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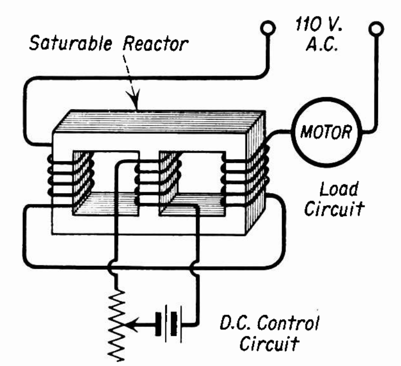
The Magnetic Amplifier

By the Engineering Department, Aerovox Corporation

THE magnetic amplifier, like the transistor and the dielectric amplifier, is an electronic device which is currently undergoing extensive exploitation as a vacuum tube substitute. Like these promising contemporaries, it has advantages in certain applications which make its use preferable to the electron tube. This article discusses these advantages and the operating principles which make them possible.

The major field of application for the magnetic amplifier at the present time is in industrial control circuitry such as a.c. and d.c. motor speed control, servo systems, voltage and current regulators, temperature controls, and industrial safety circuits. The sphere of usefulness is rapidly being expanded, however, to include audio and radio frequency amplification for communication purposes extending up to several megacycles. These advantages are being made possible largely because of improvements in the ferromagnetic materials employed in the saturable reactors. These include the grain-oriented silicon steels and gapless toroidal cores. Strides are also being made in improved circuits and better selenium and germanium rectifiers for use in amplifier circuits.



ELEMENTARY MAGNETIC AMPLIFIER
FIG. 1

The magnetic amplifier is useful because of its high power handling capabilities, low cost (intermediate between that of tube and dielectric amplifiers), and extreme ruggedness. It is being applied to power amplifications ranging from a few watts to thousands of kilowatts. Its economy and reliability are certain to assure it a permanent place in electronics.

Theory of Operation

The magnetic amplifier completes the family of electronic devices which function because a control voltage causes a variation in one of the basic electrical properties of a circuit component. The vacuum tube amplifier, for example, may be thought of as a device in which a change in the control voltage on the grid causes the cathode-plate *resistance* to vary. In the dielectric amplifier (See RESEARCH WORKER for August, '52) a change in a control voltage effects a change in the *capacitance* of a condenser and therefore its reactance. In the magnetic amplifier, the variation of a control voltage brings about a change in the *inductance* of a coil and, hence, its inductive reactance. In all three cases, the control power required to effect the change is less than the power controlled, so that the devices are classed as amplifiers.

The saturable reactor, which is the basis of magnetic amplification, functions because of the *ferromagnetic* properties of the core materials utilized. A simple saturable reactor which will illustrate this principle is shown in Fig. 1. Three windings are arranged on an "E"-type transformer core and connected as shown. The alternating current to be controlled flows in the windings on the outer legs and the d.c. control current flows in the center-leg winding. Note that this arrangement prevents the induction of

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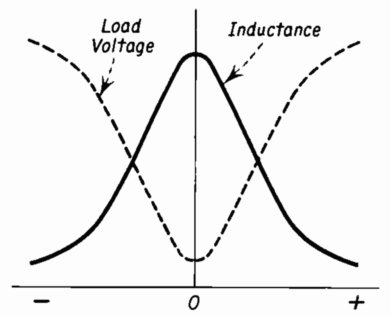
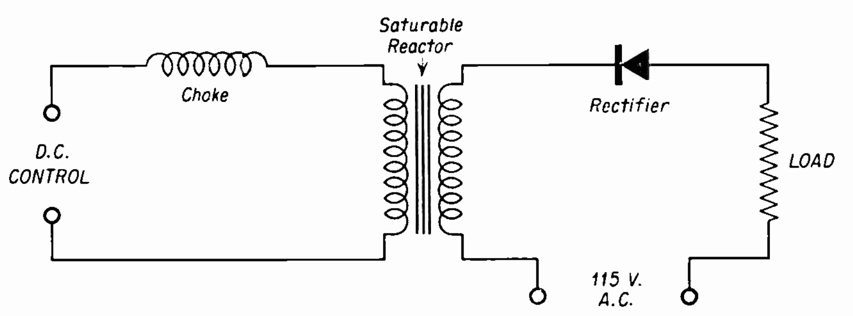


