Digital Computer Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: <u>MAGNETIC AND DIELECTRIC AMPLIFIERS</u>

To: Jay W. Forrester

From: Dudley A. Buck

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Abstract: This paper was prepared at the request of Professor Arthur R. von Hippel for presentation at a summer symposium on the Theory and Applications of Dielectric Materials, September 3-12, 1952, at the Massachusetts Institute of Technology.

A. INTRODUCTION

The prime motivation behind recent magnetic and dielectric amplifier research is the quest for amplifiers which are more reliable and more rugged than vacuum-tube amplifiers. Amplifiers of increased reliability and ruggedness are needed in military and industrial control circuits, in communication circuits, and in information-handling machines.

Before describing how a piece of iron alloy or a thin sheet of barium titanate can act as an amplifier, let us briefly consider amplifiers in general. The term amplifier here refers to a power amplifier.

Power amplifiers are three terminal-pair devices (Fig. 1). One terminal pair is associated with the input, or signal to be amplified; one terminal pair is associated with the output, or load; and the third terminal pair is associated with the power supply.

The power supply contains no information, that is, it contains no meaningful fluctuating component that is to be amplified. The power supply can be a direct voltage, a sinusoidal voltage, a sequence of pulses, or any other waveform for which the amplifier is designed to operate. Vacuum-tube and transistor amplifiers normally use direct voltage power supply, while magnetic and dielectric amplifiers, by their very nature, must use alternating current or pulsed power supplies.

Power amplification, or power gain, may be defined as the average output power divided by the average input power, without reference to the average power delivered by the power supply.

The non-linearity in the electrical properties of ferromagnetic and ferroelectric materials makes possible their use in three terminal-pair devices which are capable of supplying more average power at the output terminals than is supplied to them at the input terminals. These devices are called magnetic and dielectric amplifiers. We shall consider them in this order.

B. MAGNETIC AMPLIFIERS

1. OPERATING PRINCIPLES OF MAGNETIC AMPLIFIERS

Magnetic amplifiers can be divided into two categories--those in which magnetic flux changes produce a voltage which subtracts from the output voltage, and those in which magnetic flux changes produce a voltage which adds to the output voltage. Amplifiers of the first category are called saturable inductors while those of the second category are called saturable transformers.

A large variety of circuits have been worked out for both categories, a few of which will be described here.

a. Saturable Inductors

Figure 2A illustrates a simple one-core saturable inductor. The reactance winding has been placed in series with the alternating current power supply and the output. Voltage across the reactance winding, caused by flux changes in the core, subtracts from the voltage available to the output. As long as flux in the core is changing, very little voltage is applied to the load. If, during the cycle, the core should reach saturation so that the flux can no longer change, then the voltage across the reactance winding of the core drops to zero and the full supply voltage is applied to the output.

The curve traced by the core material in the hysteresis-loop plane varies with the input (control) voltage (Fig. 2B). With zero input voltage, the hysteresis loop is asymmetrical due to the bias mmf. Input voltages which add to the effect of the bias voltage make the flux change smaller, that is, the core material is made to traverse a smaller hysteresis loop. Conversely, input voltages which subtract from the effect of the bias voltage cause the core material to go through a larger change in flux and thereby traverse a larger loop. In the two extremes, the input voltage may become so large in one direction that the core is always saturated, giving maximum output (load) voltage, or in the other direction so large that the major (largest possible) hysteresis loop is traversed each cycle, giving minimum output (load) voltage.

If the input winding and the bias winding were to be removed from the single-core saturable inductor of Figure 2, one might recognize the device as the ballast used with fluorescent fixtures to drop line voltage. One could wind an input winding on a fluorescent light ballast, making it a saturable inductor, and cause the light to shine brighter at will by applying a voltage to the input winding. This is indeed the device in common use at movie houses for turning the lights on during intermission, the d.c. sometimes being supplied by a small motor-generator set.

One cannot dim the lights by applying a voltage of opposite polarity to the input winding, however, for the core material is already traversing its largest possible hysteresis loop at zero input voltage. An input voltage of either polarity will cause the lights to shine brighter. To make possible a lowering of the output voltage with input voltages of one polarity and an increase of the output voltage with input voltages of the opposite polarity, the bias voltage is added. Let us say that the bias voltage turns the lights half-way on. Then input voltages which assist the bias voltage will brighten the lights, while input voltages which oppose the bias voltage will dim the lights.

Bias voltage is here applied to a separate bias winding. Often a separate bias winding is not required, the bias voltage being simply added in series with the input voltage.

As a practical device, this particular circuit has the disadvantage of relatively large power losses in the input circuit. An improvement can immediately be made by connecting two such saturable inductors (Fig. 3) with their reactance windings in series aiding and their control windings in series opposition. The voltage induced in the control winding of one inductor will be opposite in sign to that induced in the control winding of the other, and the two voltages will therefore tend to cancel whenever flux is changing in both cores. The reactance windings, whose voltages add, will operate as before.

Using a straight-line approximation for the hysteresis loop of a core material having a near-rectangular loop, the voltage, current, and flux waveforms of a saturable inductor can be derived. Figure 4A shows the loaded saturable inductor at one input voltage. Figure 4B shows the same waveforms, actually observed, for a resistance-loaded saturable inductor using Deltamax cores.[1] Load current curves are given for three different input voltages. It can be seem that as the input voltage is increased, the load current increases and lasts for a greater portion of each cycle, thus increasing the power delivered to the load. The position in the a.c. cycle at which saturation occurs and load current starts to flow, measured from the start of the cycle in electrical degrees, is called the <u>firing angle</u>.

b. Saturable Transformers

Figure 5A illustrates a simple one-core saturable transformer. The operation is similar, but inverse in logic, to the operation of the saturable inductor just described. Here, flux changes in the core produce the output voltage rather than a voltage which subtracts from the output voltage. The asymmetrical hysteresis loops of Figure 2B can also be used to describe the operation of the saturable transformer, remembering that traversal of a large loop now means a large output voltage, while traversal of a small loop now means a small output voltage.

Neglecting the effect of the bias voltage for the moment, it will be noted that with zero input voltage, this device has maximum output voltage--in contrast to the previous device which has miminum output voltage for zero input voltage. If a movie house found that its lights were on more than they were off (e.g.--a burlesque show) then this device might well be the more practical of the two for control of the lights.

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[1] T. G. Wilson, "Series-Connected Magnetic Amplifier with Inductive Loading," NRL Report 3923, Naval Research Laboratory, Washington, D.C., Jan. 9, 1952.

A two-core scheme (Fig. 5B) can be used once again to minimize input power losses.

c. Introduction of Feedback

A portion of the output voltage is often added to or subtracted from the input voltage so as to produce positive or negative feedback. Figure 6 illustrates the effect of feedback on the operating curve of a magnetic amplifier. Negative feedback, wherein a portion of the output voltage is subtracted from the input voltage, lowers the amplification but improves the linearity of the amplifier. Linearity, while it would probably be unimportant in the case of the movie house light dimmer, is of great importance in the case of magnetic amplifiers for voice amplification and for certain control systems. Positive feedback, on the other hand, increases amplification, but reduces linearity. In many circuits, excessive positive feedback will create instability, resulting in a "snap-action" (dotted lines). Under this condition, the output voltage will actually jump between two values as the input voltage increases or decreases through a certain range.

Figure 7 illustrates one of the many possible circuit arrangements which provide feedback. A portion of the a.c. output voltage is rectified and the resulting d.c. voltage is applied to a second input winding. As the a.c. output voltage increases, so does the rectified d.c. voltage. In the case of the saturable inductor (Fig. 7A), the feedback voltage will produce positive feedback if it assists the bias voltage and negative feedback if it opposes the bias voltage. The converse is true in the case of the saturable transformer (Fig. 7B).

The feedback schemes of Figure 7 are representative of a class which provide external feedback. Whenever a portion of the output is fed back to the input via an external loop, the scheme is known as external feedback.

A somewhat simpler means for introducing feedback (Fig. 8) is called internal feedback. Here, a rectifier is used to create a uni-directional current flow in the output circuit thereby causing feedback. As the output voltage increases, the magnitude of the uni-directional current in the output circuit increases, and the feedback increases.

Internal feedback, as thus far described, would be suitable only for driving d.c. loads. Using two cores operated in push-pull (Fig. 9), either a.c. loads (Fig. 9A) or d.c. loads (Fig. 9B) can be driven. The latter circuit gives a full-wave rectification.

d. Core and Circuit Variations

More complicated magnetic cores are often encountered in practice. The magnetic amplifiers which have been described involve one or two simple magnetic cores having but a single flux path. The two-core combinations can often be combined into a single three-legged core to facilitate fabrication. In addition, three-legged and four-legged cores can be built wherein magnetic fluxes are added and subtracted in the various legs just as voltages are added and subtracted in windings.

Many circuit variations have also been made, some involving other types of feedback and methods for controlling feedback, some involving saturable inductors in bridges, and some involving condensers which allow certain windings to be operated near resonance. For a description of these schemes, the interested reader is referred to a survey of magnetic amplifier types made by J. G. Miles[2] and to his very excellent bibliography of magnetic amplifier devices and the saturable reactor art.[3]

Very little has been said about the nature of the input voltage. Clearly, it can be variable direct voltage which adds to or subtracts from the effect of the bias. In the case of internal feedback, it is seen that the feedback voltage is not a direct voltage, but rather a pulsating direct voltage. In a similar manner, the input voltage can also be pulsating direct voltage.

e. Response Time of Magnetic Amplifiers

Response time of magnetic amplifiers, defined as the time for the output voltage to reach 63% of its final value following a change in input voltage, is usually a direct function of the power supply frequency, and as such is usually measured in cycles at the frequency. Storm[4] and Ramey[5,6] have shown that response time of many saturable inductor amplifiers is a function of the input circuit resistance, the output circuit resistance, and the square of the turns ratio between the two windings. Lower resistance in the output circuit or higher resistance in the input circuit make for shorter response time. Typical response times are from 1-1/2 to 3 cycles.

f. Half-cycle Response Time Magnetic Amplifiers

Circuits have been developed which have a response time of one-half cycle. Two such circuits will be described. The first, a saturable inductor circuit, was developed by R. A. Ramey at the Naval Research Laboratory;

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[2] J. G. Miles, Types of Magnetic Amplifiers--A Survey, Engineering Research Associates, St. Paul, Minnesota, January 24, 1951.

[3] J. G. Miles, "Bibliography of Magnetic Amplifier Devices and the Saturable Reactor Art," A.I.E.E. Transactions, Vol. 70, pp. 2104-2123 (1951); also A. I. E. E. Technical Paper 51-388, September, 1951.

[4] H. F. Storm, "Series-connected Saturable Reactor with Control Source of Comparatively Low Impedance," A. I. E. E. Technical Paper 50-123 (1950).

[5] R. A. Ramey, "On the Mechanics of Magnetic Amplifier Operation," A.I.E.E. Transactions, Vol. 70, pp. 1214-23 (1951); also NRL Report 3799, Naval Research Laboratory, Washington, D. C.

