DESIGN AND OPERATION OF SATURABLE REACTORS AND MAGNETIC AMPLIFIERS

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Burton Howard Wayne

1954

THESIS

This is to certify that the

thesis entitled

"Design and Operation of Saturable Reactors and Magnetic Amplifiers"

presented by

Burton H. Wayne

has been accepted towards fulfillment of the requirements for

M.S. degree in E.E.

[signature]
Major professor

Date May 18, 1954

O-169

DESIGN AND OPERATION OF SATURABLE REACTORS
AND MAGNETIC AMPLIFIERS

By

BURTON HOWARD WAYNE

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE

Department of Electrical Engineering

1954

7-9-54

TABLE OF CONTENTS

PREFACE

The purpose of this thesis is to present in a logical and straightforward manner the fundamentals of the operation of the saturable reactor and the magnetic amplifier. The author wishes to express his thanks to Mr. S. P. Jackson of the General Electric Company for his assistance in the design and testing of the amplistats and interpretation of the results, to Mr Edward Vidro of the Department of Electrical Engineering at M. S. C., for reading the thesis and assistance in continuity, and to D. J. A. Strelzoff of the Department of Electrical Engineering at M. S. C., for his help in the development of this thesis, and for his patience in reading this manuscript.

B. H. Wayne

INTRODUCTION

The magnetic amplifier and the saturable reactor are simular in their operation, except the magnetic amplifier is a more refined saturable reactor. Thus the saturable reactor is sometimes included in the category of magnetic amplifiers. The magnetic amplifier contains one essential component: a ferromagnetic device which has a variable inductance. The self-saturating magnetic amplifier, often called the amplistat, contains rectifiers in addition to a ferromagnetic core. The name magnetic amplifier is derived from its operation, a small d.c. signal current controls a large output current. This high ratio of output power to input power, which is called the amplification factor, may range from twenty to several thousand depending on the time of response and the size of the unit.

A simple analogy may be made between the flow of current to the load and the flow of water through a pipe to the load. The magnetic amplifier acts as a flow regulating valve in a water pipe as shown in Figure 1 and Figure 2. Figure 1 shows the analogy for a saturable reactor, whereas Figure 2 shows the analogy for a self-saturated magnetic amplifier.[1]

....

1 Coleman, H. C. Magnetic Amplifier Controls, Westinghouse Publication, September 1952

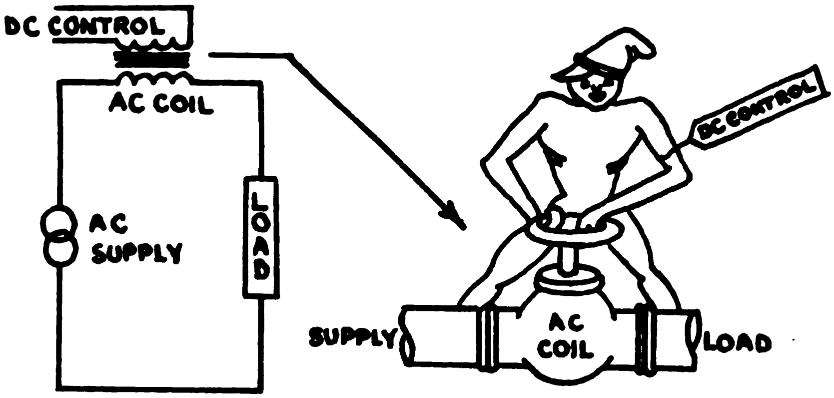


Fig. 1. Saturable reactor and its physical analogy.

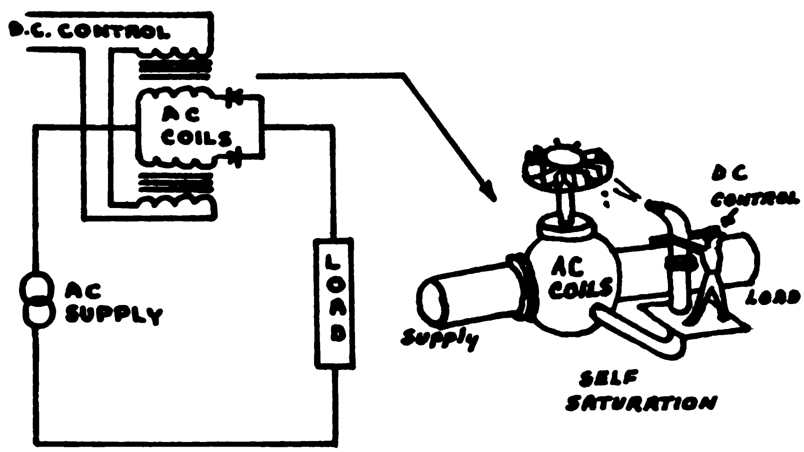


Fig. 2. Self-saturated magnetic amplifier and its physical analogy.

Magnetic amplifiers have certain limitations which must be taken into account when it is to be used in any particular application. The time of response is longer than for normal electronic circuits, but the time of response of less than .01 seconds is not very often needed in control circuits. The size and weight are usually larger than the size and weight of relay or tube circuits. The output of the magnetic amplifier contains harmonics of the a.c. supply voltage or non-ripple free direct current. Also the impedance minimum is limited by the resistance of the a.c. winding and the impedance caused by the incremental permeability, which can not be reduced to zero. The impedance also may not approach an open circuit (infinite impedance) because the incremental permeability of materials is limited. Amplistats are considerably more sensitive to voltage and frequency variations than amplidynes driven by shunt motors, hence requiring constant voltage transformers.

Even with the above limitations on the performance of the amplistat, it has many advantages over the electronic and amplidyne regulating circuits. It is a stationary device with no moving parts, hence requires very little maintenance. There are no tubes to replace, contacts to clean, bearings to oil, etc.; thus it may be placed in rural districts without requiring a maintenance man on duty at all times. The device has no starting delay or warm up time which is required in the other regulating circuits. In case of overload, which would burn out the other circuits, the only effect it has on the magnetic amplifier is overheating. Thus as soon as the overload is removed the amplistat will cool and return to normal operation with very little if any harm to the device. It is a sturdy device, may withstand shock, and has a long life. The magnetic amplifier is dustproof and tamperproof when placed in a sealed unit. The only noise due to the vibrating of the laminations may be damped out. It is less costly to install than the amplidyne because it may be panel mounted and requires no conduits or floor space. In the case of the rectifier units it is sometimes mounted inside the unit itself. As in the electronic circuits the amplistat may be cascaded to increase the d.c. output to the required value. Thus it may operate from a fifty millivolt shunt. Also both the amplistat and the saturable reactor may be used as three phase units.

There are many different amplistat circuits, several typical circuits are shown in Figure 3 through Figure 7, giving the advantages and disadvantages of each. The circuits of these amplistats are schematic only, not showing the core arrangement. The core arrangement will be shown and discussed in a later section of this thesis.

So that the author will not be accused of quoting out of context the following section is taken from H. E. Larson and T. Dunnegan,[2] and R. E. Morgan.[3]

Figure 3 shows a single phase bridge circuit which is the amplistat circuit most commonly used. Its advantages

....

2 H. E. Larson, T. Dunnegan Jr. A self-saturating magnetic amplifier for regulating circuits. General Electric Publication

3 R. E. Morgan, The amplistat, a magnetic amplifier. Electrical Engineering, August 1949.

and disadvantages are weighed against the particular requirements on the application prior to the consideration of any other type of amplistat circuit.

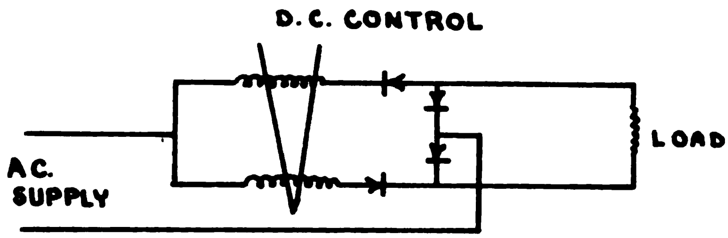


Fig. 3 Single phase amplistat bridge circuit.

The advantages of this circuit are:

1. Doesn't require a transformer when isolation of the load from the a.c. supply is not necessary.
2. Doesn't require a commutating rectifier for many inductive loads.
3. Operates well with either resistive or inductive loads.

The disadvantages of this circuit are:

1. The load is not isolated from the a.c. supply.
2. Uses more rectifiers than the other common circuits.
3. Gives unidirectional current only.
4. Requires a condensor or commutating rectifier across the load in cases of high inductive loads.

A single phase center tap circuit is shown in Figure 4.

The advantages of this circuit are:

1. Power supply and load may be grounded at the common point of the load and the supply.

2. Convenient for push pull operation.

3. Isolates the d.c. load from the a.c. supply.

The disadvantages of this circuit are:

1. Needs a center tap transformer.

2. Requires a commutating rectifier for high inductive loads.

3. Provides unidirectional current only.

4. Transformer must be oversized due to bad waveform.

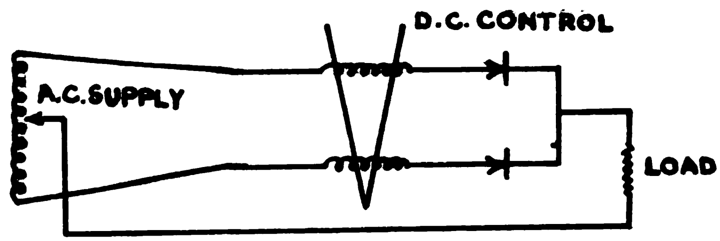


Fig. 4 Single phase center tap amplifier circuit.

The circuit in Figure 5 is a single phase voltage doubler circuit.

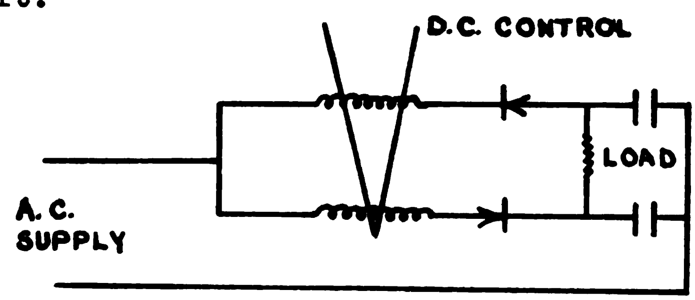


Fig. 5 Single phase voltage doubler amplistat circuit.

The advantages are:

1. Has a high amplification factor compared to other circuits.

2. Operates well on either resistive or inductive loads.

3. Doesn't require commutating rectifiers for many inductive loads.

The disadvantages of this circuit are:

1. Sensitive to voltage and frequency variation.

2. No common point between load and supply.

3. Requires condensors.

4. Gives unidirection output.

The circuit in Figure 6 is a single phase reversing center tap amplistat. Some applications require the output current of the amplistat to be varied in both the positive and negative directions from zero to maximum. This current will give this type of output.

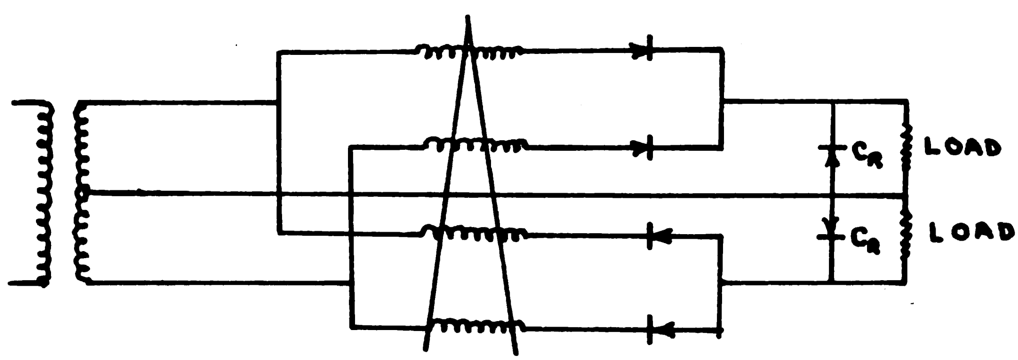


Fig. 6 Single phase reversing center tap amplistat circuit.

The advantages are:

1. Gives output current in both the negative and positive directions.

2. Less sensitive to voltage and frequency variations than other typical circuits hence makes a good first stage of a multistage amplistat.

3. Isolates the d.c. load from the a.c. power supply.

4. Provides a grounding point.

The disadvantages are:

1. Requires a transformer to get center tap.

2. Requires commutating rectifiers for inductive loads.

3. Requires two amplistats.

The circuit shown in Figure 7 is a three phase wye amplistat circuit, which is used when the frequency is lower than sixty and maximum speed of response is desired.

The advantages of this circuit are:

1. Greater maximum speeds of response are possible than with ordinary single phase circuits.

2. Output current has better form factors than single phase circuits such that the average current is more nearly equal to the root mean square current.

3. Isolates the d.c. load from the a.c. power supply.

4. Provides a grounding point.

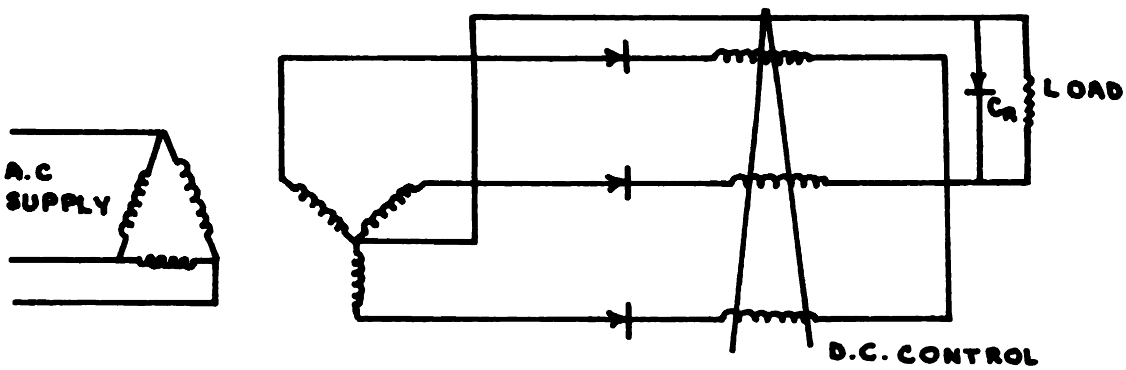
The disadvantages of this circuit are:

1. Provides unidirectional current only.

2. Requires a transformer to get the wye point.

3. Requires commutating rectifiers for inductive loads.

4. Requires more components than the single phase circuit of equivalent output.



Cr--commutating rectifier

Fig. 7 Three phase wye amplistat circuit.

This thesis consists essentially of three sections. In the first section, the fundamental operation of the saturable reactor is discussed. Also the design of the saturable reactor is explained in great detail, including the curves required for the design and a sample calculation. In the second section a discussion of the fundamental operation, characteristics and design of the amplistat is given. Also included are experimental curves showing the effects of voltage, frequency, etc., on the characteristics. There are a great many modifications of the amplistat which are used to improve its operation. A few of these are discussed in this thesis. Curves are given showing the effects of some of these modifications on the transfer characteristics. Amplistats are built using two types of cores, the spiracore and the laminated core. The amplistat design varies depending on the type of core chosen. The design of each type of amplistat is given and their characteristics are compared.

In the third section an application of the saturable reactor and amplistat is given, with experimental curves showing the results of their application as a control circuit.

FUNDAMENTAL OPERATION OF THE SATURABLE REACTOR

The operation of the saturable reactor is more easily understood by analysing the circuit shown.

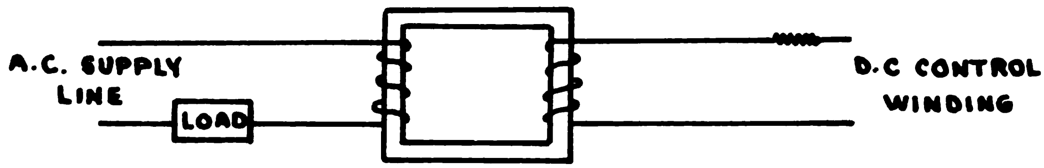


Fig. 8 Elementary circuit of the saturable reactor.

The losses in the core are assumed to be neglible and the impedance of the load and the d.c. control winding are assumed to be pure resistive. Under these conditions the magnetization curve may be drawn as shown in Figure 9.

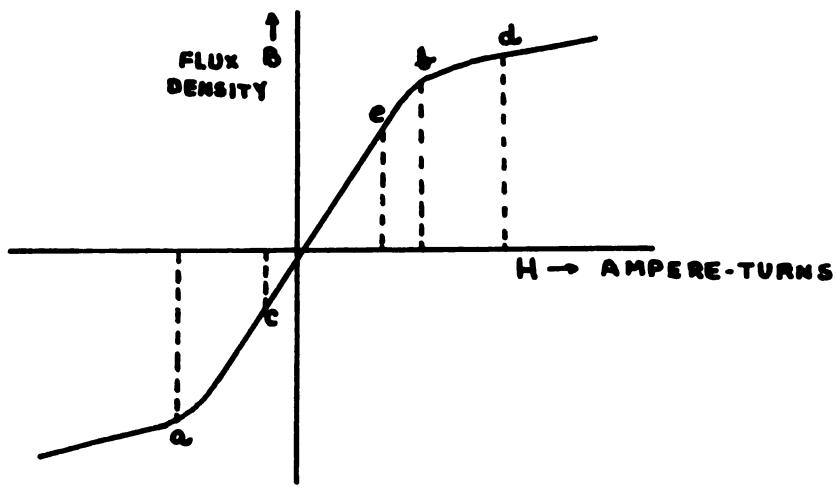


Fig. 9 Magnetization curve.

Let the magnitude of the a.c. magnetizing current be great enough such that the path of operation of the reactor on the magnetization curve is between point "a" and "b" when there is no current flowing in the control winding.

The waveform of the current through the load is shown in Figure 10, where the dotted line is the current without the reactor in the circuit. It should be noted that the current in the first part of each half cycle follows a limited sine wave because the magnetization curve has a constant slope.

The magnetization curve is a plot of flux density, which is proportional to the voltage across the coil versus the magnetic field intensity, which is proportional to the magnetizing current. Thus the slope of the magnetization curve gives an indication of the impedance of the reactor. From the magnetization curve it is seen that the slope of the magnetization curve is essentially constant except near the points "a" and "b". For magnetic materials used in the design of saturable reactors, the slope of the curve is very high, consequently the impedance is high thus limiting the flow of current through the load. Also the knee of the magnetization curve is very sharp, actually changing from maximum permeability to the permeability of air in approximately five electrical degrees. Hence as the flux density approaches either the point "a" or the point "b" the impedance of the circuit decreases quickly allowing the current to rise sharply to a high value limited only by the resistance of the load and the a.c. winding. As the current and the flux lag the voltage by approximately 90 degrees the current may rise although the voltage is decreasing.

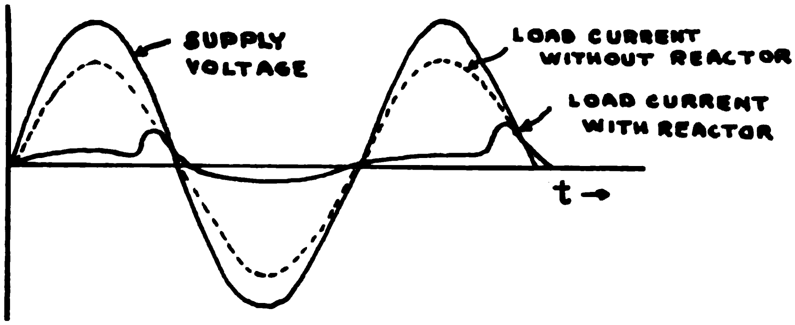


Fig. 10 Waveform of load current with zero control current.

When the current in the d.c. control winding is increased to a new point of operation "e", which is essentially biasing the reactor or as some authors call it d.c. offset, the path of operation is then between point "c" and "d". The magnetic material at point "e" has some flux which is extablished by the d.c. control current, thus the core becomes saturated earlier in the half cycle. As saturation is reached the ratio of flux density and field intensity is decreased thus the impedance of the reactor is decreased allowing more current to flow through the load. The current through the load is shown in Figure 11.

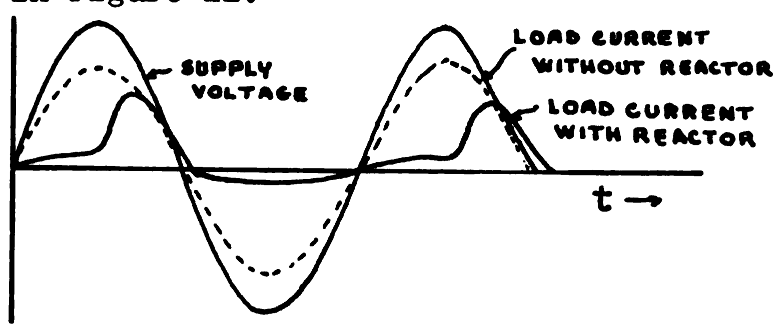


Fig. 11 Waveform of the load current with some positive current flowing in the d.c. control winding.

Consequently, as the d.c. current is applied to the reactor it becomes saturated earlier in the cycle, thus increasing the average value of the current to the load. Whereever the magnetization curve is linear the output current follows a sine wave. On the negative half cycle the slope of the magnetization is constant, hence the current follows a sine wave which is limited by the impedance of the reactor. The load current is a function of the d.c. current control, hence any variation in the d.c. control current will cause a corresponding change in the current to the load.

The preceding analysis has not been rigorous, it is intended to merely introduce the reader to the simplest understanding of the operation of the saturable reactor. From the previous analysis one may obtain an introduction to the operation of the saturable reactor, but to obtain a better understanding, the restriction that there are no losses in the magnetic core must be removed. Before proceeding with the more rigorous analysis the fundamentals of the magnetic circuits will be briefly discussed.

The magnetization curve may be obtained by plotting the flux density B against the corresponding field intensity H. There is no fixed relation between B and H, but the relationship depends on the previous history of the magnetic material. The rising characteristic and the hysteresis loop may be obtained by a step by step method.[4]

....

4 Atwood, Stephen S., Electric and Magnetic Fields

The field intensity is directly proportional to the magnetizing current hence the width of the hysteresis loop is determined by the amount of magnetizing current. Figure 12 shows the hysteresis loops obtained for three different values of maximum field intensity or magnetizing current. Arrows are placed on the curve to show the direction the curve is traced when an alternating current is applied.

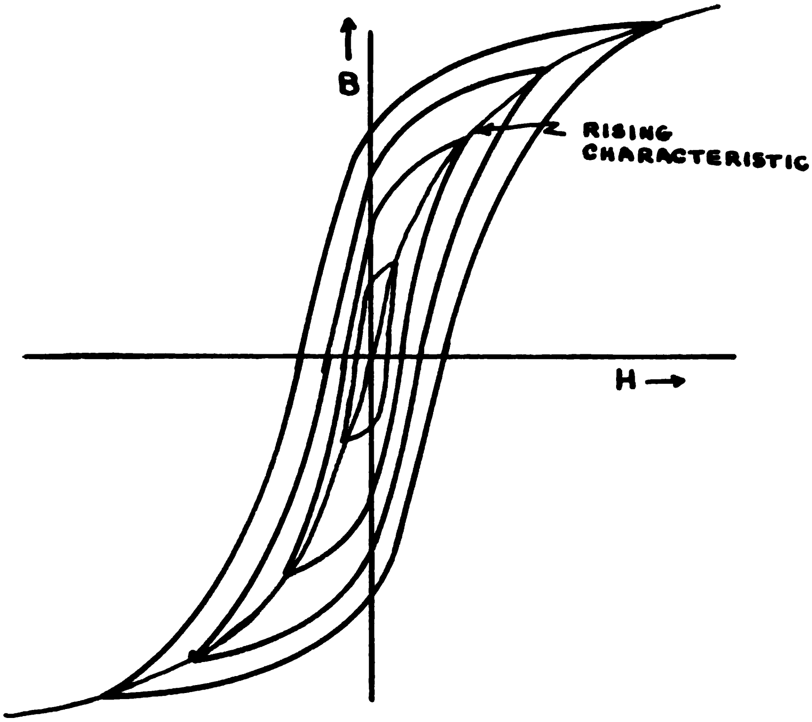


Fig. 12 Hysteresis Loops and the rising characteristic.

