TECHNICAL MONOGRAPH TMS. 768

ENGINEERING DEPARTMENT

MAGNETIC AMPLIFIERS

by

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THE
BRITISH THOMSON-HOUSTON
COMPANY LIMITED, RUGBY, ENGLAND

Edition A

0356

Magnetic Amplifiers

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MAGNETIC amplifier is a name given to a family of amplifiers, in which use is made of magnetic properties of saturable reactors for the amplification of electrical signals. This paper describes the mode of operation and basic constructional details of some magnetic amplifiers, with particular reference to self-saturation. Merits of the magnetic amplifier, in relation to other amplifiers, are also discussed.

The output power of magnetic amplifiers extends over a range from a few milliwatts to several kilowatts, A.C. or D.C. This means that they are comparable in output with electronic valve amplifiers and with rotating amplifiers or generators, such as the amplidyne.

The amplifier shown in Fig. 1 has a D.C. output and a continuous rating of 350 watts. The output voltage is variable from about 5 to 130 volts when connected to a fixed load. The continuous rating is 3·5 amp. D.C. at 100 volts. All magnetic amplifiers require an A.C. supply. The supply for this amplifier is 240 volts, 50 c/s, single-phase. The A.C. supply is rectified by selenium rectifiers to produce the D.C. output. Variation of the output is obtained by means of saturating reactors connected in circuit between the A.C. supply and the rectifier. These reactors, looking not unlike small transformers, can be seen on the left-hand side of Fig. 1. It will be noticed that the amplifier has no moving parts.

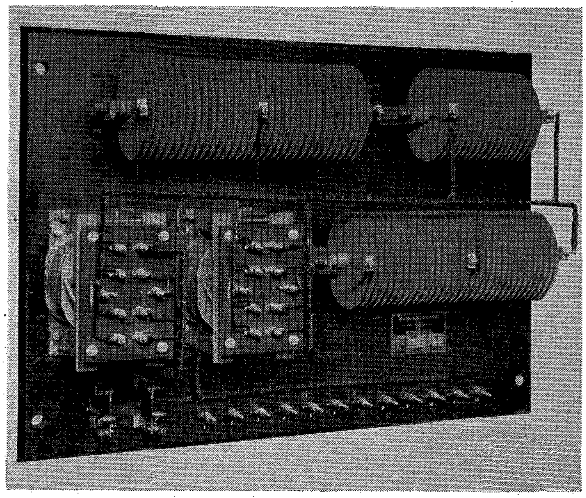

Fig. 1. A 350-watt Magnestat.

Input: 240 volts, 50 c/s
Output: 3·5 amp. D.C.
at 100 volts

'Magnetic amplifier' as a name is a little cumbersome, and manufacturers have adopted shorter names such as Magamp and Amplistat. BTH has introduced the name "Magnestat" for its magnetic amplifier, since it suggests both the magnetic principle of control and the static nature of the apparatus.

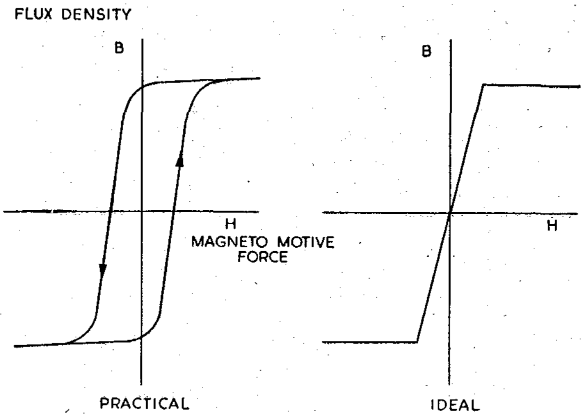

Fig. 2. *B/H* curves for saturating reactor.

Saturating Reactor

The saturating reactors are sometimes called saturable reactors or transductors. Unlike most reactors or transformers of normal design, these reactors are required to saturate. A typical *B/H* loop for the reactor core is shown in Fig. 2(a); this loop is a plot of the flux density in the reactor core against magnetomotive force. It is desirable that the *B/H* loop should exhibit a high unsaturated permeability and a sharp transition into saturation. Too much emphasis cannot be placed upon the requirement of a sharp transition and a thoroughness of saturation. The reason for this will become evident as the mode of operation of the amplifier is examined.

For the purpose of this examination, which does not pretend to be rigorous, the ideal *B/H* curve will be assumed to consist of an unsaturated section of uniform slope terminating in complete saturation of the core. The hysteresis in the core will be neglected, although in practice its presence does modify the mode of operation to be described. There are in fact two ideal *B/H* curves; the first is as shown in Fig. 2(b) and the second is a rectangular loop, with finite width and infinite permeability.

