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THE MAGNETIC AMPLIFIER

The magnetic amplifier is a useful control device which is both robust and reliable. The basic element in a magnetic amplifier is the "saturable reactor", also known as the "transductor". This, in its simplest form, consists of a core of electro-magnetic material on which are wound two windings, one carrying alternating and the other direct current. The a.c. winding is connected in series with an a.c. supply and a load, the current through which is to be controlled. By varying the current in the d.c. winding the a.c. impedance of the circuit can be changed and in this way the current through the load is controlled. With suitable windings a small change in direct current can be made to produce a large change in the load current (since the d.c. change can vary the degree of magnetic saturation of the core), and in this lies the usefulness of the device. As the change in load current is normally greater than the change in control current, a saturable reactor by itself forms a simple current amplifier. The term magnetic amplifier, however, is usually considered to imply a circuit arrangement incorporating one or more saturable reactors and other circuit elements such as rectifiers, and sometimes having additional windings on the reactors to improve, for example by means of feedback, the characteristics of the amplifier.

Basic Circuit

A simple magnetic amplifier circuit is shown in Fig. 1. The windings of two identical transformers are arranged back to back so that no voltage, at the supply frequency, appears between the terminals A and B. The only current in the a.c. circuit is the magnetising current which the transformers will draw even if a low impedance is connected across AB. If a direct current is passed from B to A through the windings

the cores will run into partial or complete saturation. The impedance they offer to the a.c. supply voltage will thus fall and the current in the a.c. circuit will rise. In this way d.c. in the additional set of windings controls the a.c. in the load.

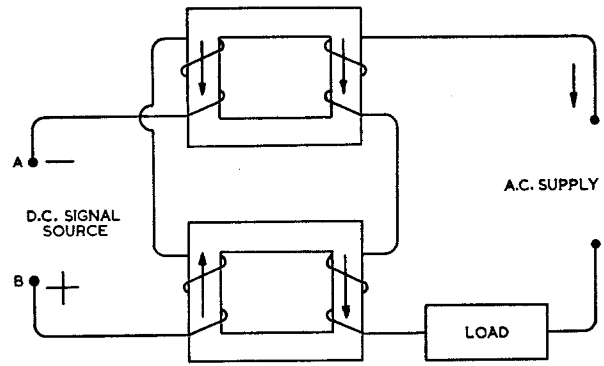

Fig. 1.—*Basic magnetic amplifier circuit.*

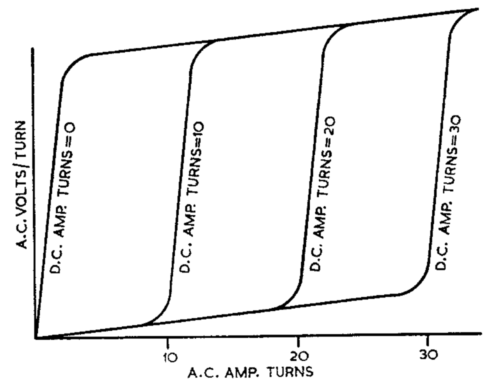

Fig. 2.—*Characteristic curves of a.c. output against applied voltage for different values of d.c. in the control windings.*

The a.c. in the load is rich in odd harmonics and even harmonics appear in the d.c. circuit. If the mean values, taken over a half-cycle of the supply voltage, are measured it is found that:

a.c. ampere-turns
= d.c. ampere-turns + magnetising ampere-turns.

If the magnetising ampere-turns are kept small by careful design, an approximately linear relationship between the average currents in the a.c. and d.c. circuits can be obtained.

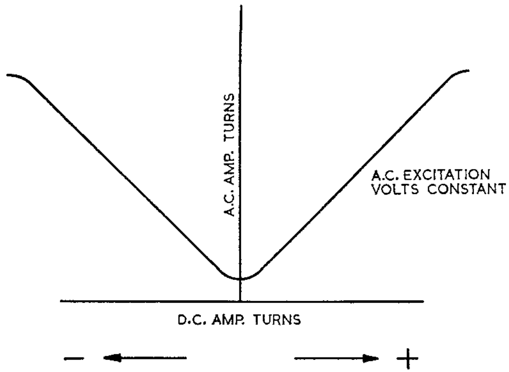

Fig. 3.—*Characteristic curve of a.c. output against d.c. input.*

By suitably proportioning the ratio of d.c. to a.c. turns, the arrangement shown in Fig. 1 can be made to amplify current and hence power in a manner substantially independent of variation in the voltage and frequency of the a.c. supply or in the resistance of the a.c. circuit. Figs. 2 and 3 illustrate these characteristics. Current gains of 10 and power gains of 40 are readily obtainable with this circuit.

