A M P L I D Y N E   C H A R A C T E R I S T I C S

A THESIS

presented to the Faculty of Graduate Studies and Research of McGill University in partial fulfilment of the requirements for the degree of Master of Engineering

by

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Montreal   April 1949

C O N T E N T S

INTRODUCTION

One of the recent developments in the field of rotating electrical machinery has been the two-stage dynamo-electric power amplifier more commonly known as the Amplidyne. The need had been felt for a long time in certain industrial processes and power engineering applications for a simple control apparatus possessing a high degree of amplification combined with a moderately quick and accurate response. The amplidyne which answers these requirements and many more as well, has gone a long way in improving existing electrical control applications and has made possible many new ones.

The amplidyne is in a sense similar to radio amplifier tubes. Just as certain vacuum tubes, through the control of minute amounts of electric power, can control the flow of large amounts of power in other electric equipment, so the amplidyne generator can amplify, hundreds or even thousands of times, the variations of power impressed upon it.

The behaviour of radio amplifiers has provided a certain measure of guidance in the aapproach to the design of power amplifiers like the amplidyne. The fact that the introduction of two or more stages in the process of amplification led to a higher ratio of amplification without any appreciable decrease in the speed of response, was observed in the operation of radio amplifiers and this property has been successfully incorporated in the amplidyne. The time constant of the machine, while slow compared to the vacuum tube amplifier is nevertheless extremely small when compared with those of other machines in the circuits where the amplidyne generator is most frequently applied.

Amplidynes are being used extensively as regulators in closed-cycle control systems. Closed-cycle systems can be defined as those systems in which the controlling agency is actuated by some function of the final output in such a manner as to reduce any deviation of the output from a certain ideal value. In such systems, a deviation must exist to obtain regulating action, or in other words, deviation from the standard can be minimised but not entirely prevented. The high amplification factor and speedy response of amplidynes make them particularly suitable to this type of control where it is very important that the time lag of each element of the system be as short as possible, if instability is to be avoided. The control of voltage, current, speed and power-factor are a few of the uses to which these machines are put, in industry and central station operation.

Besides their application in closed-cycle systems, amplidynes are also used to control directly the speed and direction of rotation of separately excited direct current motors, which operate electric gun turrets on ships and planes, searchlights and similar equipment. The quickly reversible source of armature power required for suddenly reversing the motors, is obtained with a very short time delay, thus insuring smooth dependable performance under rapidly changing conditions. However, in this type of control, the output power of the amplidyne unit will have to be sufficiently high to be able to operate the motors directly. The ratings of amplidyne units used in closed-cycle systems need be only relatively low.

This paper will primarily deal with the factors influencing the speed of response and amplification of the amplidyne, since these are the two main characteristics which decide whether or not an amplidyne is to be used in a particular control system. In the first chapter of this thesis, a brief review is given of the forerunners of the amplidyne, commencing from the common direct-current shunt wound generator. The second chapter deals with the general operation of the machine and a few of the factors that affect its characteristics. The third chapter is devoted to the study of the transient behaviour of the machine, including a mathematical derivation of an equation connecting the output voltage and time by the usage of time constants. The last chapter deals with the salient characteristics such as amplification, compensation and speed of response. To illustrate the theory, tests were conducted on a Canadian General Electric ' Metadyne Generator which was designed for the control of a d.-c. motor operating a gun turret. The test machine though designated as a metadyne, was similar in all respects to the amplidyne and was intended for use as such. A number of oscillograms taken on the test machine are also included to illustrate the response.

CHAPTER I

HISTORY OF THE DEVELOPMENT OF THE AMPLIDYNE

SHUNT GENERATOR: The first and most fundamental forerunner of the amplidyne was the conventional shunt-wound d-c generator. This machine can be regarded as a crude power amplifier, since the output power at the armature brushes is controlled by the variation of the current in the field winding. The ratio of output power to input power is very small in this machine, the excitation power being an appreciable percentage of the rated output. The high inductance of the field causes a considerable time delay in variations of terminal voltage to changes in field current. The chief application of the shunt machine is in the control of continuously running drives, where a fast response is of no importance.

THREE-BRUSH GENERATOR: This machine which utilised the principle of armature excitation for its operation, was, until a few years ago, used to charge automobile batteries. The shunt field was excited by the voltage between one of the main brushes and a third brush situated on the commutator about 45 degrees (electrical) from the other main brush. The increase of charging current at high road speeds, caused the field flux to shift due to armature reaction. The reduction in the voltage impressed on the field because of the shift, led to a decrease in the charging voltage and hence the charging current was reduced. The battery charging current was therefore kept constant within a wide range of speed.

ROSENBERG GENERATOR: This machine is fundamentally an armature excited direct current generator. It is characterized by a primary source of excitation provided by a coil wound on its poles and an extra pair of brushes placed on the commutator at right angles to the conventional pair which is short-circuited. In this respect the Rosenberg generator is similar to the amplidyne.

The open circuit output voltage of this machine varies as the square of the speed for a constant field excitation. The polarity of the output voltage is therefore independent of the direction of rotation of the armature. The Rosenberg generator, which was first described in 1905, has been extensively applied in train lighting systems in conjunction with storage batteries.

METADYNE GENERATOR: The most recent predecessor of the amplidyne was the metadyne generator. The conception of the metadyne, was largely due to the efforts of Mr.J.M.Pestarini, who conducted an investigation into the possibilities of a direct current machine operating with other sources of excitation, either internal or external to the machine, besides the conventional field winding. The results of his investigation were first published in 1930 in the " Revue Générale de l'Électricité ".

According to Mr.Pestarini, the metadyne can be defined as a generalised direct current machine consisting of an armature and commutator, any number of field poles the excitations of which may be obtained in any manner, and any number of brushes arranged to bear on the commutator in such suitable positions that permit of satisfactory commutation.

The most commonly used form of the metadyne generator is in converting power at constant potential to power at constant current. Though the amplidyne generator is almost identical with the metadyne in its physical structure and principle of operation, a slight modification in the connection of the brushes enables the metadyne to function as a sort of d-c transformer instead of an amplifier. The " figure-eight-connected " metadyne has been successfully used in electric railway systems both in England and France.

<u>AMPLIDYNE GENERATOR</u>: The amplidyne, also an armature excited machine, was the result of investigations conducted by the General Electric Company, U.S.A.,

into the possibilities of utilising various forms of metadynes for the control of industrial apparatus. The development of this machine was completed shortly before the last war. The amplidyne can be classified under the general category of metadynes designated as 'cross-connected'. The Rosenberg generator, the Pestarini metadyne and the G.E. amplidyne are all armature excited machines differing only in the applications to which they are put.

C H A P T E R 2

PRINCIPLES OF OPERATION OF THE AMPLIDYNE

The amplidyne generator is an externally driven machine, similar in outward appearance and construction to the conventional d-c generator or motor. But unlike the ordinary machine, the armature serves as the main source of excitation in addition to being the source of output power. It owes its success to its inherently unique design utilising a short-circuit between the two brushes of the d-c machine and in the introduction of a compensating winding on its stator.

DESCRIPTION OF THE PHYSICAL STRUCTURE

The amplidyne differs from the ordinary d-c machine only in the structure of the field poles. Each main field pole on the stator is usually subdivided into two halves, there being consequently four polar projections in the case of a two pole machine. This subdivision is made for providing sufficient space for the addition of interpoles which might be necessary to avoid bad commutation at the intermediate brushes. The introduction of commutating poles may or may not be found necessary depending on factors affecting commutation.

The control field winding is placed on the main pole and the space occupied by it is usually very small. This permits the winding of a number of other coils on the same pole. There are two ways of winding the compensating coil on the stator of the machine viz., the distributed winding and the block or concentrated type of winding. Though the latter method is employed commonly, the distributed windings have been found to be far superior in their compensating effect. As its name suggests, this type of winding is distributed around the stator, somewhat like the stator winding of an induction motor. In order to improve transient performance and reduce residual magnetism, the field structure is built up of laminations.

Armature: The armature of the amplidyne is wound in the usual way and is identical in all respects to that of the d-c generator. The commutator is also the same except for the connection of the brushes bearing on it. The conventional pair of brushes is short-circuited and an extra pair is placed at 90 electrical degrees to the former.

A review will now be given of the working of a two-pole amplidyne, with reference to figures 1 and

2, which illustrate the fluxes and currents in the machine. The axis along which the main control flux acts is denoted as the'direct-axis' and that along which the armature created flux acts as the 'quadrature-axis'. In what follows, reference will always be made to the fluxes along these axes as the direct-axis flux and quadrature-axis flux respectively. In addition, the current flowing in the armature due to the short-circuit is refered to as the 'quadrature-axis'current in order to distinguish it from the load current.

FIRST STAGE OF OPERATION: The input power into the control field is of the order of a watt or two, and this is usually obtained from an external d-c supply. The magneto-motive-force set up on the flow of the control current (a few milliamps in magnitude) produces a flux along the direct-axis as shown in figure 1. Due to the rotation of the armature conductors in this flux, a speed voltage is generated at the brushes on the quadrature-axis. The magnitude of this voltage is very small, since the flux causing it is weak. In the case of the test machine, the flux per pole due to the control current, was found by calculation to be only 59800 lines at rated output voltage on no load, giving an actual air-gap density of 4900 lines per square inch.