[6] R. A. Ramey, "On the Control of Magnetic Amplifiers," A.I.E.E. Transactions, Vol. 70, pp. 2124-28 (1951); also NRL Report 3869, Naval Research Lab., Washington, D. C.

while the second, a saturable transformer circuit, is becoming important in information-handling machines. The half-cycle response time saturable transformer is pulse-operated.

1.) Half-cycle Response Time Saturable Inductor

Ramey[5] has developed a saturable inductor circuit (Fig. 10A) which uses rectifier switches to alternately connect the magnetic core to the input circuit and the output circuit. The rectifier in the input circuit has an inverse voltage across it during one half of the power supply cycle, thereby effectively removing the input circuit from the core during that half-cycle. During the next half-cycle, the rectifier in the output circuit has an inverse voltage across it thereby effectively removing the load circuit from the core. (The power supply voltage in the input circuit must be higher than in the output circuit.)

During the half-cycle that the output circuit is removed from the core, the input circuit changes the flux in one direction. During the next half-cycle, the input circuit is removed, and the output circuit changes the flux back in the opposite direction. Because the core reaches saturation during the output half-cycle, the flux can change only as much as it changed during the input half-cycle. This amount is determined by the power supply voltage in the input circuit minus the input voltage. If there is zero input voltage, the input half-cycle will change the flux by the maximum amount, and the output terminals will receive the lowest possible voltage. In the other extreme, if the input voltage equals the power supply voltage, no flux change will occur on either half-cycle and the output terminals will receive the full supply voltage. Because of this isolation between input and output, this amplifier will always have a half-cycle response time.

2.) Half-cycle Response Time Saturable Transformer--A Pulse-Operated Device

Figure 10B illustrates a half-cycle response time saturable transformer derived from the preceding circuit. During the output half-cycle, the flux change in the core has been left unchanged in direction. The output current must therefore flow in the opposite direction. Therefore, the series rectifier must be reversed. This change brings about the very interesting fact that the rectifier in the output circuit need no longer be cut off by the half-cycle of supply voltage. The input voltage, as it causes flux changes in the core, induces a reverse-polarity voltage in the output circuit. The input circuit, acting along, thus effectively removes the output circuit during the input half cycle. We can use a power supply which consists of a sequence of uni-directional pulses to drive the output.

Since the change from inductor to transformer inverts the control logic, the power supply voltage and input voltage need no longer be differenced, so that the half-cycle from which the input was formerly subtracted can be eliminated. The power supply in charge of cutting off the input circuit

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[5] Ramey, loc. cit.

can also consist of a sequence of uni-directional pulses.

An amplifier of this type with a modification in the input circuit (Fig. 10C), which eliminates the input power supply at the expense of somewhat higher losses, is in wide use in information-handling machines. One large digital computer is being built almost entirely with magnetic amplifiers of this type.

2. MATERIALS AND PERFORMANCE OF MAGNETIC AMPLIFIERS

Magnetic amplifiers have been used most extensively with 60 cycles-per-second and 400 cycles-per-second alternating current power supplies. They are performing such tasks as the control of d.c. motor fields and armatures, control of a.c. motors, control of rectifier power supplies, etc.

Recently, in connection with voice amplification and computer service, power supply frequencies have been increasing. Some magnetic amplifiers are in operation with power supply frequencies in the region between 10^4 and 10^5 cycles per second.

In the low frequency applications, magnetic amplifiers are commercially available which deliver anywhere from a few watts to a few hundred watts of output power with amplification as high as 10,000. They have proven themselves rugged and reliable in mobile service. In this field, they are being used in increasing numbers both in conjunction with and as substitutes for vacuum-tube amplifiers.

It was implicit in the foregoing description of magnetic amplifier circuits that the core material should have a saturable region--one in which the flux changes but little for large changes in mmf. It may also have been evident that it is highly desirable to have a sharp break between the saturated region and the unsaturated region as mmf is increased. These desirable properties are summarized by stating that the hysteresis loop should be as nearly rectangular as possible. A rectangular hysteresis loop material, in addition, will give the greatest possible linearity in most of the circuits described.

Chiefly responsible for the recent widespread use of magnetic amplifiers are the recently available core materials with rectangular hysteresis loops. Once a laboratory curiosity, rectangular hysteresis loops are now built into commercially available core materials by processes of grain-orientation and domain-orientation. The following widely used alloys are listed in Table I with certain of their trade names and approximate compositions.[7]

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[7] F. Benjamin, "Improvements Extended Magnetic Amplifier Applications," Electronics, Vol. 25, No. 6, June, 1952.

TABLE I

MAGNETIC MATERIALS OF CURRENT INTEREST FOR MAGNETIC AMPLIFIERS AND SATURABLE INDUCTORS

Hipersil, Trancor XXX, Silectron Type C

(Grain-oriented Silicon steels -- 3% Si, 97% Fe)

Mu-Metal

(75% Ni, 2% Cr, 5% cu, 18% Fe)

Supermalloy

(79% Ni, 5% Mo, 15% Fe)

4-79 Mo Permalloy

(79% Ni, 4% Mo, 16% Fe)

Deltamax, Hipernik V, Orthonik, Permeron, Orthonol

(50% Ni, 50% Fe)

These core materials are generally available in the form of thin (.005" or less) ribbons of any desired width. Rectangular hysteresis loop properties are exhibited if the mmf is applied in the direction for which the grains or domains have been oriented. This is usually in the plane of the ribbon parallel to the edges, so that fabrication of a core involves simply winding the ribbon as on a spool. Thin insulating layers separate the wraps of tape so as to minimize eddy currents.

As one leaves the low frequency applications and increases the power supply frequency, one finds that the rectangular hysteresis loop with its steep sides causes eddy current effects to show up at relatively low frequencies. Eddy currents produce a "magnetic skin effect" which limits the depth of flux penetration in a core driven with alternating current, thereby effectively lowering the cross-sectional area of the magnetic flux path. The remedy for this ill effect, with a given material, is to use thinner and thinner ribbon as the frequency is raised. Ribbons as thin as .000125" (1/8 mil) are available (1/4 mil seems to be the thinnest ribbon in common use).

An alternate solution is to use a different material--preferably one with a higher volume resistivity. Unfortunately, the materials already mentioned all have about the same volume resistivity. A radically new core material whose volume resistivity is many powers of ten higher than the materials mentioned has recently become available with a rectangular hysteresis loop. This new material is a ferrite, composed of oxides of iron and other metals, which is manufactured by a ceramics process. Figure 2 was made from a photograph of one of these rectangular hysteresis loop ferrites. One year ago, it was not thought possible to make a ferrite--a polycrystalline ceramic--with such a rectangular hysteresis loop. It is not yet as rectangular, however, as the metallic alloys, and it has the disadvantages of relatively low saturation induction and relatively high coercive force (short, fat hysteresis loop). This material does promise, however, to extend the frequency range of magnetic amplifiers.

As one considers the computer applications of magnetic amplifiers, pulse operated, one finds it more natural to think of the eddy-current phenomena in the time domain rather than in the frequency domain. Switching time is then defined as the time required for the material to traverse one-half of its hysteresis loop. Switching time is a function of the applied mmf. With relatively high mmf's (25 times the coercive force) switching times as short as 10^{-7} sec have been observed for 1/4-mil 4-79 Mo Permalloy ribbon-wound cores.

Heating of the core material due to hysteresis loss is a second factor which limits the frequency at which magnetic amplifiers can be operated. Heating very often results in a change in the magnetic properties of the core material. With the metallic cores, this change is often irreversible upon cooling. With ferrite cores, changes in the magnetic properties due to heating seem to be reversible, but the magnetic properties often vary over a somewhat narrower temperature range.

C. DIELECTRIC AMPLIFIERS

A power amplifier can, as we have seen, be built which utilizes for its operation the non-linear electrical properties of a ferromagnetic material. In a similar manner, the non-linear electrical properties of a ferroelectric material can be used to build a power amplifier. This latter type, called a dielectric amplifier, is somewhat the electrical dual of the magnetic amplifier.

Before describing dielectric amplifier circuits and their operation, let us consider briefly the electrical properties of ferroelectric materials.

1. FERROELECTRIC MATERIALS

Ferromagnetic materials owe their non-linearity primarily to the existence within the material of domains of permanent magnetic dipoles. Recently, materials have been discovered within which domains of permanent electric dipoles exist.[8,9,10] These materials, named ferroelectrics, exhibit

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[8] A. von Hippel and co-workers, NDRC Reports 14-300 (August, 1944), and 14-540 (1945).

[9] A. von Hippel, "Ferroelectricity, Domain Structure, and Phase Transitions in Barium Titanate," Laboratory for Insulation Research Technical Report IIVII, Massachusetts Institute of Technology, March, 1950; Reviews of Modern Physics, Vol. 22, No. 3, pp. 221-237, (July, 1950).

[10] D. A. Buck, "Ferroelectrics for Digital Information Storage and Switching," Digital Computer Laboratory Report R-212, M. I. T., June 5, 1952.

hysteresis loops in the D-E plane similar to those of the ferromagnetic materials in the B-H plane (Fig. 11).

Ferroelectricity is exhibited by three groups of materials whose representatives are the tetrahydrate of potassium-sodium tartrate (rochelle salt), dihydrogen potassium phosphate and arsenate, and barium titanate. Materials of the latter group, represented by barium titanate, have been considered for dielectric amplifier use. Unlike the others, barium titanate can be prepared in the form of a rugged ceramic which exhibits ferroelectricity over a wide temperature range, and which, when compounded with other titanates, canbe tailored to a wide variety of electrical properties. This third group has recently been augmented by the addition of the ferroelectric tantalates, niobates, and tungstates, most of which have yet to be tested for dielectric amplifier use.

The hysteresis loops of Figure 12 are those of ceramic barium titanate (Glenco body "X-18"). They are not nearly as rectangular as the hysteresis loops of the magnetic cores used for magnetic amplifiers. If one desires hysteresis loops of greater rectangularity, the only available method at present is to abandon ceramics and grow single crystals of barium titanate.

As with the ferromagnetic materials, the hysteresis loop disappears as the material is heated through the Curie temperature, and the electric dipole domains within the material are no longer able to align themselves spontaneously against the randomizing action of thermal vibrations (Fig. 12).

2. DIELECTRIC AMPLIFIER CIRCUITS

Considering dielectric amplifiers as the dual of magnetic amplifiers, interchanging everywhere the words voltage and current, we immediately encounter the rather troublesome fact that ferroelectric condensers are one terminal-pair devices while magnetic cores with their windings can be multi-terminal-pair devices. The engineer recognizes this as a distinct handicap, for he must often incorporate additional circuit elements--linear condensers and linear transformers--to obtain multiple connections to the ferroelectric, d-c isolation between terminal pairs, and impedance matching.

In principle, there are two basic dielectric amplifier circuits just as there are two basic magnetic amplifier circuits--one in which the current through the dielectric adds to the output current, and one in which current through the dielectric subtracts from (shunts) the output current.