With a particular value of H under continuous operation the tip of the hysteresis loop does not lie on the rising characteristics but slightly away from it. If these points are plotted for various values of field intensity the alternating characteristics are obtained. As the rising characteristics and the alternating characteristic are slightly different that it is satisfactory to assume that they are the same on our analysis. Under this assumption the tips of the hysteresis loops all lie on the rising characteristic.

If instead of applying a sine wave as the magnetizing current a current of the form shown in Figure 13 is applied, the flux does not follow the regular hysteresis loop. After a few cycles, which removes all the transient, the time is taken as zero when the magnetizing current is a positive maximum. (Point "A"). As the current magnitude changes in accordance with the curve between the points "A" and "B", the flux density follows the normal hysteresis curve along ABC. As the magnitude of the current changes in accordance with the curve between points "C" and "A", the flux instead of following the normal hysteresis loop follows the curve CDA. The loop made by the flux density ABCDA, is called a minor or displaced hysteresis loop.

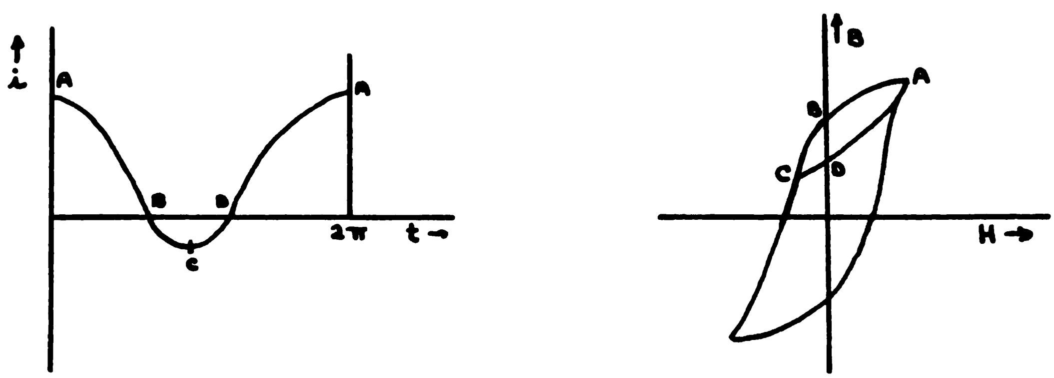


Fig. 13 Minor or Displaced hysteresis loop for a distorted magnetizing current.

The saturable reactor operates with a d.c. current superimposed in addition to the alternating current. (see Fig. 14).

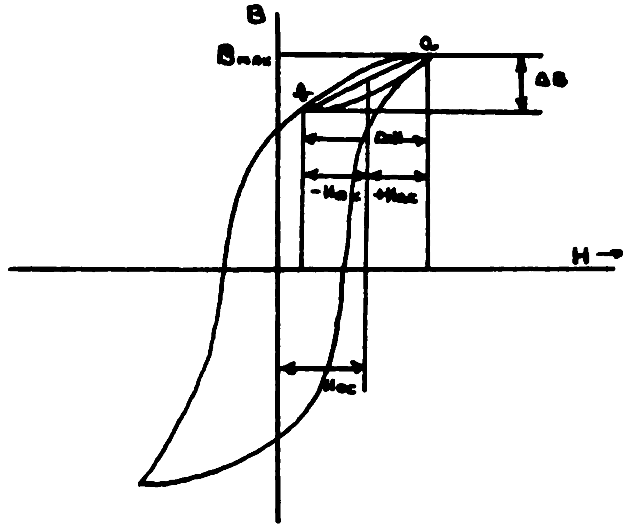


Fig. 14 Hysteresis Loop for an alternating current superimposed on a d.c. current.

When the alternating current produces a magnetomotive force in the same direction as the d.c. current, the maximum field intensity:

$$H_{MAX} = H_{DC} + H_{AC} = \frac{N_c I_c + N_a I_a}{l}$$

where: Nc is the number of control turns
Na is the number of a.c. turns
Ic is the control current
Ia is the a.c. current
l is the length of the flux path

The flux density B is found from the magnetization curve corresponding to Hmax. One half a cycle later when the alternating current has reversed the field intensity attains its minimum value which is:

$$H_{MIN} = H_{DC} - H_{AC} = \frac{N_c I_c - N_a I_a}{l}$$

The value of B corresponding to Hmin is not found on the magnetization curve, but on the hysteresis loop corresponding to

Bmax. Thus with a given amount of superimposed d.c. current the B-H variation follows a displaced hysteresis loop. When the flux is carried through a displaced hysteresis loop it becomes necessary to define a new quantity "incremental permeability, μ_Δ.

$$\mu_\Delta = \frac{\Delta B}{\Delta H}$$

The average inductance of the reactor when operating on a displaced hysteresis loop may be found as follows:

$$L = N_a \frac{\Delta \phi}{\Delta I_a} \qquad \Delta \phi = \Delta B \times A$$

$$\Delta H = N_a \frac{\Delta I_a}{l} \quad \text{or} \quad \Delta I_a = \frac{\Delta H\, l}{N_a}$$

Substituting in the equation for L.

$$L = N_a \frac{\Delta B \cdot A}{\Delta H \cdot \frac{l}{N_a}} = \frac{N_a^2 A}{l} \frac{\Delta B}{\Delta H} = \frac{N_a^2 A}{l} \mu_\Delta \qquad (1)$$

When the amount of d.c. current is varied the tip of the minor hysteresis loop lies on the magnetization curve and the minor loop follows the hysteresis loop that corresponds to the maximum flux density. The minor hysteresis loops for several values of d.c. bias are shown in Figure 15. The amount of alternating current is kept constant, thus the value of the change in field intensity ΔH is constant. The change in flux density ΔB grown less as the d.c. current is increased. When the d.c. current is zero, the change in flux density is large and from equation 1 the inductance is high. Thus the input impedance of the circuit is high limiting the amount of current to the load. When the d.c. current is large enough

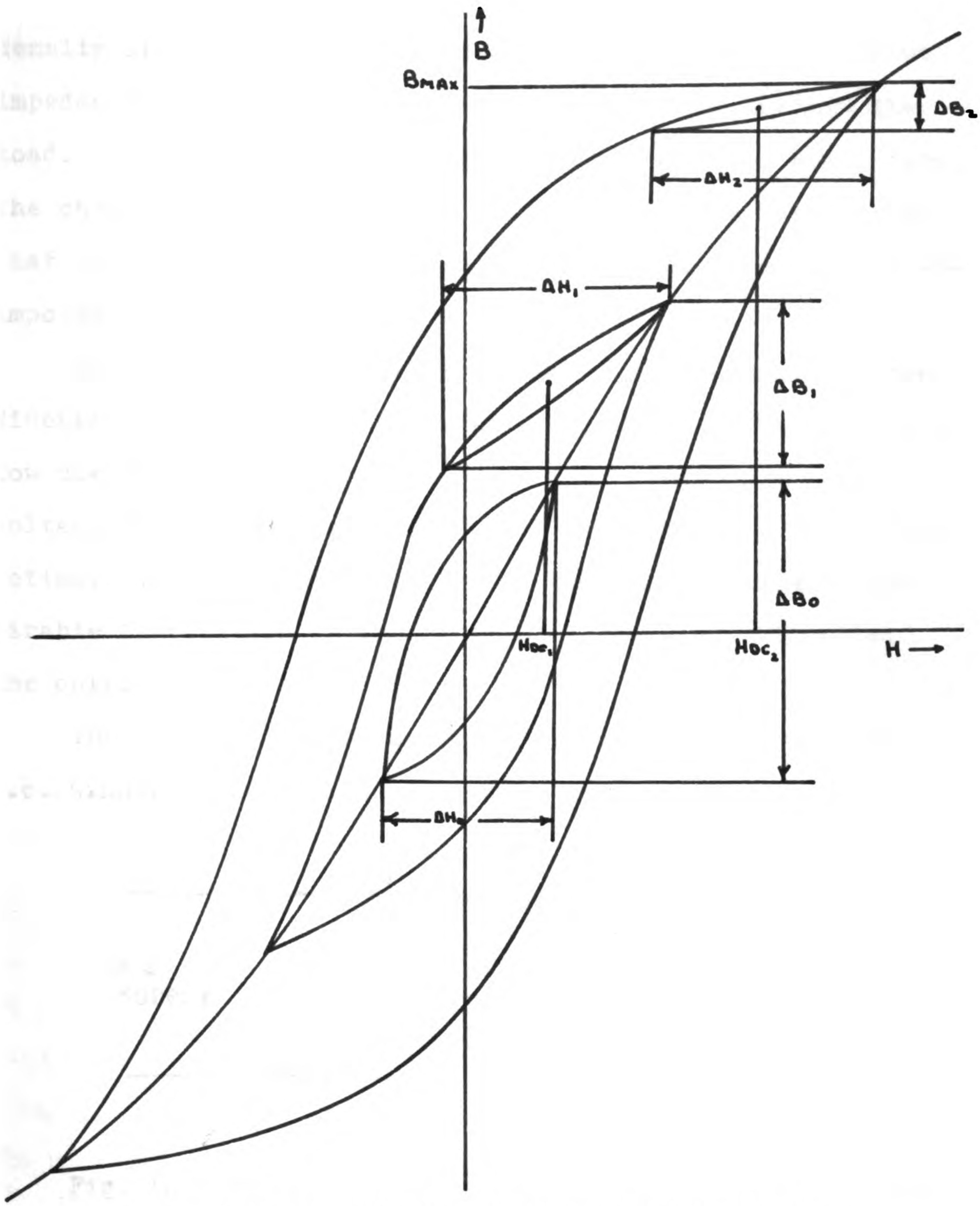


Fig. 15 Minor or displaced hysteresis loops for several values of direct current bias.

to produce a field intensity equal to Hdc_2 the change in flux density is small, hence the inductance is low and the input impedance is low allowing more current to flow through the load. As the slope of the magnetization curve is never zero, the change in flux density is never zero. From this we see that the impedance of the reactor is a function of the superimposed control current.

The simplified saturable reactor used for the previous discussion has two disadvantages: (1) The output current is low due to the half cycle pulses. (2) There is a large a.c. voltage induced in the d.c. control winding due to transformer action. This induced a.c. current may tend to produce undesirable fluctuation in the control current thus affecting the output characteristics.

The above two disadvantages are overcome by using two a.c. windings in parallel as shown in Figure 16.

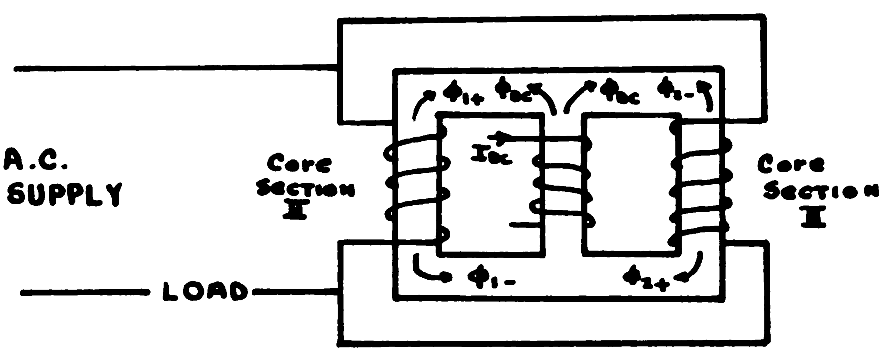


Fig. 16 Winding Schematic of a three legged saturable reactor showing the direction of the flux.

The circuit in Figure 16 is the same as using two reactors in parallel except that there is a common leg for the d.c. winding. It is possible therefore to separate the two paths for the flux and call them core section 1 and core section 2 as shown. Hence a magnetization curve may be drawn for each core (Figure 17). The magnetization curve is identical for each core section. A magnetization curve will be used in this discussion to make it readily understood by the reader. The effect of hysteresis will not alter the theory appreciably.

Let the flux produced by the control circuit be +d.c. Noting that the winding of the a.c. produces flux in opposite directions the +d.c. produces a positive flux in core section 1 and a negative flux in core section 2, when the positive supply current flows through both load windings the flux in core section 1 is in the same sense, hence the core becomes saturated, the flux in core section 2 is in the opposite sense to the d.c. flux, hence the flux through core section 2 is decreased to a low value. Therefore the impedance of the core section 1 is low allowing a high current to flow through its winding and the impedance of core section 2 is high limiting the current. When the negative portion of the a.c. supply current flows through the windings the flux in core section 2 is in the same sense as the d.c. flux hence this core becomes saturated. The flux through the core section 1 is in the opposite to the d.c. flux hence is reduced to a low value.

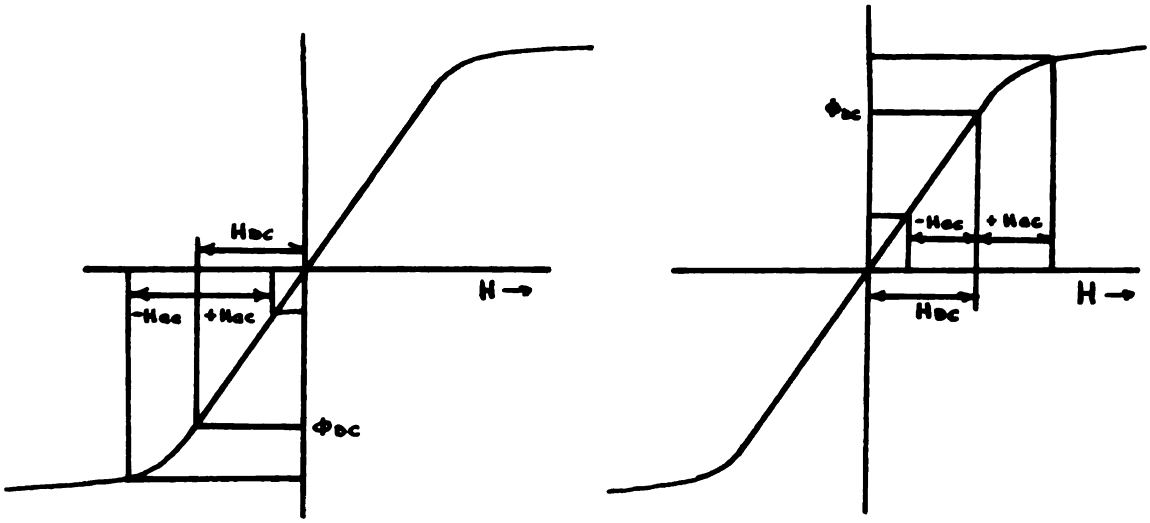


Fig. 17 Magnetization curve for each leg of a three legged saturable reactor.

Thus for a negative current the impedance of core section 2 is low allowing a large current to flow, whereas the impedance of core section 1 is high limiting the current through its winding.

Therefore the output current of the reactor has the wave form shown in Figure 18.

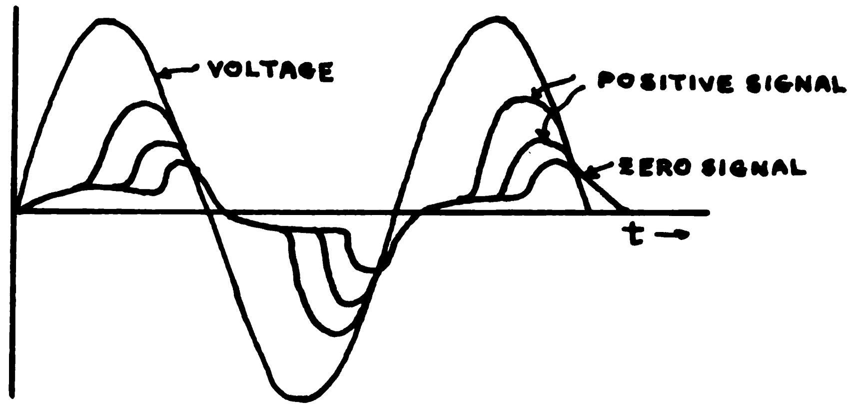


Fig. 18 Current output of a three legged saturable reactor for various values of d.c. control current.

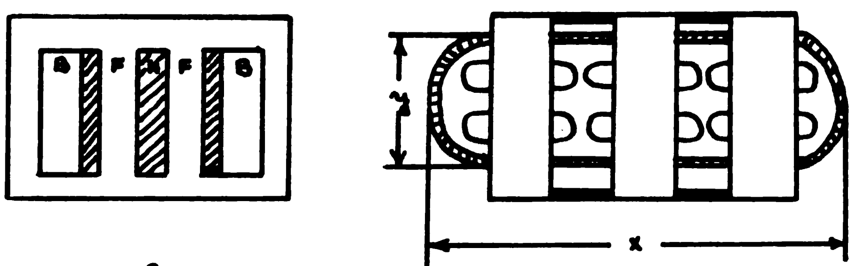
In this circuit the d.c. current again controls the amount of output. If the d.c. current is zero, neither core section may become saturated and the output current is very low. As the d.c. current is increased each core will become saturated earlier in its portion of the cycle and the output current will become larger.

From the preceding analysis it is seen that by using the circuit shown in Figure 16, the current to the load is increased because we get a complete cycle instead of a positive pulse every cycle. Also this saturable reactor will control an alternating current giving an alternating current output. The only disadvantage of this circuit is that the wave form is distorted from a normal sine wave, but nevertheless it is symetrical.

DESIGN OF THE SATURABLE REACTOR

The design of a saturable reactor requires the knowledge of the control power and the input kilovolt-amperes of the reactor. The control current and voltage are determined by the source that is available. In many cases the source is an ampistat. The line current is generally known and the a.c. coil voltage of the reactor is easily determined, depending on the load. In the single phase reactor the a.c. coil voltage is approximately the same as the line voltage. The coil voltage for a three phase reactor depends on the load connection which is usually a delta or wye.

For the single phase reactor the d.c. winding is wound over the a.c. coils. In the three phase reactor the d.c. winding encompasses all of the a.c. coils as shown in Figure 20.



a b

Fig. 20 Layout of the three phase saturable reactor showing the location of the a.c. and d.c. windings.

The flux density is chosen at approximately at the knee

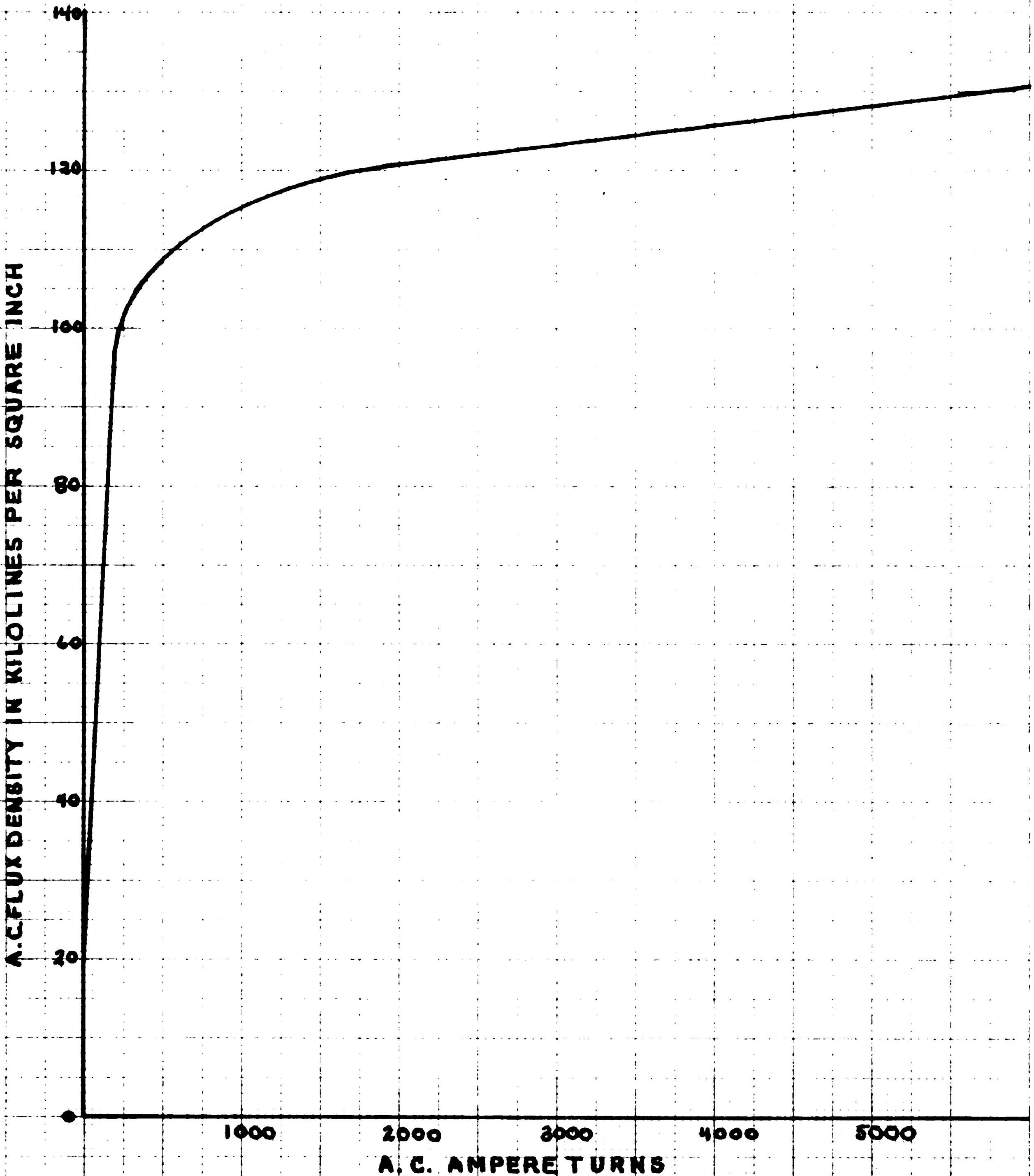


FIG. 19 - MAGNETIZATION CURVE FOR LAMINATION .025" THICK

of the magnetization curve. A sample magnetization curve is shown in Figure 19. Note the steepness of the slope and the sharp knee. A sample calculation is given using a core material that has this magnetization characteristic in a later portion of the section.

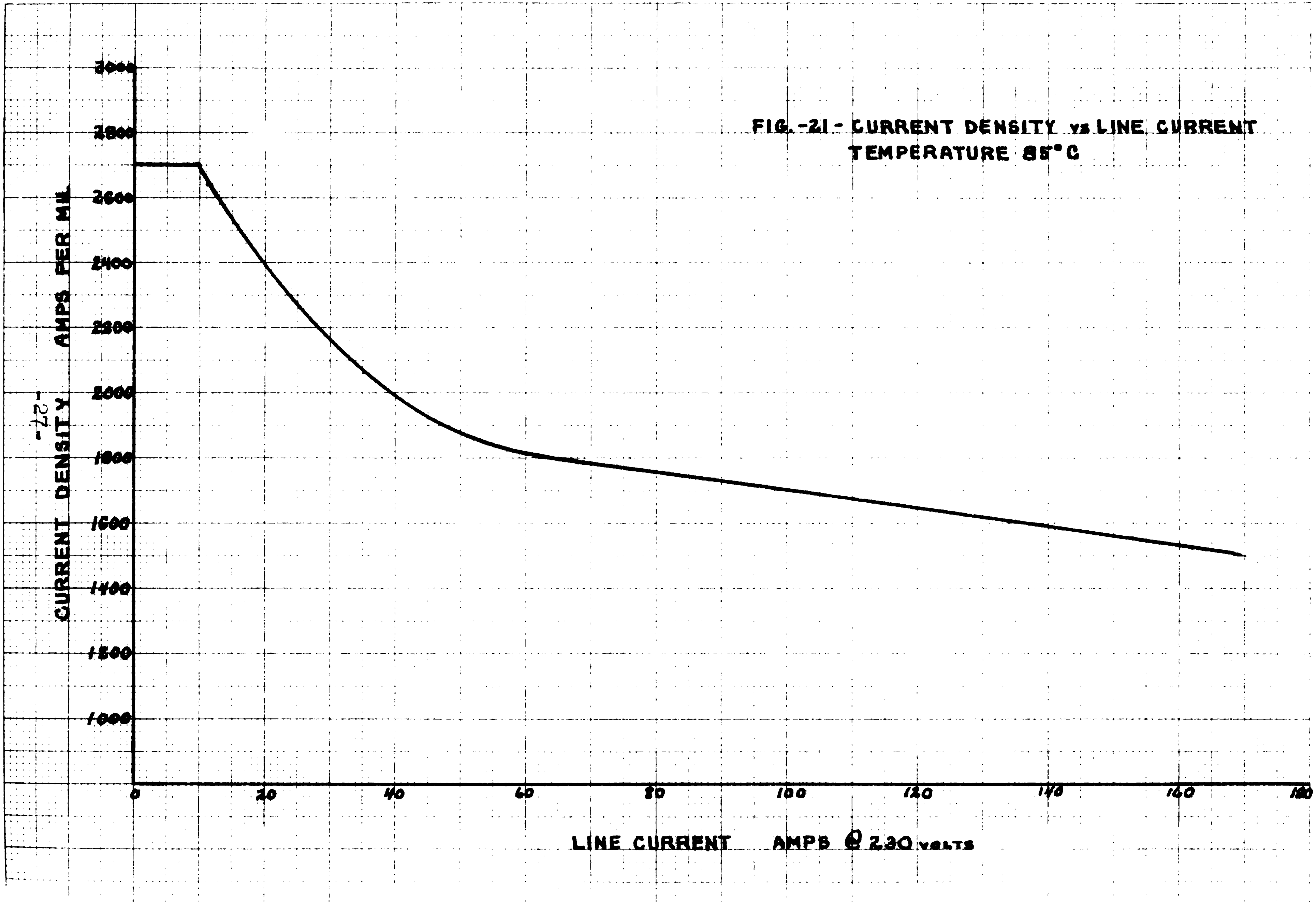
The current density must be chosen that will give the desired maximum temperature rise. This problem is very complex, and depends on so many factors on which very little data is available.

