	500	4	440	27	–	–	3,120	2,790	–	–	
	18/A/0/1	S.C.	O.C.																						
	19/A/0/1	O.C.	L	66	–	–	26	320	13·6	15·2	–	–	7·2	8·4	500	4	–	–	440	30	3,120	–	2,784	–	
	20/A/0/1	L	O.C.																						
	21/A/0/1	L	S.C.	–	2·5	435	26	320	–	–	5·2	6	7·2	8·4	–	–	440	27	440	30	–	2,790	2,784	–	
	22/A/0/1	S.C.	L																						
Shunt.	23/A/2/2	O.C.	S.C.	65	2·5	425	–	–	15	15	5·2	6	–	–	500	4	440	27	–	–	3,120	2,790	–	–	
	24/A/2/2	S.C.	O.C.																						
	25/A/2/2	O.C.	L	65	–	–	24·5	310	15	15	–	–	7·6	8	500	4	–	–	440	28	3,120	–	2,784	–	
	26/A/2/2	L	O.C.																						
	27/A/2/2	L	S.C.	–	2·5	425	24·5	310	–	–	5·2	6	7·6	8	–	–	440	27	440	28	–	2,790	2,784	–	
	28/A/2/2	S.C.	L																						
Welding	29/A/0/3	Welding.		66	–	–	32	275	15	15	–	–	7·2	8·5	500	4	–	–	440	26	3,120	–	2,780	–	5/16" Lincoln Rod.
	30/A/0/3	Welding.		65	–	–	26	305	15	15	–	–	7·2	8·5	500	4	–	–	440	26	3,120	–	2,780	–	1/4" Murex Rod.

3RD. SERIES

TABLE 4

11-9-36

BRUSHES BACK.

LOAD RESISTANCE .075 OHMS

Record Shows Current	Record No.	Switching From	Switching To	Main O.C. Volts	Main S.C. Volts	Main S.C. Amps	Main Load Volts	Main Load Amps	Shunt O.C. Volts	Shunt O.C. Amps	Shunt S.C. Volts	Shunt S.C. Amps	Shunt Load Volts	Shunt Load Amps	Supply 50~ 3Ph. O.C. Volts	Supply O.C. Amps/ph	Supply S.C. Volts	Supply S.C. Amps/ph	Supply Load Volts	Supply Load Amps/ph	Gen. Speed R.P.M. O.C.	Gen. Speed S.C.	Gen. Speed Load	Spiral Res. Value, Ω	Notes
Main.	31/A/0/1	O.C.	S.C.	47	3	470	–	–	13·9	15	1	1·5	–	–	500	5	440	50	–	–	3,165	2,400	–	·0344	
	32/A/0/1	S.C.	O.C.																						
	33/A/0/1	O.C.	L.	45	–	–	25	315	13·8	14·5	–	–	5·4	6	500	5	–	–	440	34	3,165	–	2,752		
	34/A/0/1	L.	O.C.																						
	35/A/0/1	L.	S.C.	45	3	470	25	315	–	–	1	1·5	5·4	6	–	–	440	50	440	34	–	2,400	2,752		
	36/A/0/1	S.C.	L.																						
Shunt.	37/A/2/2	O.C.	S.C.	56	2·5	475	–	–	13·8	14·3	1	1	–	–	500	5	440	50	–	–	3,165	2,400	–	·0344	
	38/A/2/2	S.C.	O.C.																						
	39/A/2/2	O.C.	L.	59	–	–	26	320	13·8	14	–	–	5	5·4	500	5	–	–	440	34	3,165	–	2,752		
	40/A/2/2	L.	O.C.																						
	41/A/2/2	L.	S.C.	–	2·5	475	26	320	–	–	1	1	5	5·4	–	–	440	50	440	34	–	2,400	2,752		
	42/A/2/2	S.C.	L.																						
Welding	43/A/0/3	Welding		50	–	–	28	275	13·4	15	–	–	7	6	500	4	–	–	440	30	3,100	–	2,850	–	Ironex 3/16" Rod
	44/A/0/3	Welding		50	–	–	32	250	13·4	15	–	–	8	6	500	4	–	–	440	30	3,100	–	2,850	–	Lincoln 1/4" Rod

4th. SERIES

TABLE 5

18 - 9 - 36

BRUSHES.... BACK

LOAD RESISTANCE .075 OHMS

Record Shows ... Current	Record No.	Switching From	Switching To	Main O.C. Volts	Main S.C. Volts	Main S.C. Amps	Main Load Volts	Main Load Amps	Shunt O.C. Volts	Shunt O.C. Amps	Shunt S.C. Volts	Shunt S.C. Amps	Shunt Load Volts	Shunt Load Amps	Supply 50~ 3PH. O.C. Volts	Supply O.C. Amps/ph	Supply S.C. Volts	Supply S.C. Amps/ph	Supply Load Volts	Supply Load Amps/ph	Genr Speed R.P.M. O.C.	Genr Speed S.C.	Genr Speed Load	Spiral Resce Value, Ω	Notes
MAIN.	45/A/0/1	O.C.	S.C.	44	2·5	370	–	–	14·6	16	1·2	1	–	–	490	4	440	36	–	–	3,154	2,740	–	·052	
	46/A/0/1	S.C.	O.C.																						
	47/A/0/1	O.C.	L	43	–	–	20	260	14·6	16	–	–	5·2	6	480	4	–	–	440	24	3,154	–	2,800	·052	
	48/A/0/1	L	O.C.																						
	49/A/0/1	L	S.C.	–	2·5	370	20	260	–	–	1·2	1	5·2	6	–	–	440	36	440	24	–	2,740	2,800	·052	
	50/A/0/1	S.C.	L																						
SHUNT.	51/A/2/2	O.C.	S.C.	41	2·5	400	–	–	14·4	15·5	1·4	2	–	–	490	5	440	50	–	–	3,100	2,792	–	·052	
	52/A/2/2	S.C.	O.C.																						
	53/A/2/2	O.C.	L	47	–	–	20	265	14·4	15·3	–	–	5	5·5	490	5	–	–	440	13	3,100	–	2,746	·052	
	54/A/2/2	L	O.C.																						
	55/A/2/2	L	S.C.	–	2·5	400	20	265	–	–	1·4	2	5	5·5	–	–	440	50	440	13	–	2,792	2,746	·052	
	56/A/2/2	S.C.	L																						
WELDING	57/A/0/1 58/A/0/1	WELDING		50	–	–	30	200	14·5	15·5	–	–	7	7	480	5	–	–	440	23	3,100	–	2,960	·052	46 Ironex Rods.

NOTE:- 59 TO 62/A/2/2 DELAYED SET TO VERIFY STEADINESS OF CURRENT AFTER 6 SECONDS - NOT REPRODUCED

5th. Series — TABLE - 6 — 24-9-36

Brushes Neutral
Load Resistance .075 Ohms

Record Shows Current	Record Nº	Switching From	Switching To	Main O.C. Volts	Main S.C. Volts	Main S.C. Amps	Main Load Volts	Main Load Amps	Shunt O.C. Volts	Shunt O.C. Amps	Shunt S.C. Volts	Shunt S.C. Amps	Shunt Load Volts	Shunt Load Amps	Supply 50~ 3PH. O.C. Volts	Supply O.C. Amps/ph	Supply S.C. Volts	Supply S.C. Amps/ph	Supply Load Volts	Supply Load Amps/ph	Gen.R Speed R.P.M. O.C.	Gen.R Speed S.C.	Gen.R Speed Load	Spiral Res.ce Value, Ω	Notes
Main.	63/A/0/1	O.C.	S.C.	62	3	510	–	–	14·8	15·5	5·6	5·2	–	–	500	5·5	440	47	–	–	3,104	2,532	–	·026	Fig. 35. –
	64/A/0/1	S.C.	O.C.																						
	65/A/0/1	O.C	L	63	–	–	27·5	340	14·8	15·5	–	–	8	8·5	500	5·5	–	–	440	38	3,104	–	2,670	·026	
	66/A/0/1	L	O.C.																						
	67/A/0/1	S.C.	L	–	3	510	28	345	–	–	5·6	5·2	8	8·5	–	–	440	47	440	38	–	2,532	2,670	·026	Fig. 39. –
	68/A/0/1	L	S.C.																						
Shunt.	69/A/2/2	O.C.	S.C.	64	3·5	520	–	–	14·8	16·2	4·8	5·5	–	–	500	6	440	45	–	–	3,125	2,632	–	·026	Fig. 36. –
	70/A/2/2	S.C.	O.C.																						
	71/A/2/2	O.C.	L	65	–	–	27·5	340	15·2	16·5	–	–	8·4	9·5	490	5	–	–	440	39	3,125	–	2,640	·026	
	72/A/2/2	L	O.C.																						
	73/A/2/2	S.C.	L	–	3·5	520	27·5	340	–	–	4·8	5·5	8·4	9·5	–	–	440	45	440	39	–	2,632	2,640	·026	Fig. 40. –
	74/A/2/2	L	S.C.																						
Welding	75/A/A/2		DOUBLE SWITCHING TEST – NOT EVENTUALLY USED.																						
	77/A/0/1 78/A/0/1	Welding		63	–	–	30	300	15	15·5	–	–	9	10	480	4	–	–	440	38	3,100	–	2,652	·026	

TABLE 7. LIST OF INSTRUMENTS.

PURPOSE.	LAB. Nº	TYPE.	NOTES.
Main Current and Voltage.	V.A.1.	Moving Coil	Multi - Range, Precision, 0 - 600 V., 0 - 750 A.
A.C. Supply Voltage.	V50	" Iron.	Correction Required.
Arc Current (Proj.ⁿ Lantern.)	A47	" Coil	
Oscillograph Field Current.	A40	" "	Accurate.
Shunt Voltage.	V29	" "	"
Shunt Current.	A38	" "	} Used in series to provide a drop to excite
Shunt Current.	A46	" "	} current ribbon of Duddell oscillograph.
Generator Terminal Voltage.	V55	" "	To determine polarity only.
Spiral Resistance Voltage.	V27	" "	Low Reading. Accurate.
Current Ribbon Control.	RB1	Standard Box.	Steps of 1, 2, 2, 5, 10, 20, 20, 50, ohms.
Timing Wave Control.	R25	Wire Slider.	1,000 ohms, ·3 amps.
Arc Resistance.	R33	Ventilated Coil	200 ohms, 20 amps.
Alternator Field Control.	R34	" "	" "
Field Discharge Resistance.	–	125 Volt Lamp.	
Inductance Tests.	A62	Induction.	Wide Scale, Accurate.

Table 8.

Switching. Tests.

Reference Number	Record from	Switching	O.C. Volts	S.C. Volts	S.C. Amps	Load Volts	Load Amps	Transformer Air Gap	Transformer Coils	Brushes	Field Current Amps S.C.	Field Current Amps Load	Notes	Fig. No.
82/B/0/4	Main	O.C.-S.C.-O.C.	66	3	330	–	–	–	–		–	–		62
83/B/0/4	"	L.-S.C.-L.	"	"	"	29	210	–	–		–	–	200 Amp Terminal.	–
84/B/0/4	"	O.C.-S.C.-L.	"	"	"	"	"	–	–		–	–		–
85/G/0/4	"	O.C.-S.C.-O.C.	70·5	"	325	–	–	–	–		–	–		63
86/G/0/4	"	L-S.C.-L.	71	"	315	26	195	–	–		–	–	Regulator All Out.	–
87/G/0/4	"	O.C.-S.C.-L.	"	"	"	"	"	–	–		–	–		–
88/G/0/4	"	O.C.-S.C.-O.C.	72·5	1·5	165	–	–	–	–		–	–	100 Amp. Terminal.	67
89/G/0/4	"	O.C.-S.C.-O.C.	"	"	"	22	125	–	–		–	–	Regulator All Out.	–
90/G/0/4	"	O.C.-S.C.-L.	50	3	288	24	92·5	–	–		–	–	200 Amp. Terminal & Shunt Control.	–
91/H/0/4	"	O.C.-S.C.-O.C.	73	"	295	–	–	–	–		–	–	200 Amp. Terminal.	64
92/H/0/4	"	L-S.C.-L.	"	"	"	27	200	–	–		–	–	Regulator All Out.	–
93/H/0/4	"	O.C.-S.C.-L.	"	"	"	"	"	–	–		–	–		–
94/H/0/4	"	"	47·5	2	197	24	92·5	–	–		–	–	Shunt Control Only.	–
95/B/0/4	"	"	65	1	125	24	95	–	–		–	–	200 Amp. Terminal.	–
96/B/0/4	"	O.C.-S.C.-O.C.	"	"	"	–	–	–	–		–	–	Regulator In.	–

TABLE 9.

SWITCHING TESTS.

Reference Number.	Record from.	Switching.	O.C.	S.C.		Load.		Transformer.		Brushes.	Field Current. Amps.		Notes.	Fig. No.
			Volts.	Volts.	Amps.	Volts.	Amps.	Air Gap.	Coils.		S.C.	Load.		
97/G/0/4	Main.	O.C.-S.C.-O.C.	63	1·2	125	24	93	—	—	—	—	—	100 Amp. Terminal. Reg.r All Out.	—
98/G/0/4	"	"	49	3	285	24	92	—	—	—	—	—	200 " " " In.	66
99/B/0/5	"	"	"	2·5	182	25·5	98	1/8"	Series.	—	—	—		65
100/B/0/4	"	"	48	2	195	24·5	95	—	—	Back.	—	—	200 Amp. Terminal. Reg.r In.	—
101/H/0/4	"	"	"	"	"	"	"	—	—	—	—	—	Do. Do.	—
102/H/0/4	"	"	68	1·3	145	24	93	—	—	—	—	—	Shunt and Divertor Control.	—
108/D/0/4	"	L.-S.C.-L.	—	2·4	247	34	247	—	—	1/4" F.	46·3	62		—
109/D/0/4	"	"	—	"	"	63·5	"	—	—	1/4" F.	"	80		—
110/D/0/4	"	"	—	"	245	126	244	—	—	"	"	118		73
111/D/0/4	"	"	—	2·3	"	63	245	—	—	1/8" F.	31	66·3		76
112/D/0/8	"	S.C.-L.-S.C.	—	2·4	"	127·5	"	1/4"	Series.	N.	20	92		—
113/D/0/8	"	"	—	"	"	126	"	1/8"	"	"	"	"		79
114/D/0/8	"	"	—	"	"	"	"	·06"	"	"	"	"		—
115/D/0/8	"	"	—	"	"	"	"	0	"	"	"	"		—
116/D/0/8	"	"	—	"	247	121	230	0	"	1/4" B.	-14	53		—

Switching — Table 10. — Tests.