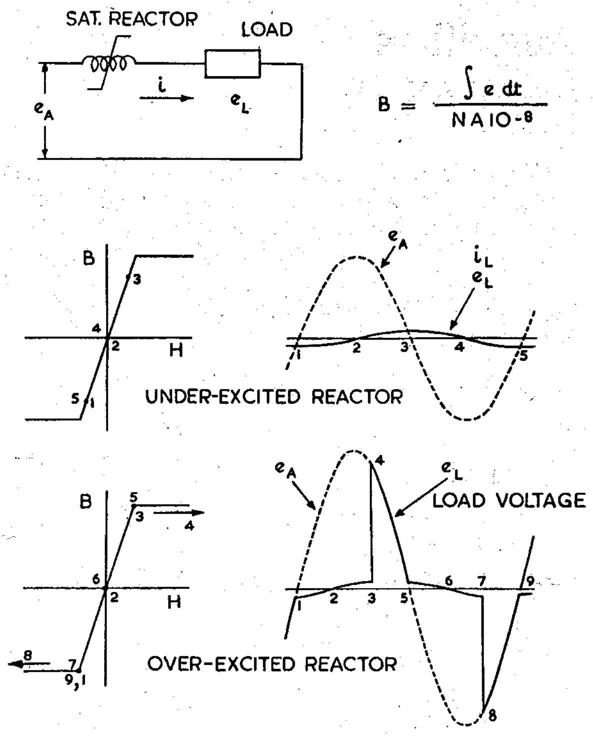

Fig. 3. Non-polarized saturating reactor.

The first step towards the understanding of a magnetic amplifier is gained by consideration of a simple circuit consisting of a saturating reactor and a resistance load connected in series to an A.C. supply (Fig. 3). The under-excited condition is when the voltage of the A.C. supply is insufficient to saturate the reactor. If the load resistance is assumed to be small compared with the unsaturated reactance with which it is in series, the phase relation between current and applied voltage is familiar. It is the case of a highly inductive circuit connected to an A.C. supply, and the current lags the voltage by almost 90 deg. At the commencement of a cycle of voltage, the core flux is at position 1 on the *B*/*H* curve, and it changes through zero at point 2 to its maximum in the reverse direction at point 3 at the end of the half-cycle. The flux changes in proportion to the time integral of voltage, which is in the area under the voltage waveform, and the instantaneous magnetization current i_L is proportional to the magnetomotive force, *H*. The load voltage e_L is in phase with, and proportional to, the magnetization current since the load is assumed to be a pure resistance.

Now, in the state of over-excitation, the flux starting at point 1 on the *B*/*H* curve reaches saturation at point 3 before the end of the half-cycle. The flux change from point 1 to 3 is represented by the area under the voltage wave from the start of the cycle to point 3. The reactor saturates at point 3, and from this instant until the end of the half-cycle the instantaneous supply voltage is applied to the load, if the assumption is made that the load resistance is much greater than the impedance of the saturated reactor coil. At point 5, the reactor core returns to an unsaturated state, which is maintained during the following half-cycle of voltage until the core saturates in the reverse direction at point 7. It will be noted that the load voltage is predominantly a series of chopped sine waves with a small component derived from the magnetization current of the unsaturated core.

Self-saturation

The next step is to examine the case when a rectifier is placed in series with the reactor and the load, as shown in Fig. 4. It will be assumed that the rectifier passes current in one direction only and with negligible voltage drop. At the start of a cycle the flux will be zero, since the presence of the rectifier in the circuit prevents the flow of negative current, which would be necessary to sustain flux in the negative quadrant of the *B*/*H* loop. Also, it will be argued that current flow ceases before the end of the cycle, and hence the flux of the core will not be greater than zero at the beginning of any one cycle. The core flux builds up from zero, at point 1, to saturation value at point 2, which is before the end of the half-cycle. The core is saturated from point 2 to almost the