A simple dielectric amplifier of the first type (Fig. 13A) can be made by simply replacing the reactance winding of the saturable inductor of Figure 2A with a saturable condenser--a ferroelectric condenser--and then describe the device somewhat as we did the saturable transformer of Figure 5A. The saturable condenser is in series with the power supply and the load, as was the saturable inductor. It passes a current which contributes to the load current whenever its charge changes. Therefore, the output power is greatest when the ferroelectric condenser traverses the largest possible hysteresis loop and smallest when the ferroelectric condenser is biased into a saturated region.

An improvement with regards to lowering of input power can be made by using more than one ferroelectric condenser. One such circuit (Fig. 13B) locates the ferroelectric condensers in two legs of a bridge and linear condensers in the other two legs. Unbalance in the bridge due to input voltage causes an output current to flow.

Quite commonly, dielectric amplifiers incorporate linear inductances which allow the circuit to operate near resonance (Fig. 14). One such mode of operation is obtained when the resonant circuit has too large a capacitance to resonate at the power supply frequency with zero input voltage. An increase of the input voltage drives the ferroelectric condensers towards saturation, effectively lowering their capacity and bringing the circuit into tune. This amplifier is of the second type; the large capacity effectively shunting the output during quiescence.

Dielectric amplifiers have been built which operate with power gains greater than 50 using power supply frequencies in the 2 megacycle region.[8] Power output levels, however, are in the milliwatts.

A dearth of suitable materials seems to be the one thing which is holding back the full scale development of dielectric amplifiers. The ceramics, inexpensive and rugged, do not exhibit saturation regions as sharply defined as is desired. Grown single crystals, while they have most of the desirable characteristics, are quite expensive.

In spite of this fact, the future of dielectric amplifiers is indeed exciting. The packaging possibilities alone offer something that is not possible with magnetic circuits, for nature made magnetic fields divergenceless so that closed paths--rings or shells--are needed for the lines of flux, whereas electric fields can start and stop on any material within which we can mobilize charge carriers. We can therefore think of many small ferroelectric condensers being fabricated side by side on a single thin sheet of ceramic or grown crystal barium titanate where fabrication involves such methods as silk-screening, evaporation, or photo-engraving. A multi-position switch[9] has been built using saturable ferroelectric condensers which illustrates one such possibility.

D. POWER SUPPLY REQUIREMENTS

Some general statements can be made regarding the various magnetic and dielectric amplifier circuits and their relationship to the relative impedances of the power supply and the load on the output terminals.

We can define a "quasi-voltage" source as a power supply whose internal inpedance is lower than that of the device to which it supplies

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[8] H. Urkowitz, "A Ferroelectric Amplifier," Philco Report No. 199-M, Philco Research Division, Philadelphia, Pennsylvania.

[9] D. A. Buck, "A Ferroelectric Switch", M.I.T. Digital Computer Laboratory Report E-460, April 16, 1952.

power, and a "quasi-current" source as one whose internal impedance exceeds that of the device to which it supplies power.

Maximum power is delivered to a load from a source when the respective impedances are equal. On either side of this matched condition, the power transferred to the load drops off. One can see immediately that if a load is driven by a quasi-voltage source, additional power is requested from the source by lowering the load impedance. If, on the other hand, the load is driven by a quasi-current source, one must increase the load impedance to request more power from the source.

One notices that in the saturable inductor circuit of Figure 2A, more power is requested from the power supply by lowering the impedance of the circuit. One should therefore use a quasi-voltage source to drive such a circuit. Indeed, one sees that a true current source could not be used to drive the circuit because the current in the load would not be controlled by the saturable inductor; it would always be the same regardless of input voltage.

In a like manner, one sees that the saturable transformer circuit of Figure 5A needs a quasi-current source for a power supply. If driven by a true voltage source, the driven winding would demand infinite current when the core material saturates.

The dielectric amplifiers described in Figure 13 require quasi-voltage sources since their impedance lowers in order to demand more power. If driven by a true current source, one sees that at saturation an infinite voltage would appear across the terminals of the ferroelectric condenser.

In the dielectric amplifier circuit of Figure 14, the ferroelectric condenser shunts the load. With a quasi-current source power supply, the circuit impedance increases at saturation thereby demanding more power.

These four basic circuits are summarized in shorthand form in Figure 15. The saturable transformer is drawn with only its magnetizing inductance showing; the leakage inductance and the usual ideal transformer are omitted.

In the literature, most emphasis has been given to the two schemes which require quasi-voltage sources. This seems quite reasonable since most power supplies are quasi-voltage sources; the commercial 60-cycle power distribution is a quasi-voltage source.

More often than not, one has a number of magnetic or dielectric amplifiers all operating from a common power supply. Minimum interaction between the amplifiers is usually desired. This dictates that amplifiers which require quasi-voltage sources be connected to parallel, while amplifires which require quasi-current sources be connected in series.

E. CONCLUSION

This paper has been written as an introduction to magnetic and dielectric amplifiers, both of which are being investigated in the quest for new and more suitable components for communication, computation and control.

Signed Dudley A. Buck
Dudley A. Buck

Approved DRB
David R. Brown

DAB/jk

Drawings attached:

A-51945	Figure	1
A-51948	"	2
A-51962	"	3
A-51970	"	4
A-51983	"	5
A-51985	"	6
A-51972	"	7
A-51971	"	8
A-51980	"	9
A-51987	"	10
A-50545	"	11
A-51351	"	12
A-52312	"	13
A-52393	"	14
A-52313	"	15

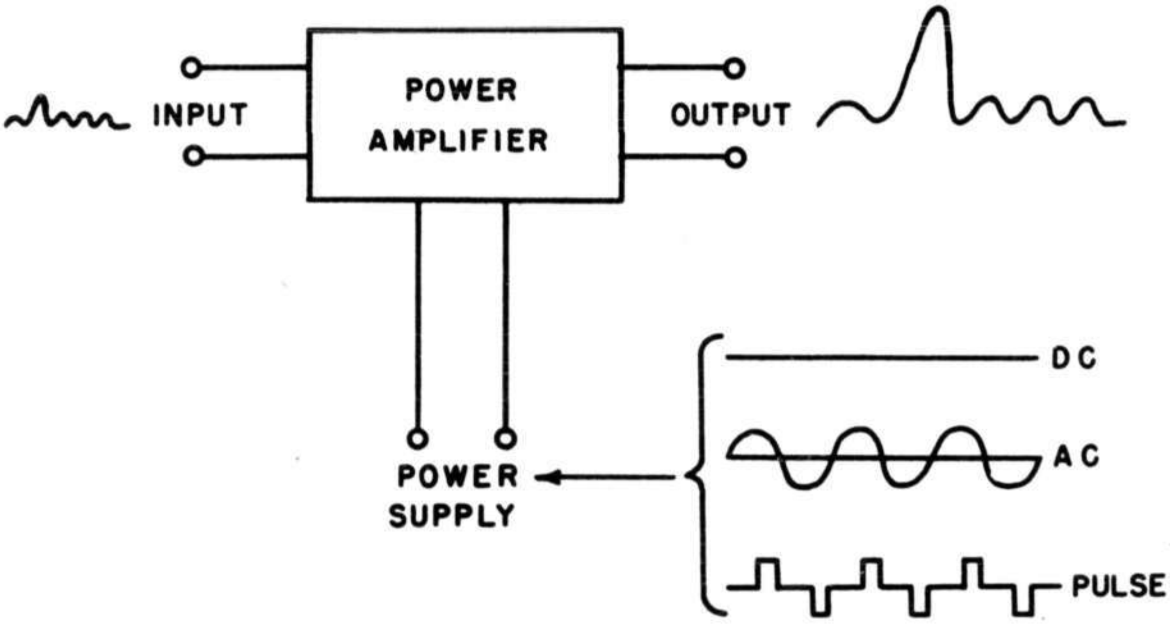
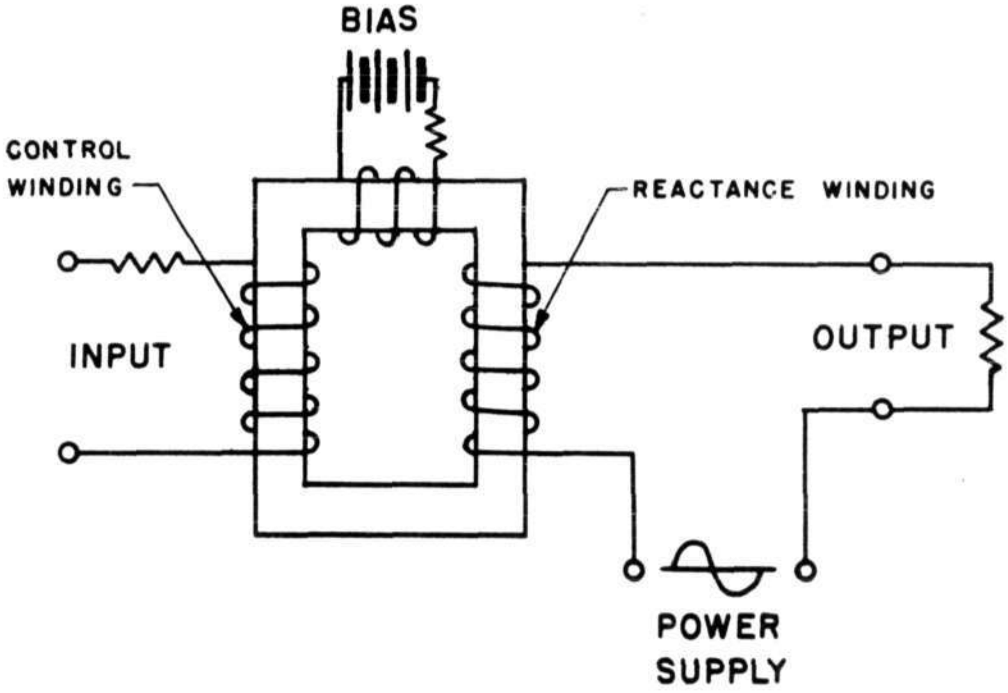