FUNCTIONAL DIAGRAM OF AMPLIDYNE ON LOAD

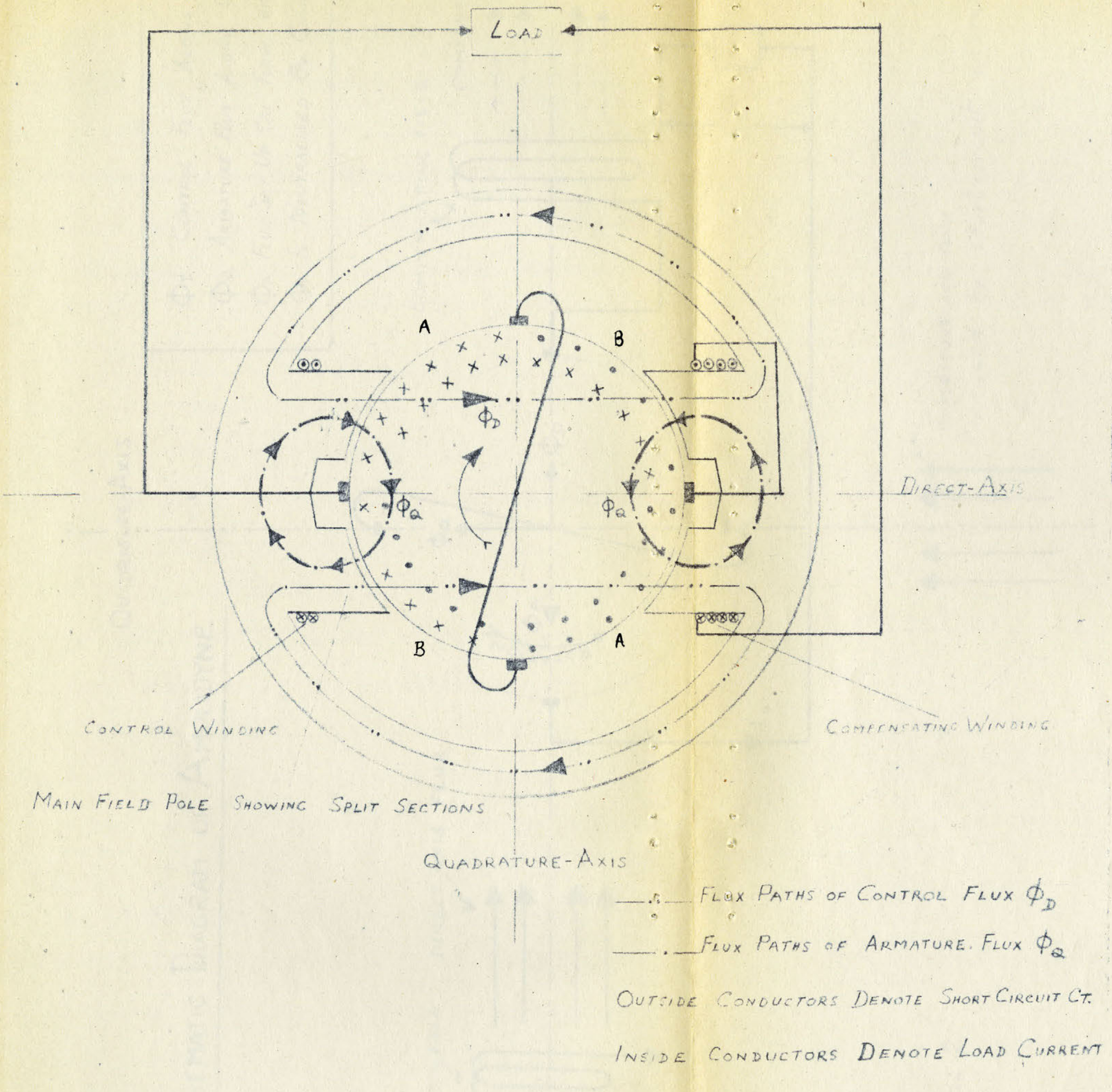


FIGURE : 1

Schematic Diagram of Amplidyne

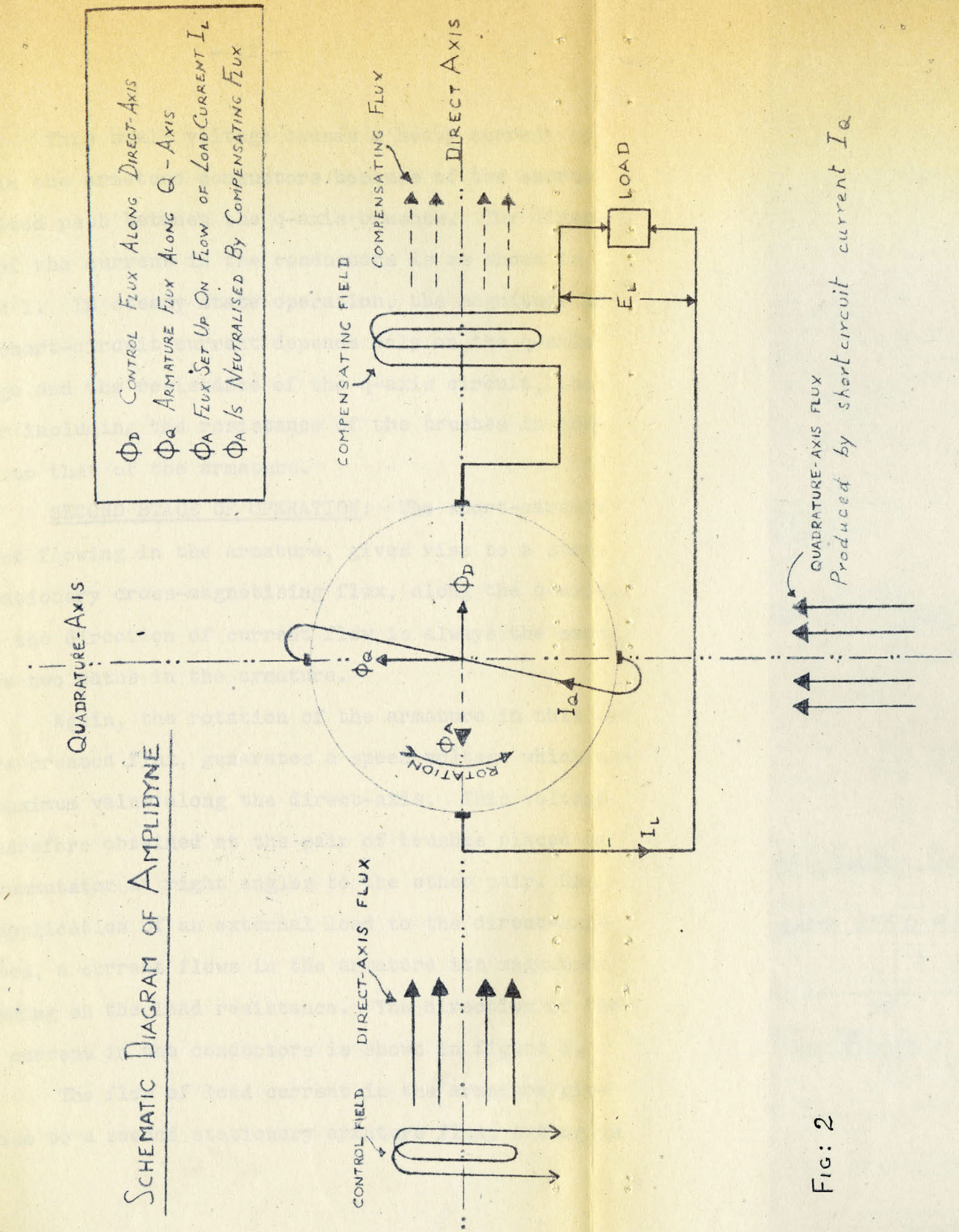


Fig: 2

This small voltage causes a heavy current to flow in the armature conductors because of the short-circuited path between the q-axis brushes. The direction of the current in the conductors is as shown in figure 1. In steady state operation, the magnitude of this short-circuit current depends only on the q-axis voltage and the resistance of the q-axis circuit, the latter including the resistance of the brushes in addition to that of the armature.

SECOND STAGE OF OPERATION: The short-circuit current flowing in the armature, gives rise to a strong stationary cross-magnetising flux, along the q-axis, since the direction of current flow is always the same in the two paths in the armature.

Again, the rotation of the armature in this armature created flux, generates a speed voltage which has a maximum value along the direct-axis. This voltage is therefore obtained at the pair of brushes placed on the commutator at right angles to the other pair. On the application of an external load to the direct-axis brushes, a current flows in the armature its magnitude depending on the load resistance. The direction of the load current in the conductors is shown in figure 1.

The flow of load current in the armature gives rise to a second stationary armature flux, acting in a direction opposite to that of the direct-axis control flux. The tendency of this load flux is therefore to wipe out the control flux. This is prevented by the action of the compensating winding which is connected in series with the armature and load. The compensating flux produced on the flow of load current, effectively neutralises the armature load flux both in magnitude and direction. This compensation therefore makes it possible for the independent control of the magneto-motive-force of the control winding by variation of the current in it.

The short-circuiting of the brushes on the quadrature- axis enables the attainment of an important objective in a power amplifier viz., the reduction of the excitation or control power to a very minute value, where it can be readily supplied and handled by precise control devices and at the same time obtaining the strong flux necessary to generate normal voltage.

AMPLIFICATION: The first stage of amplification in the amplidyne, is from the control circuit to the short-circuited brushes on the quadrature-axis. The second stage is from the short-circuited brushes to the output or load brushes on the direct-axis. First stage amplification is usually higher than that of the second stage. This type of amplification in two stages may be considered to be a sort of cascade arrangement, the overall amplification being $A_1 A_2$ where A_1 and A_2 are respectively the amplifications of the first and second stages.

FACTORS AFFECTING THE OPERATION

Brushes and brush position: Brushes in the quadrature-axis circuit play a very important part in determining the performance of the machine. Since the resistance of this circuit is very low, the brush resistance represents a considerable portion of the total value and hence for a certain current flow in the circuit, the brush drops are considerable. The circumferential dimension of the brush and the resistance across the face of the brush are factors which affect the short-circuit current in the conductors undergoing commutation, which in turn contribute magneto-motive-force in the quadrature-axis. An increase or decrease in the resistance of this circuit alters the time constant of the armature leading to a change in the response of the amplidyne. It will be shown later as to how much the speed of response can be diminished by an increase in the ratio of the inductance of the armature to its resistance.

It has been found in practice that hard carbon brushes are unsatisfactory because of the comparatively high brush drops. Soft graphite brushes have been found to give better and more satisfactory operation.

The position of the brushes with respect to the magnetic neutral axis, in either the direct or quadrature axis, is also a factor to be taken into account, when determining the effective fluxes being cut by the armature. For instance, a slight shift in the brush position on the quadrature-axis opposite to the direction of rotation, introduces a magnetising component of flux along the direct-axis aiding the control flux. On the other hand, a shift in the direction of rotation, introduces a demagnetising component. As a result of the shift, the direct-axis and quadrature-axis fluxes cannot be treated as magnetically independent of each other. A similar change in the q-axis flux takes place, when the brushes on the direct-axis are given a small shift. In general, brush shift affects both amplification and response of the amplidyne. It is important therefore, that commutation should be good with the brushes on their respective neutrals.

Commutation: In most amplidynes, commutating poles are provided both in the direct and quadrature axes, to ensure sparkless commutation of the load current and quadrature-axis current respectively. Some machines, however, are built without any commutating poles in both axes, the currents being commutated by brush resistance drop. The load and quadrature-axis currents are superimposed on each other in every armature conductor there being current additions in some and subtractions in others. When an armature coil undergoes commutation in the quadrature-axis, it is only the quadrature-axis current that reverses its direction while the load current in the same coil continues to flow in the same direction as before. Due to this, a slight distortion of flux occurs in the face of the commutating pole, if one is used. Otherwise, the current distribution across the brush face is uneven.

Saturation: In the first stage of operation in an amplidyne, saturation of the magnetic circuit does not take place even with a high control current. This is due to the very low magnitude of the control flux necessary to set up the strong quadrature-axis flux to generate normal output voltage. The voltage at the q-axis brushes has therefore a linear relation to the control current.

The flux densities in the various sections of the magnetic circuit of the test machine, when operating on normal voltage on no load, were calculated with the aid of the design data on the machine, and the values are given below to give an idea of the extremely low densities employed.

Actual air-gap density	---	4900 lines per sq. inch.
Tooth density	---	6950 lines per sq. inch.
Armature core density	---	4700 lines per sq. inch.
Yoke density	---	10000 lines per sq.inch.

The pole section was not uniform and the maximum density was about 18000 lines per sq. inch.

The ampere-turns of the control winding required to produce the small control flux need be only very low, the reluctance of the flux path being quite small. The radial length of the air-gap in amplidynes is made very small, thus reducing the ampere-turns necessary to force the flux across the air-gap. The saturation curve of the first stage is shown in figure 3 for an armature speed of 2750 r.p.m. Knowing the measured value of the self-inductance of the control field, the magnitude of q-axis voltage for various values of control current was calculated and these are included in the figure. A leakage factor of 1.2 for the field was assumed in the calculations.

In the second stage, though the flux produced by the short-circuit current is many times greater than the control flux, saturation is not present in the

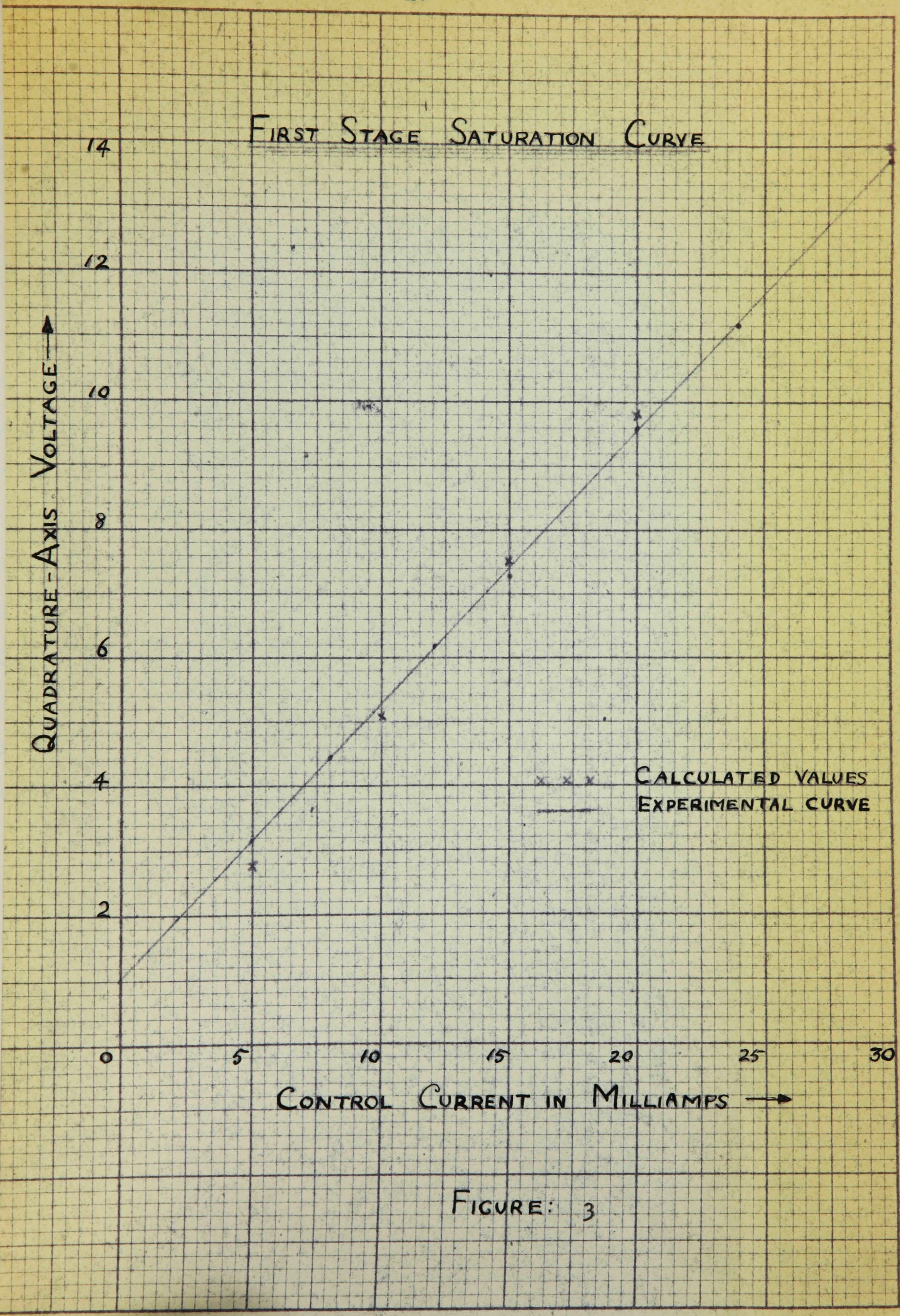

First Stage Saturation Curve
14
12
10
8
6
4
2
0
5
10
15
20
25
30
Quadrature - Axis Voltage
Control Current in Milliamps
x x x Calculated Values
Experimental Curve