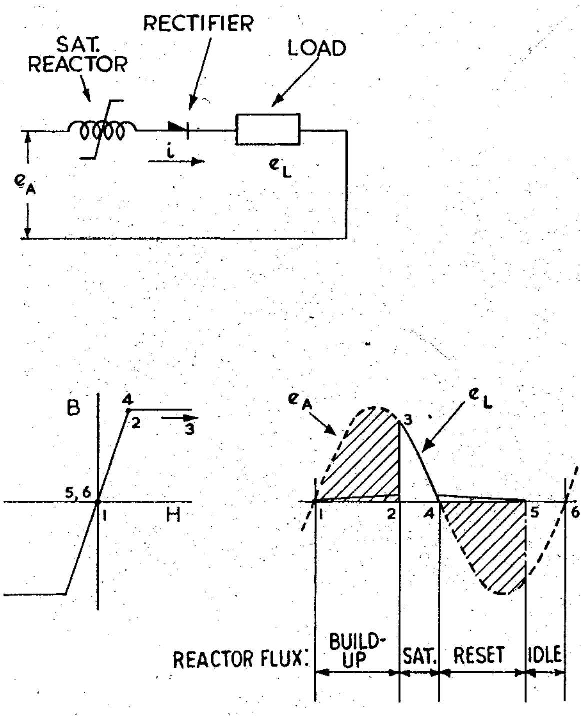

Fig. 4. Self-saturating reactor.

end of the half-cycle, point 4, and, during this period, the instantaneous supply voltage is applied to the load. The load current falls to a sufficiently low value at point 4 to unsaturate the core, and the reactor regains a high inductance. Current flow persists until point 5, by which instant the time integral of negative voltage imposed on the core has reset the flux to zero. The two shaded areas under the voltage wave must be equal if there is to be no residual flux at the end of the cycle. In each cycle there are four distinct periods: a flux build-up period, a flux-saturation period, a flux-reset period and an idle period during which there is no flux change. The circuit shown in Fig. 4 is described as self-saturated, self-polarized or auto-self-excited.

Practical use can be made of this circuit by the placing of a second winding on the reactor core, as shown in Fig. 5. This second winding provides means of controlling the reactor flux at the start of each cycle. The start point 1 is fixed by the value H_C which is an m.m.f. proportional to the current in the added winding, which will be called the control winding to distinguish it from the main, or gate winding connected in the A.C. circuit. The reactor saturates earlier in the half-cycle when H_C is positive, and later when H_C is negative. Hence, control of the voltage applied to the load is obtained by adjustment of the D.C. in the control winding. It should be noted that the reactor acts as a gate to the application of voltage to the load. The theoretical control characteristics for the amplifier is indicated in the top right-hand corner of Fig. 5. This amplifier is seldom used in practice since it suffers from the disadvantages of requiring a decoupling choke in series with the control winding and, also, of having a small output when connected to inductive loads. The reason for the choke in the control circuit is to prevent the reactor acting as a transformer with shorted-secondary.

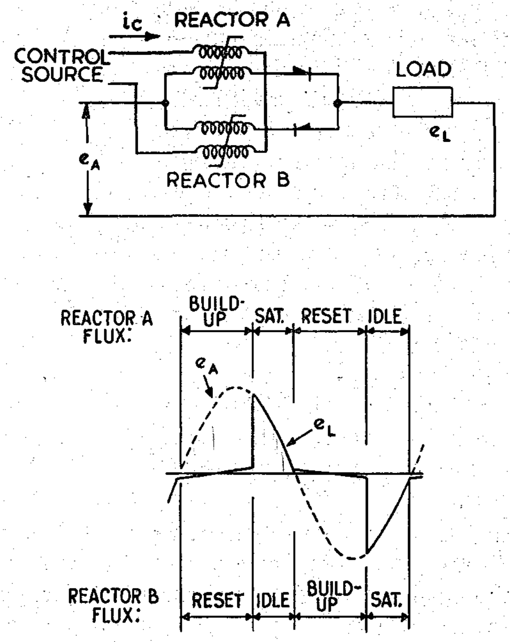

Fig. 6. Self-saturated single-phase amplifier circuit with A.C. output.