From previous heat runs on reactors an approximate curve may be drawn, but only for a particular temperature rise. In the saturable reactors used the most in applications, the temperature rise is allowed to be 85 degrees Centigrade which is the amount of heat the insulation normally used is able to withstand. A curve of current density versus line current has been drawn for an 85 degree temperature and is shown in Figure 21. Determining the correct amount of current density to obtain a temperature as near to 85 degrees as possible is one of the major problems confronting the designer.

After choosing the current density, divide it into the current to find the area of copper. From the wire tables the wire size is selected and its effective length and width is obtained.

For the lamination to be used the window size is determined, allowing for clearance of the winding and airflow. Divide the length of conductor into the effective window

FIG. -21- CURRENT DENSITY vs LINE CURRENT
TEMPERATURE 85°C



size to determine the number of turns per layer.

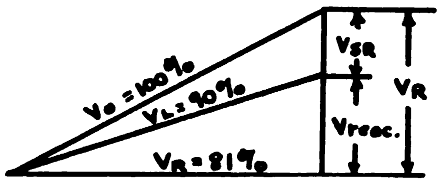
Because both the a.c. coils must fit in the center window, each winding must not cover more than half of the window also allowing a clearance for the winding. Next assume the number of layers and compute the width of winding allowing for insulation between layers plus the core insulation. The width of winding must be less than half of the width of the window.

For economical design it is desirable to fill each layer because the cost is more dependent on the number of layers than on the number of turns. So normally the layers are considered filled and the total number of turns determined. The total a.c. ampere turns are found remembering that there are two identical a.c. coils.

Using the equation: $E = 4.44\ NfA\ B_{max} \times 10^{-8}$ (2)

the area of cross-section of the iron core is found. From the lamination which is being used the width of the iron is found, therefore the height of iron is obtained. Dividing the height of iron by the stacking factor the effective height of iron is determined.

Before proceeding to the next step a slight digression is necessary. In order to get the desired control the output current must have a range from 10% to 100%. The output current may not be lower than the 10% because of the excitation current needed. The voltage must range from 16% to 100% with a maximum voltage drop across the saturable reactor of 10%. Assuming power factor of the load and the reactor to be .9 and the applied Vo to be 100% then the voltage in the load is 90% due to the power factor of the reactor. The voltage across the resistive portion of the load is 81%.



$$V_T = \sqrt{(1.0)^2 - (.81)^2} = .580$$

$$V_{reac} = \sqrt{(.9)^2 - (.81)^2} = .390$$

$$V_{SR} = .580 - .390 = .19$$

Fig. 22 Relationship of the voltages in a saturable reactor circuit.

Hence to get a control of the output current from 10% to 100%, it is necessary to have the voltage across the reactor to be 19% of the line voltage at zero control current.

Continuing the design, we now use the magnetization curve family shown in Figure 23, which has the a.c. flux density plotted versus a.c. ampereturns for various values of d.c. ampereturns. It was shown that to have the desired control, the voltage which is proportional to the flux density should be 19% of the maximum, so entering the magnetization curve with the total ampereturns and 19% of the flux

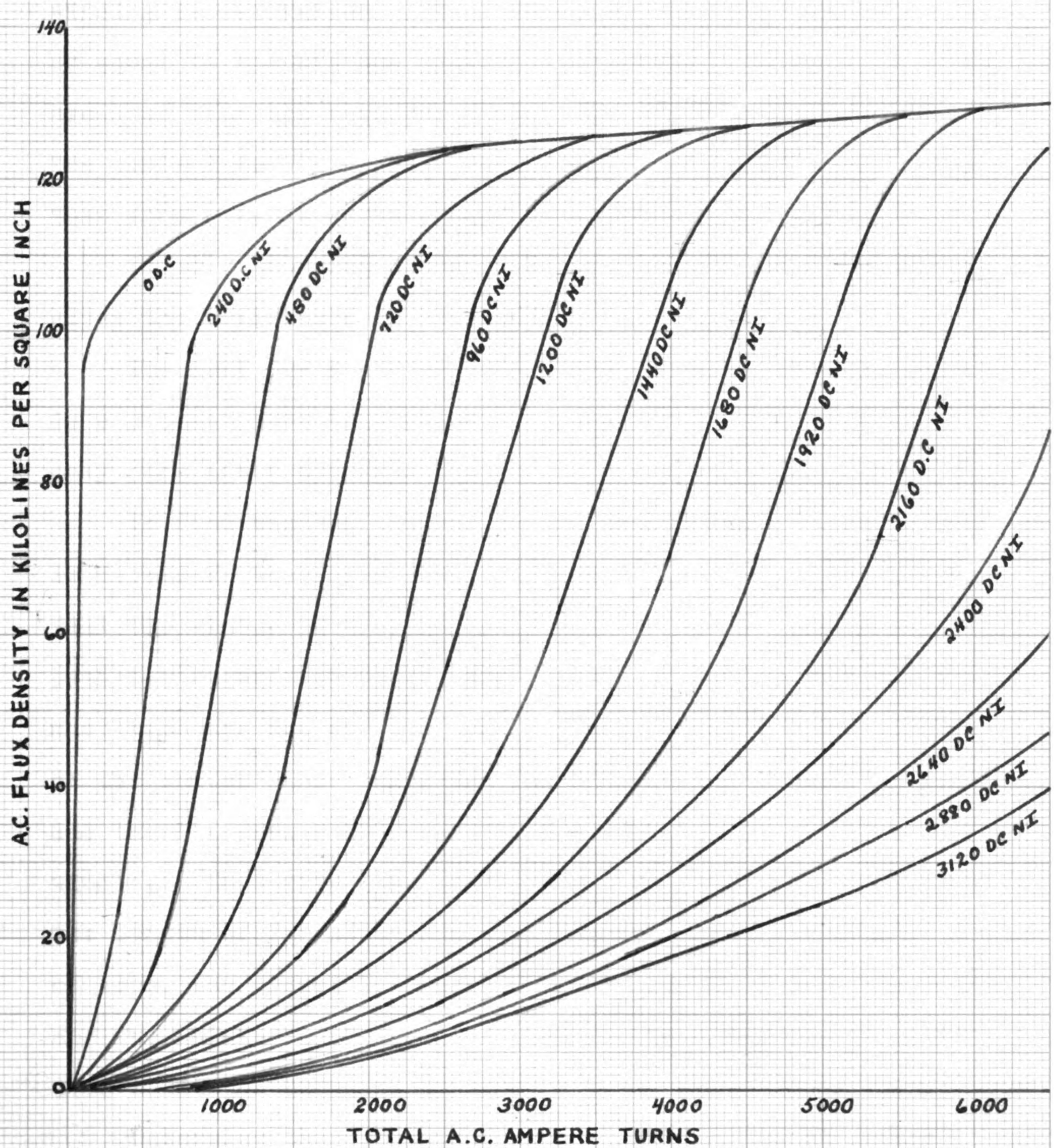


FIG. 23 Magnetization Curve Family

density, then the number of ampereturns for the d.c. control winding is determined. It is necessary to have more than or equal to the minimum number of ampereturns because if there are less than the required number the reactor will not have the control required. The designer is permitted to have more than enough turns on the control winding.

The d.c. control current and voltage are known which gives the resistance of the winding.

The next few steps use the trial and error method which is a process that is ordinarily necessary to be performed only once after the designer realizes the principle involved.

To find the mean length of path of the d.c. winding it is necessary to assume that the d.c. winding will completely fill the window of the lamination. To find the length of path for Figure 20b which is the end of the d.c. winding, we must take the sum of the width of the two legs F, the width of the center window H, twice the width of the a.c. winding and the difference between the window width and the a.c. winding. This gives the value of "y" in Figure 20a. To find the length of "x", take the sum of three times the height of iron, the spacer lengths, twice the width of the a.c. coils and the thickness of the d.c. winding that was assumed. The mean length of turn is then $2(x + y)$.

Determine the feet of copper by multiplying the length of turn by the number of turns assumed and pick the size of wire from the wire tables by dividing the desired resistance of the winding by the feet of copper. Pick the size of wire which has the closest resistance to that just calculated using the resistance at 75 degrees Centigrade which is in most wire tables.

Using this value of resistance correct the length of copper needed, the number of turns and finally the total d.c. ampereturns. Recheck the magnetization curve to be sure that there are enough d.c. ampereturns for full control.

The d.c. turns per layer and number of layers are then calculated in a similar manner as the a.c.

Compute the mean length of a.c. winding, feet of copper and the weight of iron.

For the most economical design of the larger reactor the ratio of iron to copper should be approximately 3. If the result obtained in the design is too far away from this value the same calculation is made again. If the ratio is too low reduce the number of a.c. turns which also increases the cross-sectional area of the iron. If the ratio is too high increase the number of a.c. turns which also decreases the cross-sectional area of the iron. Because the number of a.c. turns and the cross-sectional area are related, a small change in the number of a.c. turns is usually enough.

If greater accuracy is desired the calculations may be repeated using the width of the d.c. winding instead of the assumption that the winding would fill the window, that is, calculating backward.

An illustrative example of the calculation will clarify the design. A sample calculation sheet is included. (See Figure 24.)

A three-phase reactor is to be designed having:

$$I_{ac} = 16.1 \text{ amps.}$$
$$V_s = 230 - 10\% \text{ volts}$$
$$I_{dc} = 4.5 \text{ amps.}$$
$$V_{dc} = 45 \text{ volts}$$

The voltage across the coil is $\frac{230 - 10\%}{3} = 146$ volts

The flux density is chosen from Figure 19 as 115,000 lines.

From the current vs. current density from Figure 21, the flux density is chosen as 2,210 amps/mil.

Area of copper $\frac{16.1}{2210} = 4253$ cir mils

From the wire tables the wire size is .0961

The effective length and width of the conductor are .1056.

Length of the window 7 1/2 inches, allowing for 1/2 inch clearance, 7 inches.

Turns per layer $\frac{7}{.1056} = 66$ turns

A.C. window width .8625 inches--allow 1/8" clearance.

$$\begin{array}{r} .8625 \\ \underline{.1250} \\ .7375 \end{array} \qquad \frac{7375}{2} = .3687 \text{ inches}$$

Window width for one a.c. winding .3687 inches.

Assuming two layers:

Effective conductor width two layers	=	.1056 X2
		.2112
Layer insulation	=	.0100
		.2212
Core insulation	=	.0630
		.2842

Hence two layers will fit in the window.

The number of turns will then be $2 \times 66 = 132$ turns.

Total a.c. ampere turns $132 \times 16.1 \times 2 = 4250$ amp. turns.

To find the area of iron, use equation 2:

$$A \frac{E \times 10^8}{4.44\ N\ f\ B} = \frac{146 \times 10^8}{(4.44)\ (132)\ (60)\ (115{,}000)} = 3.6 \text{ sq. in.}$$

$$\text{Height of iron} = \frac{\text{Area of iron}}{\text{width of lamination}} = 3.6/1.125 = 3.2 \text{ in.}$$

The stacking factor is .94, hence the effective height of iron $3.2/.94 = 3.4$ inches.

Look on the magnetization curve Figure 23 with the a.c. ampere turns equal to 4250 turns and the flux density of 20 kilolines per square inch, which is approximately 19% of the flux density. The number of d.c. ampere turns are found to be 3100 ampere turns. Dividing by the current 4.5 amperes, the number of turns are 667.

Now the mean length of d.c. turns must be calculated. (See Figure 20)

2 x F	= 2.2500	
H	= .8625	
A.C., winding 2 x .2843	= .5686	
B - A.C. winding	= 1.0280	
	4.7091	inches

Core 3 x 3.4	= 10.2000	
Spacer 2 x 2	= 4.0000	
A.C. coil 2 x .2843	= .5686	
D.C. width	= .9440	
	15.7126	inches

The mean length of d.c. turn is $2(x + y)$, where x is equal to 4.7091 inches and y is equal to 15.7126 inches.

2 (x + y), mean length of turn

$$\begin{array}{r} 4.7091 \\ \underline{15.7126} \\ 20.4217 \\ \underline{2} \\ 40.8434 \text{ inches} \end{array}$$

Feet of copper = 40.84/12 × 690 = 2350 feet

Resistance per 1000 feet = $\frac{10}{2350}$ = 4.33 ohms/1000 feet

In the wire tables the nearest size wire is .0538 which has a resistance of 4.36 ohms/1000 feet at 75 degrees Centigrade.

Thus correcting for the feet of copper = $\frac{10}{4.36}$ = 2300 feet

For the number of turns = $\frac{2300 \times 12}{40.84}$ = 675 turns

Then the corrected total d.c. ampere turns is 3040 ampere turns which are enough to give the desired control.

A.C. mean length of turn is found allowing .250 winding clearance.

Width of iron	=	1.1250
AC winding	=	.2843
Clearance	=	.2500
		1.6593 inches

Height of iron	=	3.4000
AC Winding	=	.2843
Clearance	=	.2500
		4.9343 inches

Thus the mean length of a.c. turn is equal to 11.186 inches.

Feet of copper = 11.186/12 = 123 feet.

From the wire tables the weight of the wire is given as pounds per thousand feet. The weight of wire size .0961 is 28 pounds/1000 feet and the weight of .0538 wire size is 8.76 pounds/1000 feet.

Hence the total weight of copper is

Weight of a.c. copper = .123 x 28 = 3.44 lbs.
Weight of d.c. copper = 2.300 x 8.76 = 20.4 lbs.

Total weight of copper = 6 x 3.44 + 20.4 = 41 pounds

The weight of iron is 43.7 pounds and because there are three cores the total weight of iron is 131 pounds.

Thus the iron to copper ratio $= \frac{131}{41} = 3.27$ which means that this design is near enough to the value of 3 which is the most economical design.

SATURABLE REACTOR CALCULATION SHEET			
LAMINATION 1 1/3 in. NET WT IRON 43.7 lbs.	HEIGHT OF IRON 3.2 ---3.4 im. CORE CROSS SECTION 3.6 sq. in.		
IDENTIFICATION	AC	AC	DC
DENSITY	115,00	115,000	---
O.C. VOLTS 230 + 10	146	146	45
TOTAL AT	4250		3040
TURNS	132	132	675
RMS CURRENT	16.1	16.1	4.5
CURRENT DENSITY	2210	2210	---
AREA COPPER	7253	7253	---
WIRE SIZE	.0961	.0961	.0538
EFF COND LENGTH	.1056	.1056	.0567
LENGTH WINDOW	7	7	7
TURNS PER LAYER	66	66	123
Nº LAYERS	2	2	6
EFF COND WIDTH	.1056	.1056	.0567
WIDTH WINDING	.2112	.2112	.3402
WINDING PLUS INS	.2212	.2212	.3902
TOTAL WIDTH	.2343	.2343	.4202
WIDTH WINDOW	.3637	.3637	
MLT	11.1	11.1	40.99
FEET COPPER	123	123	2300
LBS COPPER	3.44	3.44	20.4
RESISTANCE			10 Ω @ 75°C

WEIGHT OF IRON --------- 131 lbs.
WEIGHT OF COPPER ------- 41 lbs.
RATIO ------------------3.27

FIG. 24

THE FUNDAMENTAL OPERATION OF THE SELF-SATURATING AMPLIFIER

The circuit of an elementary self-saturating magnetic amplifier is shown in Figure 25.

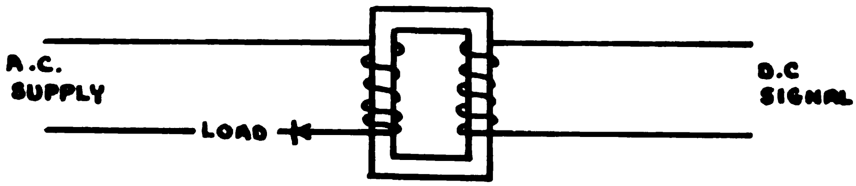


Fig. 25 Elementary circuit of a self-saturating magnetic amplifier.

The operation of the elementary self-saturated magnetic amplifier is essentially the same as the operation of the saturable reactor previously discussed, with the exception that a rectifier is added in the load circuit which gives a pulsating d.c. output current. The saturable reactor operated about a symettrical magnetization curve such that if a negative d.c. control current were applied the core would saturate in the negative direction and give the same output as for a positively applied signal except the output current would be of the opposite polarity. In the case of the amplistat which is the name generally associated with the self-saturated magnetic amplifier, the rectifier prevents the flow of negative output current. Thus the current through the a.c. coil is unidirectional and produces the bulk of the magnetizing force. The magnetizing force produced by the direct current control is usually only a small portion of the magnetizing force, but it holds the balance of power of the amplistat. Also with the rectifier in the load circuit the application of a negative d.c. control current to a point where the core can become saturated, there will be a very small output current. Due to the hysteresis effect of the core there is residual flux remaining, as the flux is decreased from its saturated value to a point where the excitation due to both windings is zero. However, due to the reverse leakage of the rectifier, there is a slight negative flow of current which produces a suicidal effect on the residual flux. But in actual practice this reverse current is not large enough to remove all the residual flux and a slight negative control current must be applied to remove all the residual flux which will bring the output current to a minimum. This will be shown when a discussion of the transfer characteristics of an amplistat is given. The average current that flows in the reverse direction through the load during the negative portion of the cycle is usually less than one percent of the average output of the amplistat.

The circuit shown in Figure 25 has two operational disadvantages: (1) The control winding normally contains more turns than the load winding of the amplistat. Consequently, due to the transformer action of the windings, a large voltage of the supply frequency is induced in the control circuit. This induced voltage causes high circulating currents in the control circuit which is normally of low impedance. The high a.c. circulating current reduce the effectiveness of the control current. (2) The load current pulses once during each cycle thereby reducing the average output current and also causing a slower time of response.

In order to remove these disadvantages the amplistat is made up of two cores with an a.c. winding on each connected in parallel and a d.c. control winding encompassing both cores as shown in Figure 26. Each coil has a rectifier in series with it such that the voltage induced in one core opposes the voltage induced by the second coil due to the phase differences of the voltages. Hence the circulating currents produced in the control windings are greatly reduced. Full wave rectifier circuits are used to produce a ripple frequency of twice the a.c. supply frequency for single phase applications. This results in larger average load currents and also improves the response.

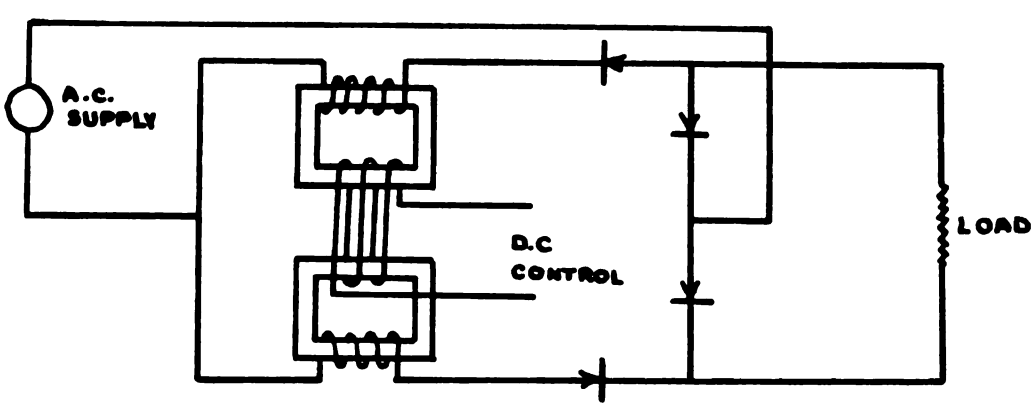


Fig. 26 Amplistat circuit showing the core arrangement.

Generally the amplistat circuit is drawn neglecting the core arrangement which is taken for granted. (Figure 27.)

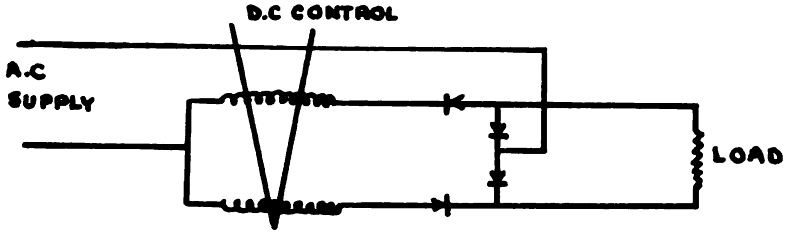


Fig. 27 Schematic of amplistat circuit.

THE CHARACTERISTICS OF THE AMPLISTAT

The input-output characteristic of an amplistat, usually called the transfer curve is a plot of the d.c. output current versus the control or signal current. The tranfer curve is only the steady state response because it doesn't indicate the time delay between the signal current and the corresponding change in the control current. This time delay is due to the high inductance of the input and output circuits. A typical transfer curve is shown in Figure 28. The normal operating range of the amplistat is that portion of the transfer curve where the output variation is high and linear with respect to the control current variation. This range is shown on the transfer curve (Figure 28) between the points "a" and "b". Above point "a", the core is practically saturated such that a change in the control current produces a small change in the output current. The point "b" is usually chosen at the minimum output current, which in most applications is of utmost importance. It should be noted that when a large negative signal is applied in excess of point "b" the output current again increases. This is due to the saturation of the core by this negative signal. This is the region of instability. Methods of overcoming this difficulty will be discussed in a later portion of this paper.