FIG. 1

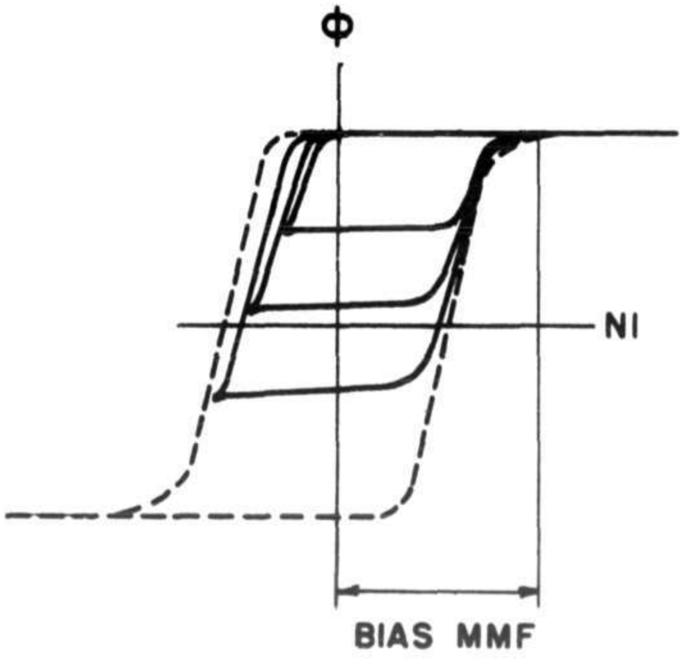
POWER AMPLIFIER

A THREE TERMINAL–PAIR DEVICE

A–51945



A. SINGLE-CORE SATURABLE INDUCTOR



B. ASYMMETRICAL HYSTERESIS LOOPS OF A RECTANGULAR-LOOP FERRITE CORE MATERIAL MF-1118(259)

FIG. 2

SATURABLE INDUCTOR

A—51948

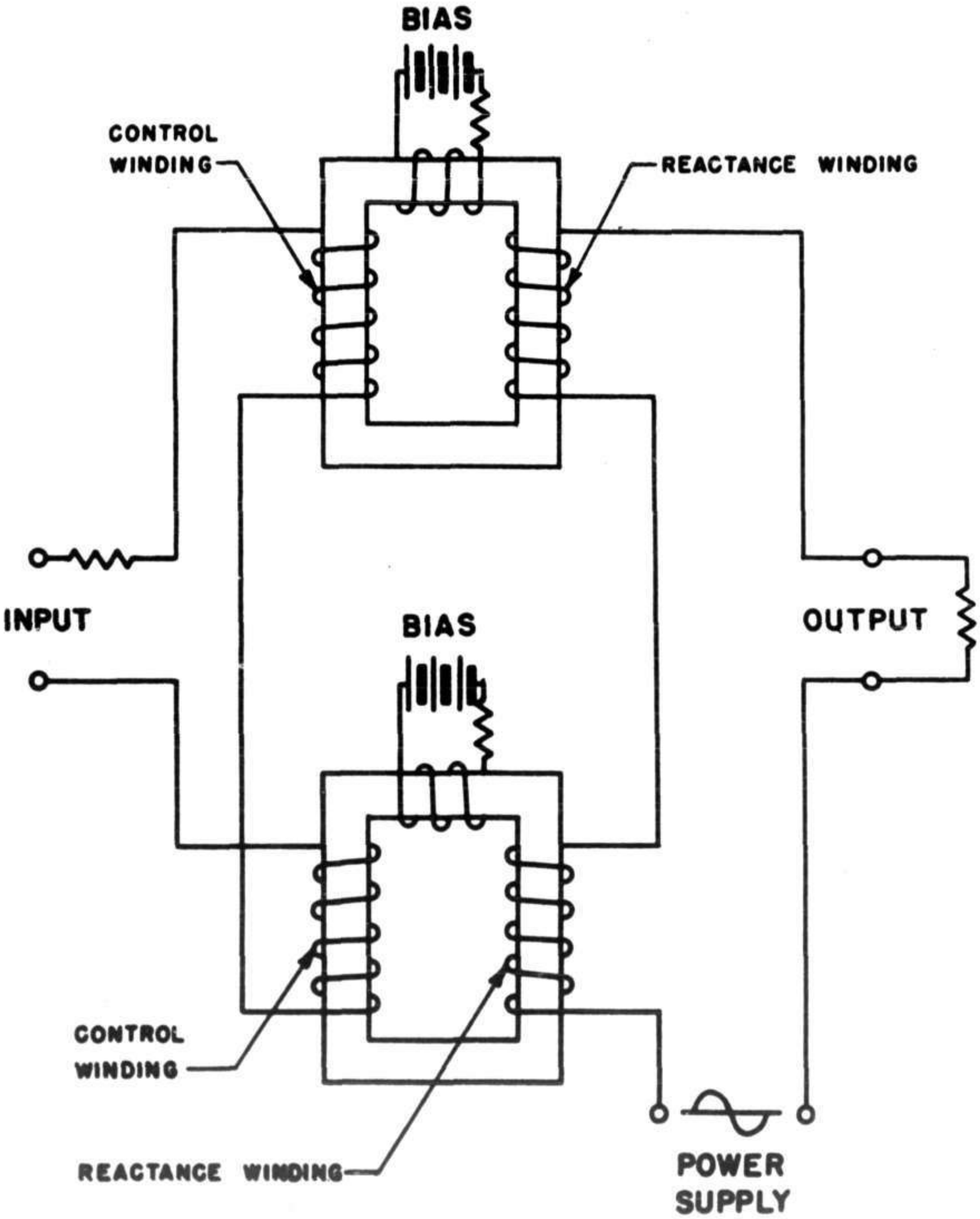
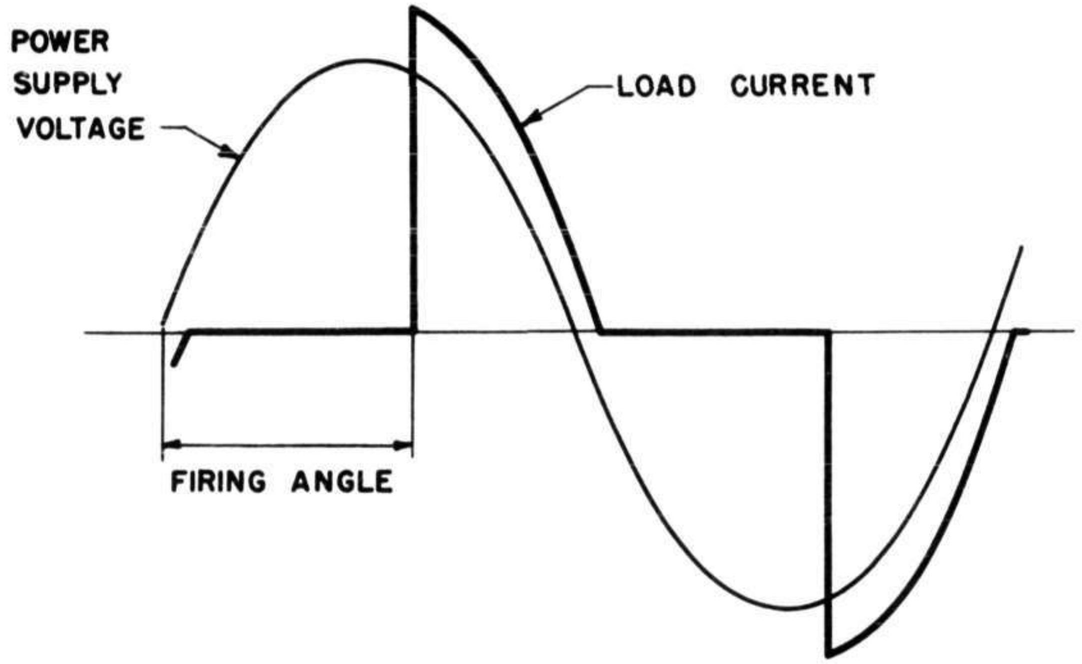


FIG. 3

TWO—CORE SATURABLE INDUCTOR

A—51962



A. DERIVED WAVEFORMS OF RESISTANCE-LOADED SATURABLE INDUCTOR USING IDEALIZED CORES

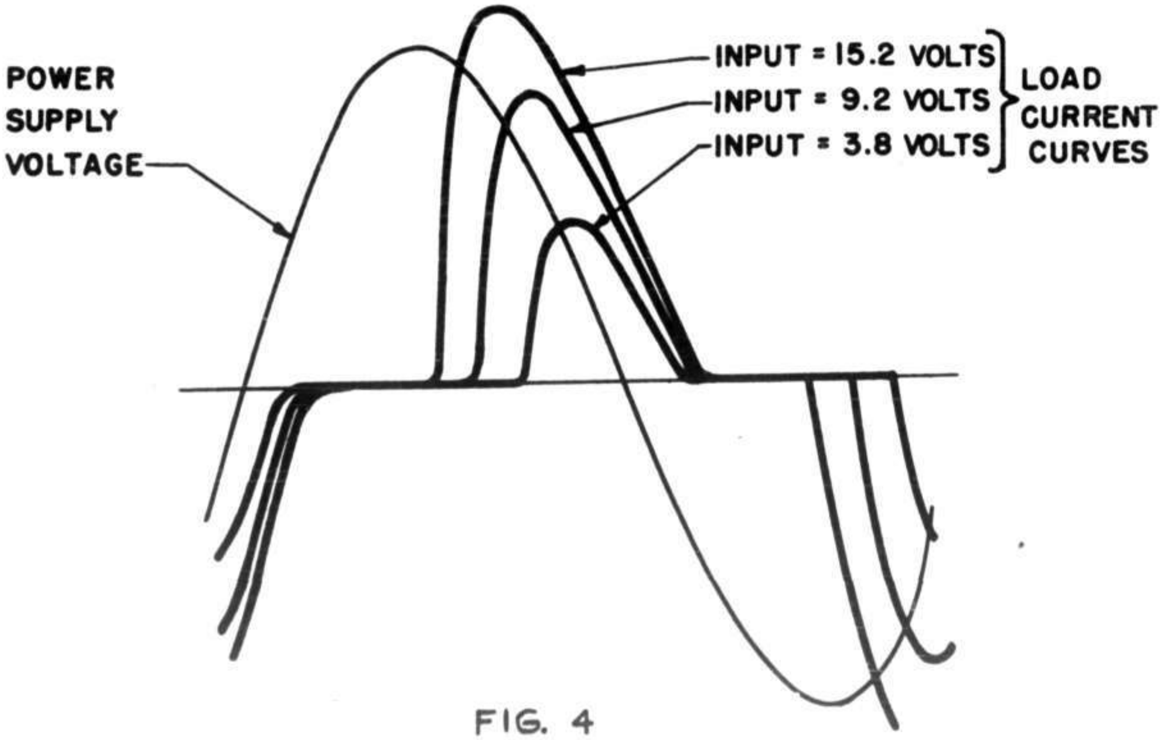
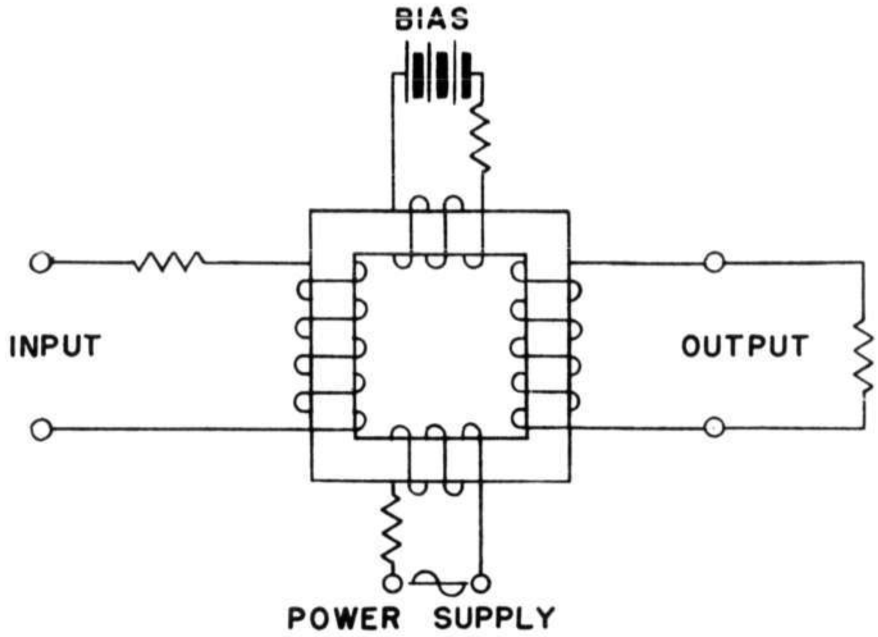