Reference Number.	Record from.	Switching	O.C.	S.C.		Load.		Transformer.		Brushes	Field Current Amps		Notes.	Fig. No.
			Volts.	Volts.	Amps.	Volts.	Amps.	Air Gap.	Coils.		S.C.	Load		
117/D/0/8	Main.	SC.- L - S.C.	–	2·4	247	121	230	·06"	Series.	¼" B	−14	53		–
118/D/0/8	"	"	–	"	"	"	"	⅛"	"	"	"	"		–
119/D/0/8	"	"	–	"	"	"	"	¼"	"	"	"	"		82
120/D/1/9	Abutment.	"	–	"	"	"	"	"	"	"	"	"	Abutment = 7·5 volts, 16·6 Amps.	83
121/D/1/9	"	"	–	"	"	"	"	⅛"	"	N	14	84	" = 8·45 " , 19 "	80
122/D/1/10	"	"	–	"	"	"	245	–	–	⅛" F	32	100	" = 8·8 " , 19·5 "	77
123/D/1/10	"	"	–	"	250	"	250	–	–	¼" F	47	119	" = 8·7 " , 19·2 "	74
124/D/2/11	Field	"	–	"	"	128	249	–	–	"	48	117		75
125/D/2/11	"	"	–	"	"	"	"	–	–	⅛" F	20·5	87		78
126/D/2/12	"	"	–	"	"	124	240	⅛"	Series.	N	12·5	77·5		81
127/D/2/12	"	"	–	"	"	"	"	"	"	¼" B	−15	51		–
128/D/2/12	"	"	=	"	"	"	"	¼"	"	"	"	"		84
129/D/0/8	Main.	"	–	"	"	248	245	⅛"	"	N	16	195		85

OSCILLATION TABLE 11. RECORDS.

Reference Number	Record from	On	Transformer Airgap	Transformer Coils	Brushes	Load Rest Ohms	Scales Record Nº	Scales Volts per Inch	Scales Amp's per Inch	Exciter Volts	Notes	Fig. Nº
78/A/0/3	Main	S.C.	See	Notes	Back	—	—	55	500	—	Temporary Transformer Used	29
79/A/0/3	"	"	"	"	"	—	—	"	"	—	These Records are merely shown as examples	30
80/A/0/3	"	"	"	"	"	—	—	"	"	—	of the original Duddell Oscillograh.	31
82/B/0/4	"	"	"	"	"	—	—	"	"	—		62
103/B/0/6	"		1/8"	Series	—	·135	—	—	—	3·35	Extra Resistance in Field = ·144 Ohms.	68
104/B/0/6	"		"	"	—	"	—	—	—	"	" " " " = ·144 Ohms	72
105/B/0/6	"	"	"	"	—	"	—	—	—	1·95	" " " " = 1·03 Ohms	69
106/B/0/6	"	L	"	"	—	·256	—	—	—	11·55	" " " " = 1·02 Ohms	70
107/B/0/7	"	"	1/4"	1 Only	—	·1574	—	—	—	—	" " " " = 1·4 Ohms.	71
130/C/2/14	Shunt	"	0	Series	Approx N.	·068	134/C/2	290	11·7	—		—
131/C/2/14	"	S.C.	"	"	"	0	"	"	"	—		—
132/C/2/14	"	L	·01	"	"	·068	"	"	"	—		89
133/C/2/14	"	S.C.	"	"	"	0	"	"	"	—		86
134/C/2	Scale	—	—	—	—	—	—	"	"	—	Scale Record on D.C. for 130 to 133.	—
135/C/0/13	Main	L	0	Series	Approx N	·068	139/C/0	100	1310	—		—

Oscillation Table 12. Records.

Reference Number	Record from	On	Transformer		Brushes	Load	Scales			Exciter	Notes	Fig.
			Aircap	Coils		Rest^ce Ohms.	Record No	Volts per Inch	Amps per Inch	Volts.		No.
136/c/0/13	Main	S.C.	0	Series	Approx N	0	139/c/0	100	1310	—		—
137/c/0/13	"	L.	·01"	"	"	·068	"	"	"	—		88
138/c/0/13	"	S.C.	"	"	"	0	"	"	"	—		87
139/c/0.	Scale	—	—	—	—	—	"	"	"	—	Scale on D.C. for 135–142	—
140/c/0/15	Main	L	0	Series	Approx N	·068	"	"	"	—		—
141/c/0/15	"	L	·01"	"	"	"	"	"	"	—		90
142/c/0/15	"	S.C	"	"	"	0	"	"	"	—		92
143/c/2/16	Shunt	L	"	"	"	·068	147/6/2	231	11·9	—		91
144/c/2/16	"	S.C	"	"	"	0	"	"	"	—		93
145/c/2/16	"	L	0	"	"	·068	"	"	"	—		—
146/c/2/16	"	S.C.	0	"	"	0	"	"	"	—		—
147/c/2	Scale	—	—	—	—	—	"	"	"	—	Scale on D.C. for 143 to 146	—
148/A/0/13	Main	S.C.	1/4"	Series	1/4" Back	·012	183/A/0	120	1870	—	Rec^B Partly In.	—
149/A/0/13	"	"	1/8"	"	"	"	"	"	"	—	" " "	94
150/A/0/13	"	L	"	"	N	·08	"	"	"	—	" " "	—

OSCILLATION TABLE 13. RECORDS.

Reference Number	Record from	On	Transformer Airgap	Transformer Coils	Brushes	Load Res^ce Ohms	Scales Record No.	Scales Volts per Inch	Scales Amps per Inch	Exciter Volts	Notes	Fig. No.
151/A/0/13	Main	L	1/8"	Series	N	·08	183/A/0	120	1870	—	Load Resistance includes part of Reg^R	96
152/A/0/13	"	S.C.	"	"	"	·012	"	"	"	—	Reg^R Partly In.	—
153/A/0/13	"	"	1/4"	"	"	"	"	"	"	—	" " "	98
154/A/0/13	"	L	"	"	1/4" Back	·068	"	"	"	—	Reg^R All Out.	100
155/A/0/13	"	"	1/8"	"	"	"	"	"	"	—	" " "	—
156/A/2/14	Shunt	"	"	"	"	"	181/A/2	750	62	—	" " "	—
157/A/2/14	"	"	"	"	"	·08	"	"	"	—	Reg^R Partly In.	—
158/A/2/14	"	S.C.	"	"	"	·028	"	"	"	—	" " "	95
159/A/2/14	"	L	1/4"	"	"	·08	"	"	"	—	" " "	101
160/A/2/14	"	S.C.	"	"	"	·028	182/A/2	750	178	—	" " "	—
161/A/2/14	"	L	"	"	N	·08	181/A/2	750	62	—	" " "	—
162/A/2/14	"	S C	"	"	"	·028	182/A/2	750	178	—	" " "	99
163/A/2/14	"	L	1/8"	"	"	·08	181/A/2	750	62	—	" " "	97
164/A/2/14	"	S.C.	"	"	"	·028	182/A/2	750	178	—	" " "	—
165/A/0/13	Main	L	1/4"	"	"	·08	183/A/0	120	1870	—	" " "	—

Oscillation. Table 14. Records.

Reference Number	Record from	On	Transformer Aircap	Transformer Coils	Brushes	Load Res^ce Ohms	Scales Record No	Scales Volts per inch	Scales Amp's per inch	Exciter Volts	Notes	Fig. No
166/A/0/15	Main	S.C.	1/4"	Series	N	·028	183/A/0	120	1870	—	Reg^r Partly In.	102
167/A/0/15	"	"	1/8"	"	"	"	"	"	"	—	Reg^r Partly In	—
168/A/0/15	"	L	"	"	"	·08	"	"	"	—	" " "	104
169/A/0/15	"	"	"	"	1/4" Back	"	"	"	"	—	" " "	106
170/A/0/15	"	S.C.	"	"	"	·028	"	"	"	—	" " "	—
171/A/0/15	"	L	1/4"	"	"	·08	"	"	"	—	" " "	108
172/A/0/15	"	S.C	"	"	"	·028	"	"	"	—	" " "	—
173/A/2/16	Shunt	L	"	"	"	·08	181/A/2	750	62	—	" " "	109
174/A/2/16	"	S.C.	"	"	"	·028	"	"	"	—	" " "	—
175/A/2/16	"	L	1/8"	"	"	·08	"	"	"	—	" " "	107
176/A/2/16	"	S.C.	"	"	"	·028	"	"	"	—	" " "	—
177/A/2/16	"	L	"	"	N	·08	"	"	"	—	" " "	105
178/A/2/16	"	S.C.	"	"	"	·028	"	"	"	—	" " "	—
179/A/2/16	"	L	1/4"	"	"	·08	"	"	"	—	" " "	—
180/A/2/16	"	S.C.	"	"	"	·028	"	"	"	—	" " "	103

Oscillation. Table 15 Records.

Reference Number	Record from	On	Transformer Aircap	Transformer Coils	Brushes	Load Res^ce Ohms	Scales Record No.	Scales Volts per Inch	Scales Amps per Inch	Exciter Volts	Notes	Fig. No.
181/A/2	—	—	—	—	—	—	181/A/2	750	62	—	Scale Record (20 Amp Shunt.)	—
182/A/2	—	—	—	—	—	—	182/A/2	"	178	—	" " (60 " ")	—
183/A/0	—	—	—	—	—	—	183/A/0	120	1870	—	" " (600 " ")	—
184/A/0/15	Main	S.C.	1/8"	Series	N	·028	"	"	"	—	Rec^r Partly In – Narrow Brushes	—
185/A/0/15	"	"	1/4"	"	"	"	"	"	"	—	" " " " "	110
186/A/0/15	"	"	"	"	1/4" Back	"	"	"	"	—	" " " " "	—
187/A/0/15	"	"	1/8"	"	"	"	"	"	"	—	" " " " "	—
188/A/2/16	Shunt	"	"	"	"	"	181/A/2	750	62	—	" " " " "	—
189/A/2/16	"	"	1/4"	"	"	"	"	"	"	—	" " " " "	—
190/A/2/16	"	"	"	"	N	"	"	"	"	—	" " " " "	111
191/A/2/16	"	"	1/8"	"	"	"	"	"	"	—	" " " " "	—
192/A/2/14	"	"	"	"	"	"	"	"	"	—	" " " " "	—
193/A/2/14	"	"	1/4"	"	"	"	"	"	"	—	" " " " "	113
194/A/2/14	"	"	"	"	1/4" Back	"	"	"	"	—	" " " " "	—
195/A/2/14	"	"	1/8"	"	"	"	"	"	"	—	" " " " "	—

OSCILLATION. TABLE 16. RECORDS.

Reference Number.	Record from.	On.	Transformer. Air Gap.	Transformer. Coils.	Brushes.	Load. Resist^{ce} Ohms.	Scales. Record Nº	Scales. Volts per Inch	Scales. Amps. per Inch.	Exciter Volts.	Notes.	Fig. Nº
196/A/0/13	Main	S.C.	1/8"	Series.	1/4" Back	·028	183/A/0	120	1870	–	Reg^{r} Partly In Narrow Brushes	–
197/A/0/13	"	"	1/4"	"	"	"	"	"	"	–	Do. Do.	–
198/A/0/13	"	"	"	"	⊓	"	"	"	"	–	Do. Do.	112
199/A/0/13	"	"	1/8"	"	"	"	"	"	"	–	Do. Do.	–

TABLE 17.
CALCULATION TABLES.

$M = -7/10^4$	1 PERIOD		ANGLE 2π			TIME $1/f$ SECS			MAX VALUE
ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	
TIME	$1/76.5$	$1/38.2$	$1/25.5$	$1/19.1$	$1/15.3$	$1/12.8$	$1/11$	$1/9.55$	
$-at$	$87/76.5$	$87/38.2$	$87/25.5$	$87/19.1$	$87/15.3$	$87/12.8$	$87/11$	$87/9.55$	
e^{at}	$\frac{1}{3.13}$	$\frac{1}{9.73}$	$\frac{1}{30.7}$	$\frac{1}{96}$	$\frac{1}{295}$	$\frac{1}{903}$	$\frac{1}{2785}$	$\frac{1}{8900}$	
bt	$\frac{18.5}{76.5}$	$\frac{18.5}{38.2}$	$\frac{18.5}{25.5}$	$\frac{18.5}{19.1}$	$\frac{18.5}{15.3}$	$\frac{18.5}{12.8}$	$\frac{18.5}{11}$	$\frac{18.5}{9.55}$	
e^{bt}	1.27	1.62	2.07	2.63	3.35	4.24	5.35	6.9	
$\sin \omega t$	.707	1	.707	0	−.707	−1	−.707	0	
$\cos \omega t$	.707	0	−.707	−1	−.707	0	.707	1	
θ'	.32	.103	.033	.01	.0034	.0011	.00036	.00011	
θ''	.9	1.62	1.47	0	−2.37	−4.24	−3.8	0	
θ'''	.9	0	−1.47	−2.63	−2.37	0	+3.8	6.9	
$A\theta'$	−228	−73	−23	−7.1	−2.4	−.78	−.26	−.08	
$B\theta''$	1200	2160	1960	0	−3160	−5650	−5070	0	
$C\theta'''$	603	0	−984	−1770	−1590	0	2550	4630	
S	248.5	248.5	248.5	248.5	248.5	248.5	248.5	248.5	
i	1824	2436	1202	−1528	−4504	−5402	−2270	+4880	
$A_1\theta'$	−272	−88	−28	−8.5	−3	−.9	−.3	−.09	
$B_1\theta''$	960	1730	1570	0	−2530	−4520	−4050	0	
$C_1\theta'''$	765	0	−1250	−2240	−2017	0	3240	5870	
VS+W	250	250	250	250	250	250	250	250	
i_1	1700	1890	542	−2000	−4550	−4270	−560	6120	
$A_{11}\theta'$	9.2	3	.95	.3	.1	.03	.01	.003	
$B_{11}\theta''$	15.6	28	25.4	0	−41	−73	−66	0	
$C_{11}\theta'''$	73.5	0	−120	−215	−194	0	310	565	
$\frac{R}{K_2}S$	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	
i_2	121	53	−71	−192	−213	−51	266	587	