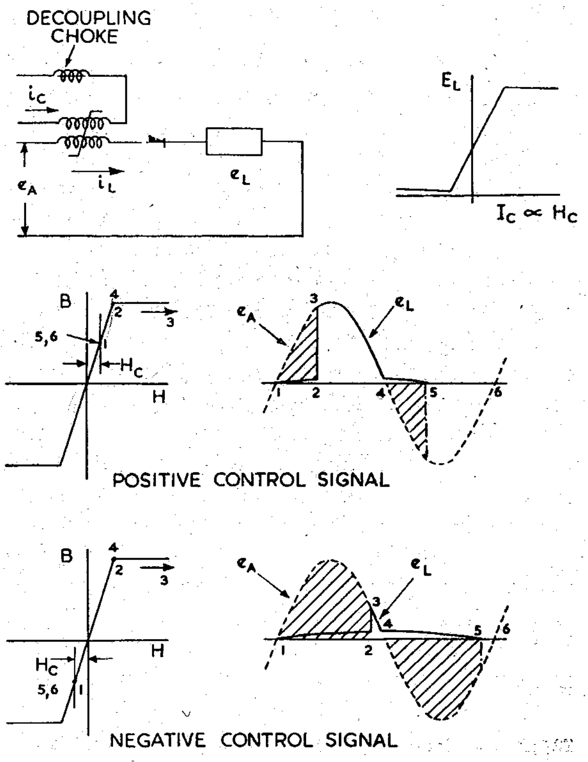

Fig. 5. Half-wave magnetic amplifier with self-saturation.

Single-phase Amplifier

A more practical form of amplifier* is shown in Fig. 6. The circuit contains two reactors, each in series with a rectifier and arranged in parallel with each other and jointly in series with the load. As in the half-wave amplifier, the reactor cores pass through four flux periods in every cycle of the A.C. supply. When the **flux in core** A is building-up, the flux in core B is resetting; and when core A saturates, core B is idle. In this circuit, the voltage applied to the load is A.C., it consisting of a series of chopped sine-waves the magnitude of which depends upon the current passing through the control winding.

Two circuits for D.C. output are shown in Fig. 7.

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*British Patent No. 508,847.

The upper circuit is similar to that in the previous diagram except that the A.C. load is replaced by a full-wave rectifier bridge with output load. The rectifiers connected directly to the reactor windings permit self-saturation of the reactor cores. The lower circuit is a re-arrangement of the upper circuit. The left-hand rectifiers perform the dual function of permitting self-saturation of the reactor cores and of rectifying the load current. The right-hand rectifiers have only the single function of rectifying the load current.

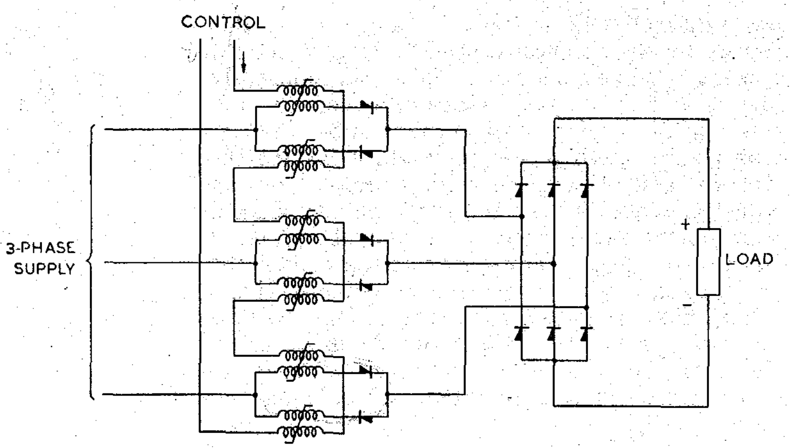

Fig. 8. Self-saturated three-phase amplifier circuit with D.C. output.

An essential feature of the self-saturated amplifier is the prohibition by rectifiers of current flow in the main winding of the unsaturated reactor during the idle-flux period when the other reactor is conducting current. Any flow of current in the main winding of the unsaturated reactor during this period must be countered by a positive control current so as to maintain an ampere-turn balance on the unsaturated core. Hence, rectifier leakage will cause a degeneration of amplifier sensitivity. It is usual to de-rate the working voltage of the rectifiers to minimize the influence of leakage.

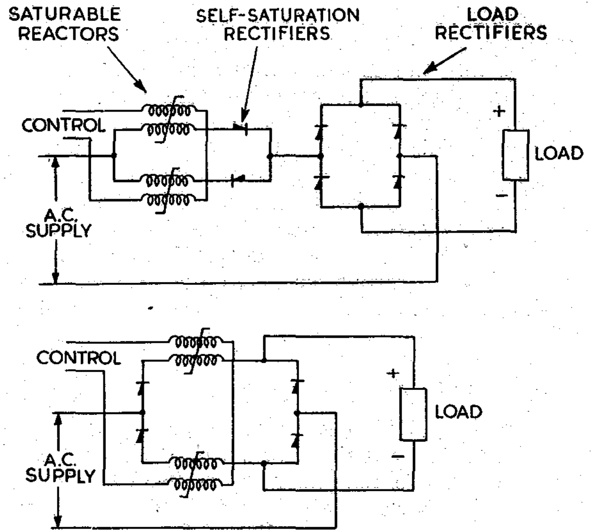

Fig. 7. Two self-saturated single-phase amplifier circuits with D.C. output.