FIG. 4

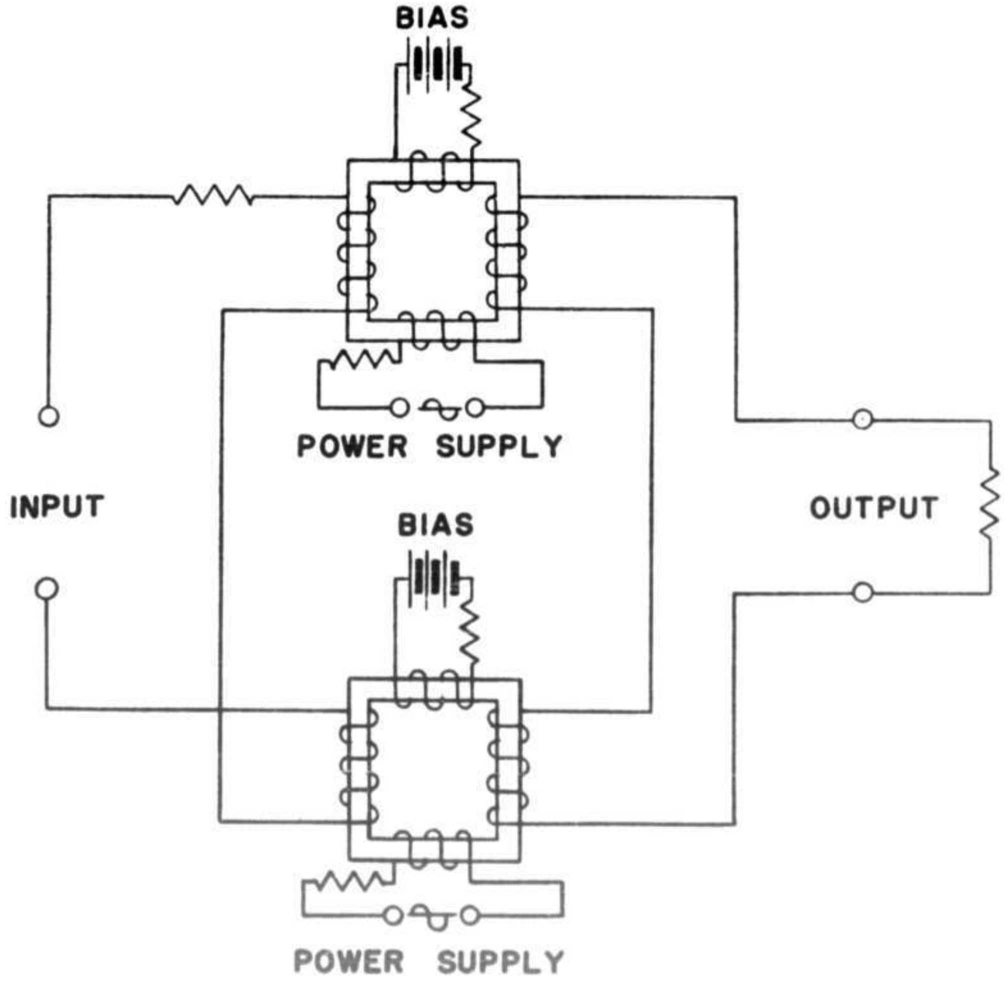
B. OBSERVED WAVEFORMS OF RESISTANCE-LOADED SATURABLE INDUCTOR USING DELTAMAX CORES (AFTER T.G. WILSON)

A-51970

SATURABLE INDUCTOR WAVEFORMS



A. SINGLE-CORE SATURABLE TRANSFORMER



B. TWO-CORE SATURABLE TRANSFORMER

FIG. 5

SATURABLE TRANSFORMER

A-51983

APPROVED FOR PUBLIC RELEASE. CASE 06-1104.

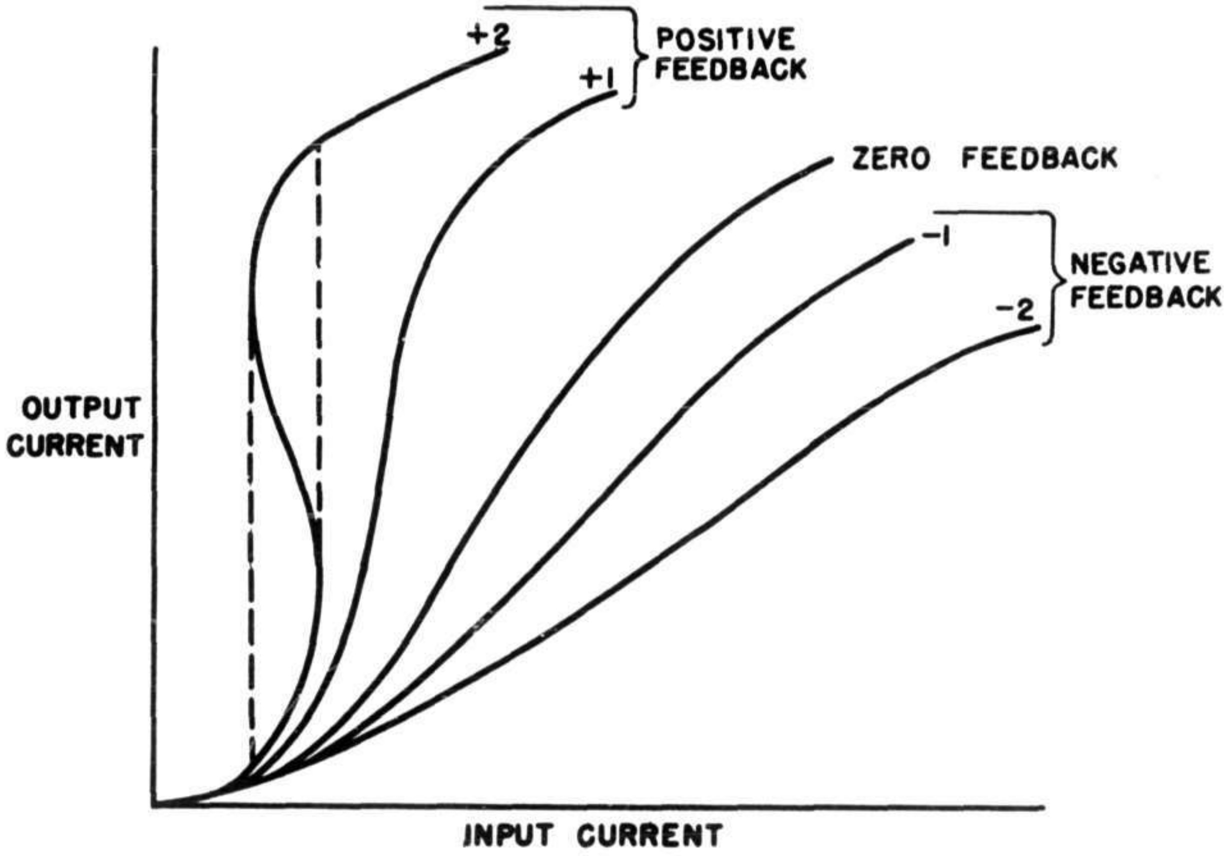
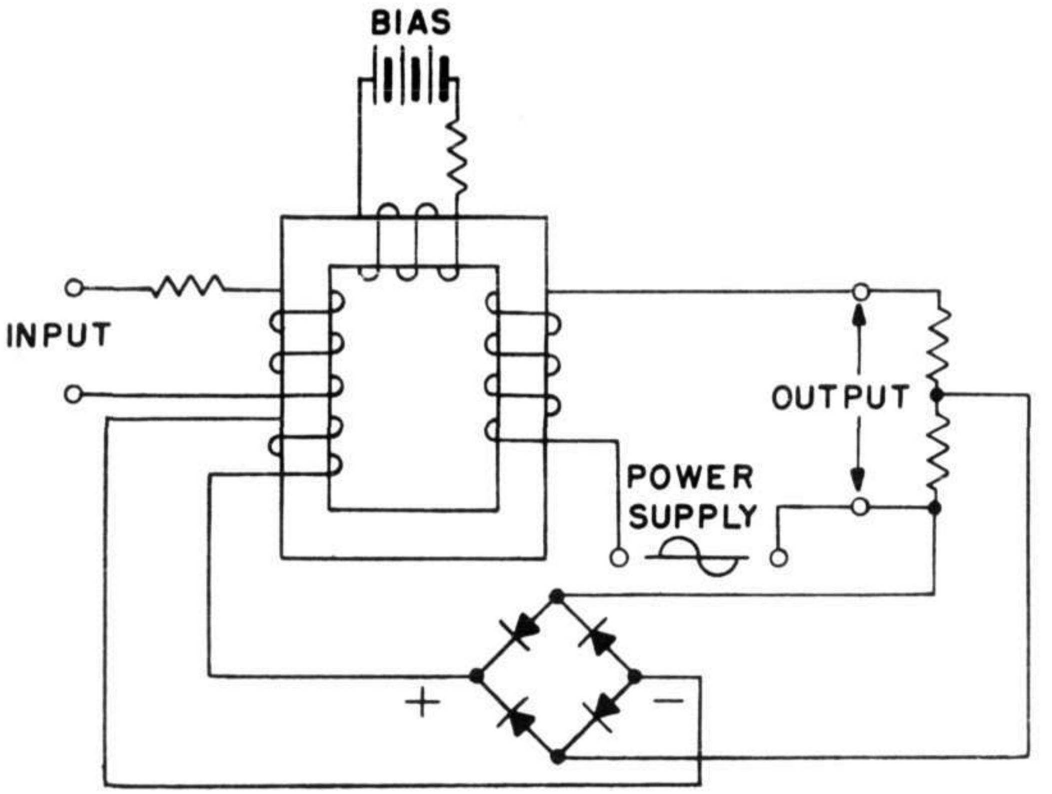
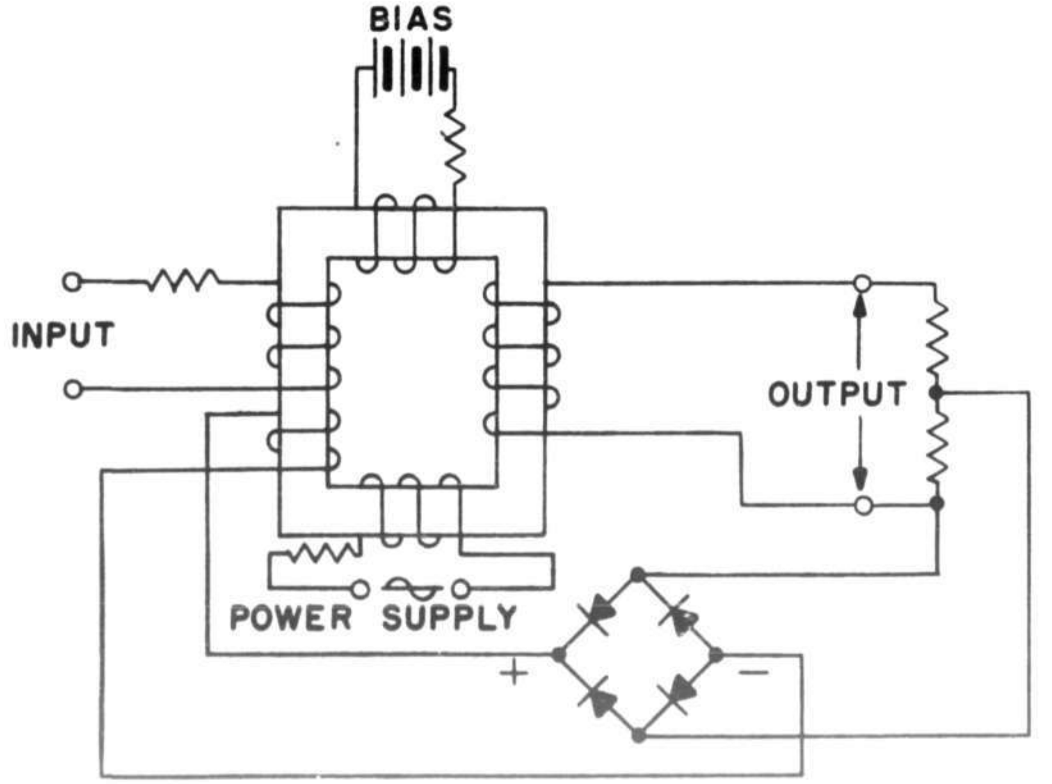