TABLE 18
CALCULATION TABLES

M = 0	1 PERIOD		ANGLE 2π			TIME 1/f SECS			MAX VALUE
ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	
TIME	$\frac{1}{176}$	$\frac{1}{88}$	$\frac{1}{58\cdot6}$	$\frac{1}{44}$	$\frac{1}{35\cdot2}$	$\frac{1}{29\cdot3}$	$\frac{1}{25\cdot1}$	$\frac{1}{22}$	
$-at$	0	0	0	0	0	0	0	0	
e^{at}	0	0	0	0	0	0	0	0	
bt	$-\frac{13\cdot9}{176}$	$-\frac{13\cdot9}{88}$	$-\frac{13\cdot9}{58\cdot6}$	$-\frac{13\cdot9}{44}$	$-\frac{13\cdot9}{35\cdot2}$	$-\frac{13\cdot9}{29\cdot3}$	$-\frac{13\cdot9}{25\cdot1}$	$-\frac{13\cdot9}{22}$	
e^{bt}	·925	·854	·786	·73	·675	·62	·574	·532	
$\sin \omega t$	·707	1	·707	0	−·707	−1	−·707	0	
$\cos \omega t$	·707	0	−·707	−1	−·707	0	·707	1	
θ_{I}	·655	·854	·557	0	−·478	−·62	−·406	0	
θ_{II}	·655	0	−·557	−·73	−·478	0	+·406	·532	
θ_{III}	0	0	0	0	0	0	0	0	
$A\theta_{I}$	694	904	590	0	−506	−656	−430	0	
$B\theta_{II}$	−26·6	0	22·6	29·6	19·4	0	−16·5	−21·6	
$C\theta_{III}$	0	0	0	0	0	0	0	0	
S	248·5	248·5	248·5	248·5	248·5	248·5	248·5	248·5	
i	916	1152	861	278	−238	−407	−199	227	
$A_{I}\theta_{I}$									
$B_{I}\theta_{II}$									
$C_{I}\theta_{III}$									
VS+W									
i_{1}									
$A_{II}\theta_{I}$	8·3	10·8	7·1	0	−6·1	−7·9	−5·15	0	
$B_{II}\theta_{II}$	83·3	0	−71	−92	−61	0	51·6	67·5	
$C_{II}\theta_{III}$	—	—	—	—	—	—	—	—	
VS	4·85	4·85	4·85	4·85	4·85	4·85	4·85	4·85	
i_{2}	96·5	16·6	−59	−87	−62·2	−3	51·3	72·5	

Table 19
Calculation Tables

$M = +\frac{7}{10^4}$	1 Period		Angle 2π			Time $1/f$ secs.			Max. Value
Angle	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	
Time	$\frac{1}{275}$	$\frac{1}{137}$	$\frac{1}{91}$	$\frac{1}{69}$	$\frac{1}{55}$	$\frac{1}{46}$	$\frac{1}{39}$	$\frac{1}{34.3}$	
$-at$	$\frac{7.2}{275}$	$\frac{7.2}{137}$	$\frac{7.2}{91}$	$\frac{7.2}{69}$	$\frac{7.2}{55}$	$\frac{7.2}{46}$	$\frac{7.2}{39}$	$\frac{7.2}{34.3}$	
e^{at}	1.025	1.05	1.08	1.11	1.14	1.17	1.2	1.23	
bt	$\frac{-21.4}{275}$	$\frac{-21.4}{137}$	$\frac{-21.4}{91}$	$\frac{-21.4}{69}$	$\frac{-21.4}{55}$	$\frac{-21.4}{46}$	$\frac{-21.4}{39}$	$\frac{-21.4}{34.3}$	
e^{bt}	·924	·853	·792	·734	·675	·628	·577	·534	
$\sin \omega t$	·707	1	·707	0	−·707	−1	−·707	0	
$\cos \omega t$	·707	0	−·707	−1	−·707	0	·707	1	
θ'	1·025	1·05	1·08	1·11	1·14	1·17	1·2	1·23	
θ''	·654	·853	·56	0	−·477	−·628	−·409	0	
θ'''	·654	0	−·56	−·734	−·477	0	+·409	·534	
$A\theta'$	3·18	3·26	3·35	3·44	3·53	3·66	3·72	3·82	
$B\theta''$	466	610	400	0	−340	−448	−292	0	
$C\theta'''$	−28·5	0	+24·4	+32	+20·8	0	$\bar{1}7·8$	$\bar{2}3·3$	
S	248·5	248·5	248·5	248·5	248·5	248·5	248·5	248·5	
i	669	862	676	284	−67	−196	−58	229	
$A_1\theta'$	3·18	3·26	3·35	3·44	3·53	3·66	3·72	3·82	
$B_1\theta''$	$\bar{4}65$	$\bar{6}08$	$\bar{4}00$	0	340	447	290	0	
$C_1\theta'''$	$\bar{2}·03$	0	1·74	2·28	1·48	0	$\bar{1}·27$	$\bar{1}·65$	
$VS+W$	250	250	250	250	250	250	250	250	
i_1	−214	−355	−145	255	595	701	542	252	
$A_{11}\theta'$	·039	·04	·041	·042	·043	·044	·045	·047	
$B_{11}\theta''$	7·35	9·6	6·3	0	$\bar{5}·36$	$\bar{7}·05$	$\bar{4}·6$	0	
$C_{11}\theta'''$	72	0	$\bar{6}1·5$	$\bar{8}0·7$	$\bar{5}2·5$	0	45	58·8	
$\frac{R}{K_2}S$	22·3	22·3	22·3	22·3	22·3	22·3	22·3	22·3	
i_2	102	32	−33	−58	−35	15·3	63	81	

Details from Table 20 the Records

Figure No.	Reference No.	Transformer Air Gap	Brush Position.	Load Resistance	Total Resistance, ohms		Scale		Max^m Amplitude.	
					Load Circuit, R	Field, R_2	Volts/inch.	Amps/inch.	Volts.	Amps.
94	149/A/0/13	1/8"	1/4" B	·022	·057	1·45	110	1870	13·5	660
95	158/A/2/15	1/8"	1/4" B	·038	·073	1·45	750	62	260	14·5
96	151/A/0/13	1/8"	N	·09	·125	1·45	110	1870	35	320
97	163/A/2/14	1/8"	N	·09	·125	1·45	750	62	195	15·5
98	153/A/0/13	1/4"	N	·022	·057	1·45	110	1870	13·5	670
99	162/A/2/14	1/4"	N	·038	·073	1·45	750	178	225	34
100	154/A/0/13	1/4"	1/4" B	·078	·113	1·45	110	1870	35	280
101	159/A/2/14	1/4"	1/4" B	·09	·125	1·45	750	62	75	7
112	198/A/0/13	1/4"	N_ω	·038	·073	1·45	110	1870	15·5	560
113	193/A/2/14	1/4"	N_w	·038	·073	1·45	750	62	225	31
71	107/B/0/7	1/4" OL	N	·158	·192	2·2	—	—	—	—
87	138/C/0/13	·01"	N	·01	·045	25·5	100	1310	15	650
86	133/C/2/14	·01"	N	·01	·045	25·5	290	11·7	130	6
88	137/C/0/13	·01"	N	·078	·113	25·5	100	1310	17	130
89	132/C/2/14	·01"	N	·078	·113	25·5	290	11·7	35	1

Table 21.

Details from — **The Records**

Figure No.	Reference No.	Transformer Air Gap	Brush Position	Load Resis.ce R Ω	Arm. Circuit Resis.ce R_1	Field Circuit Resis.ce R_2	Scale		Max.m Amplitude	
							Volts/inch	Amps/inch	Volts	Amps.
102	166/A/0/15	1/4"	N	·038	·035	1·45	120	1870	16	650
103	180/A/2/16	1/4"	N	·038	—	1·45	750	62	45	31
104	168/A/0/15	1/8"	N	·09	·035	1·45	120	1870	38	310
105	177/A/2/16	1/8"	N	·09	—	1·45	750	62	75	14
106	169/A/0/15	1/8"	1/4" B	·09	·035	1·45	120	1870	40	330
107	175/A/2/16	1/8"	1/4" B	·09	—	1·45	750	62	75	16
108	171/A/0/15	1/4"	1/4" B	·09	·035	1·45	120	1870	36	300
109	173/A/2/16	1/4"	1/4" B	·09	—	1·45	750	62	75	6·7
110	185/A/0/15	1/4"	N	·038	·035	1·45	120	1870	16	640
111	190/A/2/16	1/4"	N	·038	—	1·45	750	62	225	31
90	141/C/0/15	·01"	N	·078	·035	25·5	100	1310	13	115
91	143/C/2/16	·01"	N	·078	—	25·5	230	11·9	37	72
92	142/C/0/15	·01"	N	·01	·035	25·5	100	1310	13	670
93	144/C/2/16	·01"	N	·01	—	25·5	230	11·9	140	5·4

Table 22. Circuit and Figure Nos.

Circuit No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Figure No	22	22	28	49	50	51	52	53	54	55	56	57	58	59	60	61

Table 23. Details from the Records.

Figure No	Reference No.	Arc Circuit				Field Circuit				Brush Position
		Load		S.C.		Load		S.C.		
		Volts	Amps.	Volts	Amps.	Volts.	Amps.	Volts.	Amps.	
37	5/A/0/1	25	315	2·5	405	15·8	15·5	15·8	15·5	Forward
38	11/A/2/2	25	315	2·5	405	15·8	16	15·8	16	Forward
39	67/A/0/1	28	345	3	510	8	8·5	5·6	5·2	Neutral
40	73/A/2/2	27·5	340	3·5	520	8·4	9·5	4·8	5·5	Neutral

TABLE 24

CALCULATION TABLE GEN^{R} A

LOAD TO S.C. BRUSHES FORWARD

1ST COMPLETE PERIOD ANGLE 2π TIME $1/f$ SECS

ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	
TIME	$\frac{1}{27·8}$	$\frac{1}{13·9}$	$\frac{1}{9·26}$	$\frac{1}{6·94}$	$\frac{1}{5·56}$	$\frac{1}{4·63}$	$\frac{1}{3·97}$	$\frac{1}{3·47}$	
$-bt$	1·055	2·11	3·17	4·225	5·27	6·33	7·38	8·45	
e^{bt}	·348	·1225	·0422	·01485	·00514	·00182	·0004	·000219	
$\sin \omega t$	·7071	1	·7071	0	−·7071	−1	−·7071	0	CURVES—FIG. 114
$\cos \omega t$	·7071	0	−·7071	−1	−·7071	0	·7071	1	
θ_{1}	·2475	·1225	·0298	0	−·00373	−·00182	−·00028	0	
θ_{11}	·2475	0	−·0298	−·01485	−·00373	0	·00028	·000219	
$A\theta_{1}$	245	121	29·5	0	−3·69	−1·8	−·28	0	
$B\theta_{11}$	−22·25	0	2·68	1·34	·336	0	−·0255	−·0197	
$C = S$	405	405	405	405	405	405	405	405	
i_{1}	627·75	526	437·2	406·34	401·65	403·2	404·7	404·99	
$A_{1}\theta_{1}$	8·25	4·08	·995	0	−·1245	−·0608	−·00945	0	CURVES—FIG. 115
$B_{1}\theta_{11}$	0	0	0	0	0	0	0	0	
$C_{1} = VS·W$	15	15	15	15	15	15	15	15	
i_{2}	23·25	19·08	15·995	15	14·88	14·94	14·99	15	

TABLE 25

CALCULATION TABLE — GEN^{R} A

LOAD TO S.C. — **BRUSHES NEUTRAL**

1ST COMPLETE PERIOD — **ANGLE 2π** — **TIME $1/f$ SECS.**

ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	
TIME	$\frac{1}{22.96}$	$\frac{1}{11.48}$	$\frac{1}{7.64}$	$\frac{1}{5.74}$	$\frac{1}{4.58}$	$\frac{1}{3.82}$	$\frac{1}{3.27}$	$\frac{1}{2.87}$	
$-bt$	1·265	2·53	3·8	5·06	6·33	7·6	8·86	10·1	
e^{bt}	·283	·0794	·0224	·00645	·00178	·00046	·000145	·000043	
$\sin\omega t$	·7071	1	·7071	0	−·7071	−1	−·7071	0	CURVES – FIG. 116
$\cos\omega t$	·7071	0	−·7071	−1	−·7071	0	·7071	1	
θ_{1}	·20	·0794	·0159	0	−·00126	−·00046	−·0001045	0	
θ_{11}	·20	0	−·0159	−·00645	−·00126	0	·0001045	·000043	
$A\theta_{1}$	214	85	17	0	−1·35	·492	·112	0	
$B\theta_{11}$	−20	0	1·59	·645	·176	0	−·01	−·004	
$C = S$	440	440	440	440	440	440	440	440	
i_{1}	634	525	458·6	440·6	438·8	440·49	440·1	439·99	
$A_{1}\theta_{1}$	1·6	·634	·127	0	0	0	0	0	CURVES – FIG. 117
$B_{1}\theta_{11}$	−·5	0	·0398	·0161	·0036	0	−·00026	−·000108	
$C_{1} = VS + W$	3·6	3·6	3·6	3·6	3·6	3·6	3·6	3·6	
i_{2}	4·7	4·234	3·767	3·616	3·604	3·6	3·5998	3·599	

TABLE 27.

CALCULATION TABLE GEN^R A

OPEN TO S.C. **BRUSHES FORWARD**

1^ST COMPLETE PERIOD ANGLE 2π TIME $1/f$ SECS.

ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	1·166 rad.
TIME	$\frac{1}{34{\cdot}3}$	$\frac{1}{17{\cdot}15}$	$\frac{1}{11{\cdot}42}$	$\frac{1}{8{\cdot}56}$	$\frac{1}{6{\cdot}86}$	$\frac{1}{5{\cdot}72}$	$\frac{1}{4{\cdot}9}$	$\frac{1}{4{\cdot}28}$	
$-bt$	·525	1·049	1·575	2·102	2·622	3·15	3·675	4·2	
e^{bt}	·592	·351	·207	·122	·0724	·0432	·0254	·015	
$\sin\omega t$	·7071	1	·7071	0	-·7071	-1	-·7071	0	CURVES – FIG. 118
$\cos\omega t$	·7071	0	-·7071	-1	-·7071	0	·7071	1	
θ_1	·418	·351	·146	0	-·0511	-·0432	-·0159	0	
θ_{11}	·418	0	-·146	-·122	-·0511	0	·0159	·015	
$A\theta_1$	1,380	1,158	482	0	-168·5	-142·5	-52·4	0	
$B\theta_{11}$	-184	0	64·2	53·6	22·25	0	-7	-6·6	
C = S	440	440	440	440	440	440	440	440	
i_1	1636	1590	986·2	493·6	293·75	297·5	380·6	433·4	MAX AMP^DE -1873
$A_1\theta_1$	45	37·7	15·68	0	-5·38	-4·64	-1·71	0	CURVES – FIG. 119
$B_1\theta_{11}$	0	0	0	0	0	0	0	0	
C_1 = VS÷W	15	15	15	15	15	15	15	15	
i_2	60	52·7	30·68	15	9·62	10·36	13·3	15	

TABLE 28

CALCULATION TABLE GEN^R A

OPEN TO S.C. BRUSHES NEUTRAL

1ST COMPLETE PERIOD ANGLE 2π TIME $1/f$ SECS.

ANGLE	$\frac{\pi}{4}$	$\frac{2\pi}{4}$	$\frac{3\pi}{4}$	$\frac{4\pi}{4}$	$\frac{5\pi}{4}$	$\frac{6\pi}{4}$	$\frac{7\pi}{4}$	$\frac{8\pi}{4}$	·6423 rad.
TIME	$\frac{1}{22.96}$	$\frac{1}{11.48}$	$\frac{1}{7.64}$	$\frac{1}{5.74}$	$\frac{1}{4.58}$	$\frac{1}{3.82}$	$\frac{1}{3.27}$	$\frac{1}{2.87}$	
$-bt$	1·265	2·53	3·8	5·06	6·33	7·6	8·86	10·1	
e^{bt}	·283	·0794	·0224	·00645	·00178	·00046	·000145	·000043	
$\sin\omega t$	·7071	1	·7071	0	−·7071	−1	−·7071	0	
$\cos\omega t$	·7071	0	−·7071	−1	−·7071	0	·7071	1	
$\theta_{,}$	·20	·0794	·0159	0	−·00126	−·00046	−·0001045	0	
$\theta_{,,}$	·20	0	−·0159	−·00645	−·00126	0	·0001045	·000043	
$A\theta_{,}$	1010	402	80·5	0	−6·36	−2·33	−·528	0	
$B\theta_{,,}$	−88	0	7	2·84	·554	0	−·046	−·002	
C = S	440	440	440	440	440	440	440	440	
$i_{,}$	1362	842	527·5	442·84	434·2	437·67	439·4	439·998	MAX. AMP^RE =1412·5
$A_{,}\theta_{,}$	3·52	1·39	·28	0	−·0222	0	0	0	
$B_{,}\theta_{,,}$	2·32	0	−·184	−·0746	−·0146	0	0	0	
$C_{,}$=VS+W	3·42	3·42	3·42	3·42	3·42	3·42	3·42	3·42	
i_{2}	9·26	4·81	3·23	3·345	3·383	3·42	3·42	3·42	

CURVES – FIG. 120

CURVES – FIG. 121

Details from Table 26. The Records.

Figure No.	Reference No.	O.C. Volts.	S.C. Volts	S.C. Amps.	Field Circuit O.C. Volts	Field Circuit O.C. Amps.	Field Circuit S.C. Volts	Field Circuit S.C. Amps	Brush Position.
33	1/A/0/1	63	2	405	15·8	15·5	15·8	15·5	Forward
34	7/A/2/2	63	2·5	405	15·8	16	15·8	16	Forward
35	63/A/0/1	62	3	510	14·8	16·2	4·8	5·5	Neutral
36	69/A/2/2	64	3·5	520	14·8	16·2	4·8	5·5	Neutral

Details from Table 29. The Records

Figure No	Reference No	Exciter Volts	Extra Res^{ce} in Field	Load Resistance	Ser. Reg^{r} Resistance	Totals Load	Totals Field
68	103/B/0/6	3·35	·143 ohms	·135 ohms	—		
72	104/B/0/6	3·35	·143 "	·135 "	—		
69	105/B/0/6	1·95	1·02 "	·135 "	—	·17 ohms	1·7 ohms
70	106/B/0/6	11·55	1·02 "	·135 "	·12 ohms	·29 "	1·7 "

TABLE 30

DETAILS FROM THE RECORDS

FIGURE No.	REFERENCE No.	S.C. VOLTS	S.C. AMPS.	LOAD VOLTS	LOAD AMPS.	ABUTMENT VOLTS	ABUTMENT AMPS	FIELD CURRENT S.C.	FIELD CURRENT LOAD	BRUSH POSITION
73	110/D/0/4	2·4	245	126	244	—	—	46·3	118	¼" FORWARD
74	123/D/1/10	2·4	250	121	250	8·7	19·2	47	119	¼" FORWARD
75	124/D/2/11	2·4	250	128	249	—	—	48	117	¼" FORWARD
79	113/D/0/8	2·4	245	126	245	—	—	20	92	NEUTRAL
80	121/D/1/9	2·4	247	121	230	8·45	19	14	84	NEUTRAL
81	126/D/2/12	2·4	250	124	240	—	—	12·5	77·5	NEUTRAL

DETAILS FROM TABLE 31 THE RECORDS

FIGURE	REFERENCE	S.C.		LOAD		ABUTMENT		FIELD CURRENT		BRUSH
No.	No.	VOLTS	AMPS.	VOLTS	AMPS.	VOLTS	AMPS	S.C.	LOAD	POSITION
76	111/D/0/4	2·3	245	63	245	—	—	31	64·3	1/8" FORWARD
77	122/D/1/10	2·4	247	121	245	8·8	19·5	32	100	
78	125/D/2/11	2·4	250	128	249	—	—	20·5	87	
82	119/D/0/8	2·4	247	121	230	—	—	−14	53	1/4" BACK
83	120/D/1/9	2·4	247	121	230	7·5	16·6	−14	53	
84	128/D/2/12	2·4	250	124	240	—	—	−15	51	

WELDING UNITS — TABLE 32 — DESIGN DETAILS

REFERENCE LETTER	A.	B.	C.
Nominal Output Kw.	9	6	6
Full Load Volts	30	30	30
Full Load Amps	300	200	200
Speed RPM	3000	1500	1500
Motor Drive	3ph 50~ 440v	230v DC	3ph 50~ 440v
No. of Poles Generator	4	4	4
Field System	Laminated	Laminated	Laminated
Type of Field Winding	Distributed	Distributed	Salient Poles
ARMATURE			
Dia. of Core	7"	9"	9"
Gross Length of Core	2·25"	4"	4
Net Length of Core	2·06"	3·6"	3·6"
No of Armature Slots	23	69	33
Size of Armature Slots	5/16" × 15/16"	·15" × 1"	·365 × ·9
Total Armature Cond^rs	138	138	198
Conductor Size	·065" × ·35"	·09" × ·36"	·065" × ·35"
Type of Winding	Series Wave	Series Wave	Series Wave
Resistance (Hot) Ohms	$1{\cdot}1/10^2$	$1{\cdot}1/10^2$	$2{\cdot}2/10^2$
COMMUTATOR			
Diameter	5"	7"	7"
Length	3·75"	3·75"	2·5
No. of Plates	69	69	99
Pitch of Plates	·23"	·32"	·22
BRUSHES			
No. of Arms	4	4	4
Brushes per Arm	3	3	2
Size of Brushes	1" × ½"	1" × ½"	1" × ½"
FIELD SYSTEM			
No. of Slots	24	24	Salient Poles
Size of Slots	·6 × 1⅜"	¾ × 1½"	—
Air Gap (Single)	·025"	·025"	·025"
Stator Slot Skewed	½"	1⅛"	—
COMPENSATING WINDING			
Total No. of Cond^rs	72	72	No
Cond^rs per Slot	3	3	Compensating
Cond^r Size	·16" × ·3"	·18" × ·4"	Winding
Winding Span	1 to 4	1 to 4	
Turns per Pole	9	9	No
Coupling of Poles	Series	Series	Interpoles
Resistance (Hot)	$1{\cdot}4/10^2$	$1/10^2$	

Table Continued

TABLE 32, CONT^D.

REFERENCE LETTER	A.	B.	C.
FIELD WINDING			
Total No. of Cond^rs	960	840	Salient Poles
Cond^rs per Slot	40	30	–
Cond^r Size	·098" dia	·109" dia.	·048" dia.
Winding Span	1 to 4	1 to 4	–
Turns per pole	120	52·5	430
Coupling of Poles	Series	2 Ser., 2 Par^l.	Series
Resistance (Hot) Ohms	1·2	2/10	25
EXCITER			
Nominal Output Kw.	·225	·27	None
Full Load Volts	15	9	–
Full Load Amps	15	30	–
OTHER DETAILS			
Open Circuit Characteristic Fig. N^o	126	128	130
Volt-Ampere Characteristic Fig. N^o	127	129	131
Circuit Parameters. Table.	33	33	33

TABLE 33.

CIRCUIT PARAMETERS FOR WELDING UNITS

REFERENCE LETTER	A			B	C
BRUSH POSITION	FOR^D.	NEUT^L.	BACK	FOR^D.	NEUT^L.
R Ohms	$3{\cdot}5/10^2$	$3{\cdot}5/10^2$	$3{\cdot}5/10^2$	$3/10^2$	$3{\cdot}5/10^2$
R_2 Ohms	1	1	1	$3{\cdot}2/10$	25
r Ohms	0	$2{\cdot}6/10^2$	$5{\cdot}2/10^2$	0	–
L Henries	$13/10^4$	$11{\cdot}5/10^4$	$13/10^4$	$1/10^3$	$4{\cdot}5/10^3$
L_2 Henries	$2/10$	$2/10$	$2/10$	$1/10$	11
M Henries	$-6/10^3$	0	$6/10^3$	$-6{\cdot}5/10^3$	0
N ratio Series/Shunt	$-3/10^2$	0	$3/10^2$	$-8/10^2$	–
K Constant	8	8	8	4·2	62
E_2 Volts.	15	15	15	9	–

CONSTANT CURRENT UNITS.	TABLE 34.		DESIGN DETAILS.
REFERENCE LETTER.	**D.**	**E.**	**F.**
Nominal Output Kw.	70	160	320
Full Load Volts	300	640	640
Full Load Amps	250	250	500
Speed R.P.M.	1500	1000	1000
Motor Drive	3ph. 50~ 440v.	3ph. 50~ 440v.	220 D.C.
No. of Poles, Generator	4	6	6
Field System	Laminated	Laminated	Solid Yoke
Type of Winding.	Distributed	Distributed	Salient Poles.
ARMATURE.			
Dia. of Core	14"	20"	25·6"
Gross Length of Core.	7"	12"	15"
Net Length of Core.	6·1"	9·75"	12·3"
No. of Slots	39	88	96
Size of Slots	·475" x 1·44"	5/16" x 1 5/8"	·355" x 1·53"
Total Conductors	234	352	576
Cond.rs Size	·1" x ·54"	·09" x ·65"	·069" x ·59"
Type of Winding	Series Wave	Series Wave	Par.l Lap
Resistance (Hot) Ohms	$2/10^2$	$3/10^2$	$9/10^3$
COMMUTATOR			
Diameter	11·25"	15"	15·76
Length	4·75"	3·25"	7·1"
No. of Plates	117	176	288
Pitch of Plates	·32"	·27"	·172"
BRUSHES			
No. of Brush Arms	4	6	6
Brushes per Arm	4	3	
Size of Brushes	1/2" x 1"	5/8" x 7/8"	
FIELD SYSTEM.			
No. of Slots.	44	66	6 Salient Poles
Size of Slots	·65" x 1·75"	9/16" x 2 9/16"	—
Air Gap (Single)	·075"	·075"	·22"
Stator Slot Skewed	·7"	·9"	—
COMPENSATING WINDING			
Total Conductors	120	180	6 off 1·77" x 9·06"
Cond.rs per Slot	3	3	Lam.d Int.poles
Cond.r Size	·165 x ·72	·135" x ·9"	·157" x 3·94
Winding Span	1 to 7 with Blank Slot	1 to 7 with Blank Slot	—
Turns per Pole	15	15	11
Coupling of Poles	Series	Series	Series
Resistance (Hot) Ohms	$1{\cdot}3/10^2$	$2{\cdot}5/10^2$	$2{\cdot}3/10^3$

Table Continued

TABLE 34. CONT^D

REFERENCE LETTER	D.	E.	F.
FIELD WINDING.			
Total Conductors	120	180	Salient Poles
Cond^rs per Slot	3	3	—
Size of Cond^rs	·165" × ·72"	·135" × ·9"	·059" × 3·94"
Winding Span	1 to 6	1 to 6	—
Turns per Pole	15	15	36
Coupling of Poles	Series	Series	Series
Resistance (Hot) Ohms	1·3/10²	2·5/10²	3·5/10²
EXCITER			
Nominal Output Kw.	·7	·8	·83
Full Load Volts	3	4·5	5·5
Full Load Amps	230	180	150
Speed R.P.M.	1500	1000	1000
Nº of Poles	4	4	4
Field System	Laminated	Solid Yoke	Solid Yoke
Type of Field Winding	Distributed	Salient Poles	Salient Poles
ARMATURE			
Dia. of Core	9"	11"	11·4"
Gross Length of Core	2·5"	3"	8·7"
Net Length of Core	2·25"	2·7"	6·7"
No. of Slots	69	33	41
Size of Slots	·15" × 1"	½" × 1"	·394" × 1·38"
Total Conductors	138	198	246
Cond^r Size	·09" × ·36"	·12" × ·35"	·079" × ·515"
Type of Winding	Series Wave	Series Wave	Series Wave
Resistance (Hot) Ohms	1/10²	1·5/10²	2·4/10²
COMMUTATOR			
Diameter	7"	8·75"	7·9"
Length	2·5"	3·25"	4·73"
No. of Plates	69	99	123
Pitch of Plates	·32"	·28"	·2"
BRUSHES			
No. of Brush Arms	4	4	4
Brushes per Arm	2	3	
Size of Brushes	½" × 1"	5/8" × 7/8"	
FIELD SYSTEM			
No. of Slots	24	Salient Poles	Salient Poles
Slot Size	3/4" × 1½"	—	—
Air Gap (Single)	·025"	·025"	·031"
Stator Slots Skewed	·45"	—	—

Table Continued

TABLE 34, CONT^{D}.