Three-phase Amplifier

Magnetic amplifiers are not confined to single-phase circuits. Fig. 8 shows a three-phase amplifier in which six reactor elements are arranged in pairs, one pair in each A.C. line. The control windings are connected in series with each other. The main advantage of polyphase amplifiers over single-phase amplifiers is a saving in size and cost of the rectifiers when power outputs of a kilowatt or more are required. For low power outputs, single-phase amplifiers are usually preferred on account of their relative simplicity.

Amplifier Characteristics

All self-saturated amplifiers are characterized by the control curve shown in Fig. 9. The precise shape of the curve depends upon the quality of the core material used in the reactors. The curve shown is representative of an amplifier having reactors with good magnetic material and core construction. The influence of the shape of the *B/H* curve is particularly noticeable for outputs approaching maximum, that is when the control current is positive and the reactors are almost completely saturated. The minimum output is obtained with a negative control current, this minimum output being due to the magnetization current of the unsaturated reactors. A slight increase in output is obtained by increasing the control current more negatively than is required to give a minimum output. The portion of the curve normally used is the approximately linear section starting from near minimum output and rising as the control current is made more positive.

The power gain of the amplifier over its working range is obtained from the slope of the control characteristic.

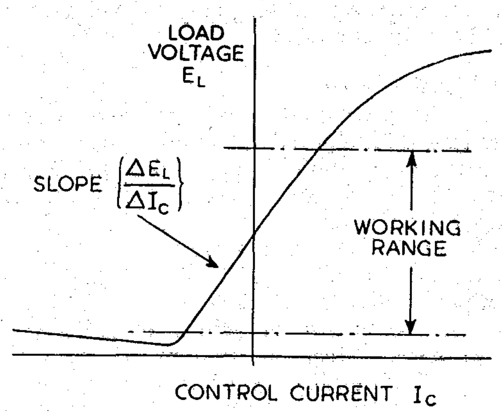

Fig. 9. Control characteristics of self-saturated magnetic amplifier.

Power Gain =

$$\left(\frac{\Delta E_L}{\Delta I_C}\right)^2 \cdot \frac{1}{R_L R_C} = \left(\frac{\Delta I_L}{\Delta I_C}\right)^2 \cdot \frac{R_L}{R_C}$$

where R_L is the load resistance, R_C is the control circuit resistance, and

$$\left(\frac{\Delta I_L}{\Delta I_C}\right)$$

is the current gain of the amplifier.

An inherent feature of magnetic amplifiers is that the control signal is a D.C. flowing in a circuit containing high inductance, and therefore a time delay must exist between the application of a voltage change to the control windings and the resultant change in control current and amplifier output. A sudden change to the control voltage of a self-saturated amplifier will give rise to an exponential change of mean output to the new value dictated by the control. The amplifier delay may be expressed as a time-constant which is substantially unchanged over the normal working range of the amplifier and approximately equal to the ratio of inductance L_C to resistance R_C of the control circuit.

Another factor of importance is the power gain per unit time-constant which is equal to

$$\frac{\Delta I^2_L R_L}{\Delta I^2_C L_C}$$

It is important because it acts as a figure of merit for the amplifier. An amplifier having a power gain of 500 with a time-constant of 0·1 sec., that is a factor of 5000, is usually preferred to an amplifier having a similar gain with a time-constant of 0·5 sec., that is a factor of 1000. Hence, when designing an amplifier it is usual to aim at obtaining the greatest power gain per unit time-constant. An interesting feature of the expression for this factor is that the numerator is the incremental power in the load and the denominator is proportional to the incremental magnetic energy derived from the control signal. Since the latter is proportional to the volume of magnetic material, it is reasonable to assume that advantage is gained by using the minimum of core material consistent with a reasonable temperature rise in the reactor windings. This, in fact, is confirmed in practice.