FIG. 6
EFFECT OF FEEDBACK ON MAGNETIC AMPLIFIER OPERATION

A-51985



A. SATURABLE INDUCTOR WITH EXTERNAL FEEDBACK

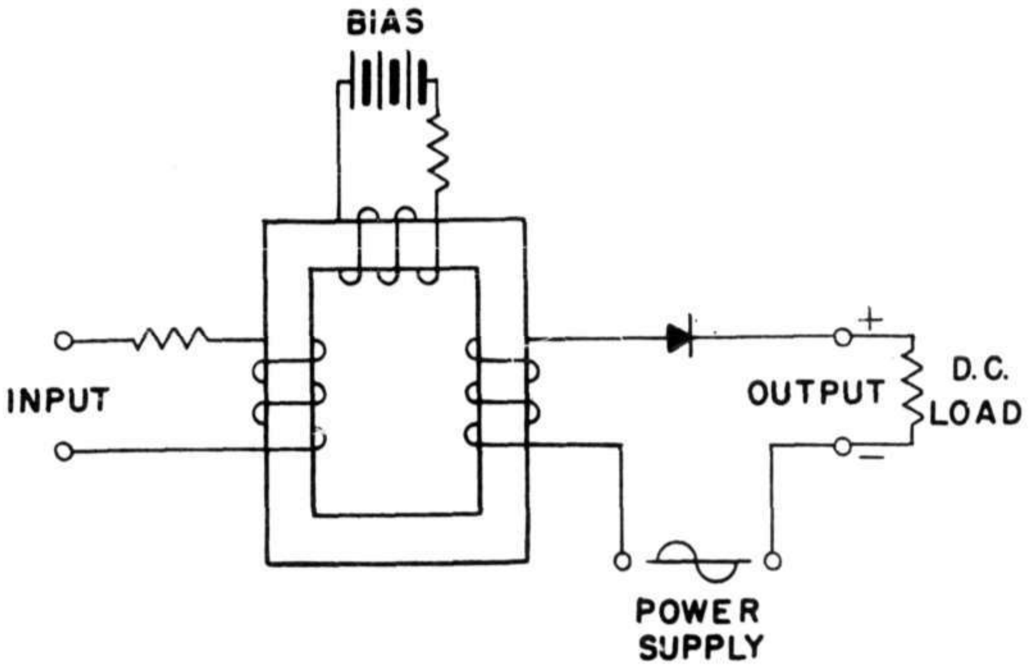


B. SATURABLE TRANSFORMER WITH EXTERNAL FEEDBACK

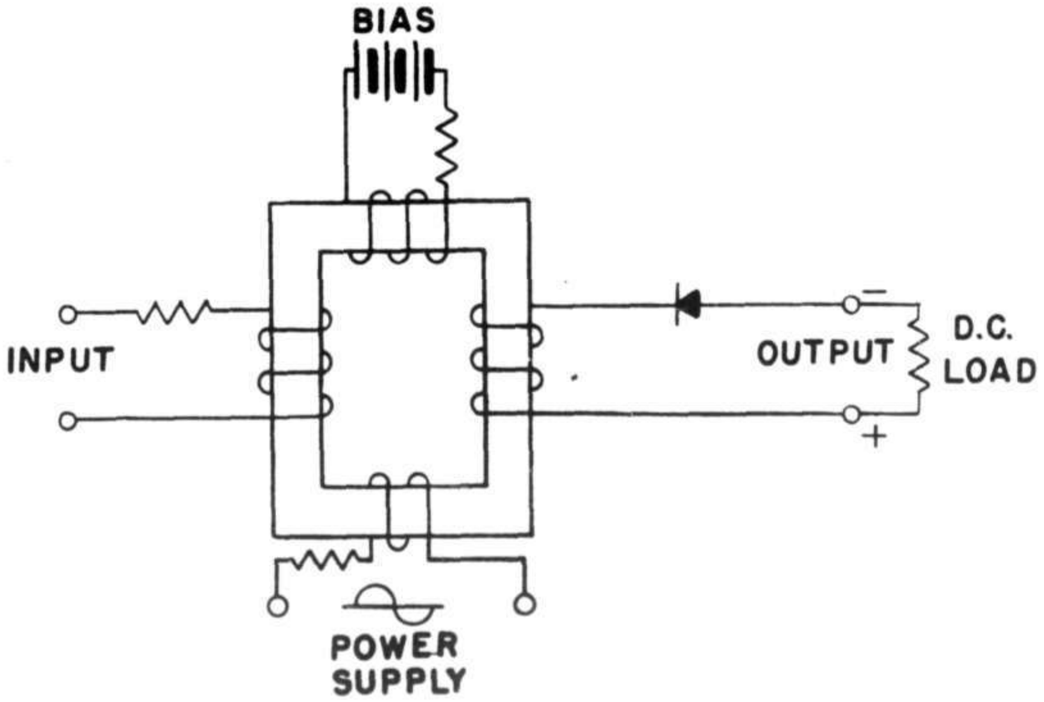
FIG. 7

EXTERNAL FEEDBACK

A-51972



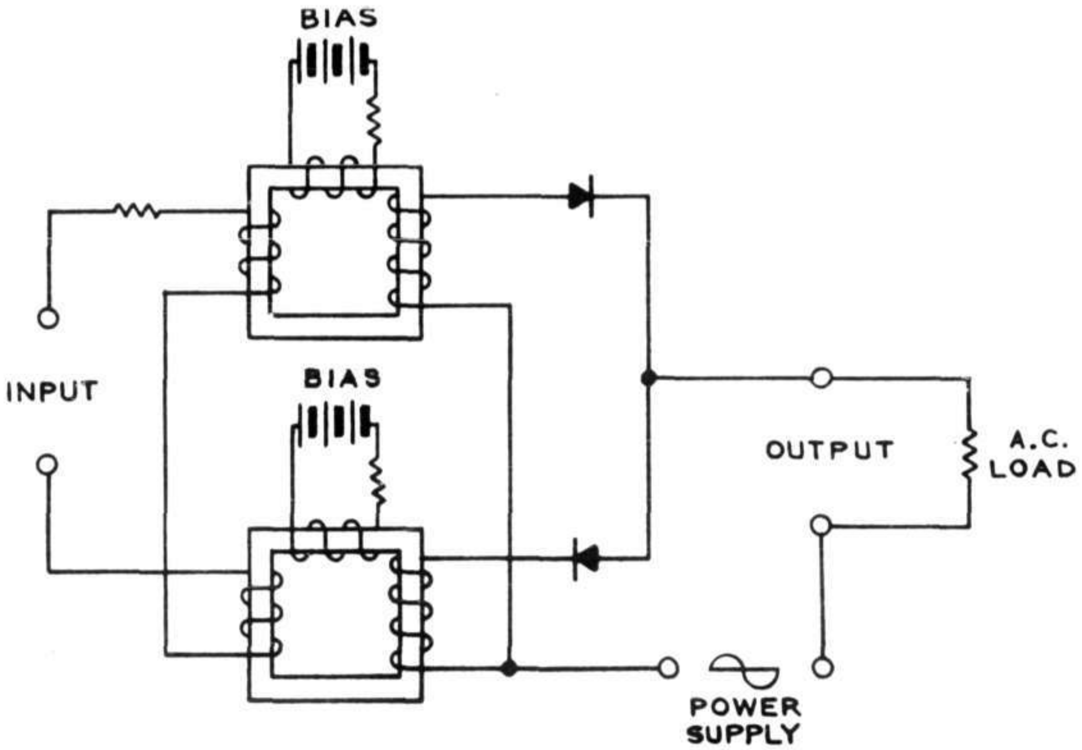
A. SATURABLE INDUCTOR WITH INTERNAL FEEDBACK