RESPONSE OF SIMPLE SATURABLE REACTOR
FIG. 2

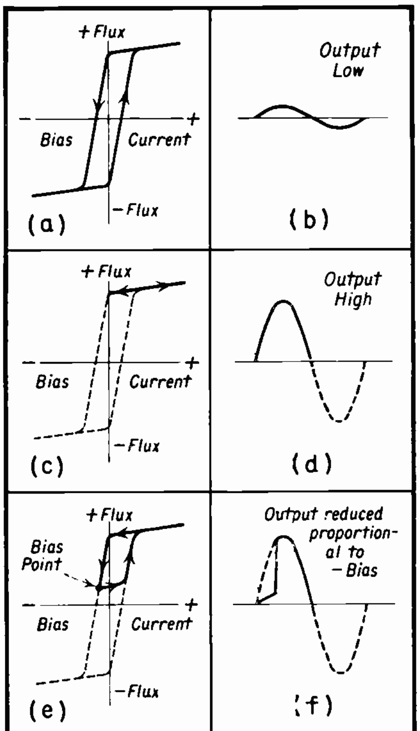


SELF-SATURATING MAGNETIC AMPLIFIER
FIG. 3

alternating current from the load circuit into the control circuit because the flux produced by the outer coils cancels in the center leg. The control winding, on the other hand, can produce saturation of the core material when energized with d.c., and thus greatly effect the permeability of the core material. The inductance of the a.c. coils are directly proportional to the permeability of the core, and the inductive reactance is directly proportional to the inductance. The way in which the load circuit inductance varies with d.c. control current is shown qualitatively in Fig. 2. The reactance, and hence the voltage drop across the coils, is maximum when the control current is zero and minimum when the core is saturated. Thus, the power applied to the load is a function of the d.c. control current.

Simple magnetic amplifiers of the type illustrated in Fig. 1 are not capable of high gain performance. They have been almost completely superceded by improved magnetic amplifiers of the *self-saturating* variety. The basic circuit of this type is shown in Fig. 3. Here a rectifier having a high front-to-back impedance ratio is inserted in series with the load circuit of a saturable reactor. The d.c. control circuit is isolated from the load a.c. by an inductance. Improved amplifiers of this type, when used in conjunction with the new square magnetization-loop core materials, are capable of power gains approaching *one million.*

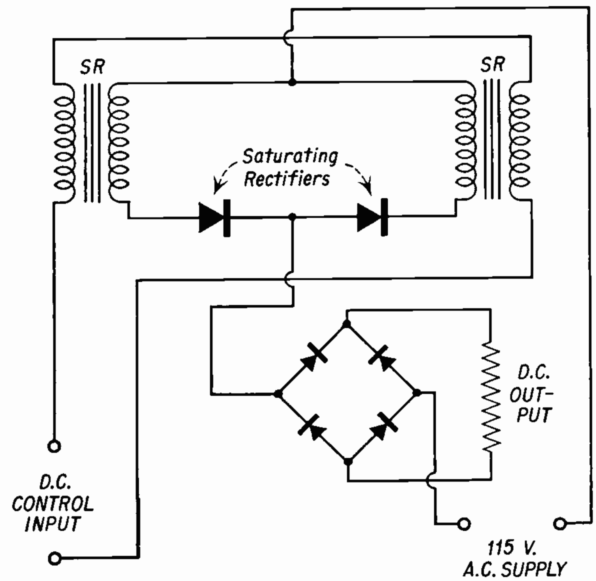
To understand the operation of self-saturating magnetic amplifiers, let us examine the typical magnetization (or hysteresis) loop of Fig. 4a. This is the kind of steep-sided, easily saturated characteristic required of the saturable reactor in the circuit of Fig. 3. In the absence of control current and without the rectifier in series with the load, the operating point would trace out the entire magnetization loop each a.c. cycle. The resulting output wave would then be as in Fig. 4b. The insertion of the rectifier eliminates alternate half-cycles of the output wave as in Fig. 4d and produces a d.c. component in the load circuit which saturates the core in one direction during conducting half-cycles. The locus of the operating point is shown then along the saturated top of the loop, as indicated by the solid line in Fig. 4c. The core remains saturated since the rectifier prevents the flow of current in the negative direction required to produce demagnetization. The output voltage is maximum under this condition, since the continued saturation of the core results in low inductive reactance in the load coil and, hence, low voltage drop across it.



ACTION OF SELF-SATURATING AMPLIFIER
FIG. 4

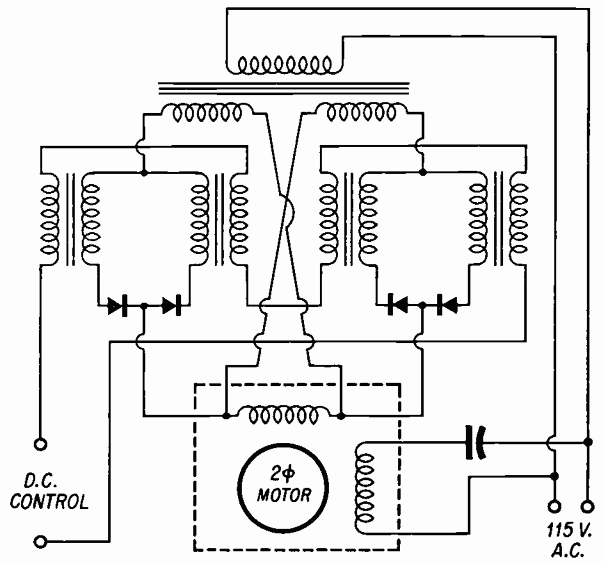
Now, suppose that a d.c. control current is introduced in the control winding in a direction which tends to produce saturation of the core in the direction opposite to that produced by the rectified load current. Then, during the half-cycle when the load rectifier is not conducting, this control current reduces the magnetization of the core to some value on the negative-going part of the loop, as in Fig. 4e. If the value of this bias current is large enough, it may even saturate the core of the reactor in the reverse direction. When the rectifier again conducts, it overcomes the effect of the control current and again saturates the core as in 4c. To do so, it must re-establish the flux density which was reduced by the negative control current. Note that the amount of flux which the load current must set up before it again saturates the core is directly proportional to the control current if the hysteresis loop has essentially straight sides.