The speed of response is defined as the time required

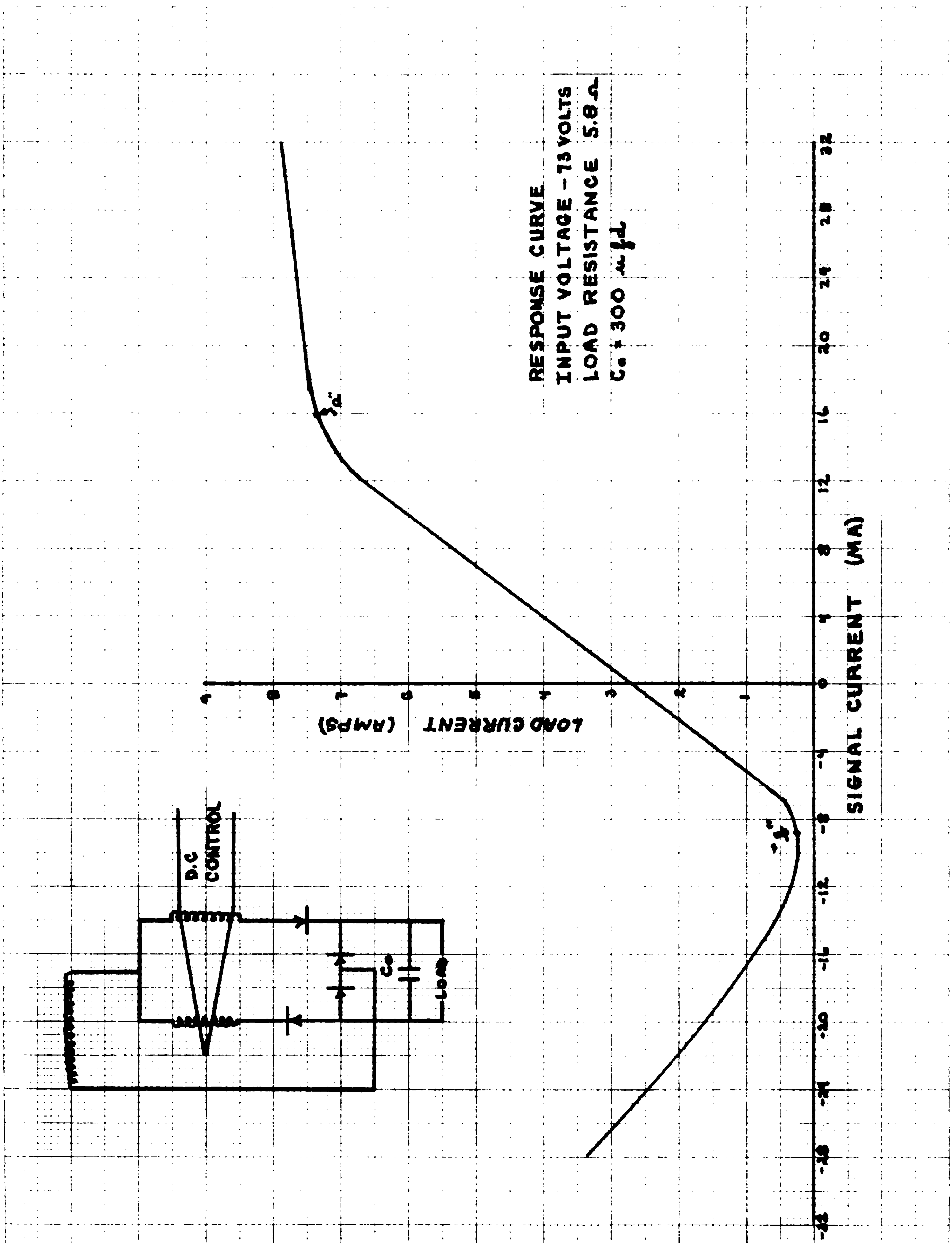


FIG 28 - TRANSFER CHARACTERISTIC OF AN AMPLISTAT

for the output current to reach 63% of its final value for a sudden change in the signal current. This definition requires that the load be pure resistive otherwise there would be an error due to the inductive load. With an inductive load there would be a time constant for the current to rise even without an amplistat in the circuit. Hence if the load is assumed to be pure resistive the time constant of the output circuit is instantaneous. Thus the speed of response is due to the time delay of the control circuit. The speed of response may be controlled by varying the resistance to inductance ratio of the signal circuit because the time constant is defined as:

$$T = L_c/R_c$$

The apparent inductance of the control circuit has been derived by H. F. Storm[5] to be:

$$L_c = \frac{1}{4f} R_L \left(\frac{N_c}{N_L}\right)^2$$

where R_l is the load resistance

f is the frequency

N_c is the number of signal winding turns

N_l is the number of load winding turns

This is a rather amazing result where the inductance is proportional to the load resistance and inversly proportional to the frequency. What is perhaps more amazing is that it is

....

5 Storm, H. F. Series Connected Saturable Reactor with Control Source of Comparatively Low Impedance, AIEE Technical Paper 50-123

independent of the core material. However this is easily explained because this equation was derived assuming a linear magnetization curve, hence it is valid only for the linear portion of the curve. This seems to indicate that it must be a function of the core material. This agrees with the equation 1 derived on page 16 which shows that the inductance is a function of the permeability.

Now the speed of response or time constant of the amplistat may be written as:

$$T = \frac{L_c}{R_c} = \frac{1}{4f} \frac{R_L}{R_c} \left(\frac{N_c}{N_L}\right)^2$$

In this equation there are many variables which have an effect on the gain also, but from the design conditions most of the factors are constant. As the amplistat is designed for a particular application the frequency and the load resistance are necessarily constant. The number of load winding turns are determined by design. Therefore we have two alternatives, either vary the resistance of the signal winding or the number of control winding turns. In order to decrease the time constant or speed of response the control circuit impedance may be increased or the number of turns on the control winding may be decreased. If the resistance of the signal winding is increased the current that flows through the signal winding is decreased for a given voltage across the terminals of the winding. Thus the sensitivity of the amplistat is decreased because much larger voltages would be required for complete control. Usually the amplistat is designed to operate on a predetermined voltage across the winding. Also to decrease the time constant appreciably a sizeable amount of resistance must be added. Hence it appears that adding resistance to the winding is not advisable in most cases. The number of turns on the signal winding are determined by design criteria but it is possible to decrease the number of turns by increasing the amount of current through the winding because the control of the amplistat is a function of the control ampere-turns. To increase the current through the winding for a prescribed voltage available, it is necessary to decrease the control winding resistance. This at first glance seems to be in opposition to the result desired. But it is noted the turns are to the squared power and the resistance is to the first power, hence the ratio of the result is increasing. Another question arises, does the decrease in the number of turns decrease the resistance enough to allow the required current to flow? If the resistance is not decreased enough, then the size of wire must be increased which in turn will decrease the resistance. In the actual design there is a limited amount of space in the window of the core to place the output and the signal winding, thus it is necessary to determine if the signal winding will fit in the window. By variation of the above factors it is possible to change the time constant of the amplistat. This is purely theoretical because the load was assumed to be pure resistive but it does give a basis for the change in time constant when the load is highly inductive. The amplistat load is in many cases inductive, such as controlling a saturable reactor or winding on a motor or generator, etc.. When the load is inductive there is a time constant due to the output circuit which tends to increase the time constant of the entire amplistat circuit. Hence the time constant of the amplistat with the resistive load is the minimum condition for the time constant. The time constant of the load can't be altered because it is fixed in the application problem so the time constant of the load circuit must be kept in mind. In a later portion of this thesis methods of minimizing the effect of time constant will be discussed.

The amplification factor is defined in many different ways. It may be defined as the ratio of the change in output current to a change in the input current, or the change in output volt-amperes to the signal volt-amperes, or as the ratio of the change in output power to the change in signal power. It is necessary to use a change in output current to a change in control current because at zero signal current there is an output current then the amplification factor would appear to be infinite. The definition that fits in any case is:

$$\text{AMP FACTOR} = \frac{(\Delta I_L)^2 R_L}{(\Delta I_c)^2 R_c} \tag{3}$$

The amplification factor is inversely proportional to the time constant of the circuit. If the time constant is decreased the number of turns on the signal winding had to be decreased and the current has to be increased and the resistance of the winding decreased. A decrease in the resistance of the control winding would tend to increase the amplification factor, but the CURRENT I_c appears to the squared power. Hence the amplification factor is decreased. Also the load current and the load resistance are determined by the particular application for which the amplistat is to be used, thus they are constant.

An increase in the amplification may be obtained with a sacrifice of the speed of response and vice versa. Thus in application design a balance between the two must be obtained.

The effect of the load and supply voltage on the transfer characteristics is of great importance. The variation of load results in various curves shown in Figure 29. This is explained very simply by recalling the operation of the saturable reactor. Before the amplistat saturates, the load on the amplistat has neglible control in limiting the output current when compared to the high inductance of the output winding. Thus the minimum output current is essentially controlled by the impedance of the output winding. When the core saturates the inductance of the output winding has been reduced to a very low value and its impedance is almost the same as the resistance of the winding. The load impedance then becomes the controlling factor. Hence when the core saturates the maximum load current is determined by the load impedance.

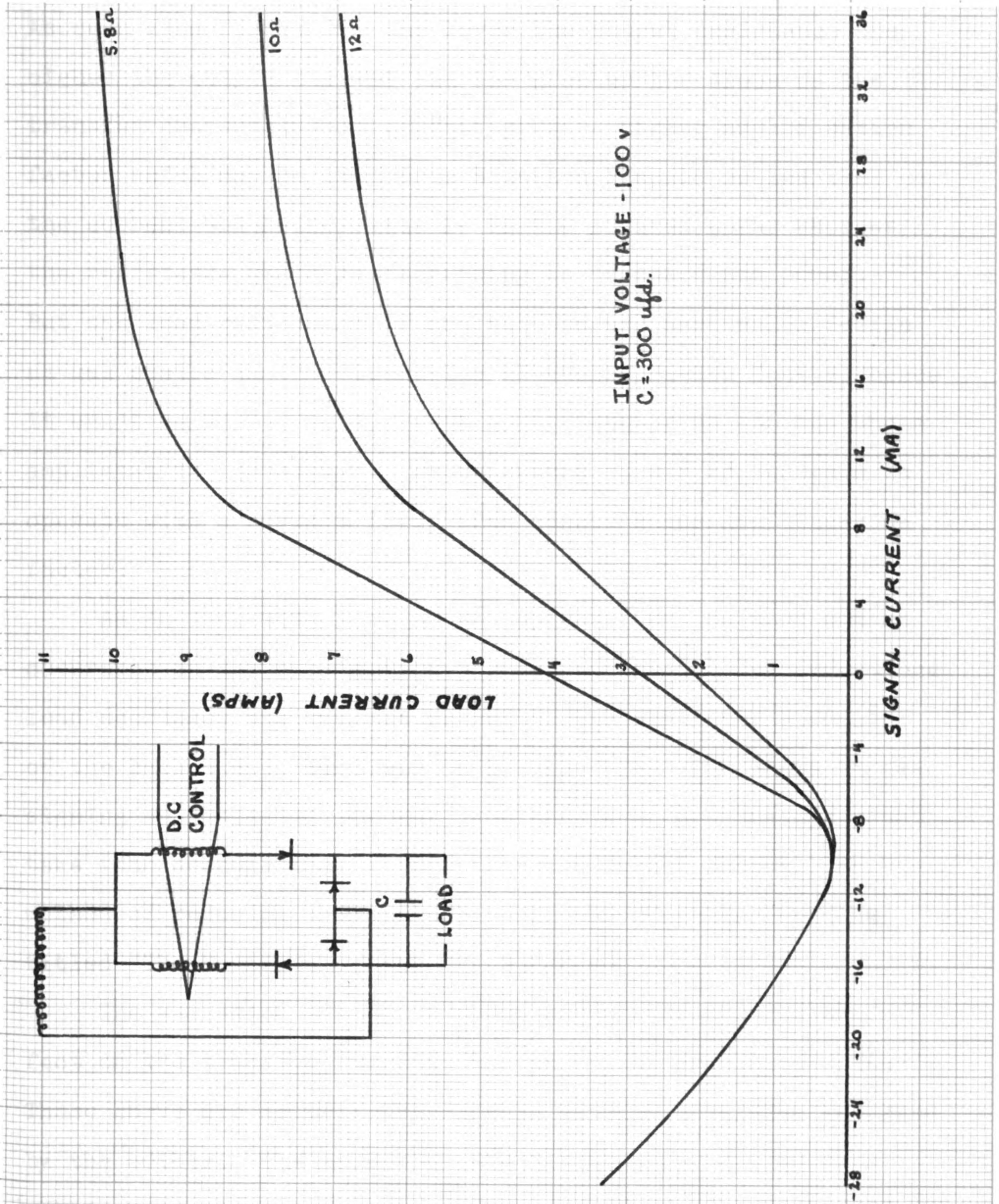


FIG. 29 - TRANSFER CHARACTERISTICS FOR VARIOUS LOADS

As seen from Figure 29, the lower the output resistance the higher the output current and the greater the slope of the transfer characteristics. This gives a higher amplification factor which may be seen from Equation 3 again noting that the current which increases is to the squared power whereas the resistance which is decreasing is to the first power. But the load resistance is constant in the particular design as was stated in the discussion of amplification factor, hence it can't be varied to increase amplification unless the whole amplistat is redesigned. An amplistat should be designed to operate with a certain load, time constant and amplification factor.

An An inductive load on an amplistat is the most common occurance in the application of the amplistat. The inductance load decreases the maximum output of the amplistat because of the back e.m.f. produced in the load itself. Hence in designing an amplistat for an inductive load, the designer must take into account this slight decrease in the output. A method of reducing this effect is discussed in the section titled "The Modification of the Amplistat".

The variation of supply voltage has a considerable effect on the transfer characteristics as shown in Figure 30. These curve are actual curves taken from an amplistat designed by the author. The amplistat was designed to operate at a supply voltage of 125 volts. The load was a resistive load of 12 ohms and a 500 microfarad condensor was placed across

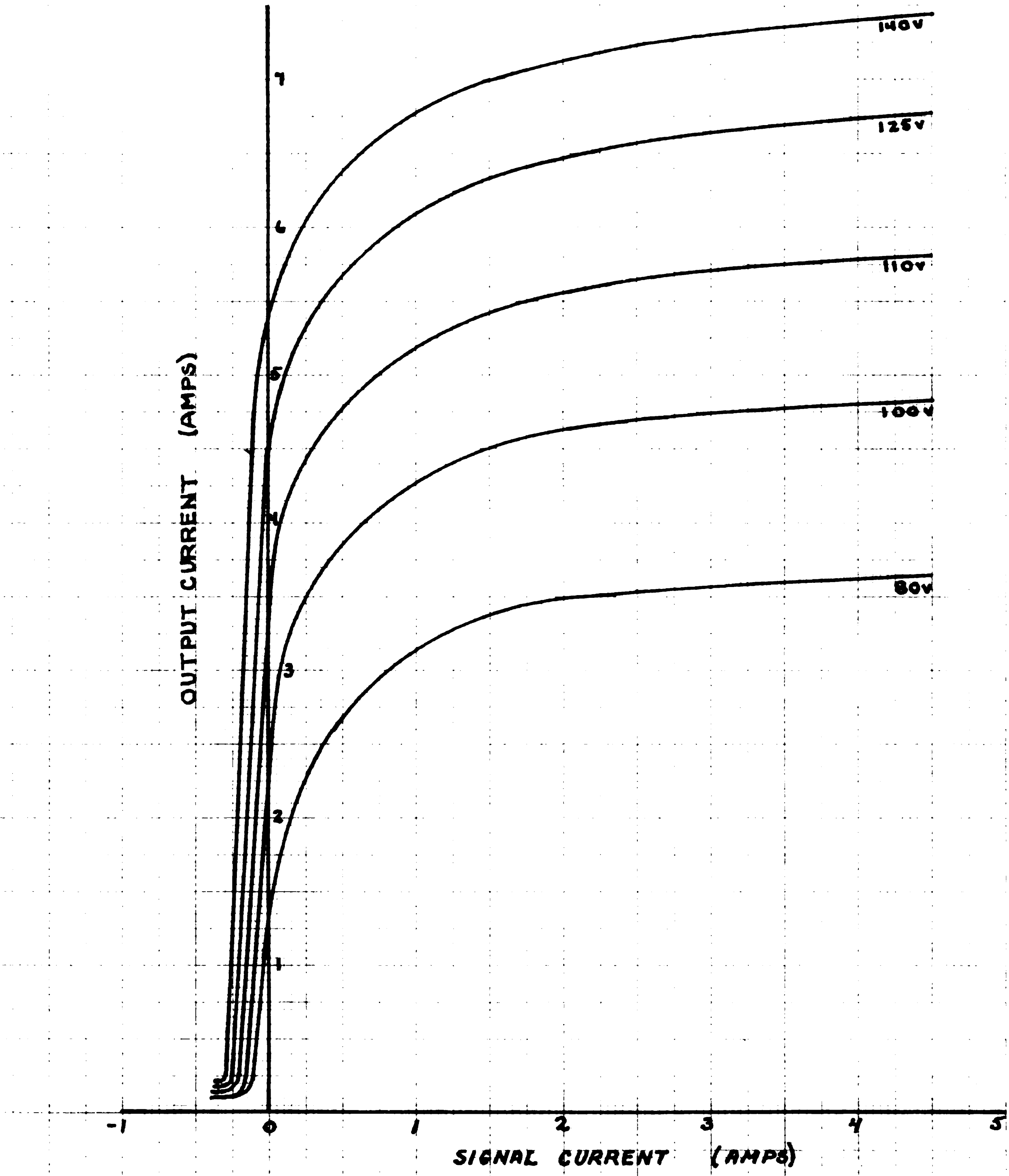


FIG. 30 - TRANSFER CHARACTERISTICS FOR VARIOUS SUPPLY VOLTAGE USING A' LAMINATED AMPLISTAT

the signal winding, the reason for this condensor is discussed in a later section. From the curves it is noted that the maximum value of the output current and the minimum value of the output current increases, as the supply voltage increases above 125 volts for which the amplistat was designed. If the supply voltage decreases from 125 volts the maximum output current decreases also but the minimum output current does not change appreciably. The line voltage of 125 volts is defined as 100% voltage. Any increase above 100% voltage causes a decrease in amplification factor and increases the maximum and minimum output current. Any decrease below 100% voltage decreases the optimum linear range, and decreases the maximum output and produces very neglible change in the minimum output. Thus if an amplistat is designed to operate at a particular voltage it should be operated as close to that value as possible. To overcome the fluctuation in the supply voltage a constant voltage transformer may be used.

One other factor which alters the transfer characteristics, which is of little importance in most applications of the amplistat, is the frequency. As amplistats are used mostly for power applications at the present time, the frequency is usually a constant, 60 cycles. In a few cases amplistats or reactors have been used with variable frequency, one case was from 60 cycles to 1000 cycles and many other problems are encountered. Increase in the frequency at a constant voltage is simular to the decrease of the supply voltage and vice versa.

MODIFICATIONS OF THE AMPLISTAT

Up to now the amplistat shown in Figure 27 has been discussed. Many modifications are necessary to obtain the desired operation and transfer characteristics. A few of these modifications will be discussed, but no analysis will be attempted. Most of the results are experimental. During the experiments two amplistats were used: (1) an amplistat to operate with a signal current range of 0-40 milliamps (2) an amplistat to operate as a second stage of cascaded amplistats with a current range of 0-4.5 amps. The complete design of the second stage amplistat is included in this paper. The design of the first stage amplistat is the same as for the second stage, hence the details are not given but just the design data is given in Figure 31. The experimental results were obtained for both amplistats.

When the effect of variation of the supply voltage was discussed it was mentioned that a 500 microfarad condensor was placed across the signal winding. From previous discussion it is known that there is a current induced in the signal winding due to transformer action. The transfer characteristics of the amplistat are improved if an impedance is placed in the signal winding that will reduce the induced current. A pure resistance may be added in series with the signal winding that will reduce the induced current. A pure resistance

AMPLISTAT	CALCULATION SHEET		
LAMINATION 3474060	HEIGHT OF IRON 1.375 in.		
NET WT IRON	CORE CROSS SECTION 2.6 sq. in.		
IDENTIFICATION	AC	AC	DC
DENSITY	90,000	90,000	----
O.C. VOLTS	115	115	
TOTAL AT	532		26
TURNS	132	132	765
RMS CURRENT	3.2	3.2	.034
CURRENT DENSITY	1575	1575	---
AREA COPPER	2030	2030	---
WIRE SIZE	.0503	.0503.	.0503
EFF COND LENGTH	.0560	.0560	.0560
LENGTH WINDOW	1.5	1.5	Pyramid
TURNS PER LAYER	26	26	
Nº LAYERS	7	7	
EFF COND WIDTH	.0560	.0560	
WIDTH WINDING	.3920	.3920	
WINDING PLUS INS	.4520	.4520	
TOTAL WIDTH	.4300	.4300	
WIDTH WINDOW			
MLT	11.5	11.5	21
FEET COPPER	175	175	1340
LBS COPPER	1.4	1.4	10.5
RESISTANCE	.64	.64	5.95

FIG. 31

may be added in series with the signal winding but this changes the amplification and time constant. How may the impedance of the signal winding be increased without affecting the time constant and amplification appreciably? By placing a condensor across the winding, the 120 cycle a.c. induced current is reduced with little effect on the d.c. signal current. Hence a condensor was placed across the signal winding and varied until it was found that for the particular amplistat a 500 microfarad condensor gave the desired transfer characteristic. It was found that adding the condensor reduced the minimum output current with no effect on the maximum output current. This is explained by the operation of the amplistat. With no signal current applied most of the voltage appears across the a.c. winding, hence a large induced current whereas with the signal current applied the voltage across the coil reduces and the induced current reduces. Thus with maximum output current the induced current is neglible.

Another modification is the addition of another winding to the amplistat called the d.c. bias winding. Without this winding the signal current must be reversed to vary the output from maximum to minimum. If this negative current is increased to too large a value the output current again begins to increase and the region of instability is reached. As the signal current is often taken from the output by feedback, this feedback is positive and the amplistat loses control of the circuit. With d.c. bias applied the minimum output current is reached at zero signal current, thus there is no reason to apply a negative signal and the region of instability is eliminated. But the d.c. bias current must be adjusted such that the minimum output current is reached at zero signal. One disadvantage of adding d.c. bias is the space which it takes up in the window of the core, necessitating the use of a larger core which means a larger and heavier amplistat or reducing the number of turns of signal winding. In many cases this requires the use of a larger core. Also to insure that the current doesn't reverse, a rectifier should be placed in the signal winding because the d.c. bias doesn't keep the signal current from reversing but only eliminates the necessity of reversing the current.

Instead of using d.c. bias, a much better method of obtaining the same results is with the use of a.c. bias. A.c. bias has a low minimum output at zero signal, also reduces the effect of supply voltage variation and gives control of the output with very high resistance loads. In the a.c. bias normally added, two condensor, two resistors and a separate power source of voltage are required as shown in Figure 32.

The actual operation details will not be included but simply a few of the experimental results will be discussed.

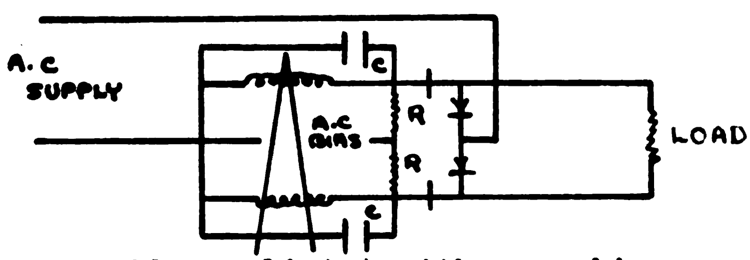


Figure 32 Amplistat with a.c. bias

Instead of discussing the effects of the various components in great detail, experimental curves are included.

The effect of variation in supply voltage is shown in Figure 33. Variation of the supply voltage with a.c. bias produces the same effect as without a.c. bias. The maximum output is reduced and the slope of the curve is decreased as the supply voltage is decreased.

Variation of the a.c. bias voltage has very little effect of the transfer characteristics. The a.c. bias voltage must be higher than the supply voltage. (See Figure 34.)

The size of the bias resistors must be large which allows only a limited amount of current to flow. The transfer curves are plotted for three values of resistance 1,000 ohms, 2,000 ohms, and 3,000 ohms. It should be noted that the slope of the curve becomes steeper as the resistance is increased. Hence a very high resistance must be used. (See Figure 35.)