Non-self-saturated Amplifier

Apart from the self-saturated amplifiers, there is another, and perhaps more basic, class which for the want of a better description will be called non-self-saturated. The circuit of such an amplifier is shown in Fig. 10. This circuit bears a close resemblance to a previous circuit (Fig. 6) except for the absence of rectifiers in series with the reactor windings. It has been shown (in Fig. 3) that, without any polarization of the core, the flux would swing symmetrically about the origin of the *B*/*H* curve, that is from point 1′ to 4′ on the *B*/*H* curve for reactor A. However, the passage of current in the control winding causes asymmetry in the flux swing. Instead of starting from point 1′, it will commence at point 1 displaced along the *H* axis by an amount equal to H_C corresponding to the m.m.f. derived from the control current I_C. Reactor A passes into saturation at point 2 before the end of the half-cycle. Now, whilst the flux in reactor A is building up the flux in core B is resetting so that, when core A saturates, core B is in an unsaturated state. Assuming a low impedance control source, the control winding on reactor A,

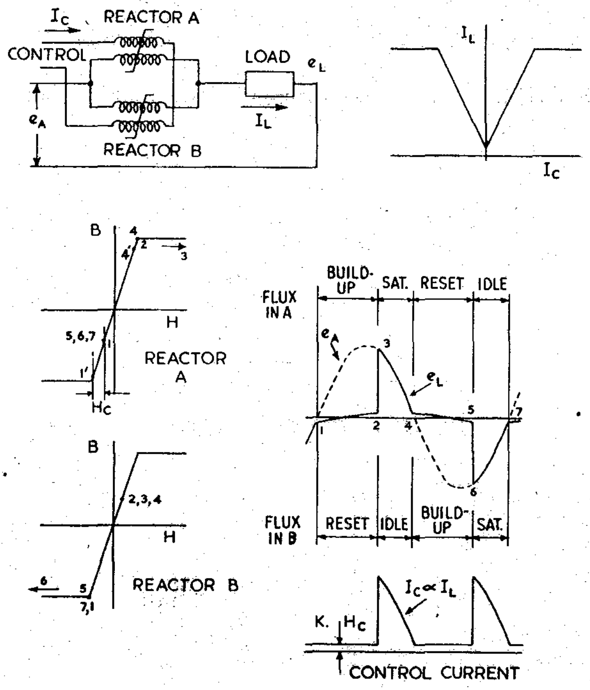

Fig. 10. Non-self-saturated magnetic amplifier.

possessing little inductance with its core in a saturated state, acts as a resistance load on the control winding of reactor B. Reactor B will therefore function as a current transformer during the phase when reactor A is saturated. Current is conducted simultaneously by both reactors A and B. It is conducted by reactor A because it is saturated and by reactor B because it is virtually a transformer with a shorted secondary. During the next half-cycle the flux in reactor A resets whilst that in reactor B builds up, followed by a current conduction phase in which reactor B is saturated and reactor A is unsaturated, both reactors again conducting current. The control current will be almost proportional to the output current because each reactor in turn functions as a current transformer during the current conduction phase. This non-self-saturated amplifier, which may have its main windings either in parallel or series, is characterized by the V-shaped control curve shown in Fig. 10. It is a less useful amplifier than one employing self-saturation owing to its greater control current and its non-directional control signal properties. It has, however, the advantage of being able to use low-grade core material since the load current is almost proportional to the control current, the magnetization properties of the core having only a small influence upon the output current.

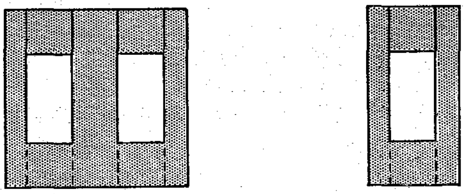

Fig. 11(a). Stacks of overlapping laminations for magnetic amplifiers.

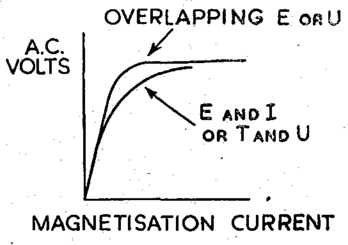

Fig. 11(b). Magnetization curves.

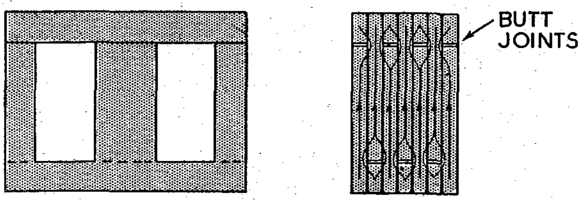

Fig. 11(c). Stack of E and I laminations for transformers.

Core Details

It will have been gathered that good quality core material is required for amplifiers using self-saturation. The desired properties have been stated as high unsaturated permeability with an abrupt transition into saturation. Mumetal and HCR are suitable core materials for low power output, each having a nickel-iron composition. For amplifiers giving outputs above about 10 watts at 50 c/s, advantage is gained in using grain oriented silicon steel on account of its higher saturation flux density, its lower relative cost and of the fact that when large cores are required it is an easier material to handle.