REFERENCE LETTER	D.	E.	F.
COMPENSATING WINDING			
Total Conductors	72	4 – 3" × 1¼"	4 – 5.9" × 1.5"
Cond^{rs} per Slot	3	Interpoles	Interpoles
Cond^{r} Size	·18" × ·35"	·09" × 1⅜"	·118" × 1·97"
Winding Span	1 to 4	—	—
Turns per Pole	9	16	21
Coupling of Poles	Series	Series	Series
Resistance (Hot) Ohms	$9/10^3$	$3/10^3$	$6/10^3$
SERIES OPPOSITION			
Total Conductors.	72	—	—
Cond^{rs} per Slot	3	—	—
Cond^{r} Size	·18" × ·35"	·05" × 2⅜"	·197" × 1·97
Winding Span	1 to 4	—	—
Turns per Pole	9	5	3
Coupling of Coils	2 Ser. – 2 Par^{l}	Series	Series
Resistance (Hot) Ohms.	$2{\cdot}3/10^3$	$2{\cdot}1/10^3$	$7{\cdot}5/10^4$
ABUTMENT WINDING			
Total Conductors	480	—	—
Condrs per Slot	20	—	—
Cond^{r} Size	·092" dia	·040" dia	·0455" dia
Winding Span.	Concentric	—	—
Turns per Pole	60	360	550
Coupling of Poles	Series.	Series	Series
Resist.^{ce} of Abut. Wdg. (Hot) Ohms.	·6	19	31
Resist^{ce} of Abut. Circuit (Hot) Ohms.	1	55	76
AUXILLIARY EXCITER			
Nominal Output Kw.	·4	·625	·64
Full Load Volts	20	220	220
Full Load Amps	20	2·85	2·9
OTHER DETAILS			
O.C. Characteristic Fig. N^{o}	134	136	—
Exciter O.C. Char. Fig. N^{o}	135	137	—
Circuit Parameters Table.	35	35	35

TABLE 35.

CIRCUIT PARAMETERS FOR C. C. UNITS

REFERENCE LETTER		D	E	F
R	Ohms	$4/10^2$	$9/10^2$	$2/10^2$
R_1	Ohms	$6{\cdot}4/10^2$	$1/10^2$	$2{\cdot}3/10^3$
R_2	Ohms	$5/10^2$	$8/10^2$	$7/10^2$
L	Henries	$2{\cdot}4/10^3$	$4/10^3$	—
L_1	Henries	$2{\cdot}3/10^4$	$7/10^4$	—
L_2	Henries	$7{\cdot}5/10^3$	$1{\cdot}5/10^2$	—
M	Henries	$-2{\cdot}3/10^4$	$-7/10^4$	—
K_1		·3	·25	—
K_2		2	4·6	4·2
K_1K_2		·6	1·15	—
E_1	Volts.	1·6	2·5	1·28

TABLE 36

AIR GAP	PRIMARY VOLTS	PRIMARY AMPS.	SECY. VOLTS	L	M	L (From Curves)	M (From Curves)	L_2 Calcd.
SOLID	38·1	50	545	$4{\cdot}85/10^3$	$6{\cdot}93/10^2$			
·02"	6·5	10	99	$4{\cdot}15/10^3$	$6{\cdot}3/10^2$	$4{\cdot}4/10^3$	$6{\cdot}4/10^2$	$9{\cdot}3/10$
	36·9	50	532	$4{\cdot}72/10^3$	$6{\cdot}75/10^2$			
·04"	5·05	10	73	$3{\cdot}21/10^3$	$4{\cdot}64/10^2$			
	31·8	50	440	$4/10^3$	$5{\cdot}6/10^2$	$3{\cdot}4/10^3$	$4{\cdot}5/10^2$	$6/10$
	43·8	100	640	$2{\cdot}8/10^3$	$4{\cdot}07/10^2$			
·08"	3·65	10	52	$2{\cdot}32/10^3$	$3{\cdot}18/10^2$			
	19·35	50	320	$2{\cdot}46/10^3$	$4{\cdot}07/10^2$	$2{\cdot}4/10^3$	$3{\cdot}5/10^2$	$5{\cdot}1/10$
	39·3	100	570	$2{\cdot}5/10^3$	$3{\cdot}63/10^2$			
·10"	3·15	10	44	$2/10^3$	$2{\cdot}8/10^2$			
	18·6	50	284	$2{\cdot}36/10^3$	$3{\cdot}6/10^2$	$2{\cdot}2/10^3$	$3{\cdot}1/10^2$	$4{\cdot}3/10$
	36	100	515	$2{\cdot}3/10^3$	$3{\cdot}28/10^2$			
·103"	3·2	10	42·5	$2{\cdot}04/10^3$	$2{\cdot}7/10^2$			
	18·3	50	270	$2{\cdot}34/10^3$	$3{\cdot}44/10^2$			
	34·8	100	490	$2{\cdot}22/10^3$	$3{\cdot}12/10^2$			
·125	2·6	10	37	$1{\cdot}65/10^3$	$2{\cdot}35/10^2$			
	16·5	50	236	$2{\cdot}1/10^3$	$3/10^2$	$1{\cdot}9/10^3$	$2{\cdot}7/10^2$	$3{\cdot}8/10$
	32	100	435	$2{\cdot}04/10^3$	$2{\cdot}77/10^2$			
·25	19·2	100	292	$1{\cdot}22/10^3$	$1{\cdot}86/10^2$	$1{\cdot}22/10^3$	$1{\cdot}85/10^2$	$2{\cdot}8/10$

NOTE:– Calculations for L and M are made on the assumption that the Resistance side of the Voltage Triangle is Negligeable.

To: Mr. Steele.

FROM
THE CLERK OF SENATE's Asst.
UNIVERSITY OF GLASGOW

This "additional paper" should be placed with Dr. James W. Macfarlane's thesis for Ph.D. (1937).

J.C. Ballantyne
16/1/41.

ON THE EQUIVALENCE OF TORSIONAL SYSTEMS IN VIBRATION AND CERTAIN ELECTRICAL CIRCUITS.

JAMES W. MACFARLANE, Wh.Sc., Dipl. R.T.C.

APRIL, 1937.

N O T E

The work outlined in this paper was performed during the period from October, 1934 to February, 1936 and is merely shown in justification of the time spent. No Conclusions are drawn since the work was left incomplete to carry out that detailed in the accompanying thesis "Transient & Oscillatory Phenomena in Dynamo Circuits", which was considered more profitable. The writer is of the opinion, however, that this line of research would be worth completing.

PRELIMINARIES

The object of this work was to confirm by experiment the mathematical work carried out by Moullin

(Aeronautical Research Committee Reports)
(and Memoranda No. 1045 April, 1926.)
( )
(E.B. Moullin.)

on the similarity between some cases of torsional vibrat--ion and certain electrical circuits. It was decided to collect a large number of examples of torsional resonance and later to simulate these electrically, paying partic-ular attention to the " scale factors " and " conversion factors " between them. To this end some time was spent in designing, collecting and making the mechanical appar--atus.

At the start, a solid base for supporting shafting was essential and a few visits to second-hand machinery merchants soon produced an old centre lathe bed 16 feet long, weighing rather over 2 tons and supported on 4 solid cast iron bearers. This was placed in a suitable corner of the laboratory and the shafting considered.

It was found convenient to use a shaft of $\frac{5}{8}$" diameter and this was supported above one of the lathe bed shears in three bearing groups arranged generally as shown in figure 1. The bearings were Hoffmann deep groove journal ball bearings and were mounted in housings cut from solid steel blanks. For the convenience of an adjustable position for at least two of the bearing groups, a small 4 feet lathe bed was equipped with sliding brackets to support the bearing housings, and the whole bolted to the two ton lathe bed. The third bearing was housed in a piece of 4" x 4" x $\frac{1}{2}$" angle section suitably bored and packed to the required centre height of 9".

The $\frac{5}{8}$" shaft itself was carefully selected from /

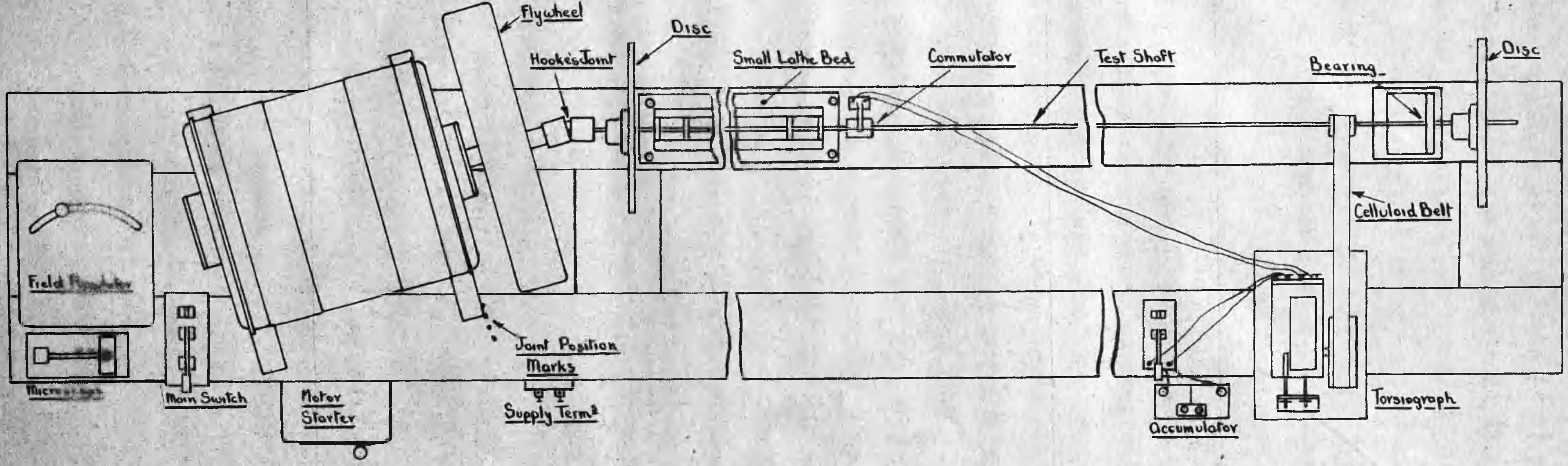


FIG. 1 — ARRANGEMENT OF MOTOR AND SHAFTING FOR HOOKE'S JOINT TESTS

SEE FIG. 7 FOR DIMENSIONS

/ from a suppliers stock for its truth of diameter and axial straightness and was about 11 ft. long. After fitting to its bearings and detailed attention paid to its lining, a pair of steel discs were mounted at each end of the shaft and secured in place by grub screws.

A variable speed D.C. Motor was next procured and mounted at one end of the shaft as a driving means and connected to a 250 volt supply through a starter and main switch. A 1000 ohm field regulator with a wire wound vernier resistance was included in the shunt circuit of the motor to provide the speed control. The motor shaft extension was connected to the test shaft by means of a hard rubber tubular coupling secured by circular clamps.

This work occupied about 2 months since the machin--ing, welding and lining was done entirely by the writer.

Means for recording oscillations were next studied and several types of torsiograph were examined. The instrument finally selected was a new design of Cambridge Rotational Accelerometer or Vibrograph. This instrument, being the forerunner of a new range of vibrographs, is worthy of further description. It consists essentially of a light aluminium pulley wheel driven by a celluloid belt from the apparatus under investigation so that it follows accurately any variations in angular velocity; this light pulley is coupled by internal springs to a flywheel, the rotational inertia of which is sufficiently high to render its angular velocity sensibly constant. The linkage between the two wheels is arranged so that their relative angular motion is transformed into a longi--tudinal movement and recorded on a moving celluloid strip by plastic deformation due to a small spherical stylus mounted on a lever which can be easily exchanged, thus providing various magnifications. A pair of auxiliary styles are mounted on the arm carrying the celluloid /

/celluloid supply and are used to provide a time base and signal mark. The celluloid strip is driven by a clockwork motor contained in the base of the instru--ment and this also operates the 1/10th second time marker whose electro-magnet is excited by a 4 volt battery, the same battery providing the power for the signal marking device.

The records are obtained on 20m.m. celluloid film and may be up to 15 ft. long. Four film speeds are available and the control is by a small sliding knob situated on the side of the instrument case beside the winding key and starting control.

The stylus-on-celluloid method of recording rapid fluctuations is the subject of British Patent No. 195,116 (Cambridge Instrument Co.Ltd.) and is based upon the fact that the elastic limit of such materials as celluloid, celastoid and ebonite is low, so that plastic deformation occurs under comparatively slight pressures. The stylus used here has a minute spherical point (radius about .01 to .03 m.m.) which, when brought into contact with the celluloid surface under a very small pressure, causes an indentation of from .002 to .004 m.m. in depth, and when moved over the surface causes smooth plastic flow, producing a permanent deformation of the material. The record thus consists of a cylindrical depression of small radius, forming a minute concave cylindrical lens whose approximate virtual focal length is .1 m.m. Shallow ridges are also produced on each edge of the record which form quasi-cylindrical convex lens of smaller focal length. Each of these ridges is further bordered by concave cylin--ders of slightly shorter focal length than that of the central depression.