Figure: 3

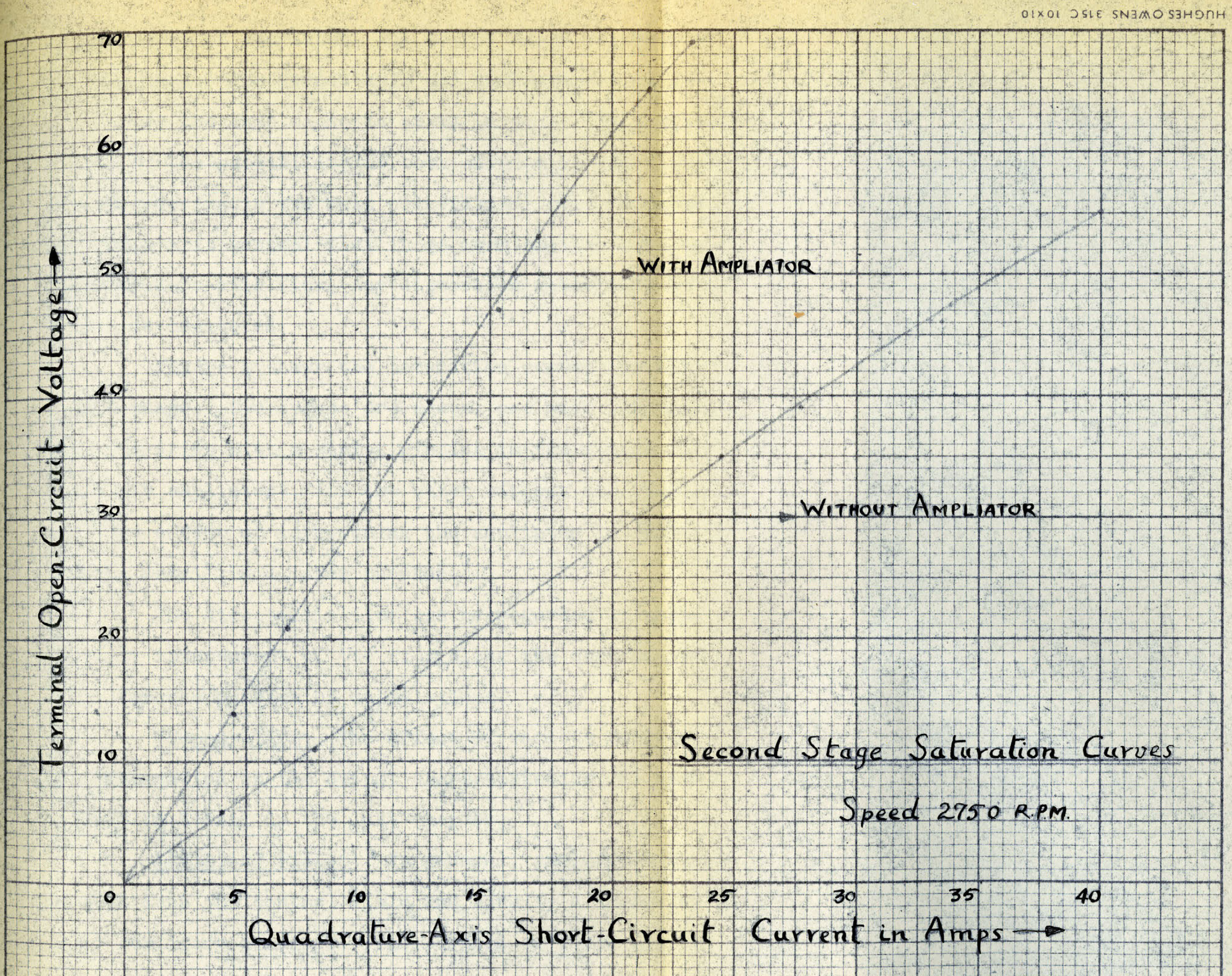

HUGHES OWENS 315C 10x10
Terminal Open-Circuit Voltage →
Quadrature-Axis Short-Circuit Current in Amps →
WITH AMPLIATOR
WITHOUT AMPLIATOR
Second Stage Saturation Curves
Speed 2750 R.P.M.
0
5
10
15
20
25
30
35
40
10
20
30
40
50
60
70

Fig: 4

normal range of operation, due to the large magnetic s-ections used. The direct-axis and quadrature-axis fl-uxes share the same magnetic paths in part. This give-s rise to the possibility of both saturation and dist-ortion occuring in the main pole-faces. But, since t-he direct-axis control flux is so much smaller than t-he quadrature-axis flux, any distortion introduced by it can be neglected.

Figure 4 shows the saturation curves for the second stage. Two curves are shown, one with the mac-hine operating with a series winding in the q-axis (t-ermed the ampliator), and the other without the windi-ng. The effect of introducing the ampliator is dealt with in detail in a later chapter.

The direct-axis flux can be regarded as magn-etically independent of the flux along the quadrature-axis, for the purpose of calculations.

Compensation: The effect of various degrees of compensation on the output characteristics, is dea-lt with in detail in the last chapter.

AUXILIARY FIELDS: In general, amplidynes ha-ve more than one control field and usually a number of other auxiliary windings. The purpose of these addit-ional windings is to produce additive fluxes either in the direct-axis or quadrature-axis, the direction depending upon their position and method of connection to the brushes of the machine. A few of the various fields are a) direct-axis series field b) quadrature-axis shunt field and c) quadrature-axis series field. If several independently excited control fields are wound on the pole, the machine will respond to their resultant action and amplify it in the same manner as for a single field.

C H A P T E R 3

TRANSIENT OPERATION

The amplidyne is analogous to a d-c generator coupled to and excited from a pilot exciter whose excitation is obtained from an external source. In this arrangement, the first stage of amplification is between the input to the pilot exciter field and the output from its armature. The second stage is from the input to the generator field to the power supplied by the generator. This arrangement results in a cumulative delay in response of the generator output voltage to variations in the input to the field of the pilot exciter.

General: An analysis of the speed of response of an amplidyne generator, must take into account the different stages involved. The machine may be considered as composed of three different but not independent circuits. The first circuit consists of a control winding connected to a source of d-c supply, in series with a variable high non-inductive resistance. In the second stage, there is a small d-c generator whose voltage is generated by the flux which the winding in the

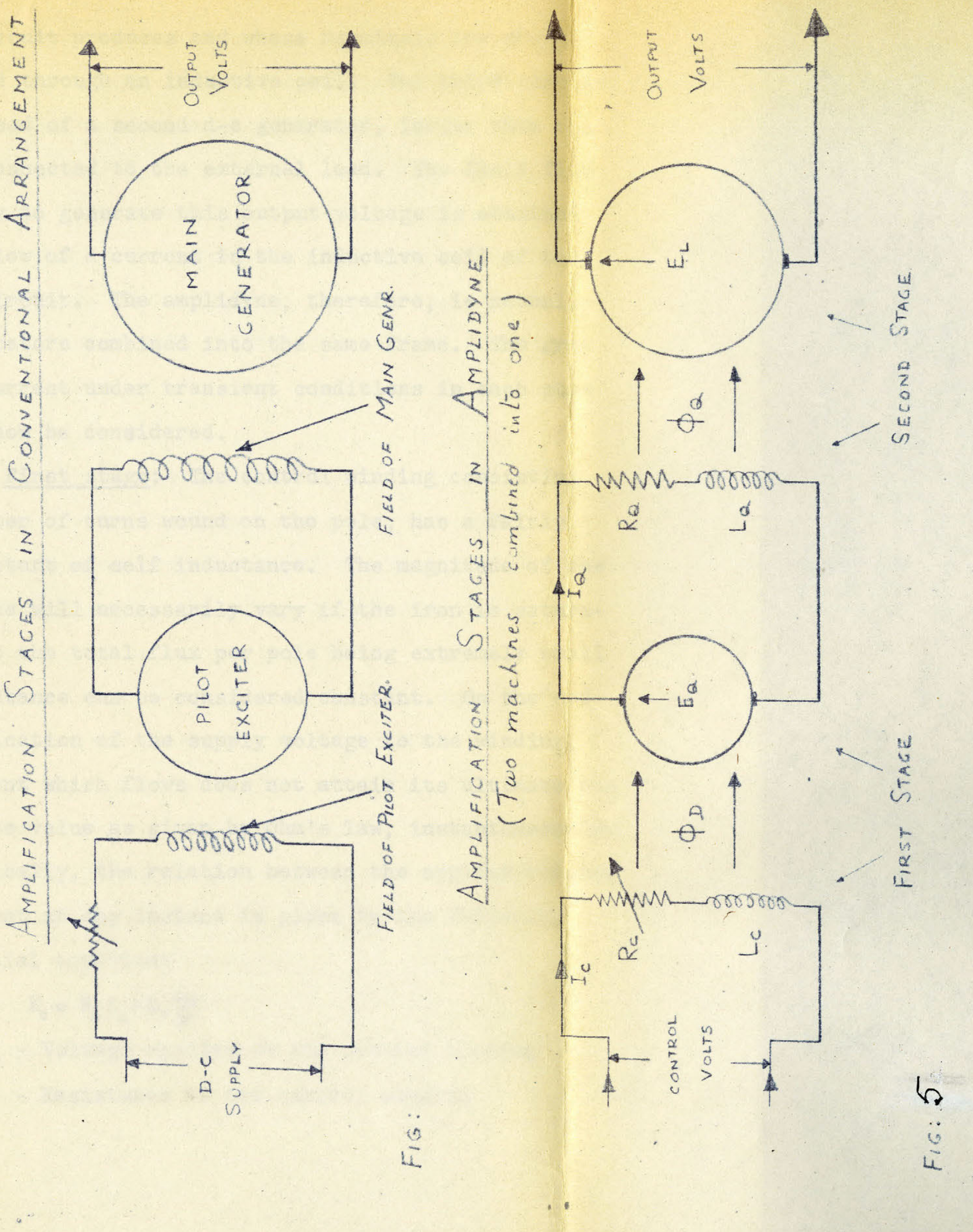


Fig: Amplification Stages in Conventional Arrangement

Fig: 5 Amplification Stages in Amplidyne (Two machines combined into one) first circuit produces and whose terminals are short-circuited through an inductive coil. The third circuit is composed of a second d-c generator, larger than the first, connected to the external load. The field flux necessary to generate this output voltage is obtained by the flow of a current in the inductive coil of the second circuit. The amplidyne, therefore, is actually two generators combined into the same frame. The growth of current under transient conditions in each stage will now be considered.

First stage: The control winding consisting of a number of turns wound on the pole, has a fairly high constant of self inductance. The magnitude of the inductance will necessarily vary if the iron is saturated. But the total flux per pole being extremely small the inductance can be considered constant. On the sudden application of the supply voltage to the winding, the current which flows does not attain its ultimate steady state value as given by Ohm's law, instantaneously. Mathematically, the relation between the applied voltage and current at any instant is given by the following differential equation:

$$E_c = R_c i_c + L_c \frac{di_c}{dt}$$

where E_c - Voltage applied to the control winding

R_c - Resistance of the control winding

L_c - Inductance of the control winding in henries

i_c - Instantaneous value of the current in the winding

The solution of this equation is:

$$i_c = E_c / R_c (1 - e^{-\frac{R_c t}{L_c}})$$

The ratio L_c / R_c is known as the time constant of the winding, it being the time taken in seconds for the current to rise to .632 of its ultimate value. The control winding can be made to have the desired time constant by the addition of a high resistance in series with the winding.

The magneto-motive-force due to the flow of the current forces the flux across two air-gaps in series and the magnetic structure of the machine. The iron losses (eddy current and hysteresis) due to the very rapid growth of flux, cause the flux to lag behind in time phase the current producing it. The iron losses depend both on the rate of growth of flux and the density in the iron parts. In the amplidyne, the flux density in the core, yoke, teeth and pole being almost negligibly small, the eddy current and hysteresis losses can be neglected and the flux and current assumed to be in time phase. To illustrate this, the induced voltage due to transformer action at the q-axis brushes, on the sudden application of the control current, was recorded on an oscillogram taken on the test machine. In the test, the armature was blocked, other windings open-circuited, and the brushes on the direct-axis raised, before the control current was suddenly applied. The oscillogram (film No.1, page 26) shows the induced voltage due to the flux to be very nearly in time phase with the current justifying the assumption stated.

Second stage: In this stage, a closed path is offered for the generated voltage E_q, which is in time phase with the control flux and consequently in phase also with the control current. The magnitude of this voltage is directly proportional to the flux, there being no saturation. Here again, in a similar manner to the first stage, the rise of current will not be instantaneous but will follow an exponential law because of the inductance of the armature.