Circuit Using Positive Feedback

Higher gains can be achieved by the incorporation of positive feedback. Fig. 4 shows the arrangement. Some loss of stability owing to supply voltage and frequency variations is inevitable with this circuit, but current gains of 200–300 and power gains of 10^4–10^5 are quite easy to obtain. The waveforms of the

currents in the a.c. and d.c. circuits are substantially the same as with the simple arrangement previously considered. The

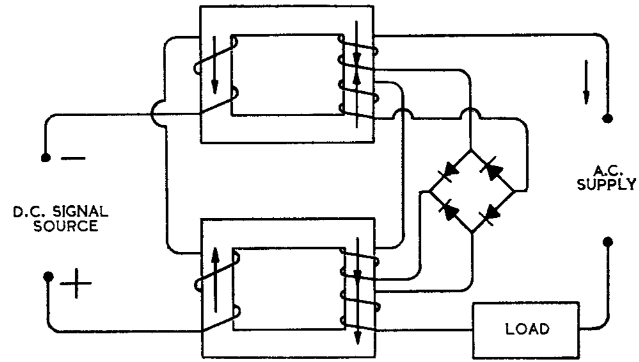

Fig. 4.—*Magnetic amplifier circuit incorporating positive feedback. The positive feedback increases the amplification and makes the amplifier sensitive to the polarity of the d.c. source.*

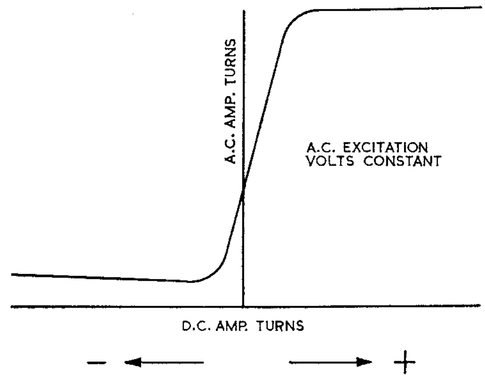

Fig. 5.—*Characteristic of a magnetic amplifier incorporating positive feedback.*

positive-feedback magnetic amplifier is, however, sensitive to the direction of the controlling direct current, as can be seen from the characteristic shown in Fig. 5. In practice biasing ampere-turns are often used to move the operating point to the middle of the linear portion of the characteristic, in a similar manner to that employed in thermionic valve amplifiers.

Response to Change in d.c. Control Voltage

The response to a sudden change in the d.c. control voltage is not instantaneous. The time-constant of the delay depends on the constants of the d.c. and a.c. circuits. It is directly proportional to power gain and inversely proportional to the frequency of the supply voltage. In practice the time-constant may be from 2 to 100 cycles of the supply frequency with amplifiers of the type shown in Fig. 4.

Herein lies the main disadvantage of magnetic amplifiers, particularly when they are used in automatic (closed-loop) control systems. Delays of this order make such systems sluggish in response and difficult to stabilise.

Further Variations

To achieve greater gain, the basic arrangements shown in Figs. 1 and 4 can be connected in cascade. These basic arrangements

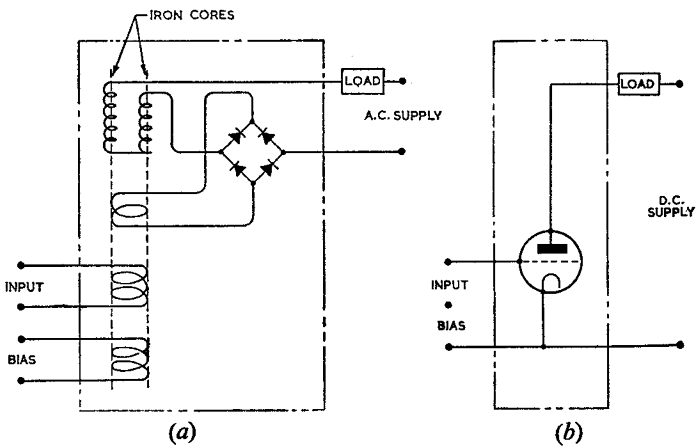

Fig. 6.—*Comparison between basic magnetic* (a) *and thermionic triode valve* (b) *amplifier circuits.*

can also be connected in push–pull, giving increased stability and providing a reversible d.c. output.

A comparison of the basic thermionic valve and magnetic amplifier circuits is shown in Fig. 6.

General Characteristics

Unlike the thermionic valve amplifier, which is a voltage-operated device having greatest efficiency when working from a high impedance source, the magnetic amplifier is a current-operated device requiring a comparatively low impedance source.