The condensors seem to produce most of the biasing effect as shown in Figure 36. As the condensor values are increased the transfer characteristic is shifted farther and farther to the right into the positive signal current portion of the plot. With too little capacitance the minimum output current is not obtained at zero signal current. If too much capacitance is used the characteristic is shifted such that the minimum output current is obtained at too large a value of signal current. The ideal value of capacitance is that value where the minimum current is at zero signal and the

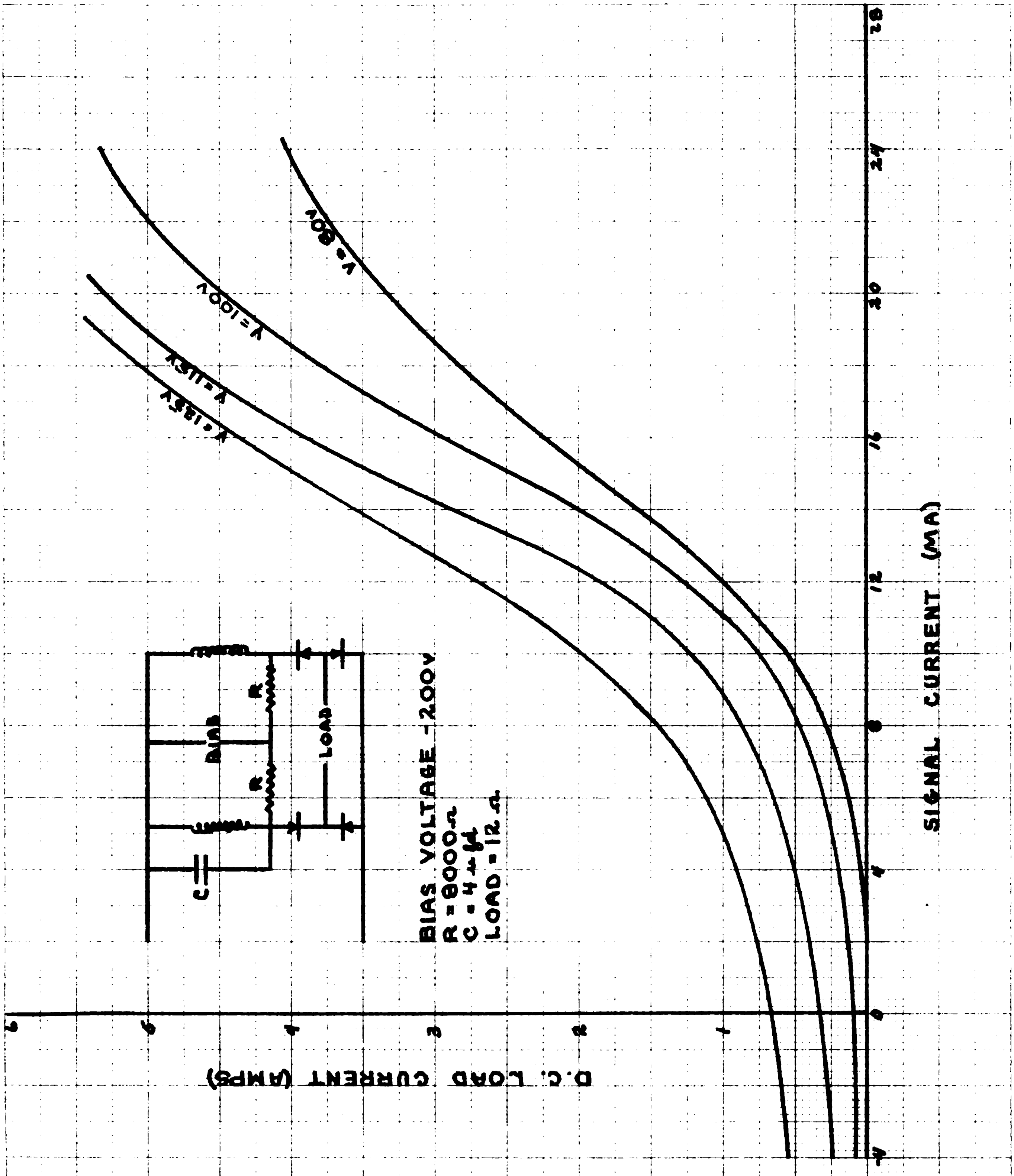


FIG. 33-TRANSFER CHARACTERISTICS FOR VARIOUS SUPPLY VOLTAGES WITH A.C. BIAS.

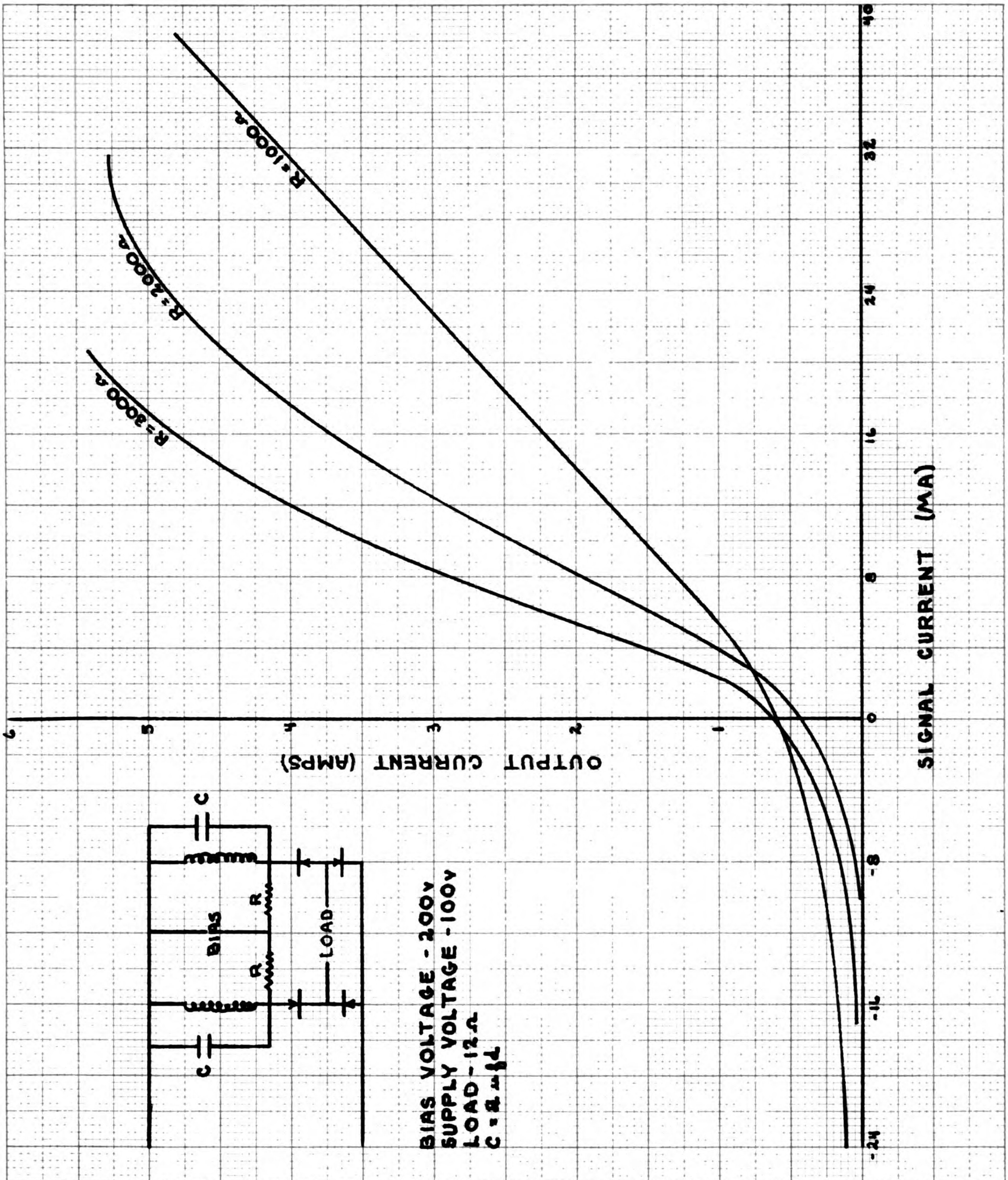


FIG. 35 - TRANSFER CURVES FOR AMPLISTAT WITH A.C. BIAS FOR VARIOUS RESISTANCE "R".

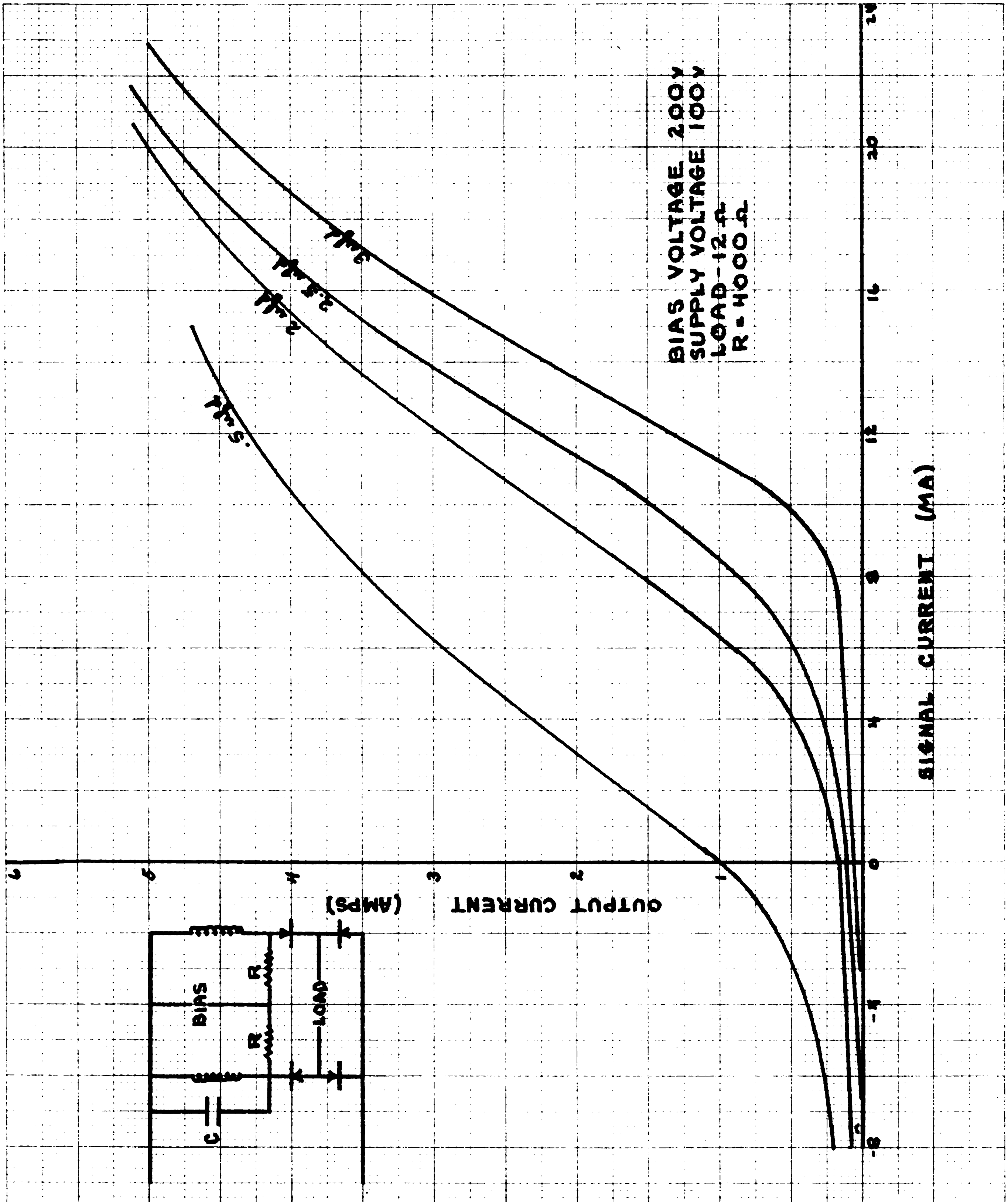


FIG. 36-TRANSFER CHARACTERISTICS FOR AMPLISTAT WITH A.C. BIAS FOR VARIOUS CONDENSERS

maximum current output is obtained at the lowest value of signal current. The amplistat for which the curves of Figure 36 are drawn, gave the best results with the capacitance value of two microfarad.

After obtaining the preceding results experimentally it was the author's opinion that the condensors produced most of the bias effect. Hence the a.c. bias voltage was removed and the experimental curves were approximately the same. Then the resistors were removed with no effect on the transfer curves. Thus it was discovered that a.c. bias could be obtained without the use of the a.c. bias voltage or the resistors.

Not satisfied with this, one of the two condensors was removed and curves were taken for various values of the single condensor. It should be noted from the curves of Figure 37, that if the remaining condensor is equal to the value of the sum of the two in the previous circuit the same transfer curve is obtained.

A.C. bias has been obtained with the use of only a single condensor across one of the a.c. coils. This is a much easier method to obtain the same results as obtained by d.c. bias. A.C. bias may be applied after the amplistat is completely designed and built.

When the load on the amplistat is inductive, commutation is often required. In the introduction commutating rectifiers were shown in many of the difference amplistat circuits. By experimentation it was found that a condensor across the out-

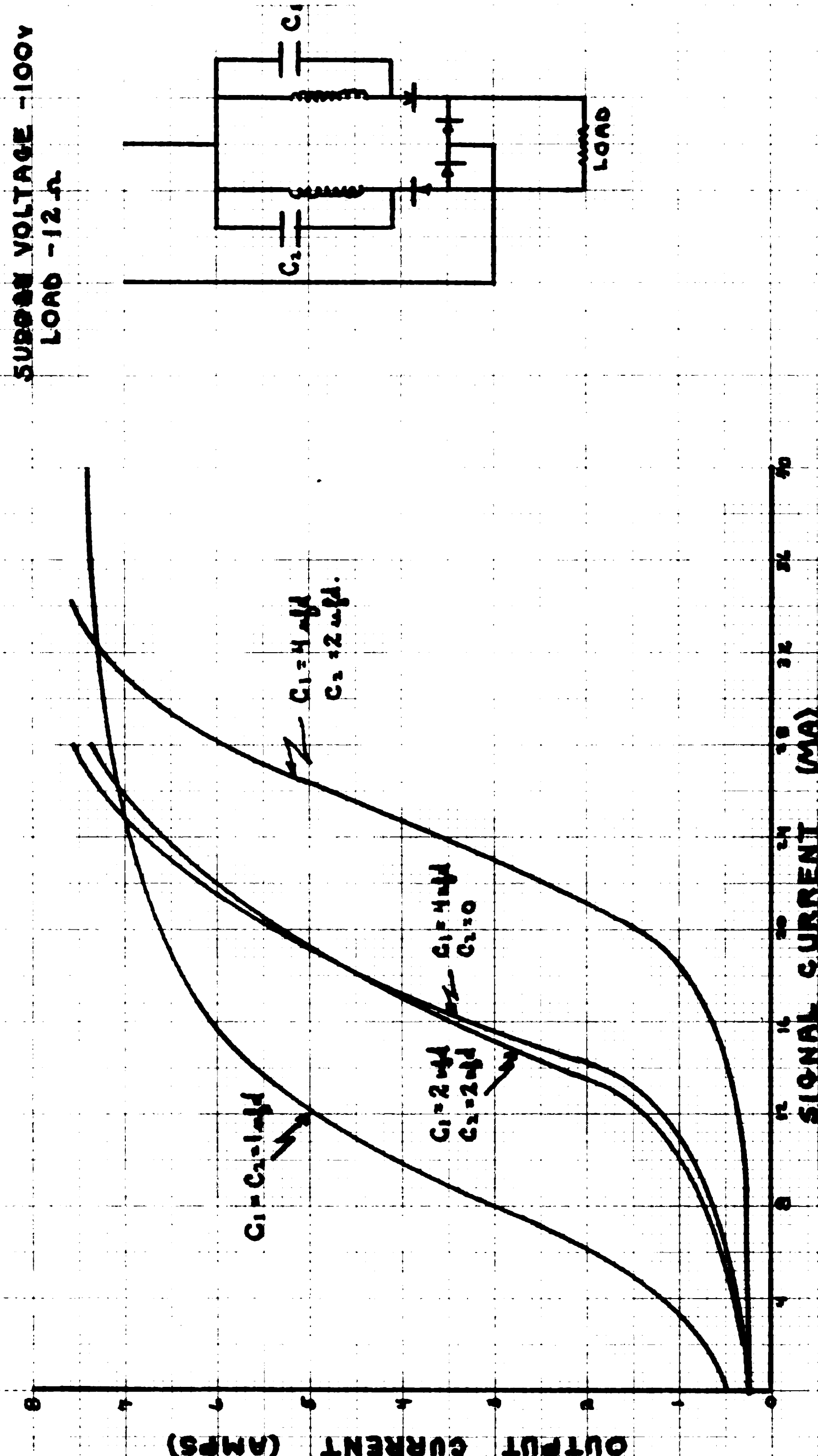


FIG. 37 - TRANSFER CHARACTERISTICS FOR VARIOUS VALUES OF BIAS CONDENSERS.

put when the load was inductive produced the same effect and in many cases was better. When a condensor is placed across the load there must be a degree of filtering because the d.c. output is pulsating. The maximum output current is much higher with the condensor across the load than without it. (See Figure 38.)

Also the time of response is varies with the size of the condensor placed across the load. The time of response and transfer characteristics are plotted in Figure 39 and 38 respectively for various values of capacitance. It should be noted that there is a condensor value which gives the shortest time of response and also the best transfer characteristic.

Experiments were run with various values of rectifiers across the load and these transfer characteristics were compared with results obtained with condensors. The condensor produced much better results than the rectifiers as shown in Figure 40.

Cascading the amplistats requires some experimentation. The circuit of two cascaded amplistats is shown in Figure 41 and the parameters of the circuit are labelled. The amplistats used are the two which are designed in this thesis. An over-all transfer characteristics is given in Figure 42. The steepness of the curve should be noted, for the two cascaded amplistats have very high amplification. Note that the signal current is milliamps and the output current is amperes.

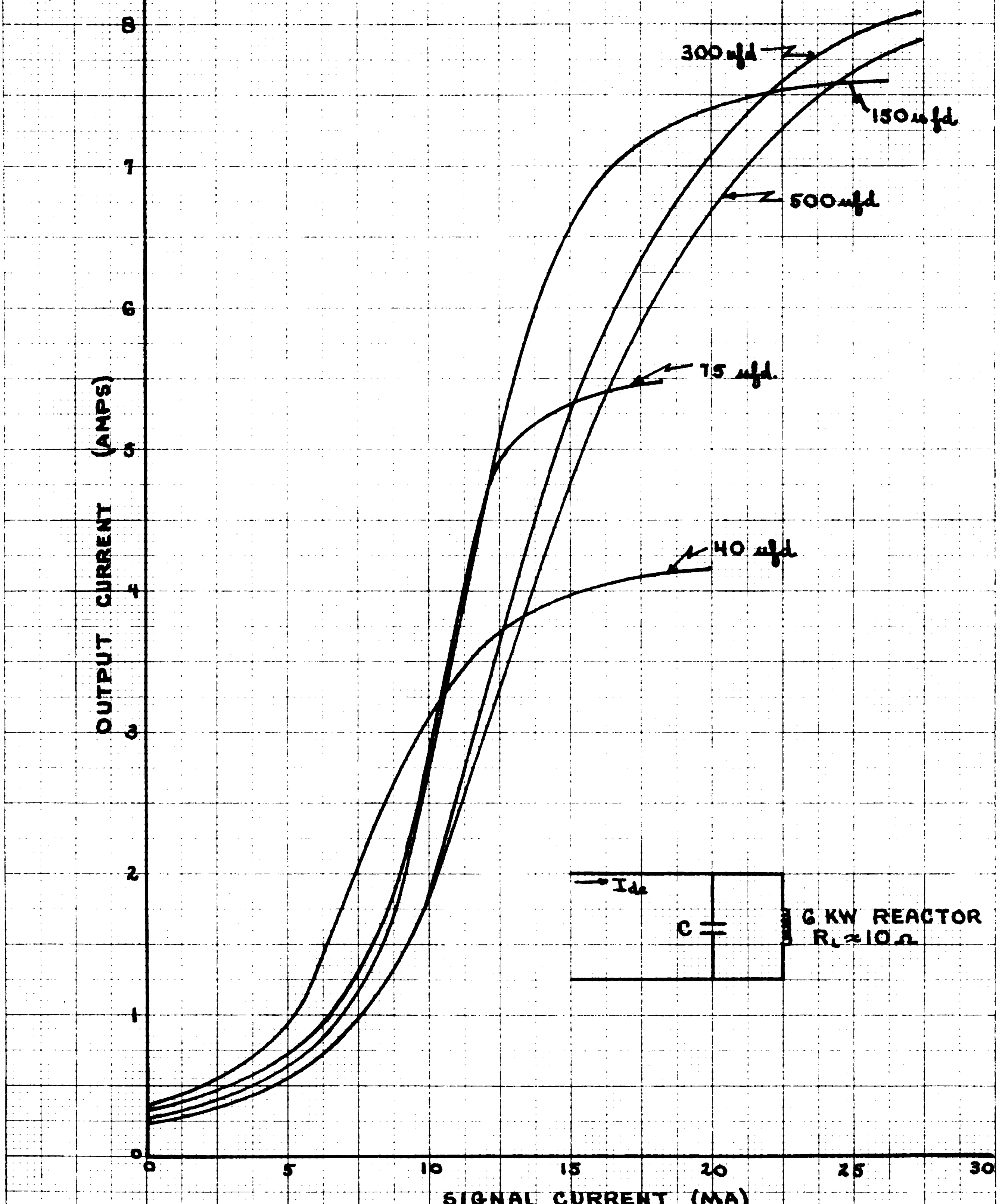
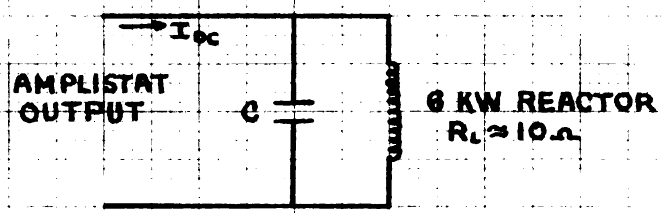