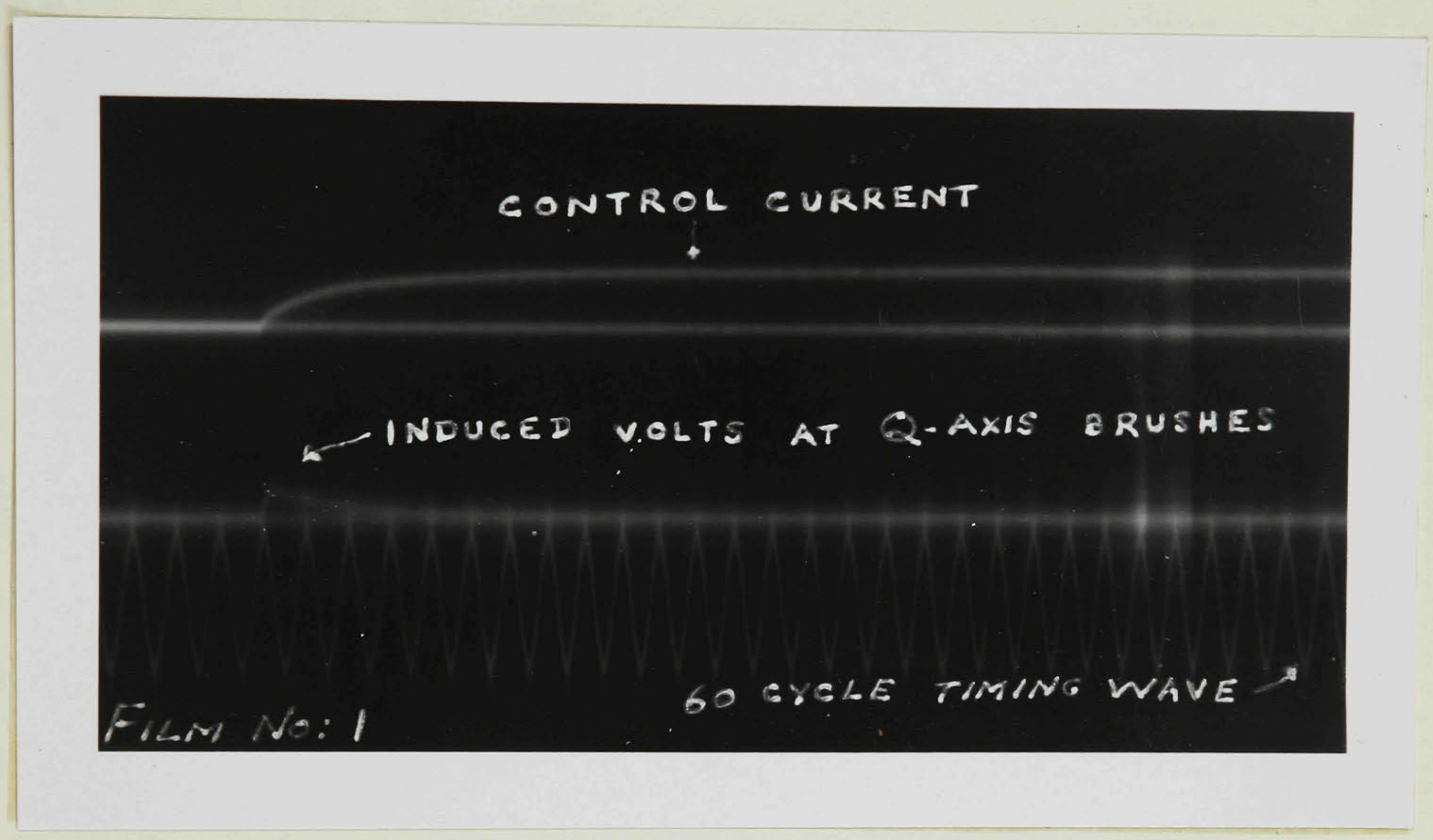
If the voltage E_q were to be suddenly applied to the second circuit, the rise of current can be expressed by the equation $E_q = R_q i_q + L_q \frac{di_q}{dt}$, where

R_q - Resistance of the circuit

L_q - Inductance of the armature in henries

i_q - Instantaneous value of current

The solution of the above equation is $i_q = E_q/R_q(1 - e^{-\frac{R_q}{L_q}t})$, the time constant of this stage being L_q/R_q. The time constant of the quadrature-axis circuit is very small compared with that of the control winding, the rise of



Film No.1.

Oscillogram showing the induced voltage due to transformer action at the q-axis brushes on the sudden application of the control current.

current in it being practically instantaneous. But when a series winding is included in the circuit the time constant is considerably increased.

<u>Output stage</u>: Current can flow in the third stage only when the load is connected to the terminals; The rate of rise of current will therefore depend largely on the constants of the load circuit though the resistance and inductance of the armature will not be negligible.

<u>Overall response</u>: The rise of current in each of the two stages mentioned above is not instantaneous but is exponential. The time delay in the current rise is greater in the second stage than in the first it being assumed that the time constant of the first stage is made extremely small by a series resistance. It is due to the time delay factors of similar magnitude, of these two sequential stages of an amplidyne that there is a measurable delay in the rise of output voltage.

It is possible to derive an equation to represent the rise of output voltage of an amplidyne, by using the time constants of the first and second stages and the resistances of the two stages. In order to simplify the solution of the differential equations involved, the following assumptions will be made:

a) Saturation in both the direct-axis and quadrature-axis magnetic structure is negligible.

b) Eddy current and hysteresis losses in the iron are negligible. A good approximation to the effect of hysteresis is an additional phase lag, which is independent of frequency in the low-frequency range and therefore cannot be represented in terms of a time constant.

c) The fluxes acting along the direct-axis and quadrature-axis are magnetically independent of each other, i.e. there are no mutual flux linkages between the two.

Let, R_c - Resistance in the control circuit

R_q - Resistance of the quadrature-axis circuit.(includes resistance of the brushes and q-axis series coil if connected)

L_c - Inductance of the control circuit

L_q - Inductance of the q-axis circuit

E_c - Voltage applied to control circuit

e_q - Instantaneous value of voltage generated at q-axis brushes

e_t - Instantaneous value of the output voltage

E_t - Final value of output voltage

i_c - Instantaneous value of control current

i_q - Instantaneous value of q-axis current.

k_1 - Slope of first stage saturation curve.

k_2 - Slope of second stage saturation curve.

Current build-up in the first stage can be expressed as: $E_c = R_c i_c + L_c di_c / dt$ (1)

The solution is: $i_c = E_c / R_c (1 - e^{-\frac{R_c}{L_c} t})$ (2)

The voltage in the second stage is in time phase with i_c and also proportional to it.

$$e_q = k_1 i_c = R_q i_q + L_q di_q / dt \quad (3)$$

Substituting for i_c from equation (2) in the above,

$$k_1 E_c / R_c (1 - e^{-\frac{R_c}{L_c} t}) = R_q i_q + L_q di_q / dt \quad (4)$$

The solution of this equation for i_q will consist of two parts a) a complementary function and b) a particular integral.

To find the complementary function:

$$R_q i_q + L_q di_q / dt = 0$$

The solution is: $i_q = Ae^{-\frac{R_q}{L_q} t}$ (5)

Let the particular integral be of the form

$$i_q = C_1 + C_2 e^{-\alpha t}$$

$$di_q / dt = -\alpha C_2 e^{-\alpha t}$$

Substituting these two quantities in equation (4),

$$k_1 E_c / R_c (1 - e^{-\frac{R_c}{L_c} t}) = -L_q \alpha C_2 e^{-\alpha t} + R_q C_1 + R_q C_2 e^{-\alpha t} \quad (6)$$

Equating like coefficients on both sides,

$$R_q C_1 = k_1 E_c / R_c$$

Therefore, $C_1 = k_1 E_c / R_c R_q$ (7)

Equating the terms involving e,

we have $$-k_1 E_c / R_c \cdot e^{-\frac{t}{T_c}} = (R_q C_2 - L_q \alpha C_2)\, e^{-\alpha t}$$

Therefore, $$\alpha = 1 / T_c \qquad (7a)$$

where $$T_c = L_c / R_c$$

And $$L_q / T_c \cdot C_2 - R_q C_2 = k_1 E_c / R_c$$

From which, $$C_2 = k_1 E_c / R_c \cdot \left\{ 1 / (L_q / T_c - R_q) \right\}$$
$$= k_1 E_c / R_c R_q \cdot \left\{ 1 / (L_q / T_c R_q - 1) \right\}$$
$$= k_1 E_c / R_c R_q \cdot \left\{ 1 / (T_q / T_c - 1) \right\} \qquad (7b)$$

where $$T_q = \text{Ratio } L_q / R_q$$

Hence i_q can be written as:

$$i_q = A\, e^{-\frac{t}{T_q}} + k_1 E_c / R_c R_q + k_1 E_c / R_c R_q \cdot \left\{ 1 / (T_q / T_c - 1) \right\} e^{-\frac{t}{T_c}} \qquad (8)$$

Applying initial conditions,

At the instant $t = 0$, $i_q = 0$

Therefore, $$0 = A + k_1 E_c / R_c R_q \cdot \left\{ 1 + 1 / (T_q / T_c - 1) \right\}$$
$$= A + k_1 E_c / R_c R_q \cdot \left\{ T_q / (T_q - T_c) \right\}$$
$$A = -k_1 E_c / R_c R_q \cdot \left\{ T_q / (T_q - T_c) \right\}$$

The final solution for i_q is the following:

$$i_q = -k_1 E_c / R_c R_q \cdot \left\{ T_q / (T_q - T_c) \right\} e^{-\frac{t}{T_q}} + k_1 E_c / R_c R_q + k_1 E_c / R_c R_q \left\{ 1 / T_q / T_c - 1 \right\} e$$
$$= k_1 E_c / R_c R_q \left\{ 1 + T_c / (T_q - T_c)\, e^{-\frac{t}{T_c}} - T_q / (T_q - T_c)\, e^{-\frac{t}{T_q}} \right\} \qquad (9)$$

The output voltage e_L is proportional (directly) to i_q,

Therefore $e_L = k_2 i_q$

Or output voltage is equal to:

$$e_L = k_1 k_2 E_c / R_c R_q \left\{ 1 + T_c / (T_q - T_c)\, e^{-\frac{t}{T_c}} - T_q / (T_q - T_c)\, e^{-\frac{t}{T_q}} \right\} \qquad (10)$$

The final expression for the **instantaneous** magnitude of the output voltage of an amplidyne generator is seen to be the sum of a series of exponentials. When $t = \infty$, the exponentials attain a zero value and the output voltage is equal to $k_1 k_2 E_c / R_c R_q$. The resistance of the q-axis circuit is seen to be in the denominator of the above term and hence the lower its value the greater is the output voltage. When calculating the response with this equation, it was found that the term $+ T_c / (T_q - T_c).e^{-\frac{t}{T_c}}$ within parentheses, is negligibly small after a time interval of 3 cycles (1 cycle = 0.0167 sec.). The time of build-up therefore, depends to a large extent on the negative term $- T_q / (T_q - T_c).\ e^{-\frac{t}{T_q}}$. The higher the magnitude of the time constant T_q, the greater is this term resulting in a slower response. The introduction of a series field in the quadrature-axis circuit greatly increases the time constant T_q which in turn results in a slow response.

In practical amplidynes, the speed of response of the voltage to sudden changes in control current, is slower than the theoretical equation would seem to indicate. This characteristic is taken up in detail in the next chapter.

CHAPTER 4

CHARACTERISTICS

This chapter will deal with the characteristics of an amplidyne such as amplification, compensation and response, with experimental evidence in support of the theory wherever necessary. The test machine was a Canadian General Electric Metadyne Generator used as an amplidyne for the control of a motor.

Description of test machine: The machine had four main poles each pole being subdivided into two, near the pole face, the subdivision designed for the presence of the ampliator (i.e. the q-axis series winding) on each of the two halves. A special arrangement in the connections to the terminals of the field windings, enabled only any two of the opposite poles to be excited at a time. Since each of the two opposite poles was wound to give rise to a South pole effect, the arrangement was equivalent to utilising all the four poles at the same time with half the number of turns on each pole. A switch-over from one pair of opposite poles to another reversed the direction of the control flux resulting in a reversal of the polarity of the output voltage. The reversal of the armature voltage in this case, was necessary to reverse the direction of rotation of the separately excited d-c motor connected to the generator terminals. The control winding had 4800 turns per coil with one coil per pole.

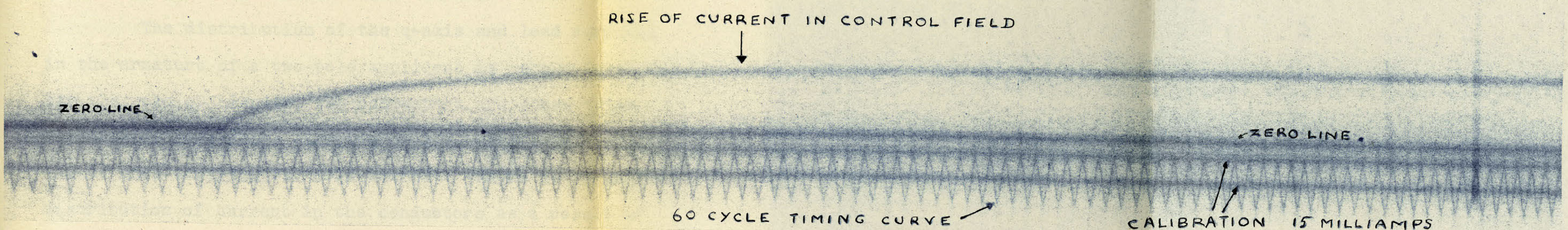
The rise of current in the control field on the sudden application of the voltage, without the addition of any resistance is shown in the oscillogram on page 34 (film No.2). The measured time constant was found to be high being 0.1565 sec. the inductance being 100 henries. The rise of current in the same winding when a high resistance was connected in series, is shown in film No.1 page 26, from which it can be noted that the time constant has been considerably reduced.