The magnetic amplifier contains no moving parts, is quiet, can be hermetically sealed and has an almost unlimited life. Its size is about three times that of a transformer having the same power output, varying, as with transformers, inversely with the supply frequency. As there is no warming-up time, it functions as soon as it is switched on. Unlike thermionic valves, whose impedance is ohmic producing considerable internal power loss, there is, because their impedance is mainly reactive, very little internal dissipation in magnetic amplifiers.

The input and output circuits of a magnetic amplifier are completely isolated electrically. Several input circuits can be provided, each electrically isolated from the others and from the load and the supply, the output being dependent on the algebraic sum of the ampere-turns of all the input circuits. D.C. input information can be converted to an a.c. or, if rectified, to a d.c. output at a higher power level.

The magnetic amplifier, being inherently a low input impedance device, is particularly suitable for operation from low voltage, low impedance sources such as thermocouples, semiconductor photocells and resistance strain gauges. The impedance match to transistors is also good.

Performance

The following information on impedances, amplification, power supplies and other details is intended as a guide. Many of the performance figures given are interdependent and all cannot necessarily be obtained at the same time; better figures can often be obtained under special circumstances.

The power supply is normally single-phase a.c.; a transformer is usually required to provide the correct voltage to the amplifier. Frequencies of 50–2,000 c/s are normally used; the effect of supply frequency on size and response time has already been noted.

The input may be d.c. or low frequency a.c. The input resistance is normally in the range of 0·1–3,000 ohms. The output can be d.c. or a.c. into impedances of 10–2,000 ohms using a 50 c/s supply. Higher frequency supplies allow proportionately higher values to be used. The d.c. output can be made reversible by push–pull techniques and an a.c. output can be made to change phase by 180 degrees.

Single-phase power gains of up to 10^4 are common, and amplifiers are possible with gains of 10^6 in one stage; higher gains can be obtained by cascade operation of two or more stages. With applications to low power amplification, the drift under normal operating conditions (including ± 10 per cent supply-voltage and ± 5 per cent supply-frequency variations) is equivalent to an input power of about 10^{-12} W. Linearity and stability are usually between 0·5 and 10 per cent of the maximum output current.

Response Time

It has been pointed out previously that the rather long time-constants of magnetic amplifiers when responding to sudden changes in the d.c. control voltage can be a disadvantage in some applications. Various methods of reducing the time-constant have, however, been devised. For example, the time-constant is inversely proportional to the frequency of the supply. Thus, driving the amplifier from, say, a 500 c/s instead of a 50 c/s supply will reduce the time-constant to one-tenth of its value at 50 c/s. Owing to the difficulty of obtaining such frequencies by other than electronic means, it is seldom practicable to work at frequencies higher than 1,000–2,000 c/s. Again, as the time-constant varies directly with gain, reduction

of gain reduces the time-constant; since, however, gain is usually what is required, this method is somewhat limited in application. The gain should, however, always be kept as low as practicable.

Cascade Circuits

When two or more magnetic amplifiers are arranged in cascade the overall time-constant is approximately equal to the sum of the separate time-constants while the overall amplification is the product of the separate amplifications. Thus a

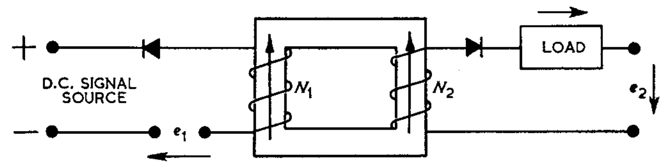

Fig. 7.—*Basic circuit of the Ramey half-wave magnetic amplifier e_1 and e_2 are a.c. supply voltages of the same frequency and of the phase shown by the arrows. Their amplitudes are such that $e_1/e_2 = N_1/N_2$ where N_1 and N_2 are the turns of the signal and load windings respectively. There is one current pulse in the load every cycle of the supply voltage. Response time is one cycle of the supply frequency.*

shorter time-constant for a given amplification can be obtained by employing two or more stages in cascade.

In 1951 Ramey introduced a magnetic amplifier circuit which responds within one cycle of the supply frequency but with sacrifice in power gain. Fig. 7 shows the basic circuit of this type of amplifier, which gives power gains of the order of 100–200 as against 10,000 for the type previously described. The basic arrangement shown in Fig. 7 only gives a half-wave output; Fig. 8 shows the Ramey circuit developed to give full-wave output.

Where power gain can be sacrificed for fast response, or where a multi-stage amplifier is acceptable, the high-speed circuits shown in Figs. 7 and 8 should be used. Where, however, a long time-constant can be tolerated, for example in control systems having comparatively long time-constants themselves (process control), it is usually advantageous to use the circuit shown in Fig. 4 in view of the high power gain that can be obtained with this.