FIG. 38 - TRANSFER CHARACTERISTICS FOR VARIOUS CONDENSERS ACROSS LOAD



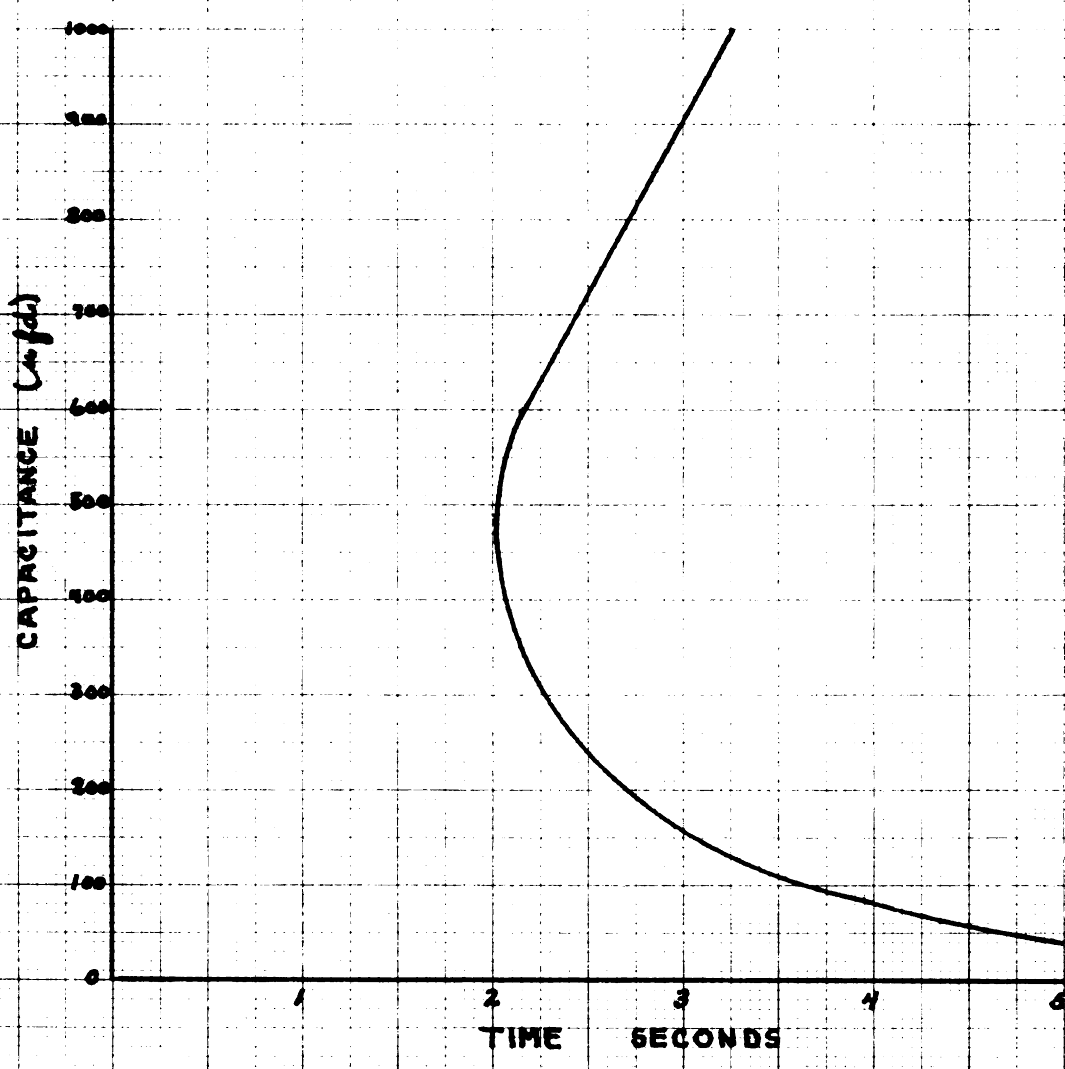


FIG. 39 - TIME OF RESPONSE VERSUS CAPACITANCE

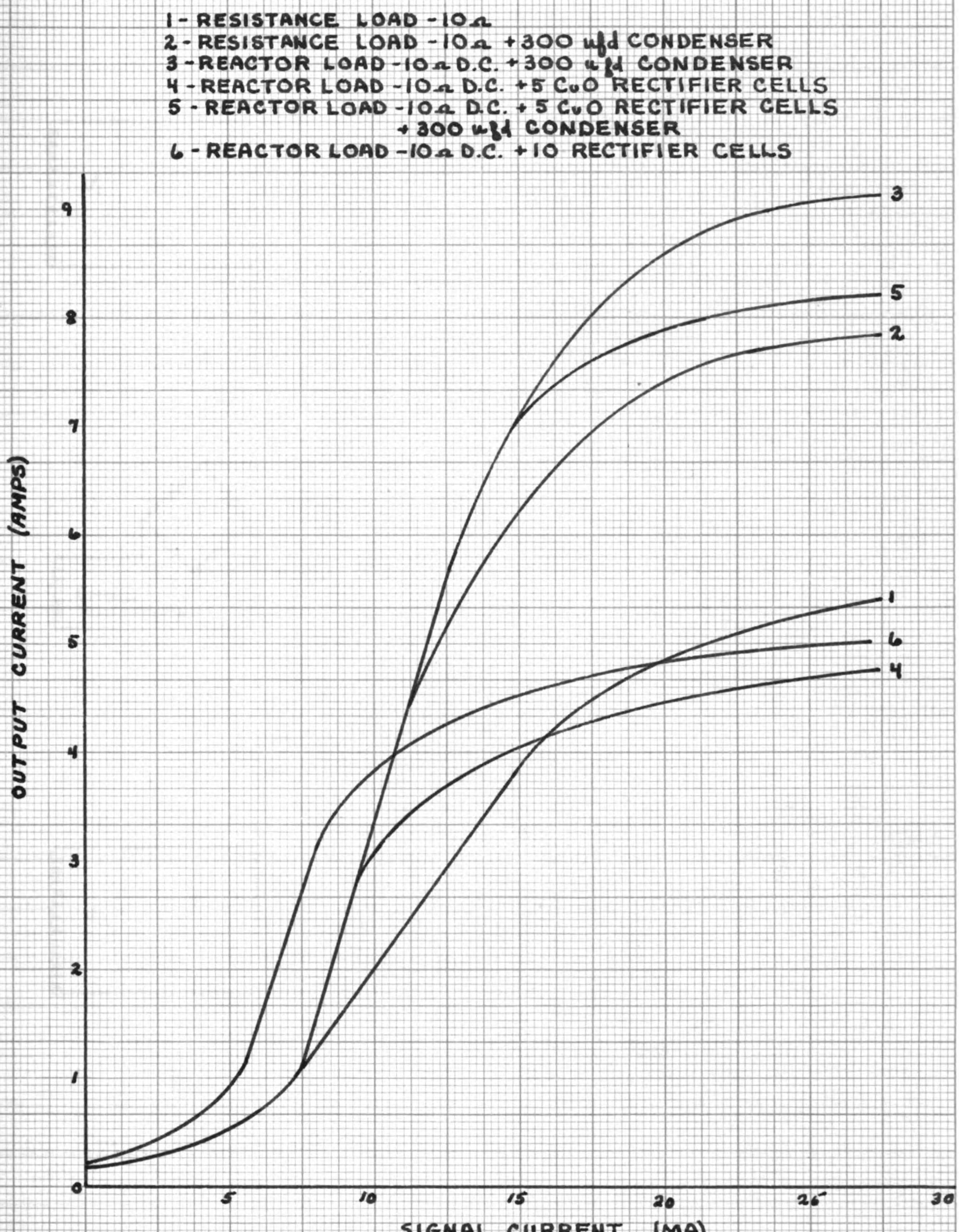


FIG. 40 - TRANSFER CURVES FOR AMPLISTAT WITH COMMUTATING RECTIFIERS AND/OR CONDENSERS ACROSS LOAD

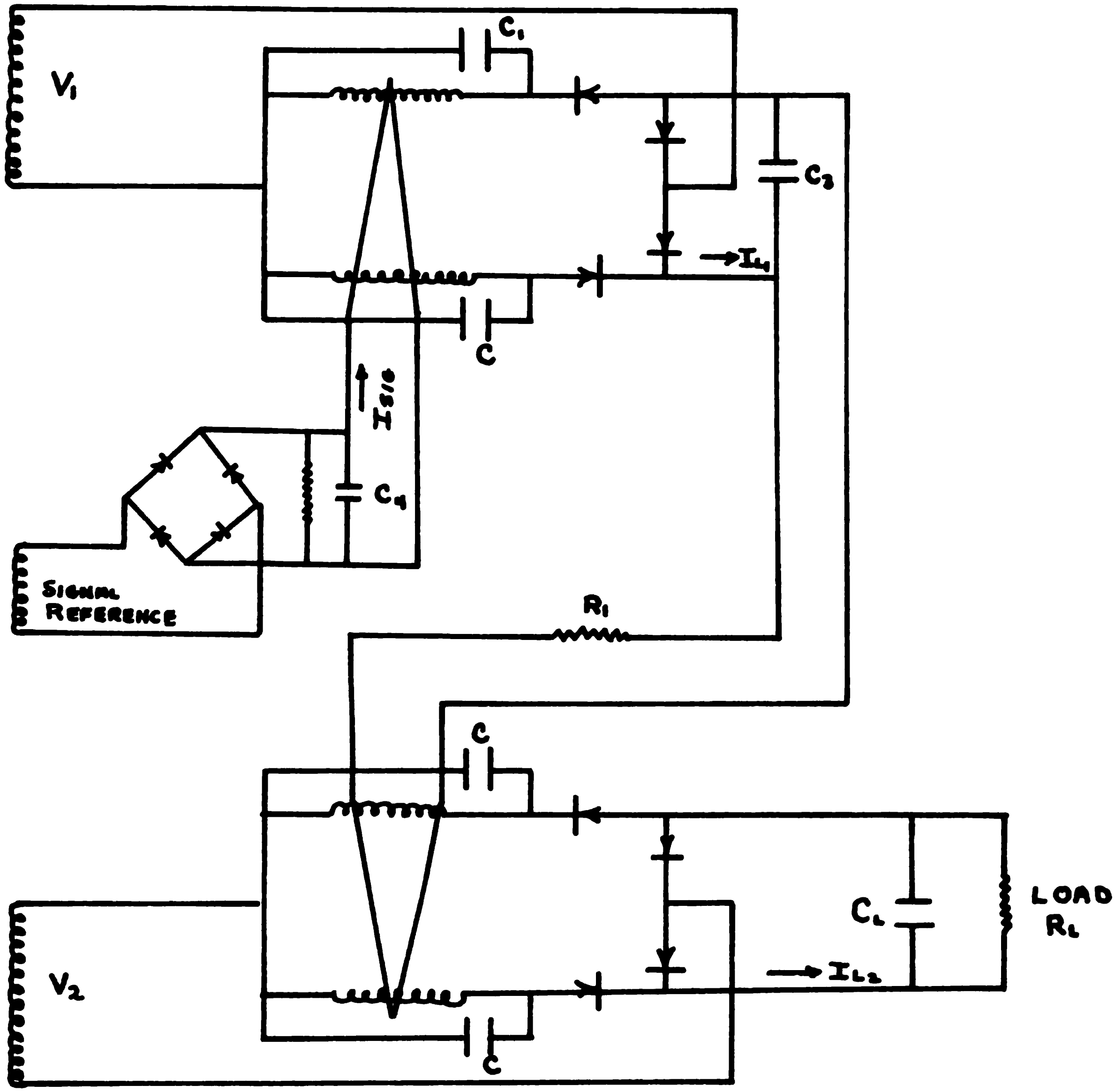


Fig. 41 Cascaded Amplistat Circuit.

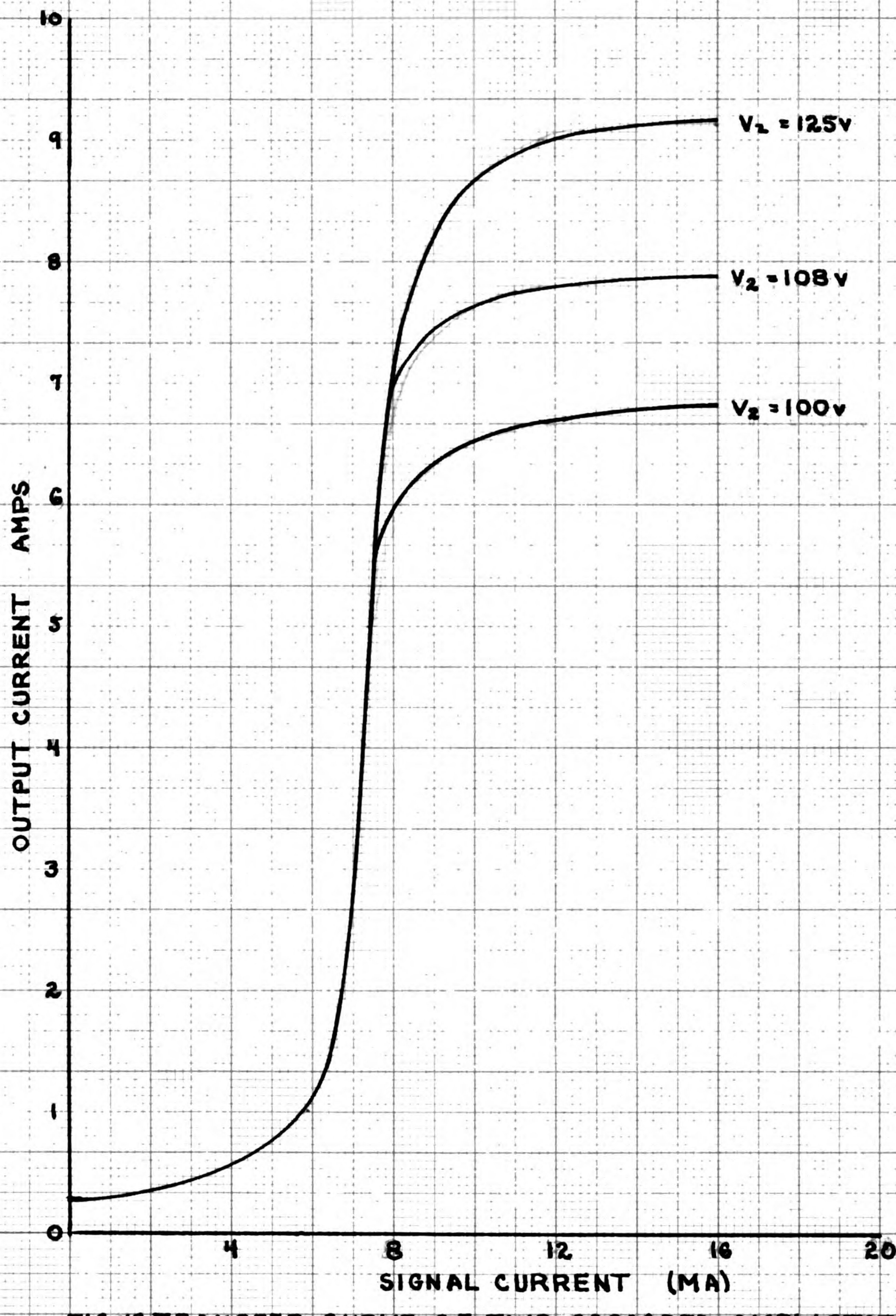


FIG.42-TRANSFER CURVE OF TWO CASCADED AMPLISTATS FOR VARIOUS SUPPLY VOLTAGES APPLIED TO THE SECOND AMPLISTAT.

Both amplistats when operated separately with a.c. bias and the correct a.c. bias condensor values for each was found to be four microfarads. But when the two amplistats were cascaded and the transfer curve taken, it was found that the curve had been transfered too much. Hence the condensors on the first amplistat were reduced to two microfarads and the characteristic replotted. Both of the characteristics are shown in Figure 43.

Another problem which arises when cascading amplistats is loading the first amplistat to the correct value. In the output winding of the first amplistat there is a resistor labelled R 1. This resistor must be varied until the best transfer characteristics are obtained. If this resistor is too low or omitted the first amplistat becomes unstable and the circuit so-to-speak takes off, in other words the control of the circuit is lost. Also if the resistance is too high the range of linearity of the over-all transfer curve is reduced as shown in Figure 44.

In some cases the condensor across the output of the first amplistat produces oscillations, which if it is removed are eliminated. This effect is due to the resonance of the inductances and capacitances of the two amplistats.

The cascading of amplistats is very important in many of their applications.

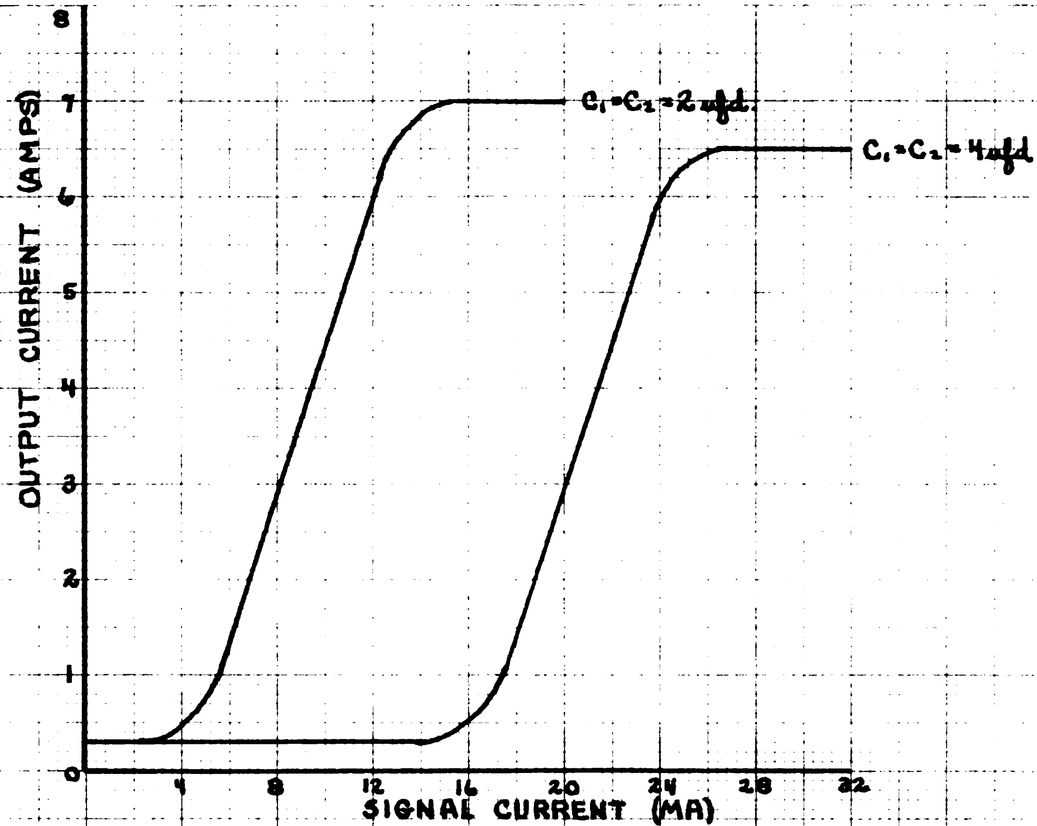


FIG. 43 - TRANSFER CURVES OF TWO CASCADED AMPLISTATS FOR TWO VALUES OF BIAS CONDENSERS.

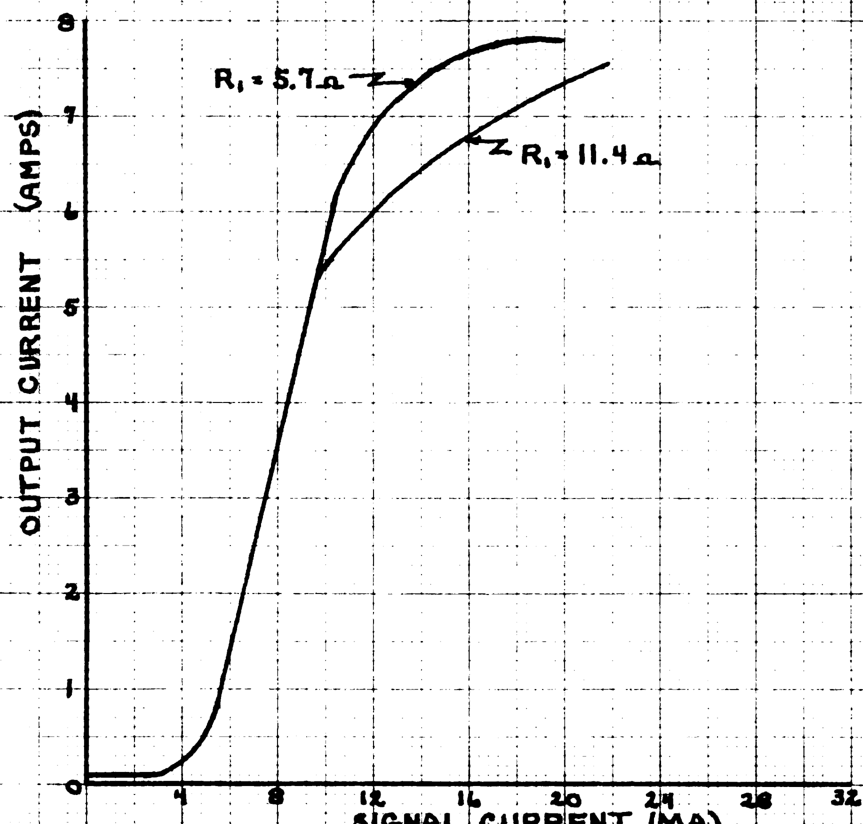


FIG. 44 - TRANSFER CURVES OF CASCADED AMPLISTATS FOR TWO VALUES OF CONNECTING RESISTANCE "R_1".

THE DESIGN OF THE AMPLISTAT

The design of the amplistat requires the knowledge of the load or the current output desired, the current which is available for the control signal, and the frequency. Most amplistats should have a low minimum output and operate with Class A insulation which allows 40° C temperature rise.

The output current is essentially from a full wave rectifier bridge, which is fed by a.c. coils. Thus each coil must carry half of the current supplied to the rectifiers. To find the amount of a.c. current flowing in each coil, the output d.c. current is multified by the form factor of the full wave rectifier bridge, which is 1.15 and then divided in half.

The flux density is then selected. The curve shown in Figure 45 was determined experimentally by the author. This curve was plotted using the amplistat for which the design is shown in this thesis. A curve was plotted for both the Spiracore and the laminated core amplistat, the core material in each case is the same. By varying the applied voltage it is possible to change the maximum flux density without affecting the other constants of the circuits. As the maximum flux density is increased the minimum output is increased. At about 70,000 lines the slope of the curve increases appreciably, hence in order to get a low minimum the flux density is

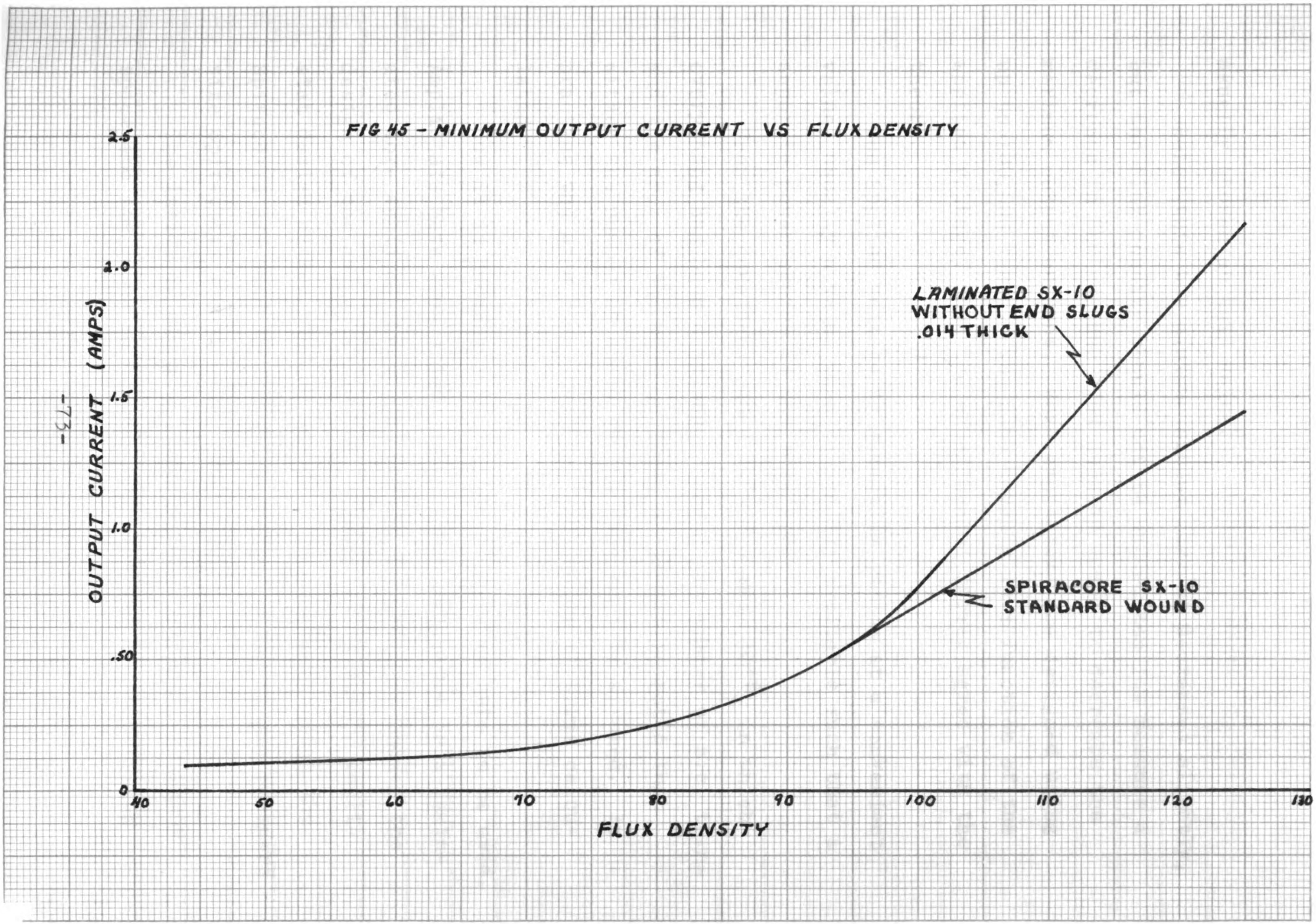


FIG 45 - MINIMUM OUTPUT CURRENT VS FLUX DENSITY

usually chosen at this value.

Below this the minimum output current decreases slightly, but the flux density should not be chosen too low because a decrease in the maximum flux density tends to decrease the maximum output current. Some amplistats are designed using up to 100,000 lines. The flux density is a function of the applied voltage, thus the experimental curves agree with the theory.

The applied voltage is generally chosen at a convenient value, usually a value that is readily available such that a separate power source is not required.

From the equation: $E = 4.44\ N\ f\ A\ B_{max}\ 10^{-8}$, in which everything has been determined except the number of a.c. turns and the area of the core section, it should be noted that either the number of turns or the area must be assumed. In practice the area is assumed and the number of turns calculated.