STEADY STATE CHARACTERISTICS

Ampliator: The presence of the ampliator in the q-axis circuit affects the operation of the amplidyne from the standpoints of both amplification and speed of response.

The additive turns of the ampliator increase the resistance of the q-axis circuit as a result of which the current in the circuit for a certain q-axis voltage is reduced. The smaller current flowing through the greatly increased number of magnetising turns, increases the flux along the q-axis. For a certain power input into the control winding, the q-axis flux with the ampliator

FILM No:- 2


RISE OF CURRENT IN CONTROL FIELD
ZERO-LINE
ZERO LINE
60 CYCLE TIMING CURVE
CALIBRATION 15 MILLIAMPS

in circuit, is many times greater than the flux without it. In other words, the control power required for generating rated output voltage, with the ampliator, need be only a fraction of the amount required to generate the same voltage without the winding. In the case of the test machine, it was observed that only 0.02 watts input were required in the first case, whereas, 0.80 watts were required to obtain rated voltage with the winding disconnected.

The distribution of the q-axis and load currents in the armature of a two-pole amplidyne is shown in figure 1. For the sake of clarity, the conductors are shown twice, the outside conductors carrying q-axis current and the inside ones carrying the load current. There is an unequal distribution of current in the condubtors as a result of additions in AA and subtractions in BB. The introduction of the ampliator, in decreasing the magnitude of the short-circuit current, improves the condition of unequal current distribution.

COMPENSATION The axis of the output circuit of an amplidyne is on the same magnetic axis as the control circuit. Since this gives rise to a direct magnetic back coupling between the output and control circuits, the compensating winding is introduced with the object of neutralising the back coupling. There are three different degrees of compensation possible in an amplidyne. They are a) Critical compensation b) Overcompensation and c) Undercompensation. The compensating flux adds directly to the control flux if the machine is overcompensated and subtracts from it if undercompensated.

Critical compensation: This degree of compensation signifies the ideal condition in which the armature flux set up on the flow of load current is completely neutralised by the compensating flux. In other words, this denotes the case when the mutual inductance between the armature and compensating coil is equal to the self-inductance of the armature. The direct-axis control flux remains unaffected whatever the load current is and as a result, the q-axis voltage and current remain constant. This can be seen from the following equations:

$$E_q = \phi_c Z N/60 \cdot p/a \cdot 10^{-8}$$

where ϕ_c - Control flux

Z - Total number of conductors in the armature

N - Speed in r.p.m.

p - Number of poles

a - Number of parallel paths in the armature

$$I_q = E_q / R_q$$

Treating the q-axis and direct-axis fluxes as independent of each other, Flux $\phi_d = \phi_c - \phi_{ARM} + \phi_{COMP}$; since $\phi_{COMP} = \phi_{ARM}$, the direct-axis flux remains constant and as a result E_q = constant.

The current I_q remaining constant, the flux produced by it is also constant. On the application of a steady load to the output terminals, the terminal voltage decreases gradually the decrease being solely due to the armature resistance drop.

Overcompensation: This can be defined as the condition at which the mutual inductance between the armature and compensating coil is greater than the self-inductance of the armature. On load, the compensating flux being greater than the armature load flux, adds directly to the control flux. The increased control flux generates a higher voltage at the q-axis brushes thereby increasing the short-circuit current. As a result the output voltage builds up to a higher value. The machine therefore, behaves like a d-c series generator, the voltage and current rising to high values on load. The amplidyne, in this case, is a regenerative amplifier in which part of the output is fed back again into the input by virtue of too many turns in the compensating coil. A high degree of overcompensation is not employed in practical amplidynes as the machine becomes unstable in operation.

Undercompensation: In this case, the number of turns on the compensating coil are reduced below the value necessary to fully neutralise the armature flux.

On the flow of a load current, the armature flux being greater than the compensating flux, diminishes the control flux. As a result, the q-axis voltage, q-axis current and output voltage decrease to lower values. The machine can be considered to be a degenerative amplifier, the output voltage and short-circuit current diminishing gradually as the load current increases. A slight undercompensation in amplidynes, makes them perfectly stable in operation.

Experimental evidence: The test machine was slightly undercompensated, the compensating coil being wound with 8 turns with one coil per pole. As the number of turns could not be altered to permit of either critical or overcompensation, experiments could not be conducted to determine the variation of terminal voltage and short-circuit current on load. However, with the aid of the complete design data of the test generator, the above values were calculated for all the degrees of compensation. The results were obtained by using the measured and calculated values of the constants of inductance and resistance of the windings, in calculating the various flux linkages involved. The following assumptions were made to facilitate the calculation of the fluxes:

a) The armature has a leakage co-efficient of 1.14.

b) The co-efficient of mutual coupling between the armature and compensating coil is unity. The position of the compensating coil on the main pole was such that the leakage to the yoke could be neglected.

c) The resistance of the q-axis circuit remains constant.

d) The direct and quadrature fluxes are magnetically independent of each other.

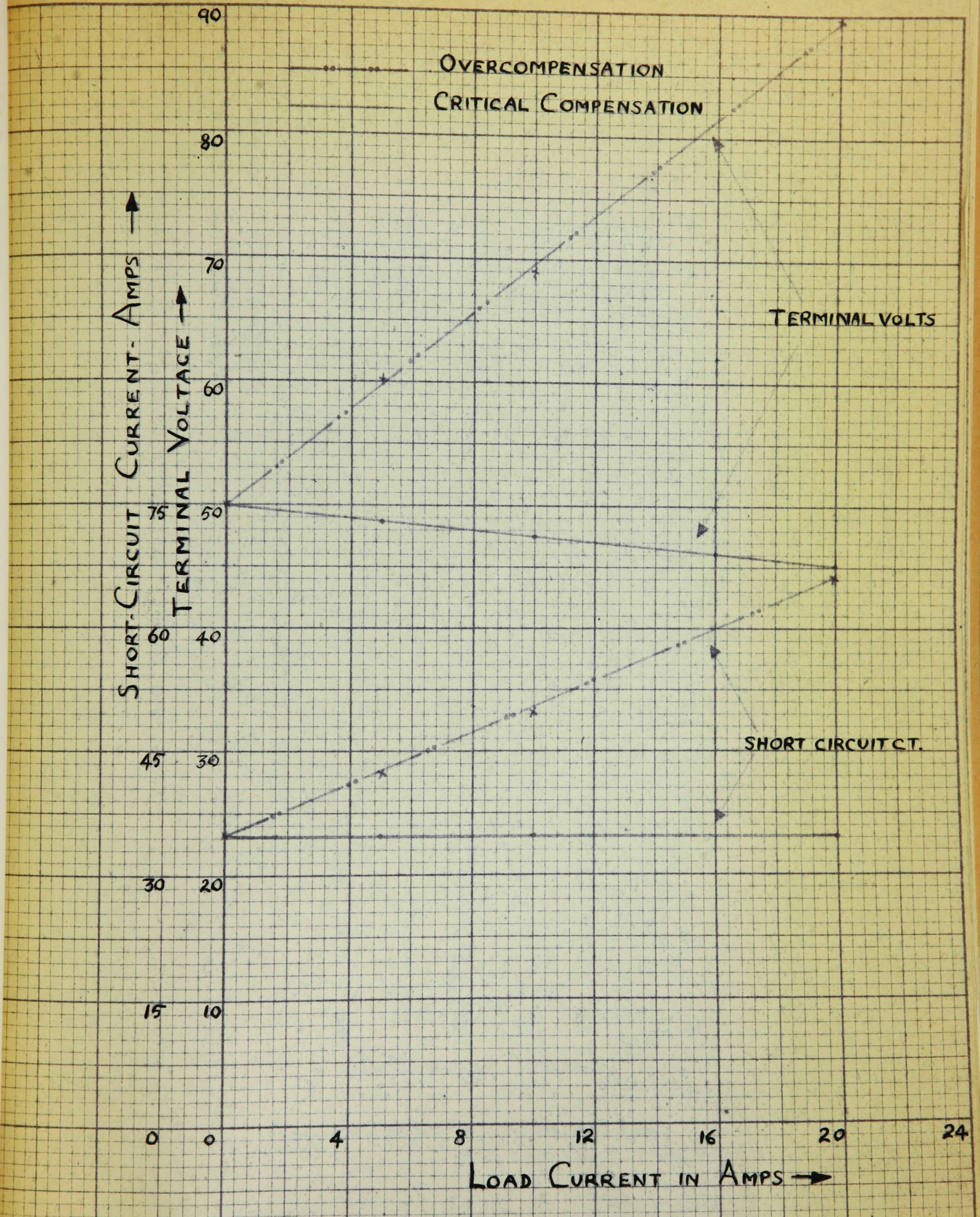
It might appear that these assumptions are too arbitrary but the purpose of the calculation is only to show how from the designer's point of view, the characteristics of voltage and current can be predicted to a fair degree of accuracy. The constants used in the calculation were:

1) Inductance of armature - 0.0022 henries

2) Inductance of compensator - 0.00118 henries

3) Resistance of armature - 0.25 ohms.

The control flux necessary to generate the initial voltage at rated speed and no load was calculated at first. Then for each load current, the sum of the armature and compensating fluxes was determined and added directly to the control flux. Knowing the altered magnitude of the control flux, the q-axis voltage, q-axis current and finally the output voltage were determined. The armature resistance drop was subtracted from the calculated value to get the terminal voltage. Figure No.6 on page 40 shows the characteristics for critical and overcompensation. The number of turns in the compensator, for the case of overcompensation, was assumed to be 14 turns per coil.



OVERCOMPENSATION
CRITICAL COMPENSATION
TERMINAL VOLTS
SHORT CIRCUIT CT.
SHORT-CIRCUIT CURRENT - AMPS
TERMINAL VOLTAGE
90
80
70
60
75 50
60 40
45 30
30 20
15 10
0 0
4
8
12
16
20
24
LOAD CURRENT IN AMPS

FIGURE: 6

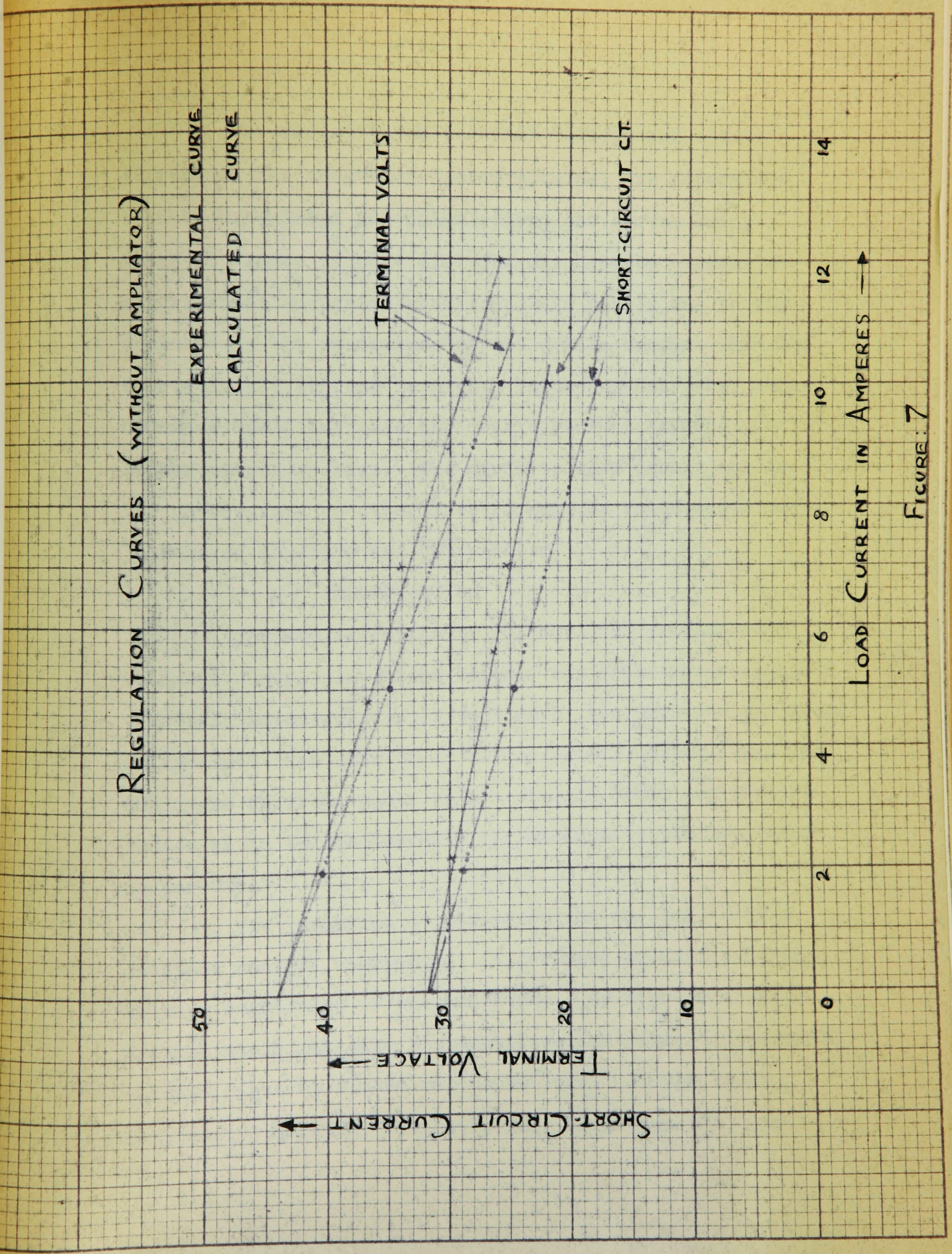

REGULATION CURVES (WITHOUT AMPLIATOR)
EXPERIMENTAL CURVE
CALCULATED CURVE
TERMINAL VOLTS
SHORT-CIRCUIT CT.
0
2
4
6
8
10
12
14
LOAD CURRENT IN AMPERES
50
40
30
20
10
TERMINAL VOLTAGE
SHORT-CIRCUIT CURRENT

FIGURE: 7

The variation of terminal voltage and q-axis current in the undercompensated machine, was determined both by experiment and calculation, the curves being shown in figure 7, page 41. The discrepency between the experimental and calculated values is partly due to the decrease in the resistance of the q-axis brushes when the short-circuit current is high. In the actual case, this decrease would increase the q-axis current leading to a higher output voltage. The error is also partly due to the uncertainty of other factors such as commutation and leakage of armature and compensator.