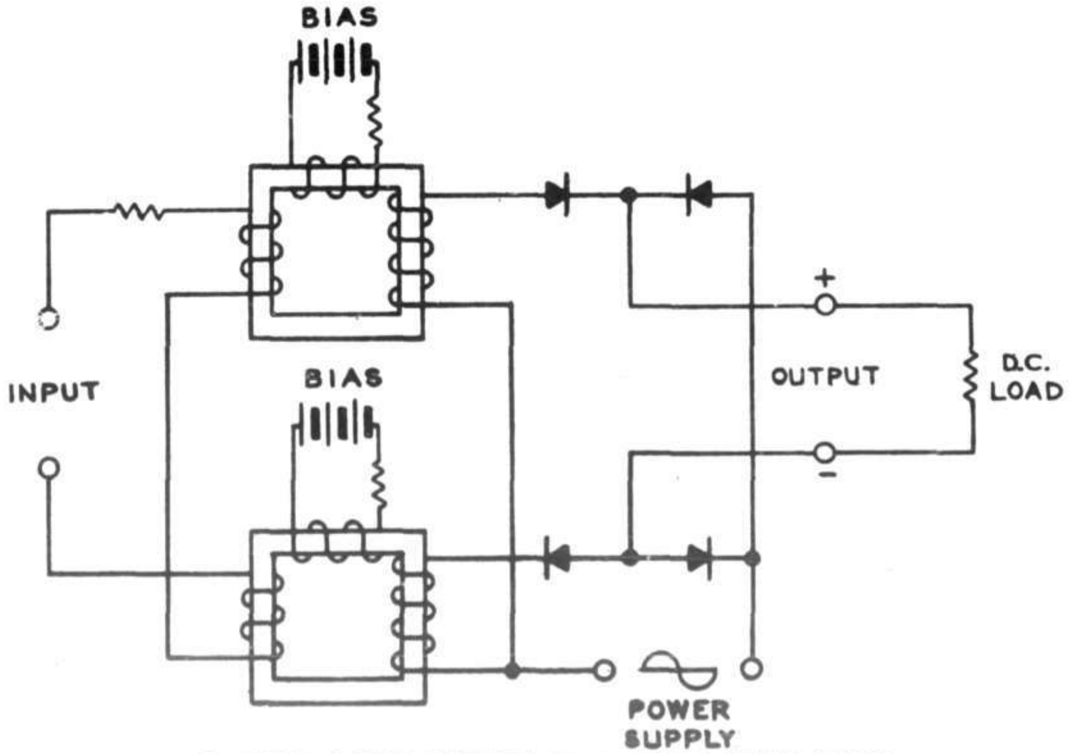
B. SATURABLE TRANSFORMER WITH INTERNAL FEEDBACK

FIG. 8
INTERNAL FEEDBACK

A-51971



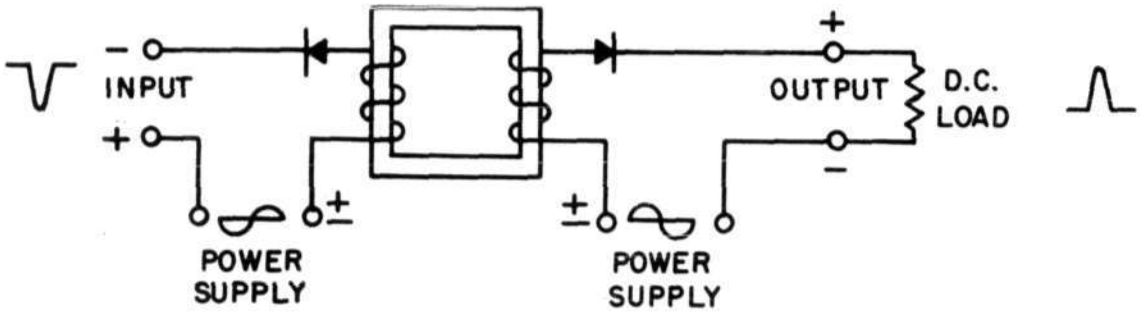
A. TWO-CORE SATURABLE INDUCTOR WITH INTERNAL FEEDBACK FOR A.C. LOAD



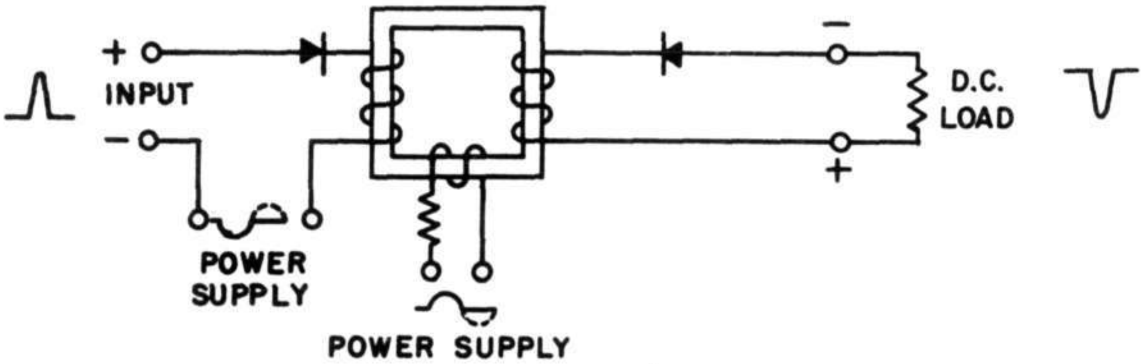
B. TWO-CORE SATURABLE INDUCTOR WITH INTERNAL FEEDBACK FOR D.C. LOAD

FIG. 9 TWO-CORE SATURABLE INDUCTORS WITH INTERNAL FEEDBACK

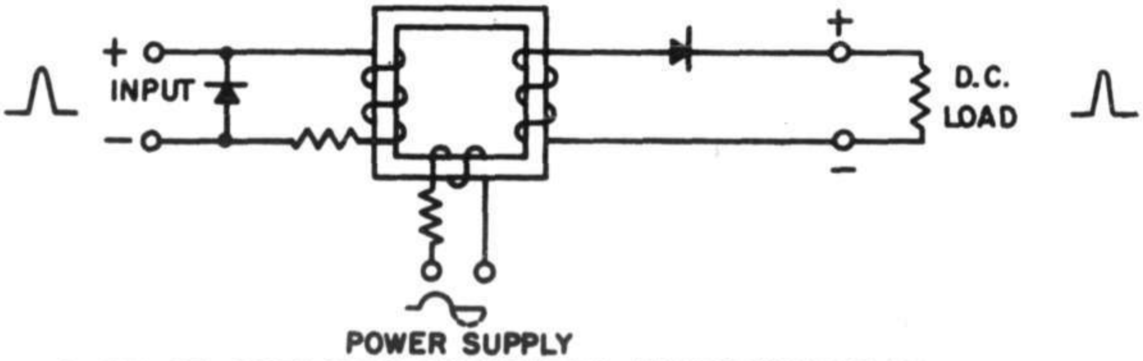
A-51880



A. HALF-CYCLE RESPONSE TIME SATURABLE INDUCTOR (AFTER RAMEY)



B. HALF-CYCLE RESPONSE TIME SATURABLE TRANSFCRMER (PULSE-OPERATED)

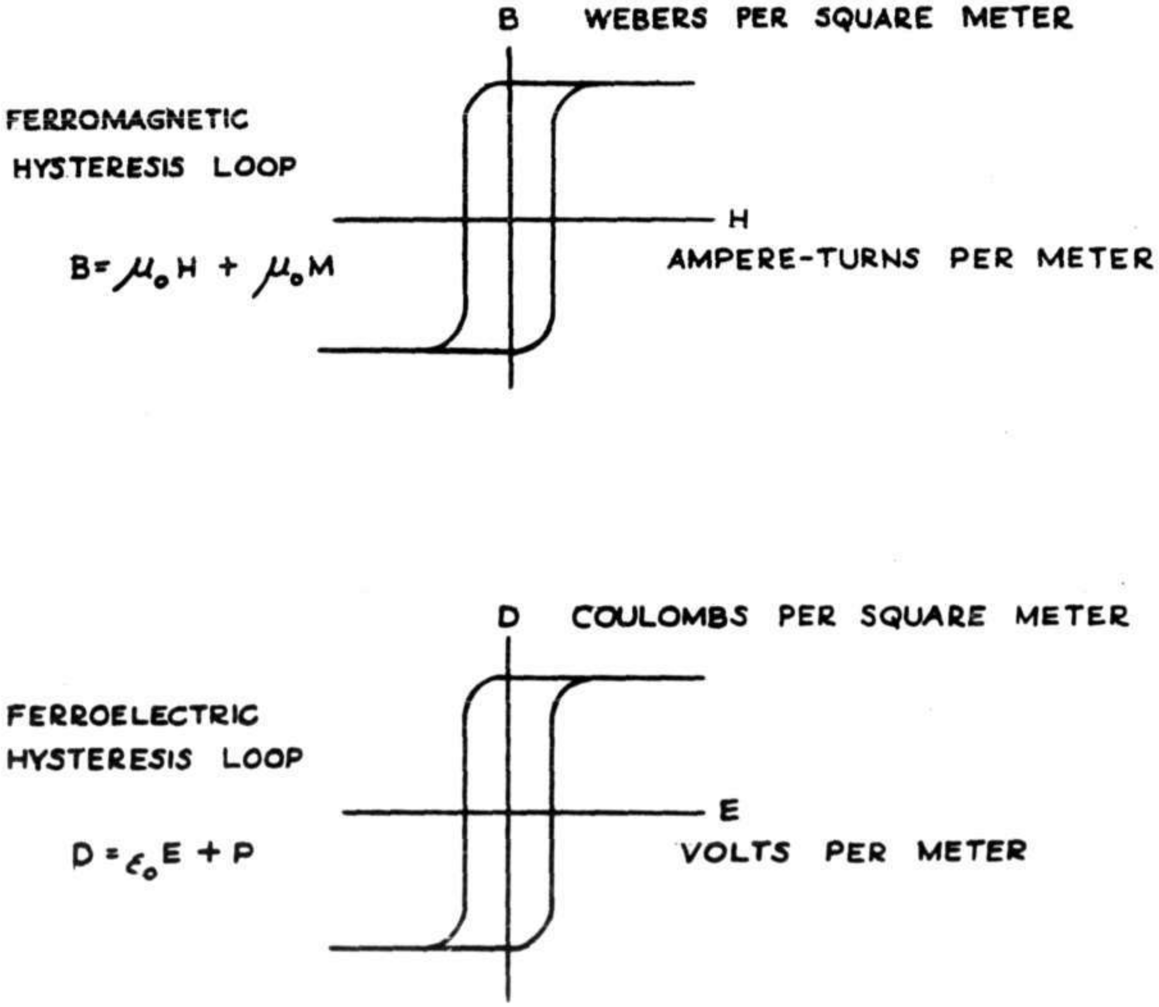


C. PULSE-OPERATED SATURABLE TRANSFORMER IN COMPUTER SERVICE

FIG. 10

HALF-CYCLE RESPONSE TIME CIRCUITS

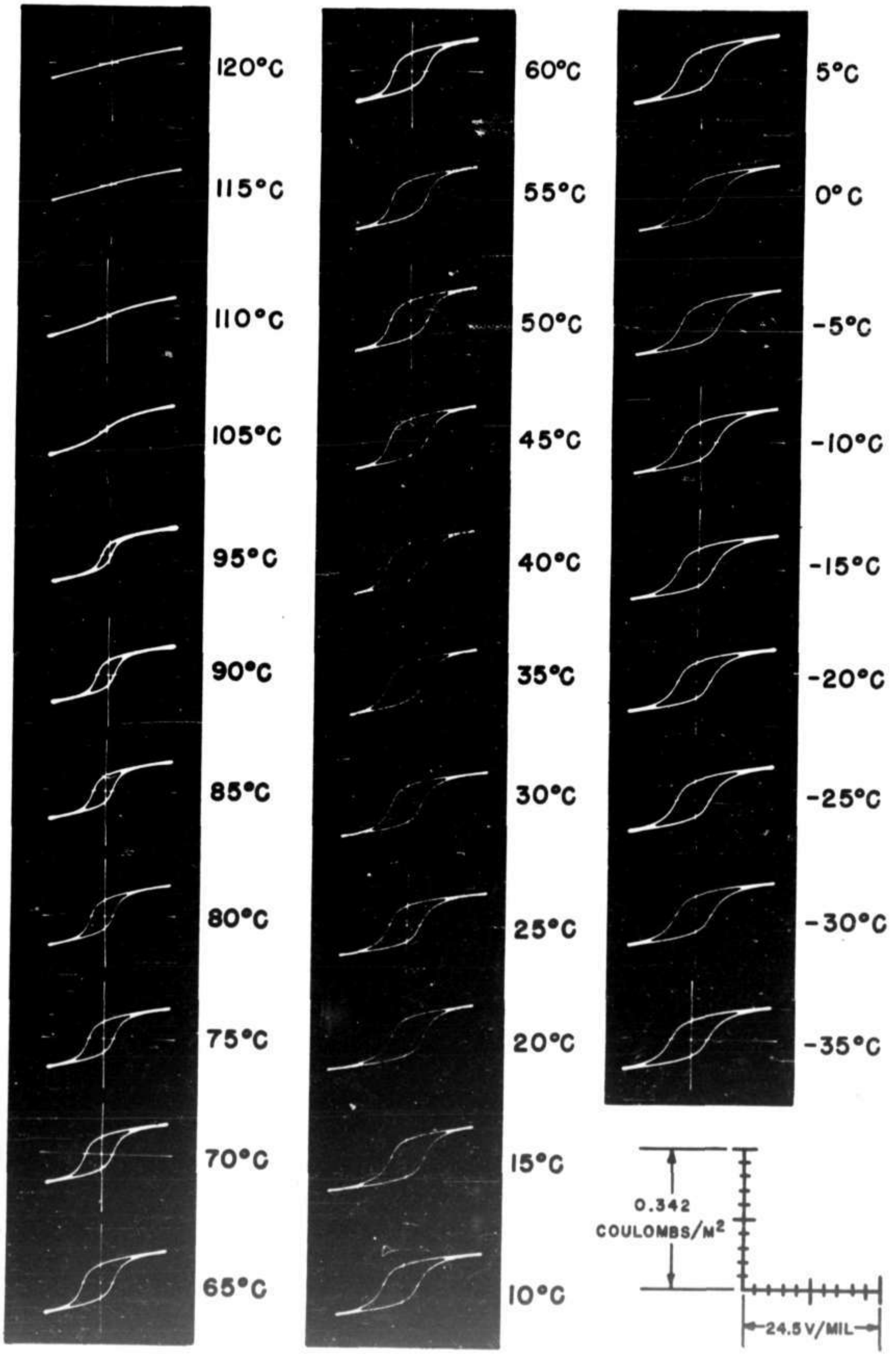
A-51987



COMPARISON OF FERROMAGNETIC
AND FERROELECTRIC HYSTERESIS LOOPS

A-50545