The construction of the core requires special attention. It must be constructed in such a way as to obtain a good degree of uniformity in flux density so that the whole core goes into saturation at about the same instant. Any local saturation will cause a rounding of the knee of the *B*/*H* loop for the reactor, with subsequent deterioration of the control characteristics. Interleaved T and U or E and I laminations such as used on small transformers are particularly unsuitable. In the lamination stack shown in Fig. 11(c), local saturation will occur in the material adjacent to the butt joints and this causes a rounding of the knee of the *B*/*H* loop of the reactor core. The use of overlapping E or U shaped laminations, Fig. 11(a), eliminates such local saturation caused by butt joints and in making the yoke of double width a reasonable uniformity of flux is obtained throughout the core.

Three other useful types of core construction are shown in Fig. 12; they are:—

(1) A ring core of wound strip over which the windings are toroidally wound. This construction gives superior results but it is penalized by the somewhat tedious operation of winding the coil over the core.

(2) A "C" core which is wound from strip material and set in shape to give a rectangular window. It is then cut across its longer sides to give two "C" shaped cores.

(3) A core formed from a stack of uncut laminations, the coil being wound on a split cylindrical bobbin placed on the centre leg.

Reactor Construction

In the reactors for a single-phase amplifier, the two cores are often linked by a common control winding as shown in Fig. 13. This connection avoids the occurrence of A.C. voltages of fundamental frequency in any section of the control circuit. Such voltages can be undesirably high if individual reactors are used and there is a high

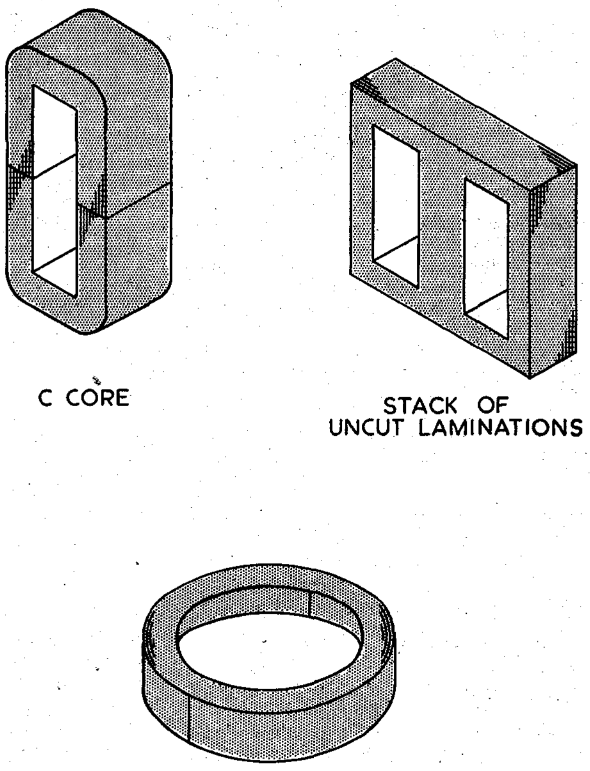

Fig. 12. Other core constructions.

turns-ratio between control and main winding. This construction also saves copper in the control circuit.

Two typical single-phase reactor constructions are shown in Fig. 14. On the left-hand side (a) is a reactor using overlapping E laminations. The centre leg of both cores has a main, or gate, winding and the control winding embraces the two main windings. On the right-hand side (b) is a reactor using wound ring cores and toroidal windings. Both ring cores are wound with a main winding and placed side by side, the control winding is then wound to embrace both main windings. The construction is not limited to a single control winding and the requirements of an application frequently necessitate a multiplicity of control windings.

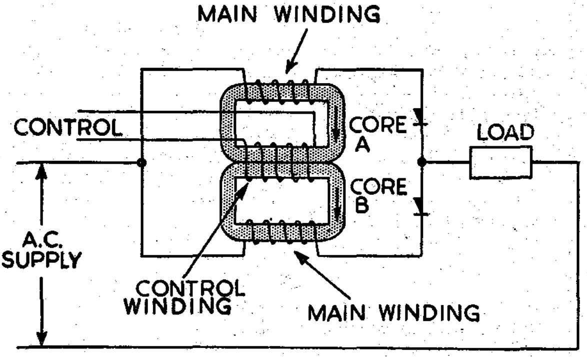

Fig. 13. Single-phase amplifier with common control winding.