These effects are shown diagrammatically in figure 2 where A represents the depression made by the

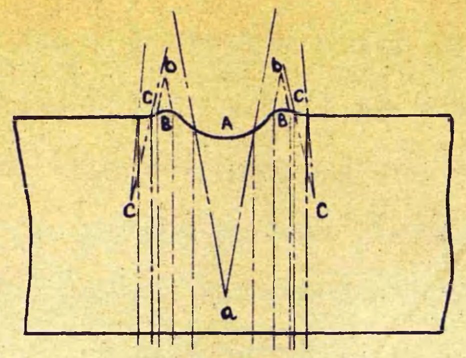


FIG. 2 - MAGNIFIED SKETCH OF CELLULOID DEFORMATION

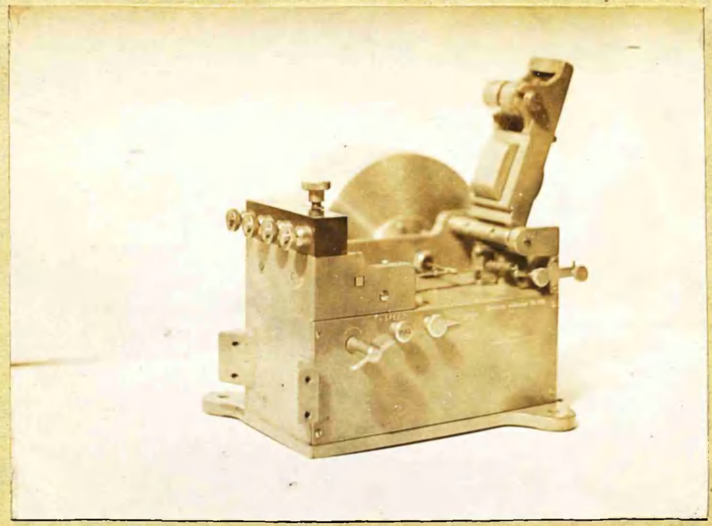


FIG 3. - PHOTOGRAPH OF TORSIOGRAPH

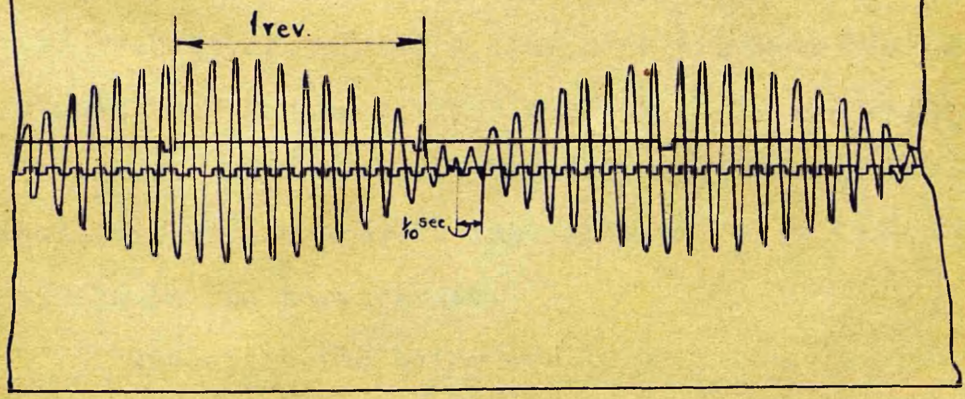


FIG. 4 - TRACING OF A MAGNIFIED RECORD

/ the stylus, B B are the ridges forming the quasi-cylinders and the C C the two outer cylinders.

From these notes it will be seen that the line produced by the recording stylus has optical character--istics entirely different from those of a scratch; when viewed through properly focussed microscope by parallel transmitted light, the indentations appear as a narrow, sharply defined band on a bright ground with a still finer bright line in the centre of the dark band. Measurements can therefore be made from the magnified record with a high degree of accuracy by a suitable microscope which should be focussed not on the record but on the virtual focal point of the indentation A (a in figure 2).

A photograph (figure 3) of the torsiograph shows the general arrangement of the instrument, and figure 4 shows a tracing of a typical magnified record.

To return to the assembly of the apparatus, the torsiograph was mounted on a welded steel carriage (shown in figure 6a) arranged to slide on one shear of the lathe bed so that it may be driven from any part of the shaft by means of a small brass pulley and a belt made from a piece of the celluloid recorder film, the belt being tensioned by means of a pair of locking screws provided on the base plate.

In order to provide a base of shaft revolutions on the records as well as a time base a commutator made of ebonite and having a brass segment in it was fixed on the shaft and two copper brushes made to bear on the commutator surface these being connected to the signal terminals on the torsiograph.

The apparatus being now largely complete, numerous tests were made but no sign of torsional resonance dis-covered. It was thought that at the resonant speed any slight out-of-balance in the apparatus would set up the vibrations but this was apparently not the /

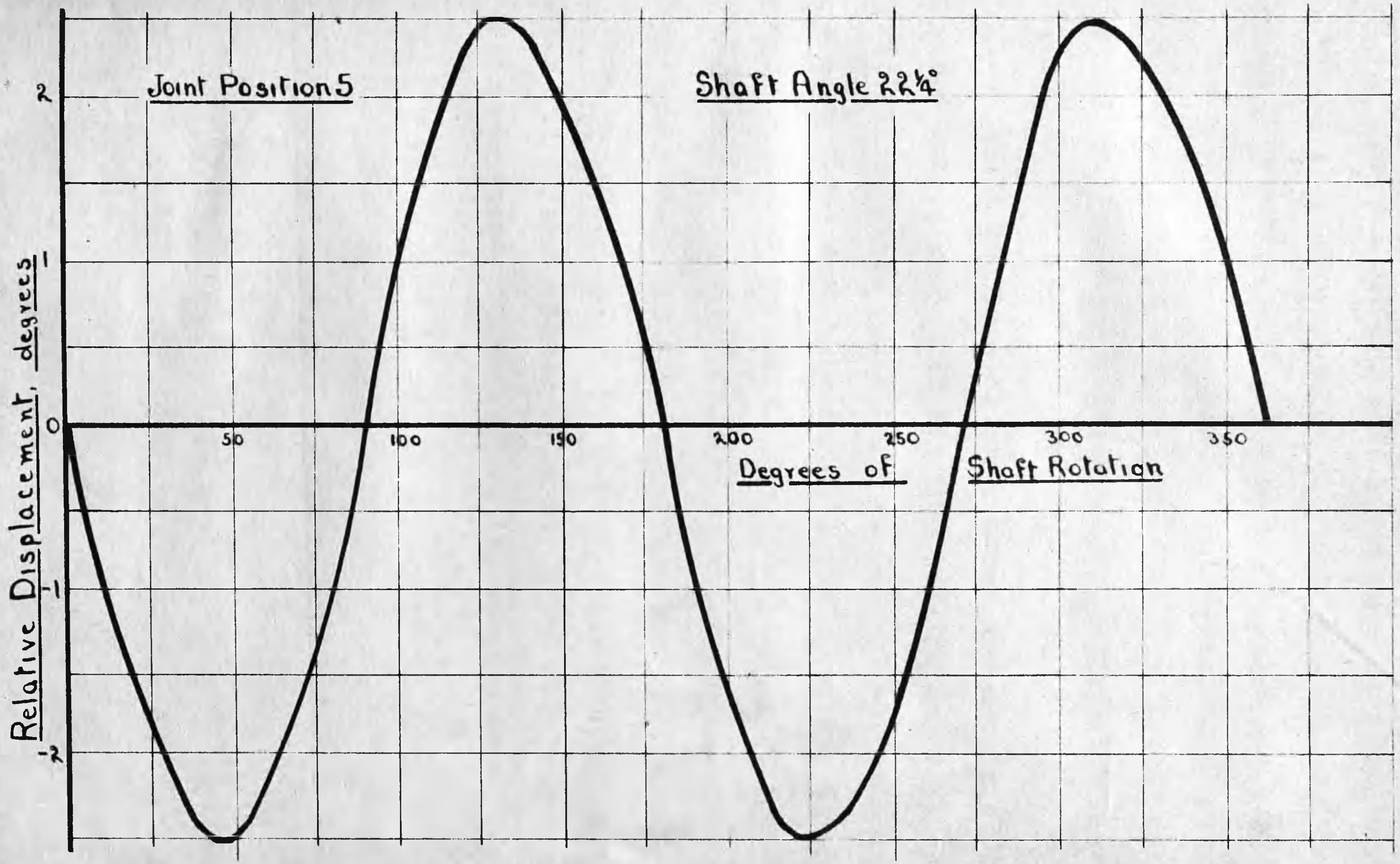


FIG. 5 – DISPLACEMENT CURVE FOR HOOKE'S JOINT

/the case and when one of the discs was purposely un-balanced, no better results were obtained. A forcing medium was obviously required and consideration was given to this.

Several schemes were tried unsuccessfully until the idea of driving the shaft through a Hooke's Joint with the motor and shaft axes at an angle was hit upon. This arrangement was immediately successful and various joint angles were selected and carefully marked on the lathe bed and tests carried out to determine the forcing curve of the joint for the various shaft angles. At first small 5" diameter protractors and a pair of sur-face gauges were used for this but the calibration was not sufficiently accurate. A pair of $15\frac{1}{2}$" diameter wooden discs were therefore carefully divided into de-grees and quarter degrees by a milling machine dividing head and temporarily mounted on the motor and test shaft spanning the joint and the calibration again tried, this time successfully. A representative <u>displacement</u> curve for the joint is shown in figure 5 and double graphical differentiation of this gives the forcing curve[2].

([2]Note:- This graphical differentiation is not shown in figure 5.)

As mentioned previously the torsiograph records had to be examined by means of a microscope and while it was not at this stage intended to make a complete and final examination as each record became available, a preliminary inspection was desirable in case a record should have to be repeated. A temporary easily access-ible microscope appeared to be the solution and one was accordingly acquired. This was mounted vertically at the extreme end of the lathe bed on an electrically weld-ed support and an incandescent lamp arranged to transmit parallel light through a brass record holder. The /

/The arrangement can be seen erected at the extreme left of the lathe bed in figure 6b which also shows the lay-out of the driving motor control gear and Hooke's Joint.

These alterations having been completed, tests for resonance were again started with very good results, and this work carried on until the existing shaft arrange--ment was deemed to have served its turn.

In order to recognise a record at a glance the system of filing mentioned below was adopted.

Each record which actually showed a vibration of importance to the investigation was inscribed with the letter T.

Each shaft arrangement was given a reference letter and this was also inscribed on the record.

Consecutive records for a given test were numbered in order as they were taken from the torsiograph, this number appearing on the record and also against the speed of the shaft in the table of results.

Thus, T B/4 means

Record taken on shaft arrangement B, fourth from start of this series.

TESTING

The tests were carried out on the following scheme for the shaft arrangements given in figure 7.

(1) Single Disc at free end of shaft.

- (a) Disc A
- (b) " B
- (c) " C
- (d) " D

(2) Equal Discs at each end of shaft.

- (a) Discs A
- (b) " B
- (c) " C
- (d) " D.

/

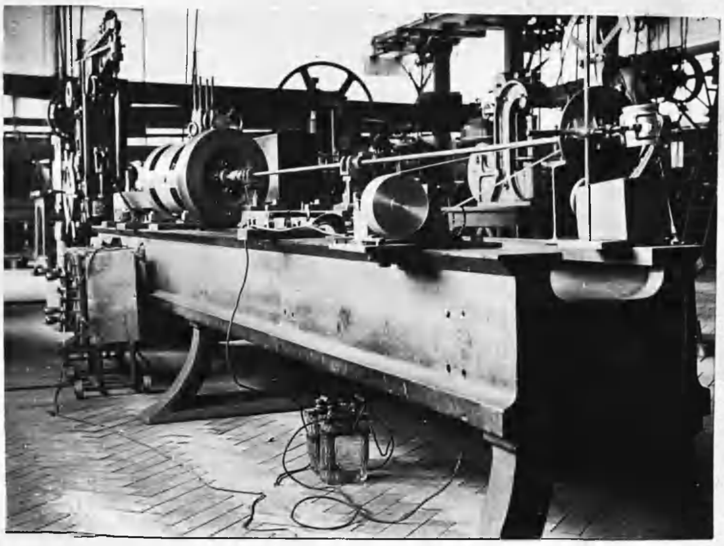


FIG. 6a — GENERAL VIEW OF APPARATUS SHOWING TORSIOGRAPH MOUNTING

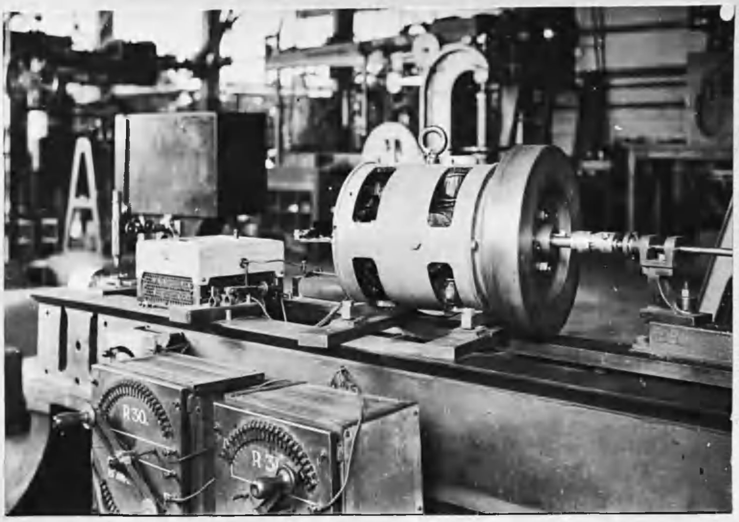


FIG. 6b — MOTOR, CONTROL GEAR, AND HOOKE'S JOINT

(3) 3 Equal Discs equally spaced on shaft.

(a) Discs A

(b) Discs B

(c) Discs C

(d) Discs D

The torsiograph was tried in each case at the position of maximum resonant amplitude and at the node, and the shaft speed was increased by approx--imately 30 r.p.m., for each reading, closer values being taken near resonance.

Each shaft arrangement was tested for the 5 Joint positions given below.