AMPLIFICATION

The amplification is the ratio of output power to input power. As stated before, the input power required to obtain rated voltage is very much less when the ampliator is included than when it is disconnected. Hence, when the amplidyne delivers power to an external load, the amplification ratio is considerably increased with the ampliator in circuit.

The variation in amplification on load, with a constant control excitation, is governed primarily by the voltage regulation of the amplidyne. An overcompensated machine would increase the amplification since the terminal voltage rises to higher values on load. In the undercompensated machine, the ratio increases when the load current is small and after a maximum value is attained decreases with further increase of load . This is due to the lower terminal voltages obtained at high load currents.

The excitation of the control field of the test machine was adjusted to give an initial output voltage of 44 v. (without the ampliator). The amplification ratio was determined both by experiment and calculation, for various load currents. The curves are shown in figure 8, page 44. The calculations were carried out with the aid of the regulation curves of figure 7, the only additional assumption being that the control winding had a leakage co-efficient of 1.20. This figure is justified as the machine had four poles and an external diameter of 12.75". The agreement between the calculated and experimental curves is closer than in the case of the voltage curves. This was apparently due to both the calculated input power and output power being lower resulting in the ratio of amplification remaining very much the same. The maximum amplification obtained was about 700.

Amplification with the ampliator: A load test on the test machine was conducted with the ampliator connected between the q-axis brushes. Three different initial control excitations were utilised for three separate load tests. It can be noted that as the control excita-

AMPLIFICATION CURVE FOR FIXED INITIAL EXCITATION

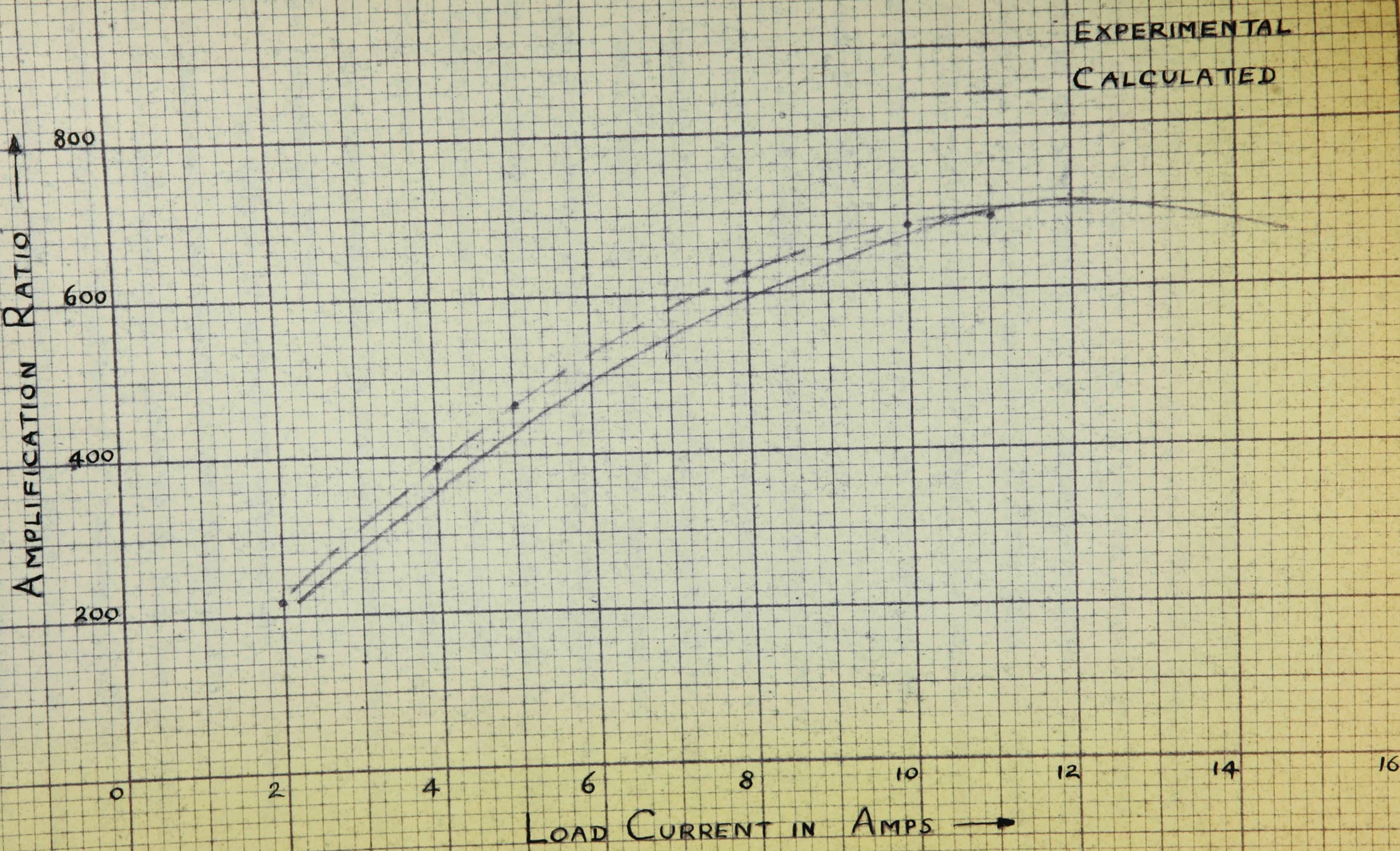


FIGURE: 8

tions are increased, the amplifications decrease. The curves are shown in figure 9 page 46. Though the higher initial excitations give rise to higher initial voltages, the ratio of the output to the input decreases since the increase in the control power is greater than the corresponding increase in the output power. The amplification ratio is in thousands, whereas, it was only a few hundreds without the ampliator.

In practice, the control excitation in an amplidyne is not kept constant but is varied, either manually or automatically, to obtain higher outputs under varied load conditions. In this case, the amplification will be reduced considerably at high outputs, the input power being correspondingly high. Figure 10 on page 47, shows the relation between amplification and output watts as the control power is increased. The amplification is about 29000 when the output is low and decreases to about 2950 at an output of 1·6 kw.

The degree of agreement between the calculated and experimental regulation curves shown in figure 7, page 41 would have been very much closer if it had been possible to measure the self-inductance of the compensating coil with a bridge. But unfortunately this could not be done as no leads of the compensator were brought outside of the test machine. As a result, the calculated value had to be used.

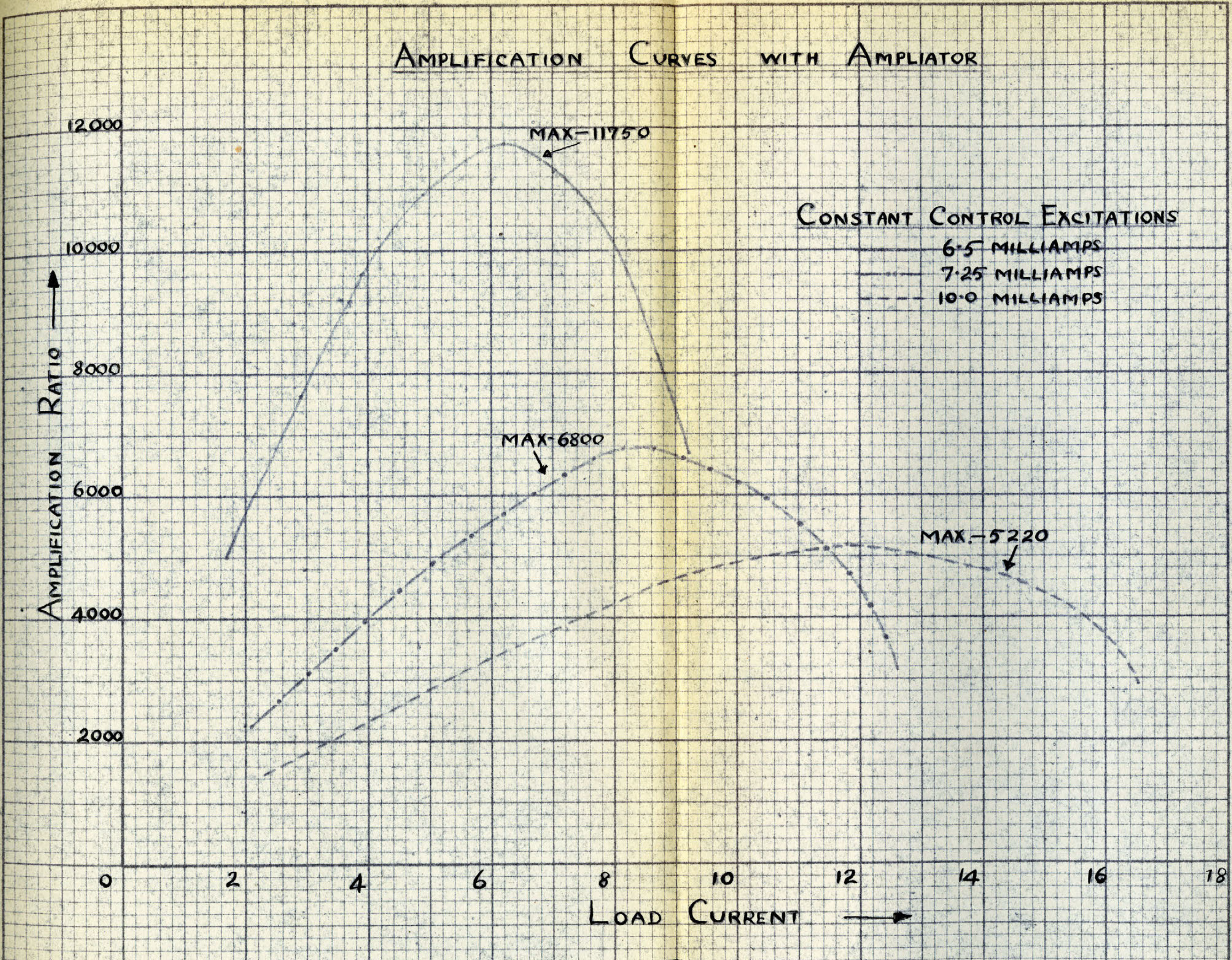

AMPLIFICATION CURVES WITH AMPLIATOR
MAX.-11750
CONSTANT CONTROL EXCITATIONS
6·5 MILLIAMPS
7·25 MILLIAMPS
10·0 MILLIAMPS
MAX-6800
MAX.-5220
12000
10000
8000
6000
4000
2000
AMPLIFICATION RATIO
0
2
4
6
8
10
12
14
16
18
LOAD CURRENT