Now it is necessary to choose the type of core to be used. Amplistats have been built using either Spiracore or a laminated core section. Depending on the type of core chosen the design of the amplistat varies. First the Spiracore amplistat design method will be given. For standardization the Spiracores are made in specified sizes. A few of the standard size Spiracores are shown in Figure 46.

The inside diameter d_1 determines the amount of window space and the cross sectional area is found by subtracting the inside diameter d_1 from the outside diameter d_2, dividing this value in half and multiplying by the height of iron. The length of flux path is found by adding half the thickness of the core to the inside diameter and multiplying by 2.

Inside diameter	Outside diameter	Height of iron
2 1/4	3 3/4	2
2 11/16	5 3/16	2
2 1/4	4 1/2	2
2 1/4	4 1/2	4
3 1/4	5 3/4	4
4	6 3/8	4
2 3/8	3 1/2	2

Figure 46 Standard sizes of Spiracores.

Now it is a trial and error method to find a core such that the required a.c. and d.c. turns will fit in the window because once the core has been chosen the cross sectional area and the mean length of path are determined, and the required number of a.c. and d.c. turns are specified. For designing most amplistats, the number of d.c. turns are determined by multiplying the mean length of path by 4 ampere turns per inch, a figure arrived at experimentally. This figure will insure the control of the amplistat. This amplistat as designed in this paper is an example of one designed to be used as the second stage of two cascaded amplistats. From previous experience, it was known that the resistance of the control winding of the second amplistat must be large enough to load the first amplistat at the value for which it was designed to operate. Hence the number of d.c. ampere turns per inch were prescribed at approximately 100 ampere turns per inch.

As the amplistat is to use Class A insulation which allows only 40 degrees Centigrade temperature rise, the current density should not exceed 1200 amperes per mil. Divide the current density into the current to find the area of copper required and from the wire tables select the size of wire to be used. The effective length and width are also given in the tables.

The side view of the core must be drawn to scale in order to see if the number of turns required will fit in the window. The a.c. and d.c. windings may both be pyramided to increase the number of turns that may be placed in the window. The process of laying out the windings will be better understood by referring to the example design. After laying the windings out if it is found that the required number of turns will not fit in the window, it is necessary for the designer to choose another core and recalculate the number of turns and lay out the core again. This process is continued until the correct number of turns will fit in the window. But caution should be taken so that the windings should nearly fill the window because spiracore's are annealed with a specified diameter will affect the magnetic characteristics of the material, due to the stresses in the material.

The windings are wound on forms called arbors. These arbors are generally made out of wood thus the designer may choose any size arbor for the windings. Of course it is more economical to use an arbor that is in stock. Hence the designer should attempt to use one that has previously been made. The arbor size is determined by using the layout for which the windings were found and drawing the top view of the amplistat. The determination of the size of the arbor will be discussed in greater detail in the example.

After the size of the arbor is found, the mean length of turn is calculated. Using the wire tables the weight of copper and the resistance of the windings may be calculated.

An illustrative example of the calculation will clarify the design. A sample calculation sheet is included. (See Figure 47.)

This amplistat is to be designed to meet the following specifications:

Supply voltage -------------125 volts
Output current -------------6.5 amperes
Load impedance -------------12.5 ohms
Control current maximum ---4.5 amperes
Frequency ------------------60 cycles
Low minimum output current
Class A insulation
Approximately 100 ampereturns on the control winding

The flux density is chosen at 70,000 lines from Figure 45 to obtain a low minimum output current.

The output current is to be 6.5 amperes, so to find the current through each coil multiply by the form factor 1.15 and divide by two.

$$\text{RMS Current} = \frac{6.5 \times 1.15}{2} = 3.75 \text{ amperes}$$

As this amplistat is to use Spiracore, the core is estimated by the previous procedure. For this amplistat the core chosen has the following dimensions.

Inside diameter ----- 2 1/4 inches
Outside diameter ---- 3 3/4 inches
Height of iron ------ 2 inches

The cross sectional ares of the core is found by the equation:

$$\frac{d_2 - d_1}{2} \times h = \frac{(3.75 - 2.25)}{2} = 1.5 \text{ square inches}$$

From the equation:

$$E = 4.44 \, N \, f \, A \, B_{max} \, 10^{-8}$$

the number of a.c. turns may be found.

$$N = \frac{E \times 10^8}{4.44 \, B_{max} \, f \, A} = \frac{125 \times 10^8}{4.44 \times 70{,}000 \times 60 \times 1.5} = 448 \text{ turns}$$

The total number of ampere turns are found:

448 turns x 3.75 amperes = 1680 ampereturns.

As this amplistat is to operate with Class A insulation the current density is chosen at 1200 amps per mil. Dividing the a.c. current by this the area of copper is found to be 3120 mils. Looking in the wire tables the closest area of copper to 3120 mils is 3260 mils. Dividing this into the current, the corrected current density is 1150 amperes per mil. Corresponding to this area of copper the wire size is .0571. Also the effective length and width of the wire is found to be .0600 mils. The d.c. wire size is chosen as .0641 mils which has an effective size of .0671 mils.

Now it is necessary to lay out the core as shown in Figure 48. A layer of .030 mil Kraft paper insulation is allowed for inside the core. The bottom line (1) is drawn arbitrarily and its length measured and found to be 1.25 inches.

Adding approximately 10 mils for winding clearance to the effective width of the conductor and dividing it into 1.25 inches, the number of turns per layer is found to be 17 turns per layer. Assuming three layers the height of this section is found as follows:

Insulation under first winding ---	.030 ------------	.030
Insulation between layers --------	.010 x 2 layers -	.020
Three layers of wires ------------	.060 x 3 layers -	.180
Insulation between pyramids ------	.030 ------------	.030
		.260 in.

Hence the second horizontal line is drawn .260 inches above the first line. This length is found is to be 1 13/16 inches. Again divide by the effective width of the conductor and the number of turns per layer are found to be 25 turns per layer.

The number of turns on the first three layers is 51 turns. Subtracting from 448, the number of turns still required are 397. Dividing 397 by 25 the number of layers in the second section are 16 layers. Now it is necessary to compute the height of the second pyramid of the a.c. coil by the same method as before. The total height of the a.c. coil is now known.

The d.c. winding pyramid is then determined in the same way and the total number of d.c. turns that will fit in the window is 97 turns. Hence the total d.c. ampere turns is 436 ampere turns which meets the specified value.

After this is complete it is necessary to compute the arbor size for both the a.c. and d.c. windings. The a.c. coil encircles the core hence it is laid out on the outside of the core. Allowing approximately 1/2 inch for clearance the center line of the amplistat is determined. The width of the a.c. arbor is found to be 1 1/8 inches which will allow clearance for the Spiracore to be spun on. The width of the arbor must be equal to the width of the winding which is 1 13/16 inches. To find the height of the arbor the top view of the amplistat must be laid out as shown in Figure 49. The height of iron is 2 inches hence to allow clearance the height of the arbor is chosen as 2 1/2 inches. Thus the a.c. arbor size is 2 1/2" x 1 1/8" x 1 13/16". The d.c. arbor width is found by measuring the distance from the center line to the inside of the d.c. winding and doubling which gives the value of 8/12 inches. The length is equal to the width of the d.c. winding which is 1 5/8 inches. The height is taken from the top view and after allowing for clearance is found to be 5 7/8 inches. Thus the d.c. arbor size is 8 1/2" x 1 5/8" x 5 7/8".

The general layout of the a.c. or d.c. arbor is shown in Figure 50. Next the mean length of turn of the a.c. and d.c. windings is computed. First the a.c. mean length of turn. The width is 2 3/8 inches from Figure 49. The length is 4 3/16 inches.

Mean length of a.c. turn 2 (2 3/8 + 4 3/16) = 13.1 in.

The d.c. mean length of turn is calculated. The width of the d.c. winding is 6 3/8 inches. The length is found from Figure 48 as two times 4 9/16 or 9 1/8 inches.

Mean length is equal 2 (6 3/8 + 9 1/8) = 31 inches.

The feet of copper is found by dividing the mean lengths of turn by 12 inches per foot and multiplying by the number of turns.

From the wire tables:

Weight of .0571 wire -------	9.87	pounds/1000 feet
Weight of .0641 wire -------	12.40	pounds/1000 feet
Resistance of .0571 wire ---	3.25	ohms/1000 feet
Resistance of .0641 wire ---	2.56	ohms/1000 feet

Hence:

Weight of a.c. winding -------	.490 x 9.87 = 4.84	pounds
Weight of d.c. winding -------	.250 x 12.4 = 3.10	pounds
Resistance of a.c. winding ---	.490 x 3.25 = 1.59	ohms
Resistance of d.c. winding ---	.250 x 2.56 = .640	ohms

Thus the design of the Spiracore amplistat is completed except for the instruction sheet that must be given to the production man. This sheet gives only the required details for the component parts of the amplistat. (See Figure 51.)

In the previous design the type of core chosen was the Spiracore, now the design of an amplistat using laminations will be given. A layout of this type of amplistat, giving the clearances and specifications that the designer must meet, is shown in Figure 52.

The design of the laminated amplistat is simular to the design previously given until the choice of core is made except that the height of iron may be chosen at any value. After choosing the size of lamination to be used and the height of iron, the total number of turns, current density and the area of copper are computed in the same manner as in the previous

AMPLISTAT	CALCULATION SHEET		
LAMINATION 5553116	HEIGHT OF IRON 2 in.		
NET WT IRON	CORE CROSS SECTION 1.5 sq. in.		
IDENTIFICATION	AC	AC	DC
DENSITY	70,000	70,000	----
O.C. VOLTS	125	125	----
TOTAL AT	1630	1630	436
TURNS	443	443	97
RMS CURRENT	3.75	3.75	4.5
CURRENT DENSITY	1150	1150	---
AREA COPPER	3260	3260	---
WIRE SIZE	.0571	.0571	.0641
EFF COND LENGTH	.0600	.0600	.0671
LENGTH WINDOW			
TURNS PER LAYER		SEE FIGURE 51	
Nº LAYERS			
EFF COND WIDTH	.0600	.0600	.0671
WIDTH WINDING			
WINDING PLUS INS		SEE FIGURE 51	
TOTAL WIDTH			
WIDTH WINDOW			
MLT	13.1	13.1	31
FEET COPPER	490	490	250
LBS COPPER	4.34	4.34	3.11
RESISTANCE	19	19	7.71

FIG. 47

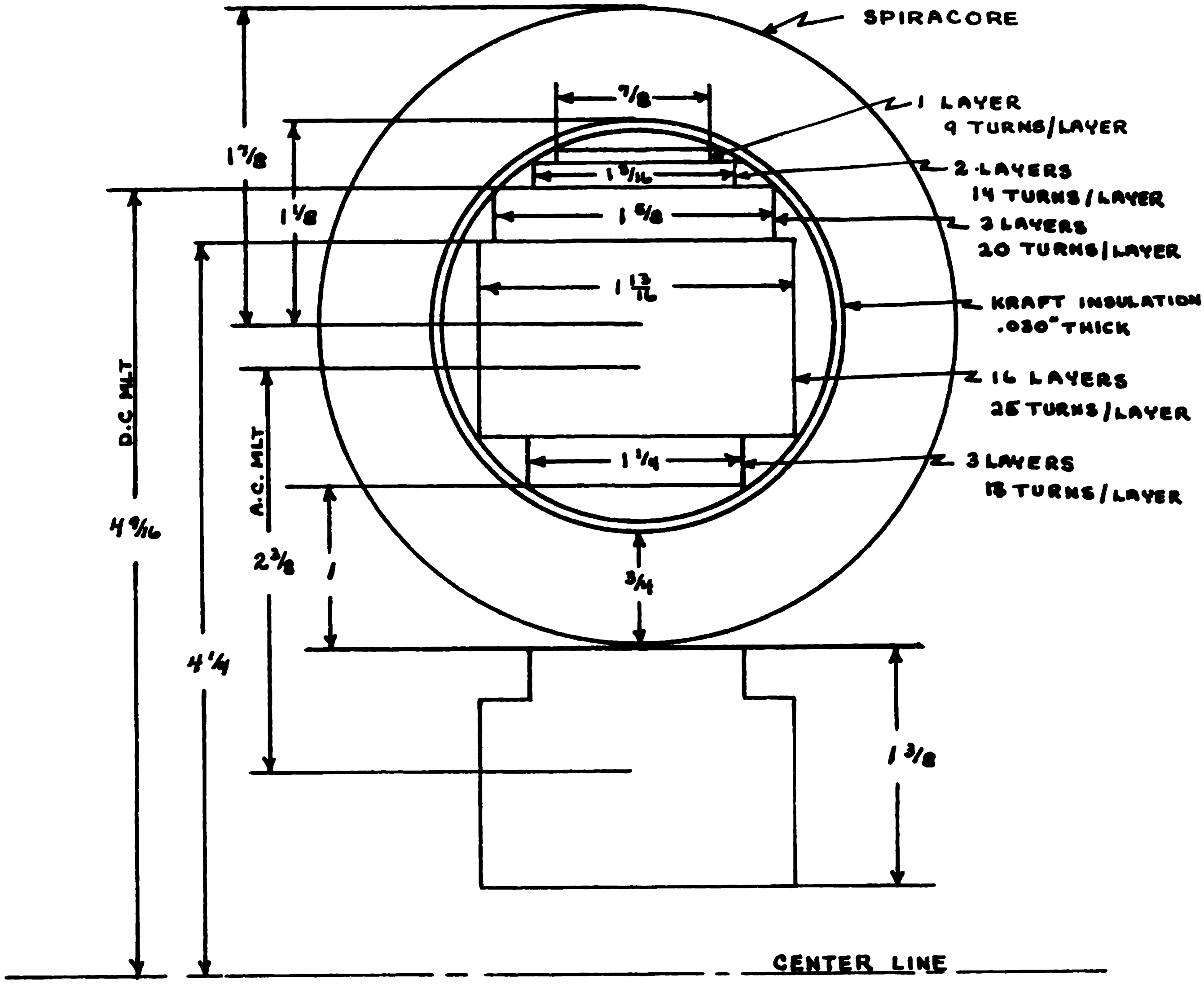


FIG. 43 Side view of the amplistat.

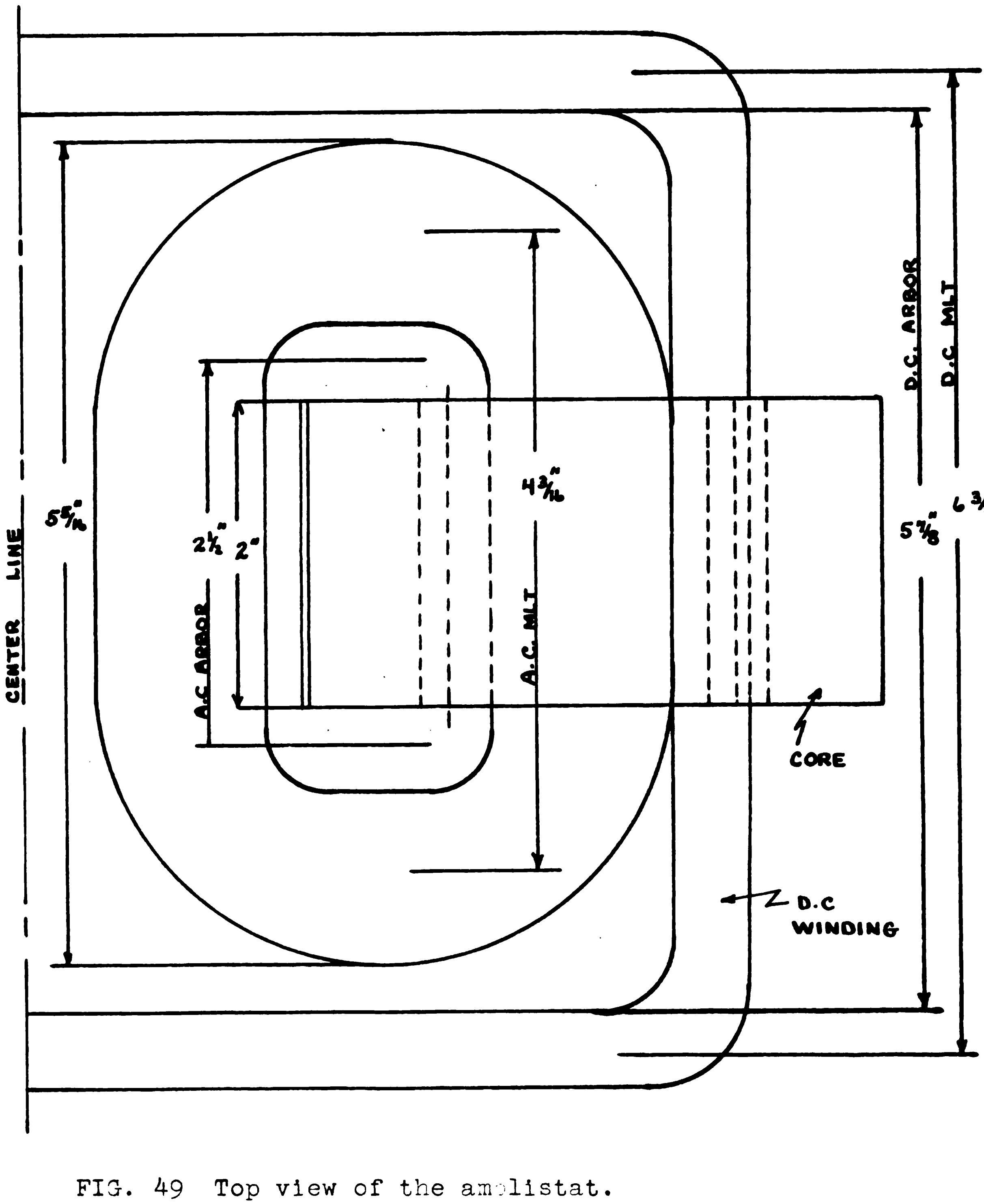


FIG. 49 Top view of the amplistat.

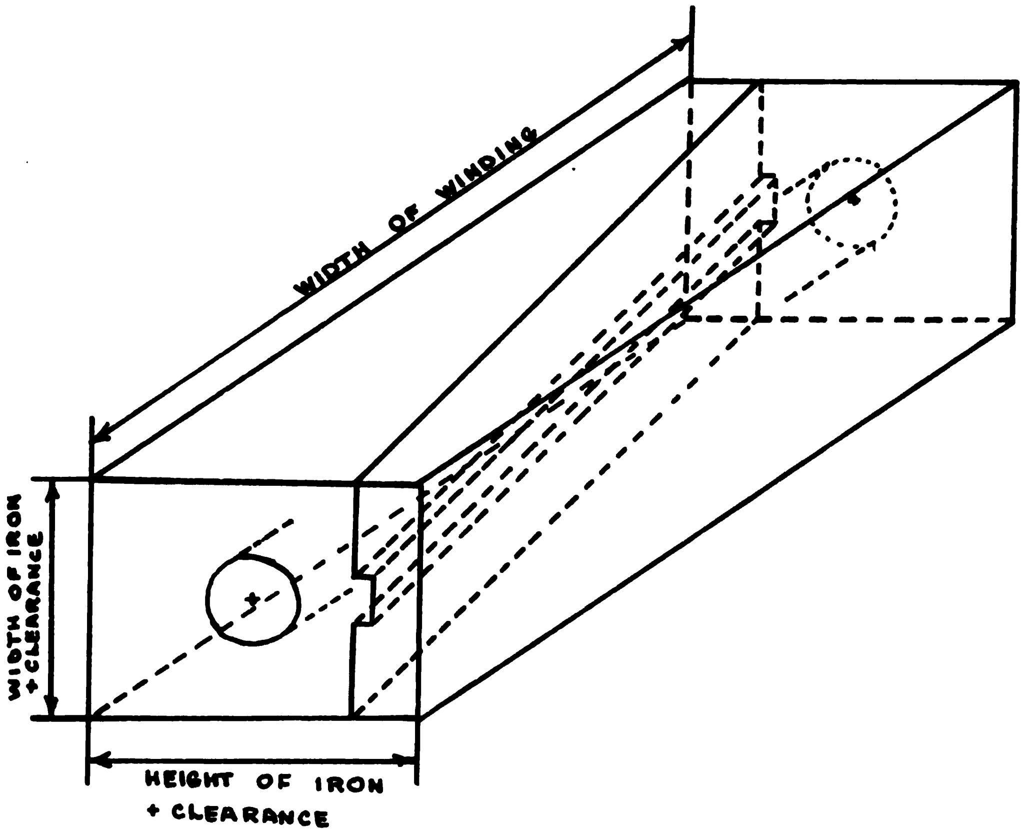


FIG. 50 The general layout of the a.c. or d.c. arbor.

WS EXPERIMENTAL	TITLE AMPLISTAT

RATING 60~ 125 V				QTY.	PT NO.	NAME	DWG NO.
ARBOR AC 2 1/2 x 1 1/8 x 1 13/16				?	1	WIRE	SEE TABLE
ARBOR DC 8 1/2 x 5 7/8 x 1 5/8				2	2	CORE	5553116
IDENT	A.C.	DC		2	3	A.C COIL	
WIRESIZE	.0571	.0641		1	4	D.C COIL	
MATERIAL	Copper				5		
INSUL	HF	HF			6		
WEIGHT	9.68	3.11			7		
TAPS	NONE	NONE			8		
LAYERS	See	Below			9		
TURNS PER LAYER	See	Below			10		
TOT. TURNS	448	97					

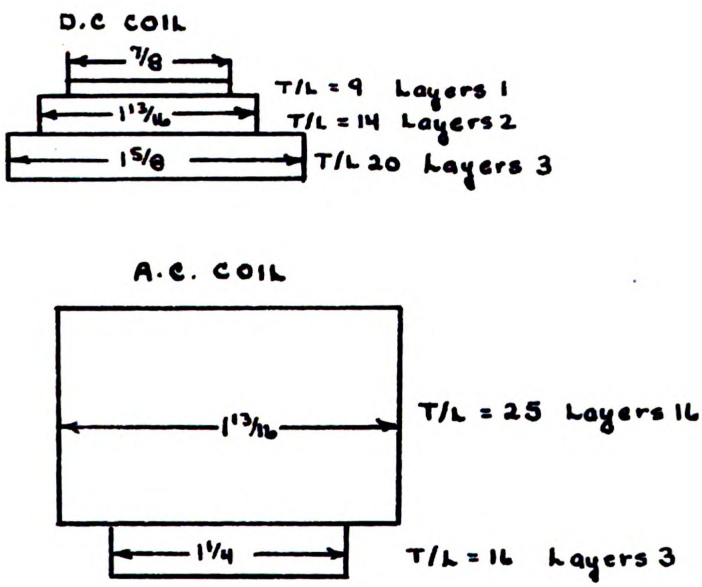


FIG. 51

design. The wire size, effective length and width of the conductor are found in the wire tables.

Once the size of lamination is chosen the length and width of the window is fixed. A clearance must be allowed to facilitate the assembly. After allowing for clearance the window length is divided by the effective a.c. conductor length to determine the number of turns per layer for the a.c. winding. Dividing the total number of turns by the number of layers for the a.c. windings are found.

The total width of the winding is then calculated. The width of the winding is the product of the number of layers and the effective conductor width. Adding the insulation between the layers the width of winding plus insulation is determined and then adding the core insulation the total width of the a.c. winding is found.

After choosing the wire size for the d.c. winding, the total width of this winding is computed in the same manner.

Now it is necessary to be sure that the a.c. and d.c. windings will fit in the window.

The mean length of turn is calculated from the layout shown in Figure 52. It should be noted that after the designer becomes familiar with this calculation it is not necessary to layout the amplistat to determine the mean length of turn.

The feet of copper, weight of copper and the resistance of both windings are found in the same manner as in the previous design.