Since it takes a finite time for the load d.c. component to produce saturation of the core, depending upon how close to negative saturation the control current has driven the core, the output (voltage) voltage is reduced until positive saturation is reached. This results in the normal output waveform of Fig. 4d being modified as in Fig. 4f. The amount of load power reduction is directly proportional to the flux increment required to saturate the core from the bias point. The distortion of the voltage waveform results from the fact that the flux increment induces a back-voltage in the load coil which opposes the applied load voltage. In other words, the inductance of the load coil is high until the core reaches saturation. The control circuit thus controls the output power by controlling the flux increment required to reach saturation. The gain of the amplifier is large if the slope of the



PUSH-PULL MAGNETIC AMPLIFIER

FIG. 6



MAGNETIC AMPLIFIER
FOR 2-PHASE MOTOR CONTROL

FIG. 7

magnetization loop is large so that a small change in control current produces a large change in output current. A typical control characteristic would appear as in Fig. 5. Like the dielectric and vacuum tube amplifiers, the magnetic amplifier operating point may be set to any part of the control characteristic by the application of a fixed d.c. bias. When used as a d.c. amplifier, the device has the properties of the long sought "d. c. transformer".

Advanced Amplifier Types

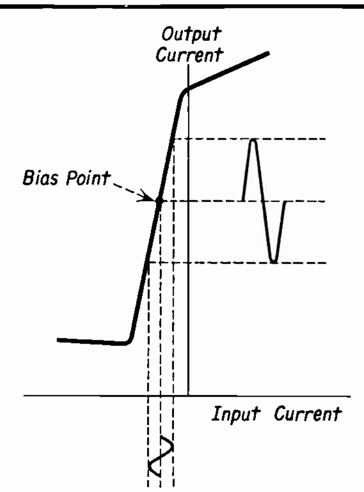
There are many variants of the basic self-saturating magnetic amplifier discussed above. Fig. 6 shows a full-wave circuit using two saturable reactors, two saturating rectifiers, and a bridge rectifier for d.c. output to the load. The saturating rectifiers are connected so that one load coil conducts on positive half-cycles and the other conducts on the negative half-cycles of the supply voltage. The control windings are in series. This connection gives the highest input impedance. Typical performance figures for an amplifier of this type are:

Input impedance	450 ohms
Load impedance	2000 ohms
Supply voltage	110 volts @ 60 cps.
Maximum power output .	15 watts
Maximum power gain . .	200,000.
Weight	3 lbs.

A further extension of the basic self-saturating circuit is shown in Fig. 7. This push-pull connection is arranged to control the speed of a 2-phase motor. Through the use of a high gain amplifier of this kind, the power required to control a large motor is relatively small and can be derived by from a small rheostat, an electronic tachometer, or some other sensing device.

Comparison With Other Amplifiers

The magnetic amplifier is a comparatively low input impedance device whereas both the vacuum tube and dielectric amplifiers have high input impedances in most circuit connections. For this reason, the magnetic type is frequently combined with these other kinds in applications which require high input impedance.



TYPICAL TRANSFER
CHARACTERISTIC

FIG. 5

Like the dielectric amplifier, the output circuit of the magnetic amplifier must be supplied with alternating current since variable reactances are involved, while the vacuum tube plate circuit is usually supplied with d.c. For satisfactory reproduction of the output wave, the a.c. supply frequency should be at least 5 times higher than the highest frequency handled.

Both the dielectric and the magnetic amplifier of the simple type of Fig. 1 act as frequency doublers when operated at the zero bias point because either a positive-going or a negative-going signal produce an increase in output. The signals are 180 degrees out of phase, however, since at zero bias the output of the simple saturable reactor is minimum while that of the dielectric is maximum. The self-saturated magnetic amplifier more nearly resembles the vacuum tube in phase relationships.

The dielectric amplifier, the transistor, and the magnetic amplifier have the advantage of requiring no filament power or warm-up time as with the vacuum tube type. The dielectric and magnetic amplifiers have the additional advantage of requiring no precision constructional techniques such as are needed in fabricating vacuum tubes and transistors. Both are characterized by almost infinite life and ruggedness. The magnetic amplifier is also considerably better than the dielectric and transistor amplifier from the standpoint of temperature dependance.

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