FIGURE: 9

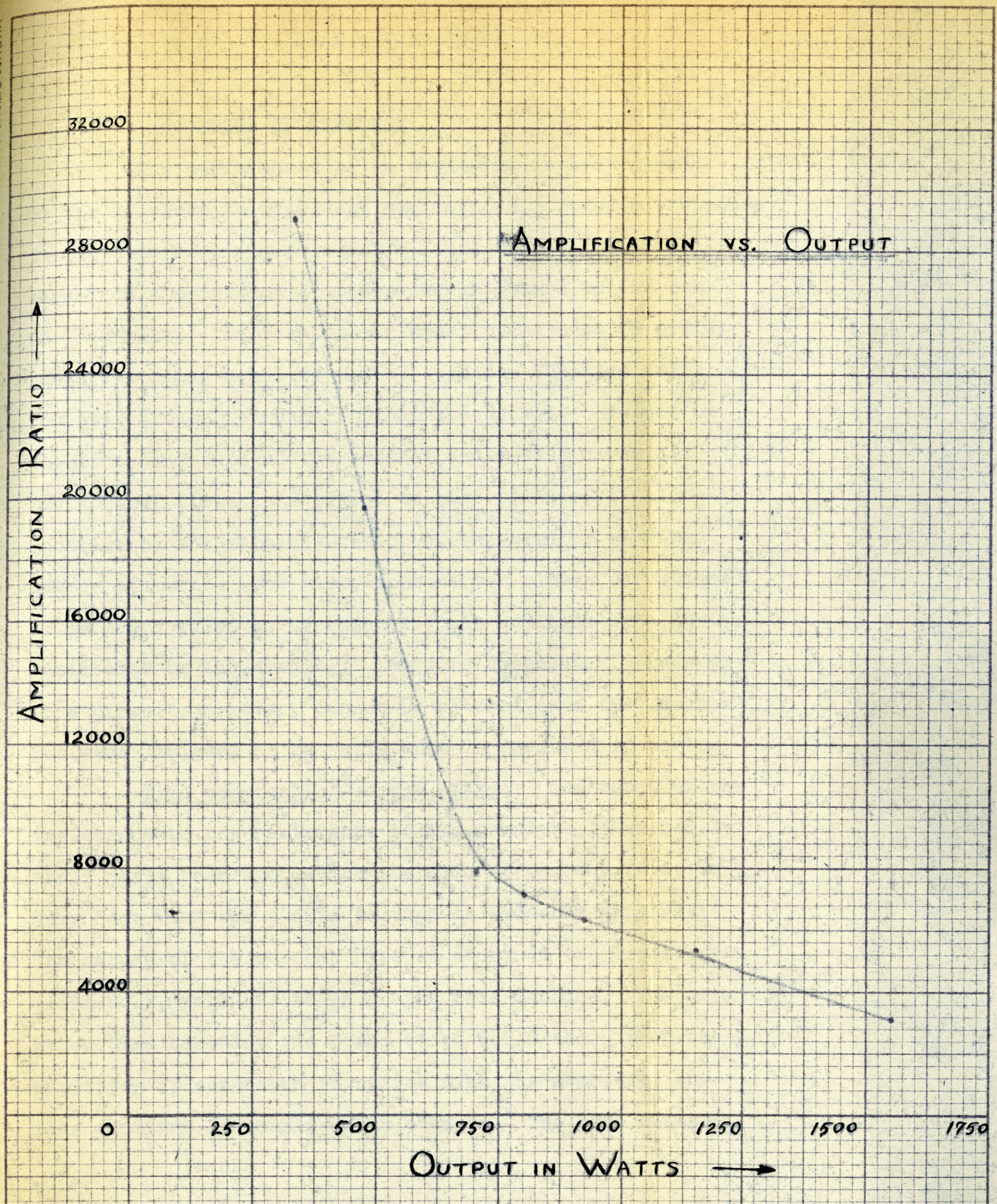
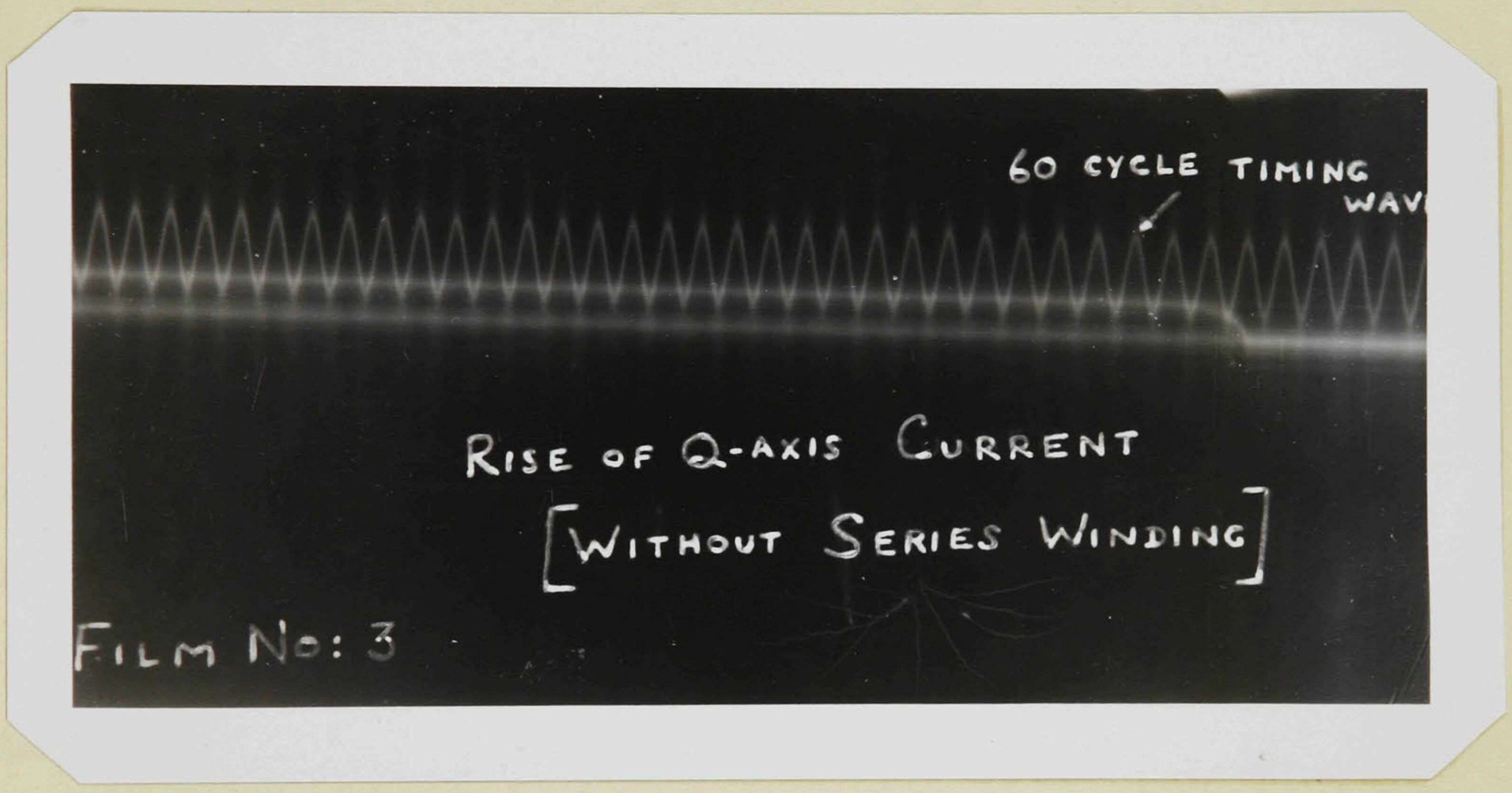

AMPLIFICATION VS. OUTPUT
AMPLIFICATION RATIO
32000
28000
24000
20000
16000
12000
8000
4000
0
250
500
750
1000
1250
1500
1750
OUTPUT IN WATTS

FIGURE: 10

SPEED OF RESPONSE

The performance of an amplidyne is best judged by its response to transient excitations. Speed of response is the time required to reach a final correction in voltage from the instant a sudden change occurs in the control current. The response is usually measured in cycles, one cycle being equal to 0.0167 second. The time taken for the voltage to reach a final steady value depends on the time constants of the control and q-axis circuits. The control field is designed to have the desired time constant by the suitable choice of the size of wire and number of turns. The time constant can always be reduced to as low a value as necessary by the addition of a series resistance to the winding. The time constant of the armature circuit, however, cannot be altered once the machine has been designed as no resistance is included in series.

Time constant of second stage: The ratio of the inductance to the resistance of the armature is extremely small, as a result of which the rise of current in it is very fast when the q-axis voltage is suddenly applied. The nature of the current rise is shown in the oscillogram (film No.3, page 49) taken on the test machine. The measured time constant was found to be 0.010 sec. When the ampliator is connected in series with the armature, the time constant is considerably changed. The time constant



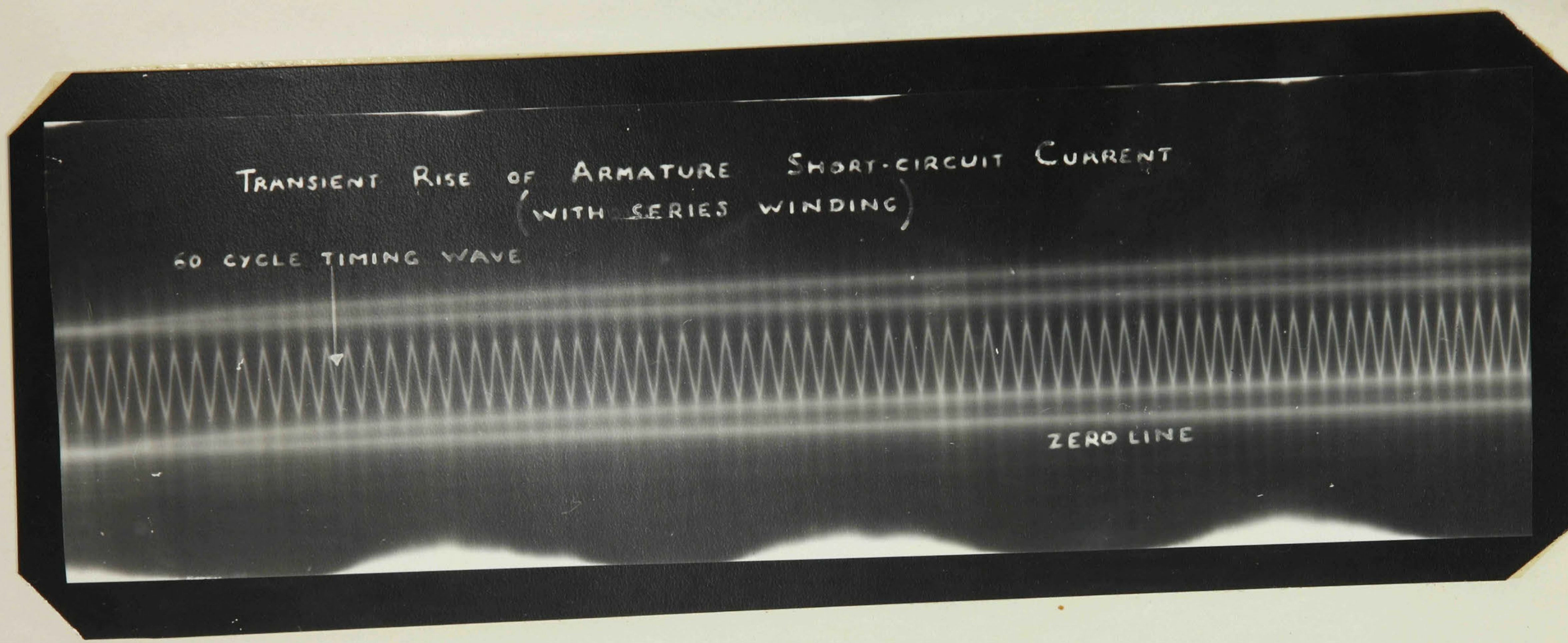
Film No.3

Oscillogram illustrating the transient rise of current in the armature q-axis circuit, on sudden application of the q-axis voltage, without the ampliator.

will either increase or decrease, depending upon the relative increases in the magnitudes of inductance and resistance of the whole circuit. In general, the increase in resistance is very much less than the increase in inductance, the net effect being to increase the time constant. The ampliator was connected to the armature of the test amplidyne and the transient rise of current recorded on an oscillogram (film No.4, page 51). The time constant was measured to be 0.043 second, about four times higher than the value obtained without the ampliator.

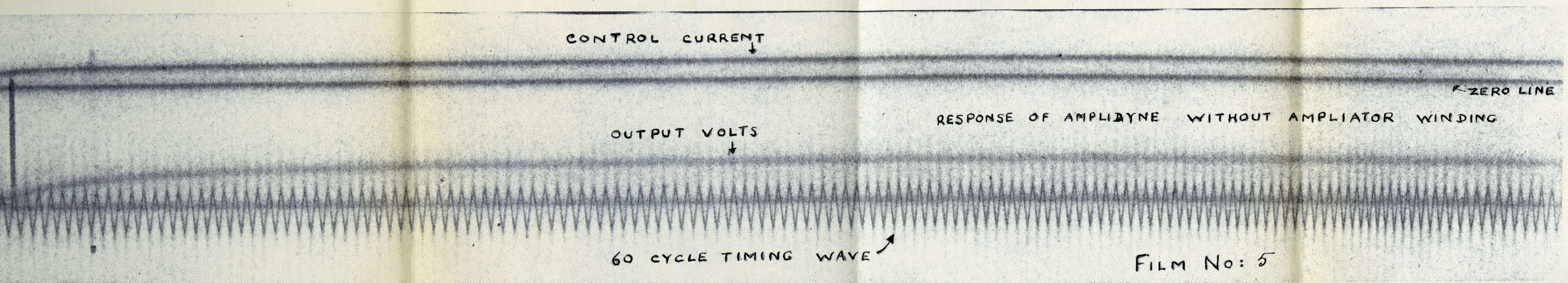
The increase in the time constant of the second stage leads to a slower speed of response. The rise of output voltage on no load, on the sudden application of the control current, was recorded for two cases, firstly without the ampliator and secondly with the ampliator. It can be noted from the oscillograms nos. 5 & 6, that a time of nearly 60 cycles is required for the voltage to attain the steady value in the latter case, whereas, only 35 cycles elapse in the former case. The overall speed is nearly doubled when the ampliator is disconnected.