Joint Position	1	Angle	0^{o}
	2		5.5^{o}
	3		12^{o}
	4		17^{o}
	5		22.3^{o}
	6		28^{o}

The dimensions of the discs were

Disc	Diameter	Thickness
A	9"	.37"
B	9"	½"
C	8"	.252"
D	8"	3/16"

In order to evaluate rapidly the moment of inertia of a given disc and its mounting hub, a trifilar suspension was arranged. This consisting of a welded steel wall bracket from which was sup--ported by 3 steel wires, a circular steel table of 11½" diameter and .4" thickness. The table was provided with a centering screw and boss to ensure that objects placed on it were co-axial with it.

/

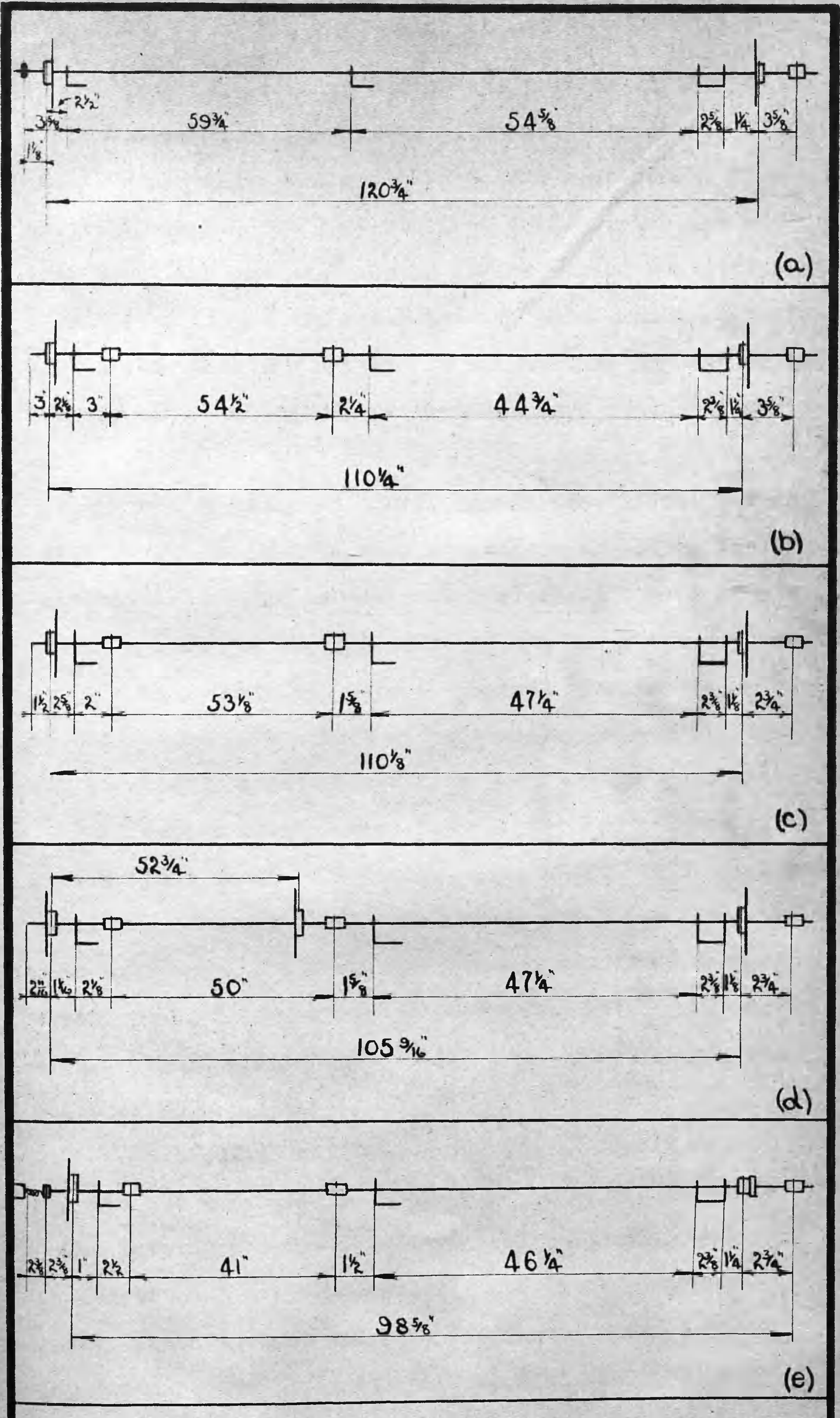


FIG. 7 SHAFT ARRANGEMENTS

/it.

DIFFICULTIES

From time to time during the testing, various difficulties were experienced and these were overcome as encountered. The method of speed measurement from the torsiograph, for instance, was inclined to take a long time when the measurement of the record was attempted. A Visual indication was required and an existing Hazler time-speed meter was affixed to one bearing housing of the driving motor so that speed readings were instantly avail--able.

The torsiograph itself caused some little diffic--ulty by scratching the records instead of making indent--ations. A visit to the makers produced a pair of new styles and on fitting one of these the trouble disappeared.

The commutator used to provide the revolution base on the record gave satisfactory results for a short time but constantly required dressing and new copper brushes. Hard carbon brushes were tried but these refused to record above about 1000 r.p.m., and, in addition, required constant refacing. The commutator was dismantled and made half brass, half ebonite and copper-carbon brushes substituted, these having grooved faces to prevent polish--ing. This arrangement worked well up to the maximum speed of 3000 r.p.m.

A peculiar marking on the record was the next trouble and many devices were tried to eliminate this. The torsiograph was dismantled and thoroughly over-hauled without any improvement, belt tensions checked, pulley truth checked and even tuning forks tried to find any resonance in the instrument itself, all to no account. This phenomenon only occurred infrequently and it was finally decided to ignore it as it had nothing to do with the work in progress.

Difficulty was experienced in keeping the shaft

/

/shaft at a constant resonant speed and to aid this a heavy cast iron flywheel was mounted on the motor shaft as shown in figure 1. This had the effect of steady--ing the speed considerably and proved a valuable addit--ion to the equipment. Since this flywheel was of cast iron and of fairly large diameter, the shaft speeds had to be kept below about 1800 r.p.m. A flywheel was there--fore machined from a solid steel blank and kept ready for fitting, but was not used during this series of tests.

It is worthy of note that, at first, resonances were discovered at one half their calculated speeds, this being due, of course, to the fact that the Hooke's Joint gives two forcing cycles per revolution (see figure 5).

MODULUS OF RIGIDITY

The apparatus was now entirely dismantled to allow of the fitting of the new steel flywheel and new Hooke's Joint the original joint having developed a fair amount of slack. During the time unavoidably spent in this operation, the opportunity was taken to make tests for the rigidity modulus of the shaft material. Portions of the shaft were cut into standard test pieces as shown in figure 8, and one of these placed in position in a Buckton Torsion Testing machine. Two gauge points were then marked off on the test piece, 2" apart and a small V-shaped frame clamped to each point by means of set screws. Each of these frames carried a small mirror. A vertical scale was next set up on a table about 15 ft. away from the test piece so that this scale could be viewed in each of the mirrors when using a small telescope which was provided with a cross wire.

When a torque was applied to the specimen, different /

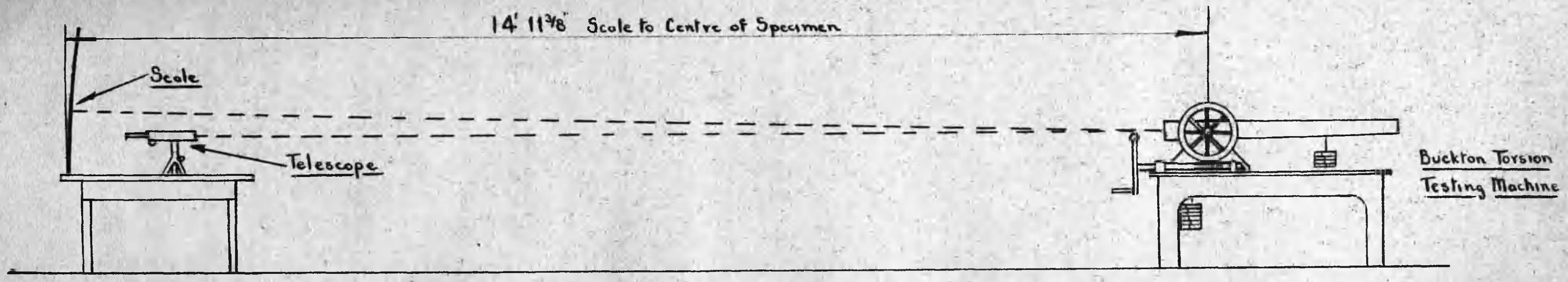


Fig. 9 — Method of Measuring Torsion Angles

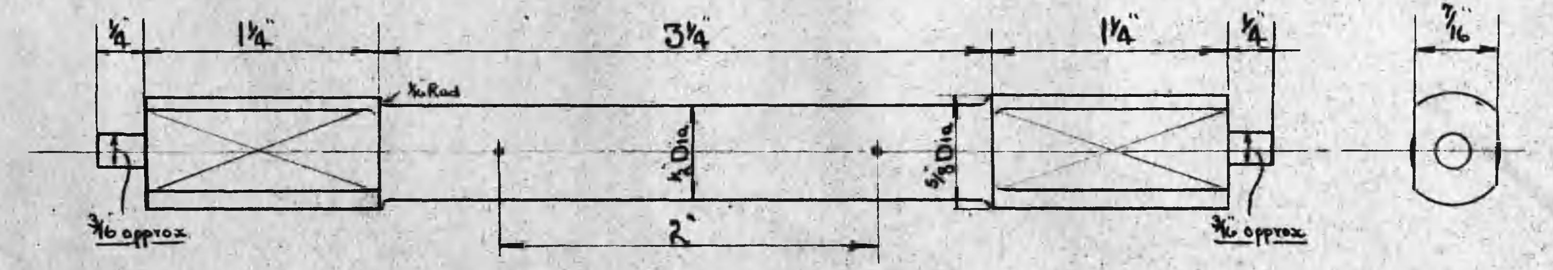


Fig 8 — Dimensions of Standard Test Piece

/different parts of the scale appeared against the telescope cross wire, the difference (in inches) being noted. A knowledge of the distance between the test piece and the scale completed the information necessary to give the angle of twist experienced by the specimen. Considerable accuracy was therefore a feature of the arrangement (sketched in figure 9) since measurements could be made to .01" in a distance of 15 feet.

Numerous specimens were tested in this manner, the average result being -

$$G = 12 \times 10^6 \quad lb/\square''$$

RE-ASSEMBLY OF APPARATUS

The apparatus was re-assembled using the steel flywheel, hub mounted to the motor shaft, and with a new Hooke's Joint. Since it might be of interest at some later date to know exactly what slack was to be found in the old joint, this was placed on a mandrel in a lathe and long pointers attached, one to each element of the joint, and their relative movements measured by means of a depth gauge. The angle of slack was .69 degrees.

Immediately on completion of the apparatus, tests were commenced and it was at once found extremely diffic-ult to keep the discs firmly fixed to the new shaft, this being ultimately overcome by putting a taper pin completely through the shaft and hub. One of these pins was found to be slightly slack, but after running the shaft at resonance for a short period, the hub siezed on the shaft and gave a rigid fit. This hub had later to be /

/be cut off the shaft when changing the arrangement.

The same series of tests as detailed on page 9 were then carried out with notably better results.

COLLECTION OF DATA

It was now decided that, as a large number of records had been collected from the present shafting, a new apparatus should be designed and meantime, a few experiments made in the examination of the records.

At first each record was individually examined by means of the microscope previously described, the measurement being effected by a small graduated scale alongside the record. This method was tedious and an arc lantern projector was employed to enlarge the records photographically, a method which entailed a large amount of labour and expense on account of the number of records (over 200) now amassed. The scheme of projecting the record on a screen by means of a lecture bench lantern was next tried but it was found difficult to obtain the same degree of enlargement for each, since the pressure of the recording style appeared to have varied, giving a different focal point for each record and thus defeating the purpose of comparison.

The scheme finally adopted is shown diagrammatically in figure 10. A Point-o-Lite arc lamp and parabolic reflector is arranged to give parallel light and this beam projected on to a plane mirror lying at 45 degrees to the horizontal. A small clamp above this mirror supports the record which it is required to examine, the actual inspection being carried out by an adjustable microscope mounted on two mutually at right angles, vernier measuring scales, each capable of reading to .001".

This gear proved suitable to the occasion and, although laborious, was certainly the most suitable gear /

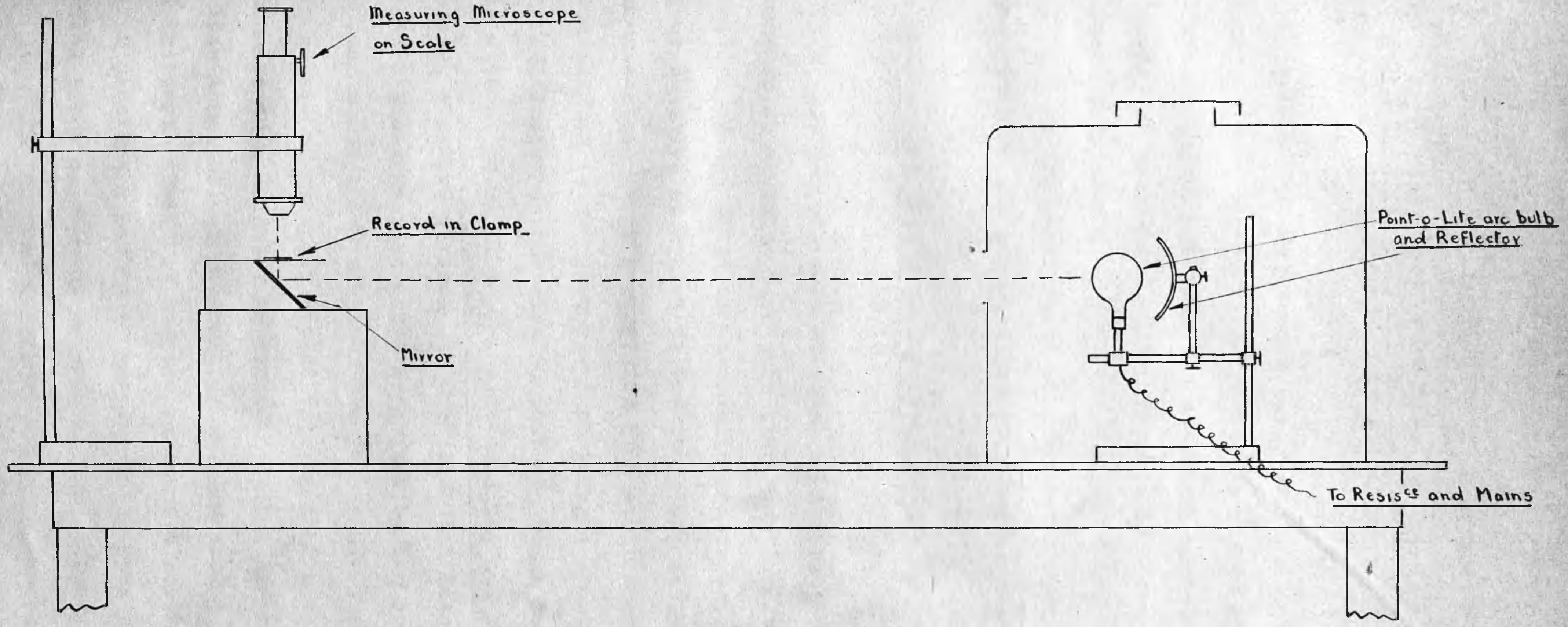


FIG.10 – POINT-O-LITE ARRG^T FOR EXAMINING RECORDS

/ gear so far tried.