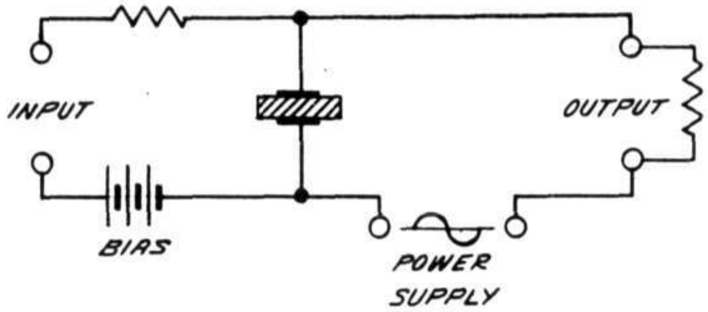
Fig. 11



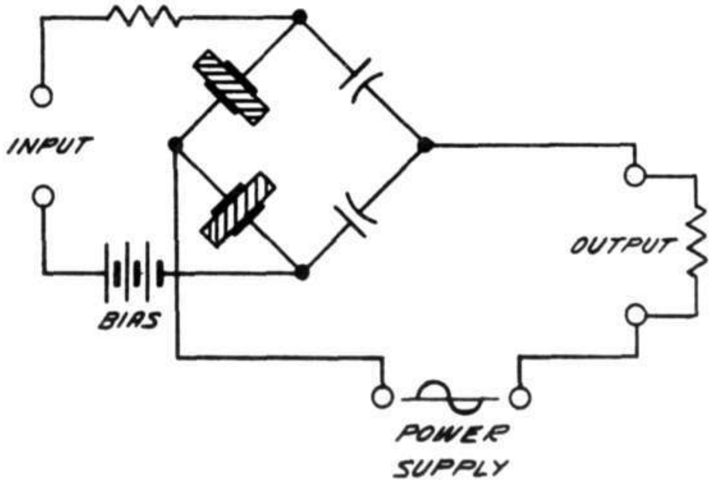
A-51351

HYSTERESIS LOOPS OF BARIUM TITANATE CERAMIC AS A FUNCTION OF TEMPERATURE

Fig. 12



A. SIMPLE ONE-ELEMENT SATURABLE CONDENSER



B. BRIDGE-CONNECTED SATURABLE CONDENSERS

FIG. 13

DIELECTRIC AMPLIFIER CIRCUITS

A-52312

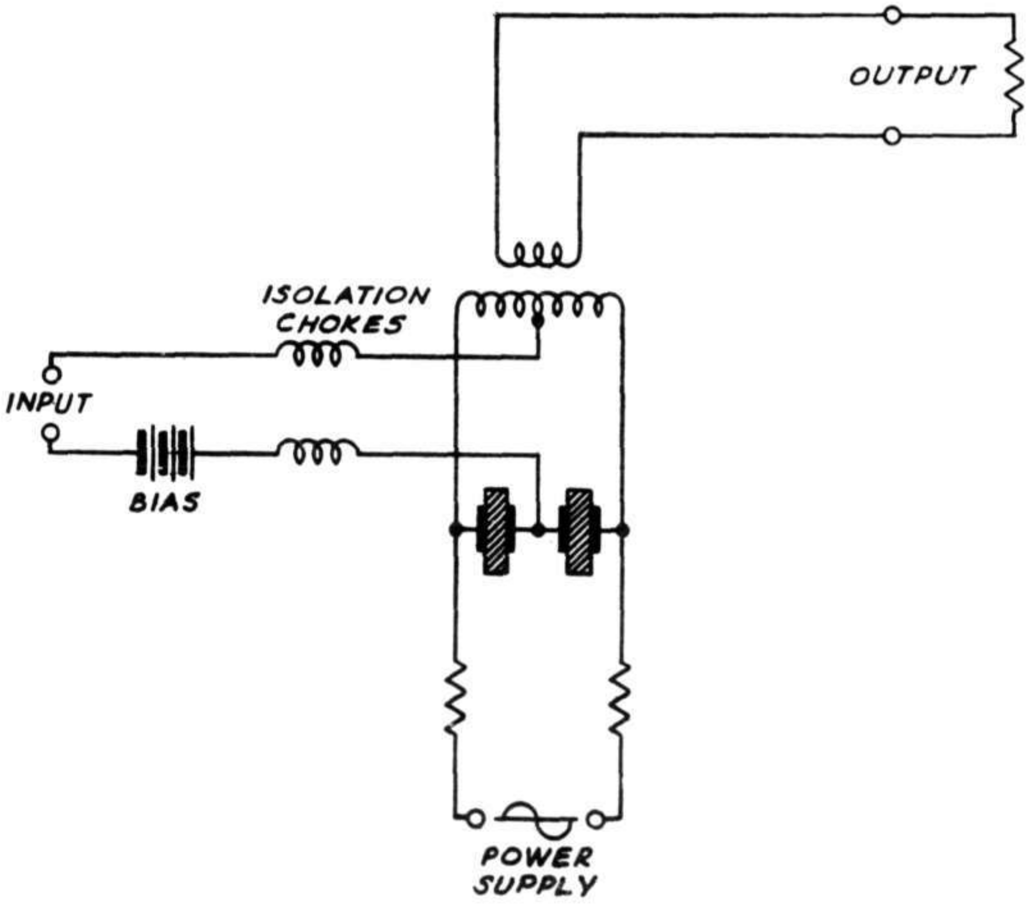
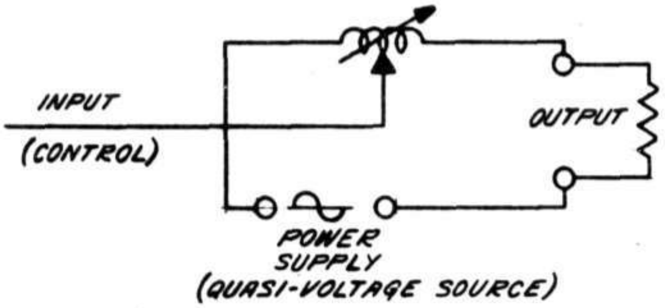


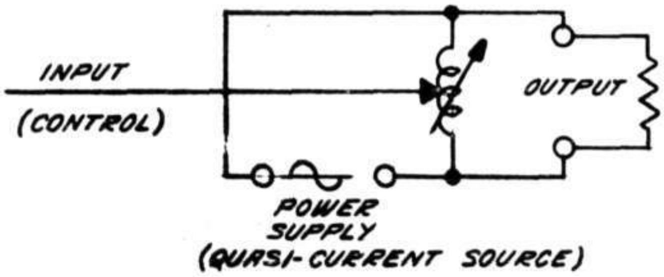
FIG. 14

DIELECTRIC AMPLIFIER
OPERATED NEAR RESONANCE

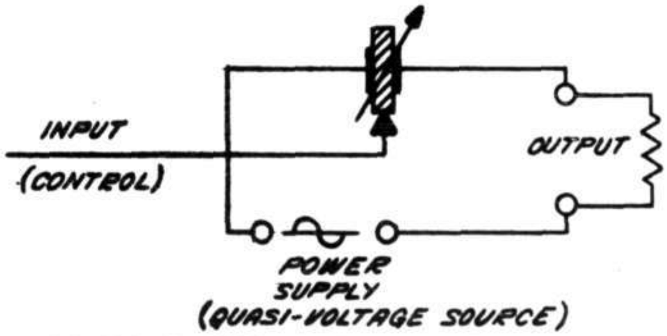
A-52393



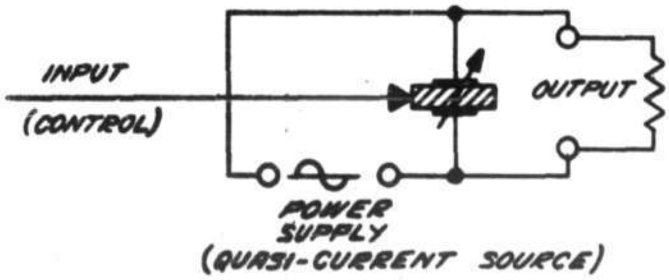
A. SATURABLE INDUCTOR EQUIVALENT CIRCUIT



B. SATURABLE TRANSFORMER EQUIVALENT CIRCUIT



C. SERIES SATURABLE CONDENSER EQUIVALENT CIRCUIT



D. SHUNT SATURABLE CONDENSER EQUIVALENT CIRCUIT

FIG. 15

MAGNETIC AND DIELECTRIC AMPLIFIER
EQUIVALENT CIRCUITS

A-52313