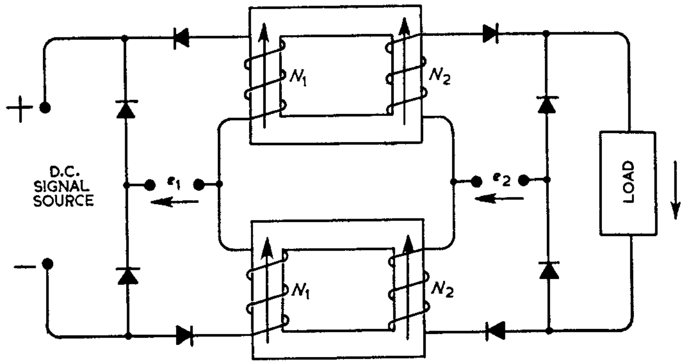

Fig. 8.—*Basic Ramey full-wave circuit. There is one current pulse every half-cycle of the supply voltage, always in the same direction, through the load. Response time is a half-cycle of the supply frequency.*

Applications

Magnetic amplifiers may be used to amplify the signals from such sources as semiconductor photocells, thermocouples and high frequency thermo-junctions, resistance strain gauges, inductive pick-ups, synchros, etc. The amplified output may be fed into heaters, lamps, relays, indicating and recording instruments, and a.c. and d.c. motors with field or armature control.

Some typical applications are: servo systems where magnetic amplifiers are used with d.c. split-field or a.c. split-phase motors and control fields of Metadyne and Amplidyne generators, temperature recording, control and alarm, recording of gas flow, photoelectric counters, voltage and frequency control of machines, automatic battery charging, automatic control of street lighting and sensitive relays.

221. **For controlling dc power output from a rectifier,** a variant of the saturable reactor, the magnetic amplifier,[1] is often used. Connected in series with the line between the rectifier transformer and the rectifier, the magnetic amplifier carries a dc component of load current. By using core steel with a sharp knee in the magnetization curve for the magnetic amplifier a very small additional dc input to a control winding suffices to modify the impedance characteristics so as accurately to control the transmitted power with a fast response.

Standard Handbook for Electrical Engineers.

McGraw-Hill. 1978

CHAPTER 14
MAGNETIC AMPLIFIERS

INTRODUCTION

The magnetic amplifier enjoyed its maximum prominence in power control and low-frequency signal-processing electronics from about 1947 to 1957. By 1957 junction transistors were readily available. Development rapidly shifted away from magnetic amplifiers toward transistor and semiconductor switch equivalents, combined magnetic/transistor amplifiers, and the host of new devices made possible by the joint use of square-loop cores and transistors. Complex magnetic-amplifier designs developed in this period must be looked on as an interim technology. Many magnetic amplifiers in present use and manufacture are the result of early design commitments which have not yet been replaced.

There are a few areas, however, in which magnetic amplifiers continue to excel. In power control, they tolerate extreme environmental and overload conditions that would be fatal to semiconductors. They may also generate less noise because of the slower switching saturable reactors. Perhaps most important, they permit the summing of a number of input signals that must remain electrically isolated. In instrumentation amplifiers, magnetic-amplifier circuits still offer high, drift-free gain with this summing feature. The development of magnetic-core transistor oscillators makes it possible to supply ac power of practically any desired frequency for these amplifiers, making them much smaller than they would be with power-frequency excitation. Similar circuits have come into increasing use in magnetometry where the unique direct transducing capability of the magnetic amplifier puts it in a class by itself.

The magnetic-core transistor oscillator, which is capable of inverting dc to ac up to about 100 kilohertz and by rectification can convert a single primary dc power source at high efficiency to several independent conductively isolated dc voltage supplies, today has all of the engineering prominence that magnetic amplifiers once enjoyed. Many of these newer circuits are, in fact, regulated and timed by magnetic-amplifier principles.

The history and present state of the art in magnetic amplifiers is documented in the proceedings of the Conference on Nonlinear Magnetics and Magnetic Amplifiers [1], and the more recent *IEEE Transactions on Magnetics* [2]. Several books ranging between texts and advanced treatments of design principles are also available [3–7]. The development of soft magnetic materials used in magnetic-amplifier circuits can be traced in the proceedings of the Annual Conferences on Magnetism and Magnetic Materials [8]. Most of the material to be found in these references deals with basic principles and the physical properties of materials. For the circuit engineer who wishes to capitalize quickly and effectively on the design rules that have emerged from this effort, the design manuals available from the manufacturers of magnetic-amplifier core materials tabulate the available material types and related design information such as wire holding capacity, insulation, and temperature characteristics. Having made the basic selection of the core windings and circuit configuration, the designer should expect to spend some time tailoring the circuit to meet design specifications.