Response on load: When a fixed control current is suddenly applied with the amplidyne terminals connected to a constant resistance load, the response will be slow. The load current at every instant sets up a demagnetising flux in opposition to the control flux. Since this load

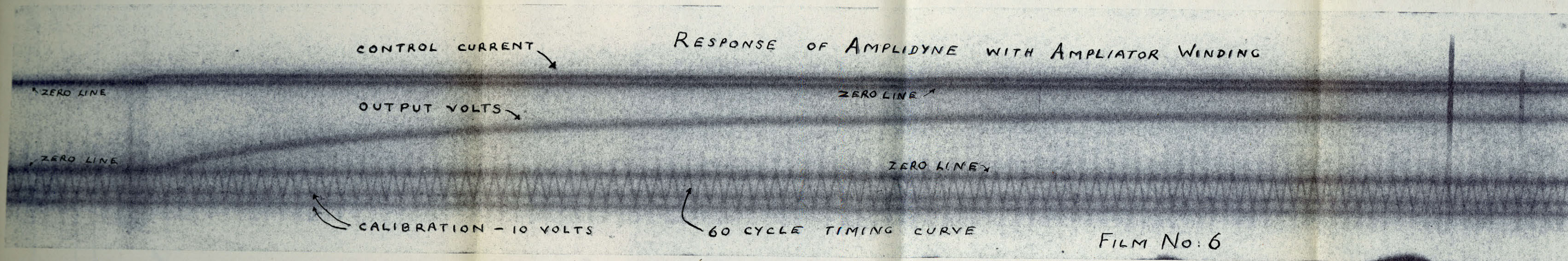


Film No. 4

(Two identical curves shown)


CONTROL CURRENT
ZERO LINE
RESPONSE OF AMPLIDYNE WITHOUT AMPLIATOR WINDING
OUTPUT VOLTS
60 CYCLE TIMING WAVE
FILM No: 5

FILM No. 5


RESPONSE OF AMPLIDYNE WITH AMPLIATOR WINDING
CONTROL CURRENT
ZERO LINE
OUTPUT VOLTS
ZERO LINE
ZERO LINE
ZERO LINE
CALIBRATION - 10 VOLTS
60 CYCLE TIMING CURVE
FILM NO: 6

FILM NO. 6

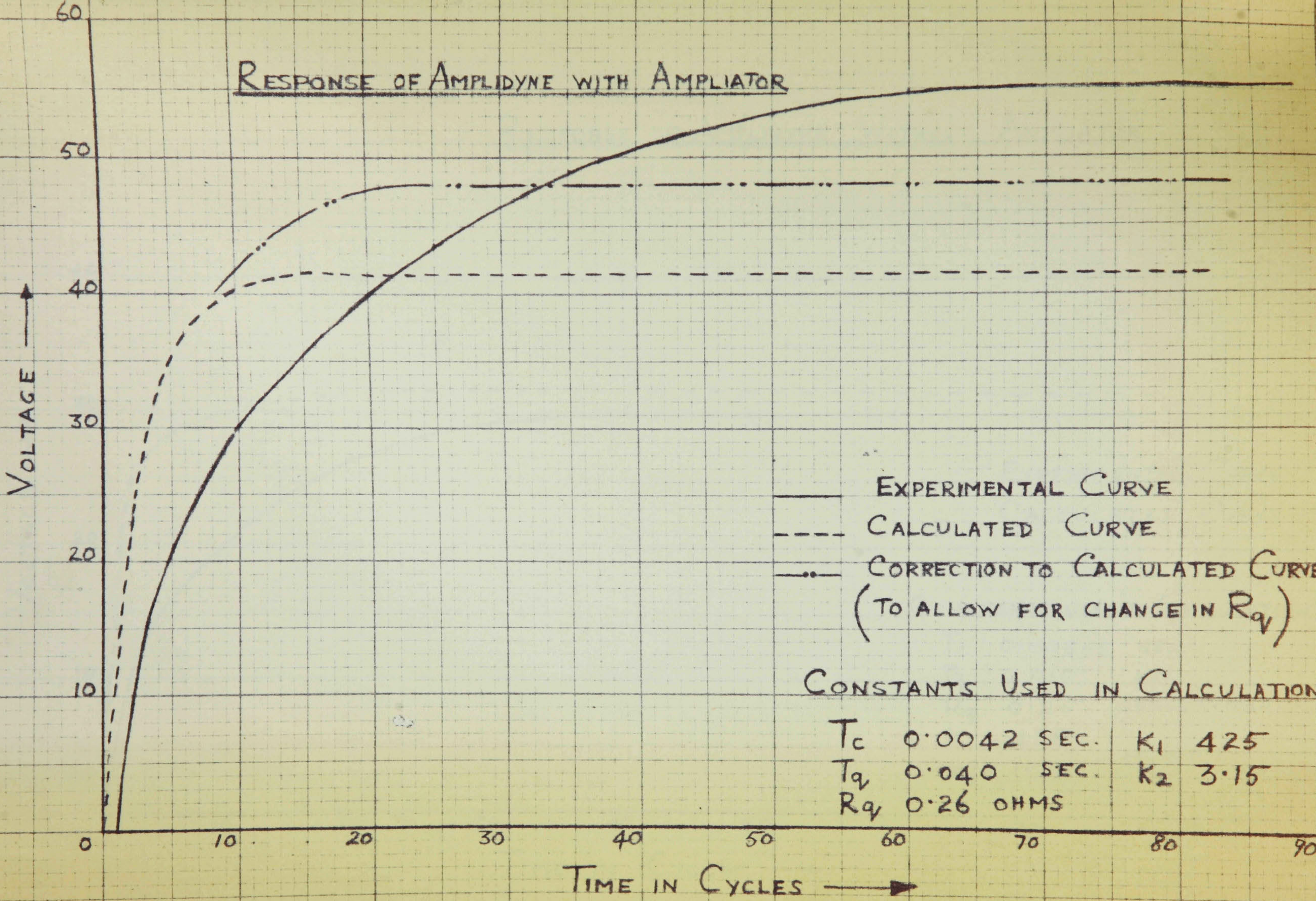

RESPONSE OF AMPLIDYNE WITH AMPLIATOR
VOLTAGE
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
TIME IN CYCLES
EXPERIMENTAL CURVE
CALCULATED CURVE
CORRECTION TO CALCULATED CURVE
(TO ALLOW FOR CHANGE IN R_q)
CONSTANTS USED IN CALCULATION
T_c 0·0042 SEC. K_1 425
T_q 0·040 SEC. K_2 3·15
R_q 0·26 OHMS

FIGURE: 11

RESPONSE OF AMPLIDYNE WITHOUT AMPLIATOR

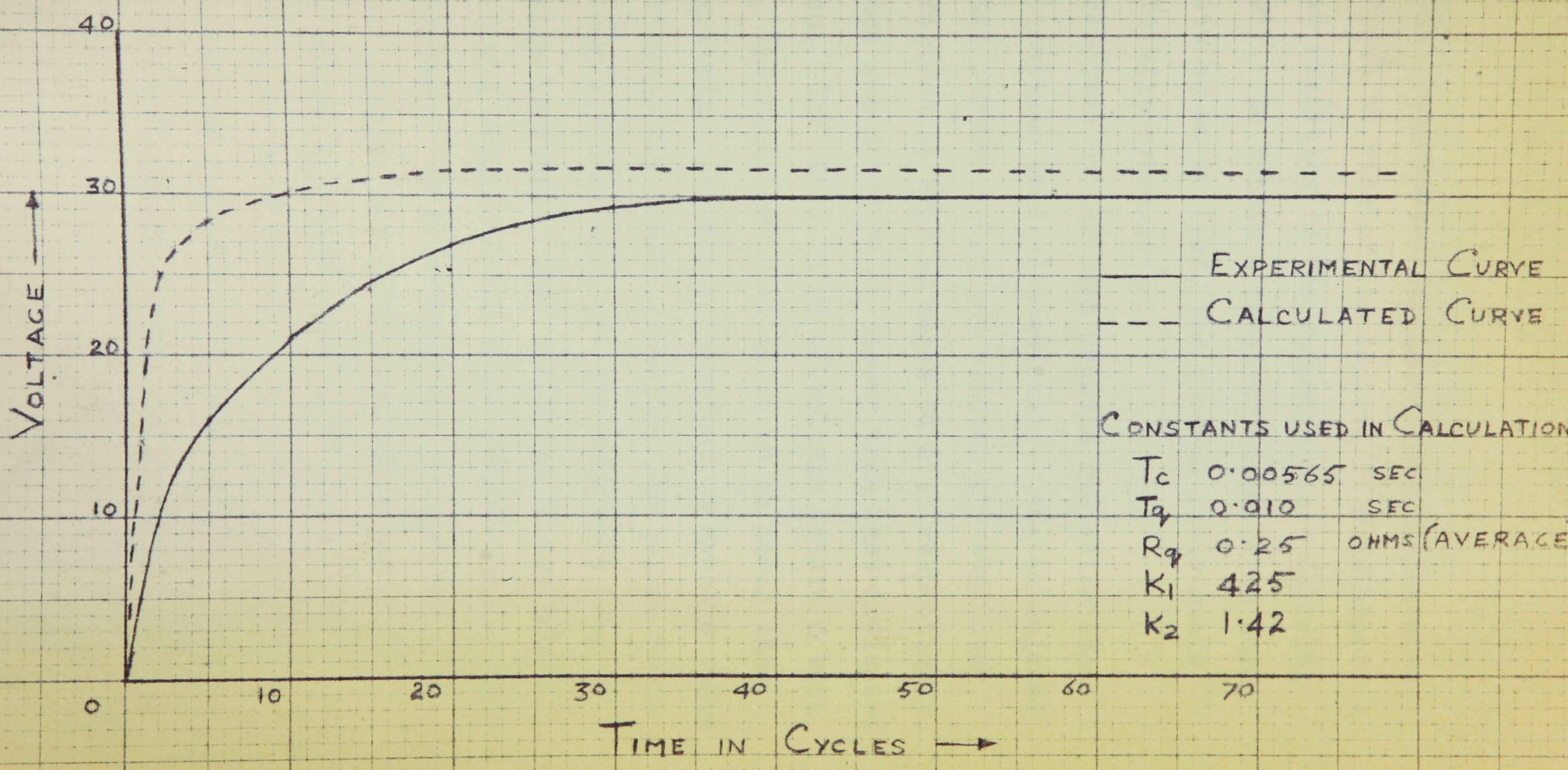


FIGURE: 12

flux is not fully compensated for in an undercompensated machine, the speed of rise of the control flux is appreciably diminished resulting in the output voltage building up rather slowly. To obtain a speed of response on load which is as fast as on no load, the control field would have to be initially overexcited.

The response of the test machine was calculated by using the equations derived previously. The calculated and experimental curves , with and without the ampliator, are shown in figures 11 & 12 on pages 54 & 55 respectively. The actual speed was noted to be slower than that indicated by the equation. The final value of voltage attained with the ampliator, was found by calculation to be lower than the actual magnitude. In the calculation, an average value of q-axis resistance was used. Actually, the q-axis resistance varied from 0.3 ohms when the currents were low, to 0.23 ohms at high currents. This variation in the resistance is due to the change in the brush resistance at higher current densities. To illustrate the increase in the final value of voltage, the calculated curve was slightly modified by taking $R_q = 0.23$ ohms, when it was found that the voltage increased by 7 volts. The actual response is slow mainly because of the transient iron losses in the second stage, which cause the excitation flux to lag behind the current.

Stability under transient conditions: Transient instability may be caused in a critically or slightly undercompensated machine if the mutual inductance between the compensating coil and control coil were to be greater than the mutual inductance between the armature and control coil. A very sudden change in the load current would induce a current in the control coil in such a direction as to increase the flux along the direct-axis. This would result in the output voltage building up to a high value before remaining steady. It is important therefore, to design the position of the compensating coil relative to the control coil in such a manner as to permit a high leakage flux between the two.

Control of a d-c motor: In the test machine, a reversal in the polarity of the armature voltage was made possible by changing over the excitation from one pair of opposite poles to the other. The speed of reversal of a separately excited d-c motor connected to the amplidyne terminals, from full speed in one direction to full speed in the opposite direction, was found to be extremely fast with the ampliator disconnected. The speed of reversal with the ampliator was comparatively slow without any over-excitation. An attempt was made to record the rate of rise of speed by a tachometer generator connected to the motor shaft. But the voltage of the tachometer generator was far too low (26 millivolts) and unsteady to be able to give a reasonably high deflection to the vibrating element of the oscilloscope. As such, the oscillogram is not included in this paper.

CONCLUSIONS

Power amplification and the speed of response of an amplidyne generator are interrelated. An increase in the amplification generally results in a decrease in the speed of response while an increase in the speed of response leads to a far lower amplification. The addition of a series winding in the quadrature-axis (ampliator) considerably increases the amplification though at the expense of the speed of response.

The compensation used should be as nearly critical as possible (without introducing tendencies towards instability) in order to obtain a greater output, high amplification and a fast response. Lastly, it is imperative that low reactance armatures be used in amplidynes to obtain a high speed of response.

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