Sealing

The reactors and rectifiers of a magnetic amplifier are readily sealed, either individually or as a whole, within oil-filled containers if conditions of operation warrant such an action. Conditions in which sealing is desirable are polluted industrial atmospheres and extreme tropical climates.

Merits of Amplifier

The robust nature of magnetic amplifiers, their absence of moving parts, and good reliability are features encouraging their general use. The output rating and performance characteristics of magnetic amplifiers tend to overlap with those of electronic amplifiers and rotating amplifiers. Basic features of electronic, magnetic and rotating amplifiers are compared in the table, Fig. 15.

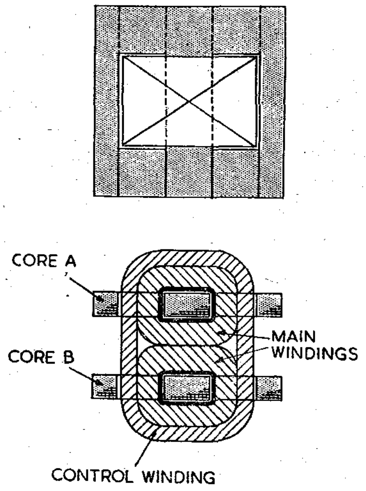

Fig. 14(a). Single-phase reactor using overlapping E laminations.

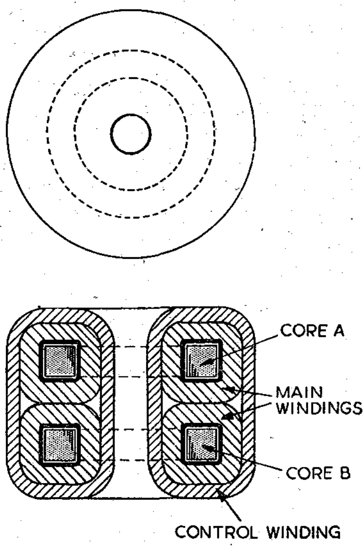

Fig. 14(b). Single-phase reactor of toroidal construction.

	Electronic Amplifier	Magnetic Amplifier	Rotating Amplifier
Output Power approx.	Up to 350 kW	Up to 50 kW	0·2 kW Upwards
Reversible Output	No	No	Yes
Starting Delays	Hard valves: 10 to 30 sec. Thyratrons: Up to 10 min.	None	Machine starting
Approx. Power Gain for 1 second Time Constant	Infinite	Self-sat. amplifier (1 kW at 50 c/s) .... 20,000 Non-self-sat. amplifier 200	One stage .... 1000 Two stage, such as Amplidyne 50,000
Normal Resistance of Control Circuit	10^3 to 10^6 ohms.	10^{-1} to 10^3 ohms.	10^{-1} to 10^3 ohms.
Isolation between Control and Output	Not easy	Yes	Yes
Maintenance	Occasional valve replacement	Nil	Routine attention to brushes and bearings

Fig. 15. Features of Static and Rotating Amplifiers.

In comparison with an electronic valve amplifier, the magnetic amplifier has the following advantages:—

(1) Robustness of construction;

(2) No heating-up time;

(3) Electrical isolation of input and output circuits;

(4) Control circuits of low resistance and working voltage.

The advantage of the absence of any heating-up time enables immediate operation to be achieved, a feature which is not easily obtained with an electronic valve amplifier.

The use of control circuits with low resistance and working voltage renders the magnetic amplifier less affected by adverse climatic conditions than the high impedance networks of the valve amplifier. On the other hand, the low resistance of magnetic amplifier control circuits becomes a disadvantage when means are sought of stabilizing automatic control systems. In this respect, the presence of a time constant also creates a disadvantage, but the time constant can be minimized by the choice of a high A.C. supply frequency and, when a high power gain is required, by placing several stages of amplification in cascade.

In comparison with a rotating amplifier, such as an amplidyne, the magnetic amplifier gains the advantage of requiring no routine maintenance. However, the output of a magnetic amplifier is basically of one polarity only, whereas a rotating amplifier has a readily reversible output polarity. A reversible output from a magnetic amplifier circuit can only be obtained by using two amplifiers placed back to back, and if this is done much power is lost in the necessary balancing resistors. In other words, a magnetic amplifier circuit having a reversing output is much less efficient than a rotating amplifier. Nevertheless, the static nature of the magnetic amplifier offers some attraction.

ACKNOWLEDGEMENT

The author wishes to express thanks to the directors of the British Thomson-Houston Co., Ltd., for permission to publish this paper.

Printed in England by Albert Frost & Sons, Ltd., Rugby, for BTH.