The main values required from a record were -

(1) Speed of shaft,

(2) frequency of vibration,

(3) amplitude,

(4) resonant speed,

and in order to note those rapidly a series of tables were duplicated, so that the necessary measurements leading to values (1), (2), (3) and (4) above could be immediately noted.

As the measurement of records proceeded attention was given to the proposed new shafting arrangement.

DESIGN OF NEW APPARATUS

It was proposed now that an apparatus should be made which would produce pure sine wave forcing oscill--ations on the shaft and the infinite connecting rod gear detailed in figure 11 was therefore designed and constructed. This consisted of a steel disc, later hub-mounted to the test shaft carrying a crank pin in a radial slot on the disc so that the crank radius could be altered at will. A slotted link, cut from steel plate, was next affixed to a $\frac{1}{2}$" diameter steel shaft so that a brass bearing block supported by the crank pin passed through the slot. The $\frac{1}{2}$" bar was then supported in a pair of phosphor bronze bearing shells suitably mounted on a welded base plate in such a manner as to allow longitudinal movement of the connecting rod only. A Whitworth thread at the end of the rod remote from the link provided a method of loading the system by means of steel discs of varying weights held in place by lock-nuts.

The general arrangement of the complete apparatus is shown in figure 12. The existing variable speed D.C. /

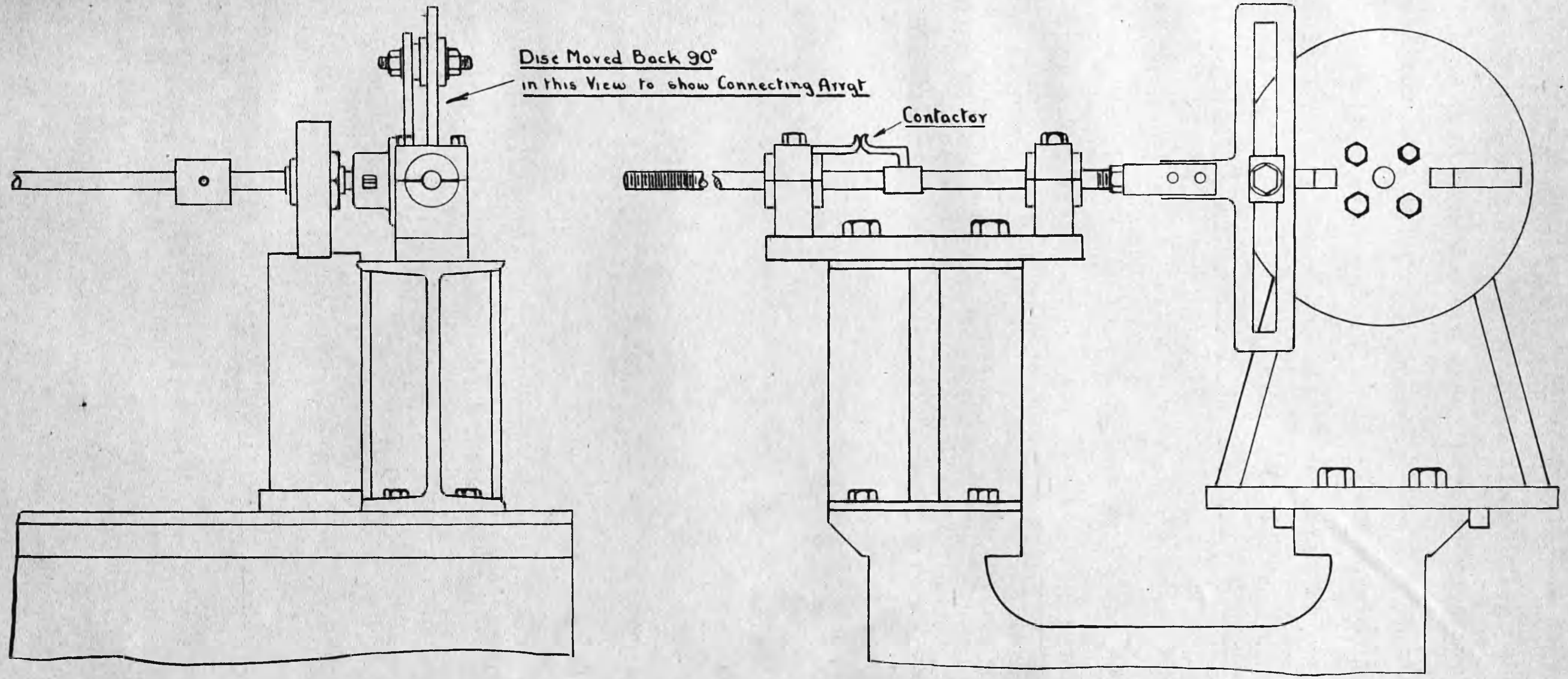


FIG 11 - DETAIL OF INFINITE CON. ROD ARRANGEMENT

/ D.C. Motor was mounted at one end of the lathe bed on a quick release carriage and provided with a pin-type flexible coupling to permit rapid dismounting, this being desirable as the motor was also intended to drive an alternator at a later date. The heavy steel flywheel was keyed to a high tensile steel shaft carried by a pair of ball bearings secured in steel housings by caps. The housings, which are gas cut from 1" steel plate, were electrically welded to steel brackets whose accurately machined bases were secured to the lathe bed. The great- -est of care was taken in the machining of the bearing housings and brackets to ensure constancy of centre height, since accurate measurements demonstrated that the lathe bed was hollowed by about .004" at the centre. Since all the housings were machined to be the same, this amount was made up by packing pieces of copper foil.

At the end of the flywheel shaft remote from the motor a massive cast iron half coupling was keyed to the shaft, this being provided with a spigot register to suit a similar half coupling intended to receive & drive the $\frac{1}{2}$" diameter test shaft.

Four further bearing brackets and housings were then constructed and spaced along the lathe bed, each supporting an adaptor mounted ball bearing. This arrangement, by using different adaptors, permitted shafts of any size up to $\frac{3}{4}$" diameter to be employed for test, and since the bearing rings were tapered and the adaptors split, no difficulty was experienced in threading the bearings over the shaft to their proper positions, a duty which caused considerable trouble in the previous shaft arrangement.

The infinite connecting rod gear previously described was now mounted at the free end of the shaft. A new welded steel torsiograph carriage (not shown in figure 12) was mounted on the opposite shear of the lathe

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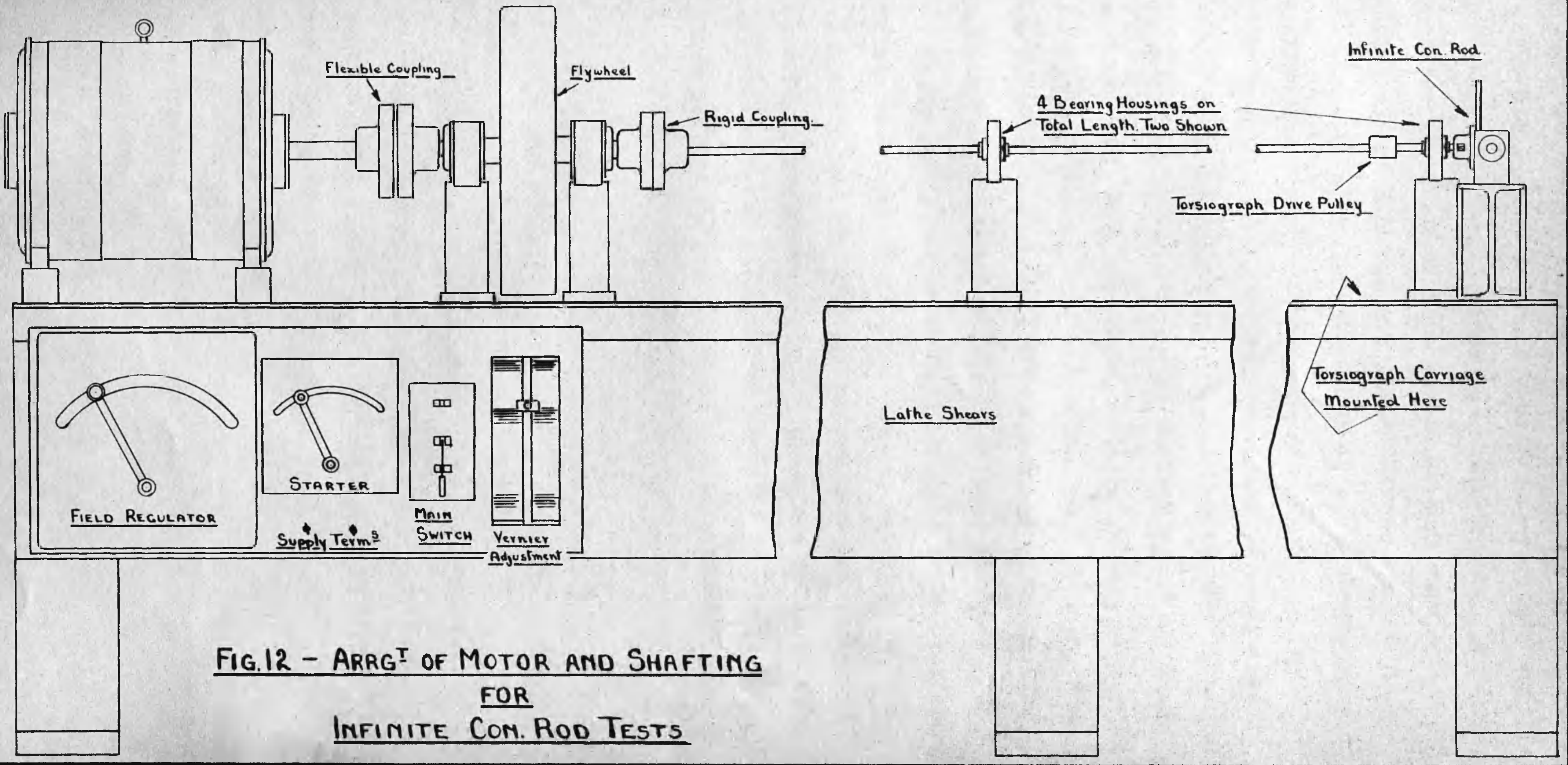

FIG. 12 – ARRG^{T} OF MOTOR AND SHAFTING
FOR
INFINITE CON. ROD TESTS

/lathe bed so that it could take up any position along the shaft and, to save time in making records from various parts of the shaft, a light aluminium torsiograph driving pulley of $1\frac{1}{4}$" diameter was placed between each bearing span and celluloid driving belts of equal length perman--ently joined over each span.

A wooden motor control panel was next constructed and mounted vertically at the motor end of the lathe bed as shown in figure 12. The control apparatus consisted of a 30 stud; 1000 ohm field regulator with a wire vernier (of rather greater resistance than that between studs of the regulator) in series with the field of the motor. A main switch and motor starter completed the gear.

The apparatus being thus complete a few preliminary trials were made with every success, except that the commutator for the time marker had been inadvertently omitted. The opportunity was therefore taken to make and fit the form of contactor sketched in figure 11 in place of the commutator and this also proved successful.

ELECTRICAL GEAR

The mechanical gear was then left and attention turned to the electrical apparatus.

A small 3 phase alternator was obtained and provided with a pin type half coupling. A channel section steel bedplate was next constructed by electric arc welding so as to mount the D.C. shaft motor and the alternator. The motor was controlled through the same gear as used for controlling the shaft by means of an additional set of terminals attached to the lathe bed.

The set was started and an excitation given to the alternator field from a battery and one phase of the stator connected to an oscillograph. Several wave forms /

Marconi List

H. D. Bickley
Cedric H. Hunt
J. H. Lyddiard.
E. Franklin.
[illegible] J. F. Morris.

Tues May 4

Torsional Systems Oct 34 – Feb 36
Engl. p 2
Ought to have seen David Robertson's work for damping
Too much detail description
drawings Vy good – Difficulties very great

No Tests No references [illegible]

No results at all & difficult to understand

/forms were then taken under varying conditions of load, the machine proving satisfactory.

At this time the opportunity was offered to start the work detailed in the accompanying thesis,"Oscillatory and Transient Phenomena in Dynamo Circuits" and the entire torsional apparatus was left.

CONCLUSION

Although this work was left unfinished, the writer is of the opinion that it would be worth completing. The possibility of electrical simulation of many mechanical problems has been well known for many years, although little actual experimental work has been done in this connection. The mathematics of the vibration of a multi-throw crankshaft, for instance, is fairly complic--ated and a simple electrical simulation would simplify the designer's work considerably.

ACKNOWLEDGMENTS

The work detailed here was performed in the James Watt Engineering Laboratories under the supervision of the late Prof. J. D. Cormack, D.Sc., C.M.G., C.B.E., to whom the writer's thanks are due for much sympathetic aid and generous provision of apparatus. After the death of Prof. Cormack, the work was carried on under R.M. Brown, Ph.D., D.Sc., to whom the writer's thanks are also due.