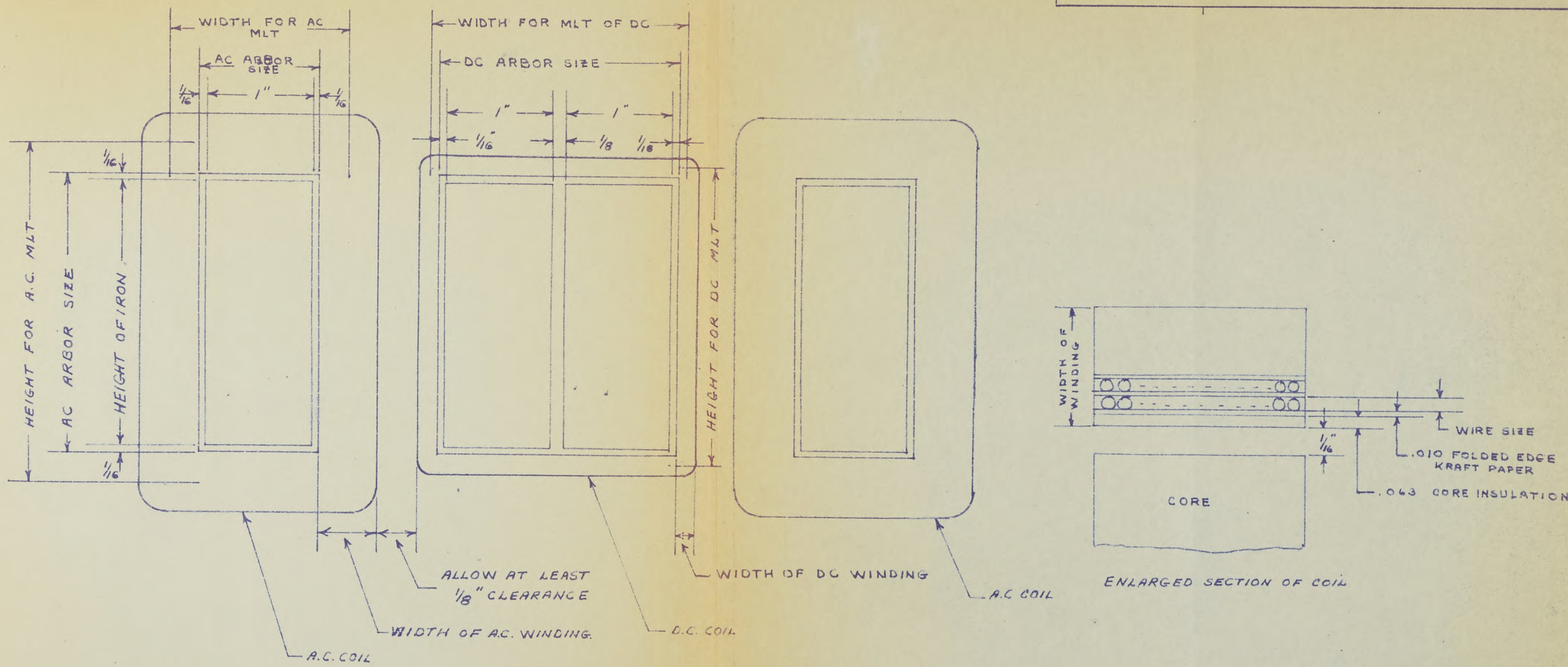


FIG. 52a Side view of the laminated amplistat.

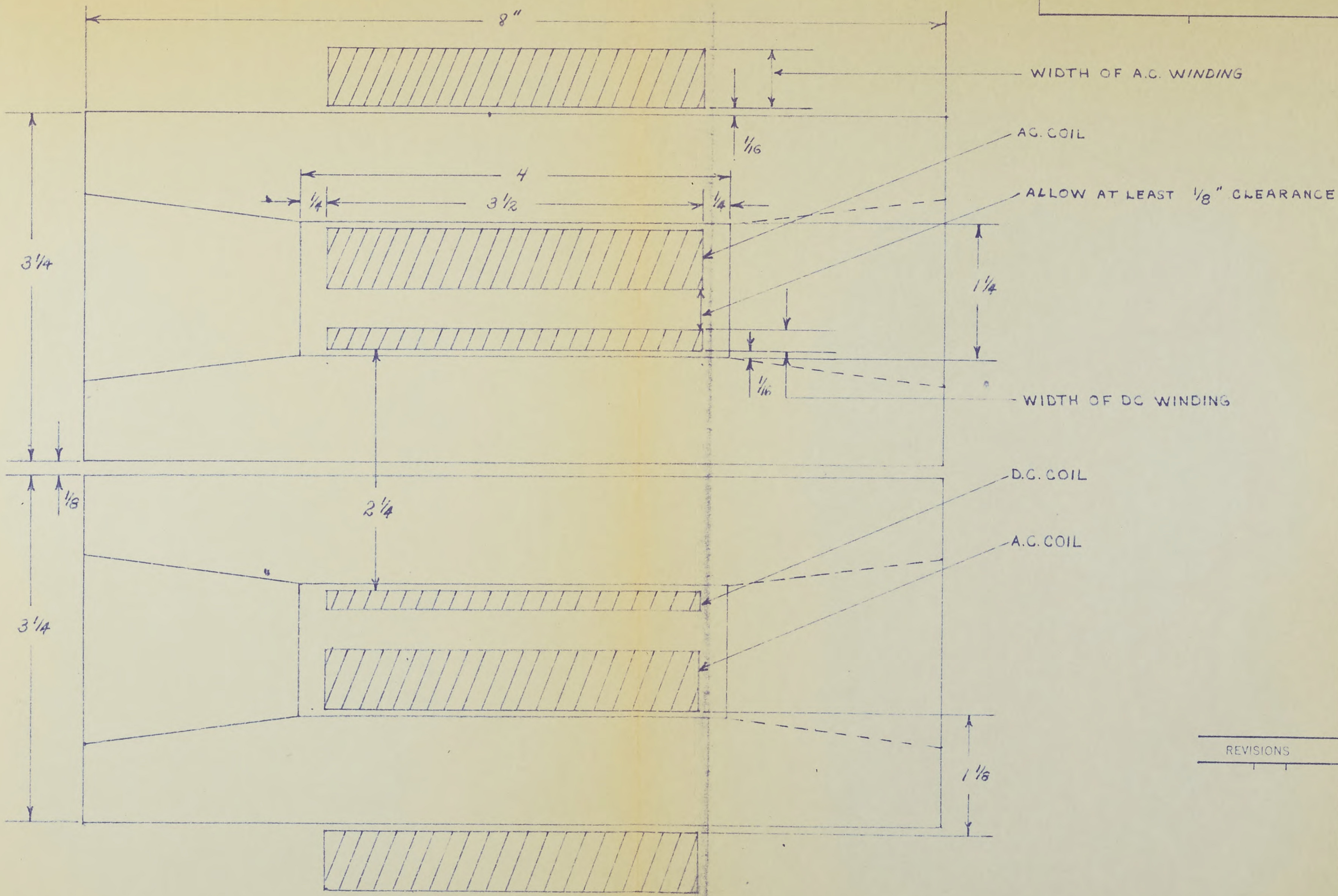


FIG. 52b Top view of the laminated amplistat.

Again an illustrative calculation will clarify the design.

This amplistat is to be designed to meet the following specifications:

Supply voltage -------------	125 volts
Load impedance -------------	12.5 ohms
Output current -------------	6.5 amps
Control current maximum ----	4.5 amps
Frequency ------------------	60 cycles
Low minimum and Class A insulation	

As in previous design:

Flux density ------------------------	70,000 lines
RMS current -------------------------	3.75 amps
Current density ---------------------	1150 amps/mil
Area copper -------------------------	3260 mils
Wire size of a.c. winding -----------	.0571
Effective conductor length of a.c. --	.0600

To make this simular to the Spiracore amplistat the height of iron was chosen as 1.5 inches. (See Figure 53.) Thus the area of the iron is the same as the value before.

The total number of d.c. turns was chosen as 68 turns which is less than those chosen for the previous amplistat design because it was found that with this type of core the control ampereturns could be reduced and still have the required control. This is of no consequence for the comparison of the two types, because they are compared on the basis of ampereturns versus output current.

The d.c. wire size was chosen as .0508 and the effective size found in the wire tables is .0537.

The lamination used in this amplistat is shown in Figure 54.

The a.c. arbor size is 1 3/4" x 2 1/4" x 3 1/2"

The d.c. arbor size is 1 3/4" x 1 1/4" x 3 1/2"

The length of the window is $3\frac{1}{2}$ inches, allowing a half inch clearance for assembly.

Dividing the length of the window by the wire size the turns per layer for the a.c. winding is 58 turns and for the d.c. winding is 64 turns.

Dividing total turns by the turns per layer the number of layers are:

a.c. winding ----- 8 layers
d.c. winding ----- 2 layers

To find the width of a.c. winding. (See the insert of Figure 52.)

Width of winding ----------	.0600 x 8 =	.480
Insulation (.010) ---------	.0100 x 7 =	.070
Winding plus insulation ---		.550
Core insulation -----------		.063
Width of a.c. winding -----		.613

To find width of d.c. winding (See insert of Figure 52.)

Width of winding ----------	.0537 x 2 =	.1074
Insulation (.010) ---------	.0100 x 1 =	.0100
Winding plus insulation ---		.1174
Core insulation -----------		.0630
Width of d.c. winding -----		.1804

Adding the width of the a.c. and d.c. winding, the space occupied by the winding is .7934 inches which allows a clearance for winding and windage because the width of the window is 1.25 inches.

To calculate the mean length of turn see the layout of Figure 52. For the a.c. mean length of turn add the width of the a.c. winding to the height of iron plus 1/8 inch clearance and multiply by two. Then take the width of the a.c.

winding add it to the width of theniron plus 1/8 inch clearance and multiply by two. The a.c. mean length of turn is then the sum of the two:

Width of a.c. winding ----	.613
Height of iron -----------	1.500
Clearance ----------------	.125
	2.238
	2
Height for mean length turn	4.476

Width of the a.c. winding	.613
Width of iron ------------	1.0000
Clearance ----------------	.125
	1.738
	2
Width for mean length turn =	3.476

Adding:

Height for mean length turn	4.476
Width for mean length turn	3.476
Mean length of a.c. turn -	7.952

The d.c. mean length of turn is computed in the same manner except the width of the iron plus the clearance is boubled because the d.c. winding encircles two cores. The mean length of turn is 9.01 inches.

The feet of copper is found by dividing the mean length of turn by 12 inches/foot and multiplying by the number of turns.

$$\text{A.C. feet of copper} = \frac{7.952}{12} \times 448 = 297 \text{ feet}$$

$$\text{D.C. feet of copper} = \frac{9.01}{12} \times 68 = 51 \text{ feet}$$

From the wire tables:

Resistance of .0571 wire ---	3.25 ohms/1000 feet
Weight of .0571 wire -------	9.87 pounds/1000 feet
Resistance of .0508 wire	4.09 ohms/1000 feet
Weight of .0508 wire -------	7.82 pounds/1000 feet

Hence:

Resistance of a.c. winding ---- .965 ohms
Weight of a.c. winding -------- 2.93 pounds
Resistance of d.c. winding ---- .209 ohms
Weight of d.c. copper --------- .298 pounds

Now the sheet which gives the required details for the component parts of the amplistat. (See Figure 55.)

Now that the two designs for an amplistat have been completed, the two types will be compared. It should be noted that the design of the laminated amplistat is much simpler than the design of the Spiracore amplistat. After designing a few of the former type the total design is merely a matter of calculations with no layout required, but in designing the latter a layout is required in order to locate and to calculate the winding layers, turns per layer and the mean length of a turn.

Before comparing the mechanics of the two amplistats their electrical characteristics should be compared. Both amplistats were operated under the same conditions and a transfer curve was experimentally taken. (See Figure 56.)

The amplistats were operated on 125 volts a.c. supply, 500 microfarad condensor across the signal control winding and with a 12 ohm resistive load. Instead of plotting the output current versus the control current, the output current is plotted versus the total ampereturns which gives a much better comparison.

The transfer curve of the laminated amplistat was taken

AMPLISTAT	CALCULATION SHEET		
LAMINATION K-3716166 NET WT IRON	HEIGHT OF IRON 1.5 in. CORE CROSS SECTION 1.5 sq. in.		
IDENTIFICATION	AC	AC	DC
DENSITY	70,000	70,000	---
O.C. VOLTS	125	125	---
TOTAL AT	1630	1630	306
TURNS	443	443	68
RMS CURRENT	3.75	3.75	4.5
CURRENT DENSITY	1150	1150	---
AREA COPPER	3260	3260	---
WIRE SIZE	.0571	.0571	.0508
EFF COND LENGTH	.0600	.0600	.0537
LENGTH WINDOW	3.5	3.5	3.5
TURNS PER LAYER	53	53	64
Nº LAYERS	8	8	2
EFF COND WIDTH	.0600	.0600	.0537
WIDTH WINDING	.4300	.4300	.1074
WINDING PLUS INS	.5500	.5500	.1174
TOTAL WIDTH	.6130	.6130	.1304
WIDTH WINDOW			1.25
MLT	7.952	7.952	9.01
FEET COPPER	297	297	51
LBS COPPER	2.93	2.93	.399
RESISTANCE	.943	.943	.218

FIG. 53

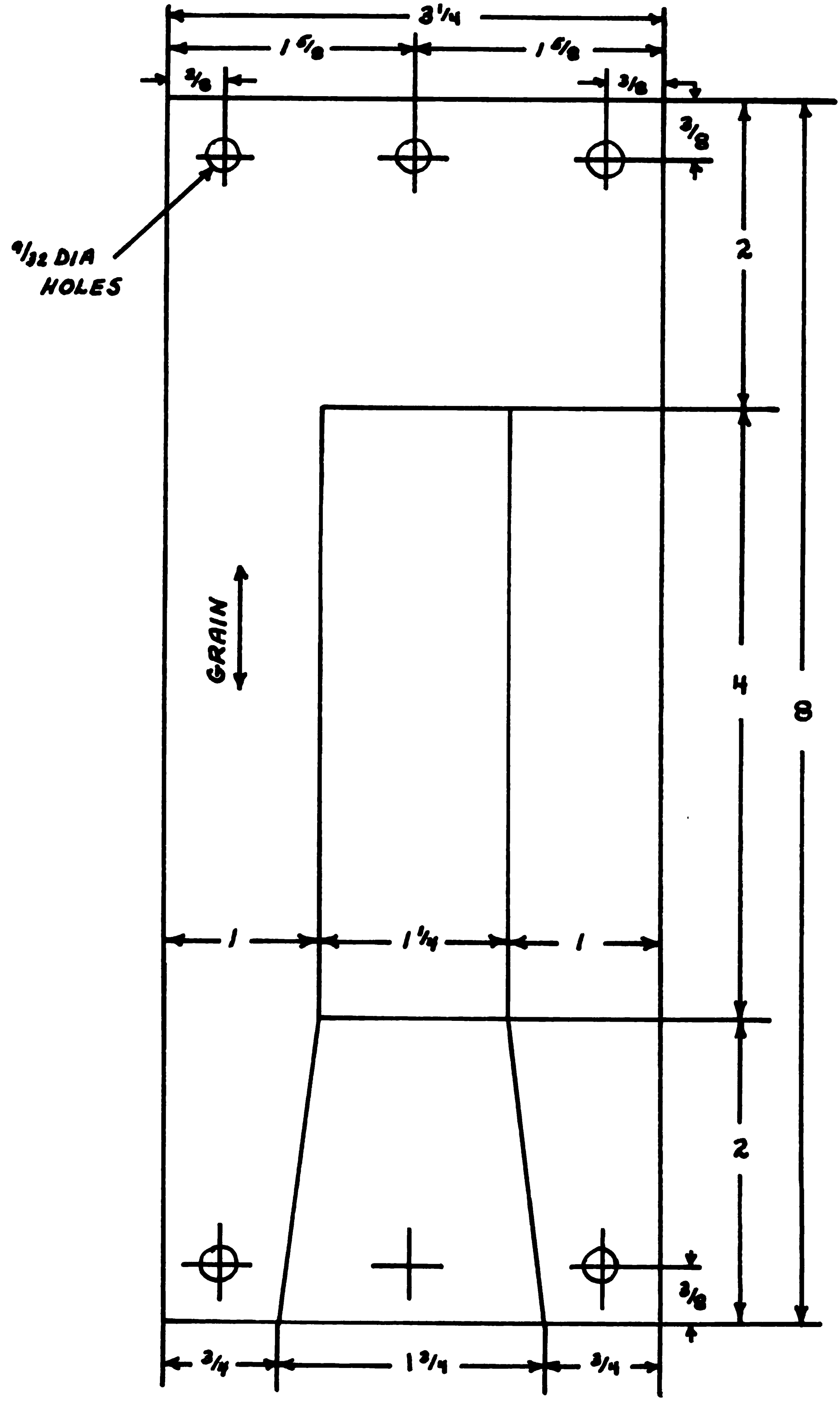


FIG. 54 Lamination used in the laminated amplistat.

WS EXPERIMENTAL	TITLE LAMINATED AMPLISTAT

RATING 60~ 125 v			
ARBOR AC 1 3/4 x 2 1/4 x 3 1/2			
ARBOR DC 1 3/4 x 1 1/4 x 3 1/2			
IDENT	A.C	D.C	
WIRESIZE	.0571	.0508	
MATERIAL	copper		
INSUL	HF	HF	
WEIGHT	3.12	.598	
TAPS	NONE	NONE	
LAYERS	8	2	
TURNS PER LAYER	58	64	
TOT. TURNS	448	68	

QTY.	PT NO.	NAME	DWG NO.
?	1	WIRE	SEE TABLE
2	2	A.C. COILS	
1	3	D.C. COILS	
214	4	CORE	K-8716166+K-8716166AB
	5		
	6		
	7		
	8		
	9		
	10		

FIG. 55

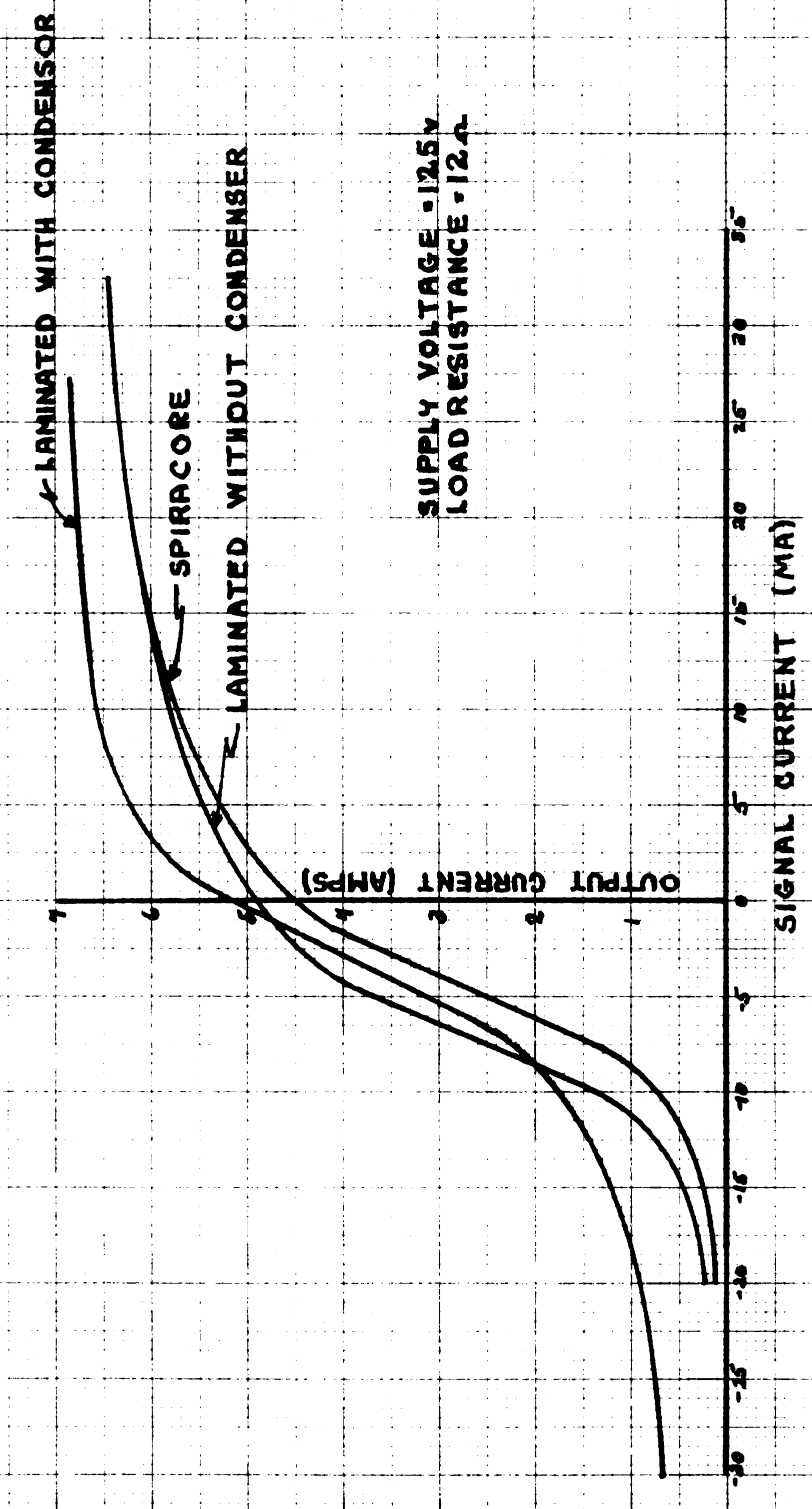


FIG. 56 - COMPARISON OF TRANSFER CURVES OF AMPLISTAT USING SPIRACORE AND LAMINATED CORE

under two conditions. One transfer curve was run with the end slugs included in the core and another transfer curve was run with the end slugs removed.

In Figure 56 it should be noted that the minimum output current is approximately the same for both of the amplistats, but the maximum output current for the laminated amplistat is higher than that of the Spiracore amplistat. Also the removal of the end slugs reduces the maximum output current slightly. The laminated amplistat has a longer linear range and the slope of the transfer curve is slightly steeper.

The electrical characteristics are not the only important feature of the amplistat. In industry the weight and cost of the amplistat is very important. A table is given below which compares the two types.

	Spiracore	Laminated	Laminated no end slugs
Weight of core ---------------	8 lbs.	16.78	15.00
Weight of a.c. copper --------	4.65	3.04	3.04
Weight of d.c. copper --------	1.28	.46	.46
Total weight of copper ------	10.58	6.54	6.54
Total weight of amplistat	21	24	22

Other characteristics:

	Spiracore	Laminated	Laminated no end slugs
Measured resistance of a.c.	1.53	1.00	1.00
Measured resistance of d.c.	.67	.241	.241
Feet of a.c. copper	472	308	308
Feet of d.c. copper --------	164	59	59

As for the cost, the figure given should not be misunderstood or quoted as they are for comparison purposes only.

Cost of Spiracore -------------------------- $ 33.00
Cost of laminated with end lamination ----- $ 29.00
Cost of laminated without end lamination -- $ 27.00

The cost to wind the a.c. coils is approximately 45% less for the laminated than the Spiracore, this is due to the Spiracore winding being pyramided. Also the cost to wind the d.c. coils for the laminated is about 20% of the cost to wind the Spiracore, again this is due to the necessity to pyramid the Spiracore windings.

The Spiracore must be wound on by hand which is an added expense. In the assembly of the amplistats the Spiracore is 40% cheaper than the laminated. But if the end slugs are left out the assembly of the laminated amplistat is reduced by about 40%.

Thus the advantages of the laminated amplistat are: (1) it is cheaper to produce, (2) the electrical characteristics are as good if not better than the Spiracore amplistat, (3) it has a much simpler design criteria, (4) the laminated amplistat doesn't require mounting brackets but may be bolted in place by the bolts which hold the laminations in place.

One of the disadvantages of the laminated amplistat is that it is slightly heavier, hence the sacrifice of the output current is made to reduce the weight, by removal of the end laminations. Some of this difference in the weight is used by the mounting brackets which the Spiracore amplistat requires.

BIBLIOGRAPHY

1. Coleman, H. C. Magnetic Amplifier Controls, Westinghouse Publication, September 1952

2. Larson, H. E., & Dunnegan, T., A Self-saturating Magnetic Amplifier for Regulating Circuits, General Electric Publication

3. Morgan, R. E., The Amplistat, a Magnetic Amplifier, Electrical Engineering, August 1949

4. Atwood, Stephen S., Electric and Magnetic Fields, 2nd Edition, 1941, New York, Wiley & sons

5. Storm, H, F., Series Connected Saturable Reactor with Control Source of Comparatively Low Impedance, A. I. E. E. Technical Paper, 50-123

6. Finzi, L. A., & Beaumariage, D. C., Magnetic Amplifier Characteristics, Electrical Engineering, December 1950 Pages 1109-1113