PRINCIPLE OF THE MAGNETIC AMPLIFIER

The elementary principle of magnetic amplification can be conveniently represented in terms of a flux-actuated switch in series with a load. The magnetic material is characterized by the nearly rectangular hysteresis loop of Fig. 1. In this figure, the narrow hysteresis loop corresponds to the loop measured at dc and the wider loop is that measured at the power supply frequency. It should be noted that this dynamic loop widens with increasing frequency. Figure 2 shows the dc hysteresis loops corresponding to three of the materials listed in Table 1.

Figure 3 shows a winding on a core in series with a resistor representing the load. At the beginning of a positive half-cycle of the supply voltage, the

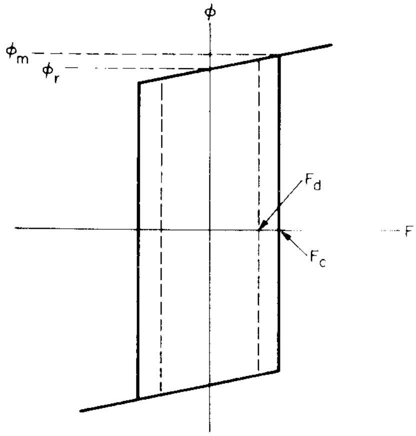

Fig. 1—Schematic representation of dynamic and dc (dotted lines) hysteresis loops.

core is in some initial flux state ϕ_0. Essentially all of the supply voltage is impressed on the core winding until the flux in the core reaches saturation. In saturation, the core becomes a very low impedance and practically all of the supply voltage appears across the resistor. This situation is diagrammed in Fig. 4A for a sinusoidal supply voltage and in Fig. 4B for a square-wave supply voltage. The lower portions of the diagrams show that the switching of the supply voltage from the core to the resistor becomes perfect when the width of the hysteresis loop is zero. In practical designs, the choice of power supply voltage and frequency, core size, winding, and load impedance is subject to the constraints of the problem. To approximate the above-mentioned ideal conditions is often the main object of the design.

Figure 5 shows integrals of portions of the supply-voltage integral in analytical form. It is clear from this figure that the average voltage applied to the load is a function of the switching angle α, which in turn depends on the initial flux ϕ_0. The half-cycle average of the load voltage is expressed in terms of ϕ_0 for the sine-wave and square-wave cases as follows.

Sine Wave	Square Wave
$\bar{v}_r = (2/T)(E_s/\omega) \times (1+\cos\alpha)$	$\bar{v}_r = E_s[1-(\alpha/\pi)]$
$(E_s/\omega)(1-\cos\alpha) = (E_s/\omega) - N\phi_0$	$(T/2)E_s(\alpha/\pi) = N(\phi_m - \phi_0)$
$\cos\alpha = \phi_0/\phi_m$	$\alpha/\pi = \frac{1}{2}[1-(\phi_0/\phi_m)]$
$\bar{v}_r = (2/T)(E_s/\omega) \times [1+(\phi_0/\phi_m)]$	$\bar{v}_r = E_s/2[1+(\phi_0/\phi_m)]$

It is further obvious that in order for there to be no output, and no excess flux capacity in the core (normal excitation), the flux linkage capacity of the core must be set equal to the volt-second capacity of the power supply. This results in the simple equations

$$E_s = B_m A\omega N \quad \text{(sine wave)}$$

$$E_s = (2/\pi) B_m A\omega N \quad \text{(square wave)}$$

relating the peak value of the supply voltage, the maximum flux density of the core (in webers/meter^2), the material cross-section (in meters^2), the angular frequency, and the number of turns.

Correspondingly, the exciting current for a given coercive force F_c in ampere-turns is $i_x = F_c/N = H_c l/N$, where H_c is in ampere-turns/meter and l is the mean length of the magnetic path in the core in meters. These equations in CGS units become

$$E_s = B_m A\omega N \times 10^{-8} \quad \text{(sine wave)}$$

$$E_s = (2/\pi) B_m A\omega N \times 10^{-8} \quad \text{(square wave)}$$

where B_m = gauss, A = cm^2, E_s = volts (peak), and N = turns.

$$I_m = 0.794 H_c l/N$$

where H_c = oersteds, l = cm, and I = amperes.

Although the above discussion contains most of the ideas basic to magnetic amplifiers, no mention has been made of how ϕ_0 is related to the control

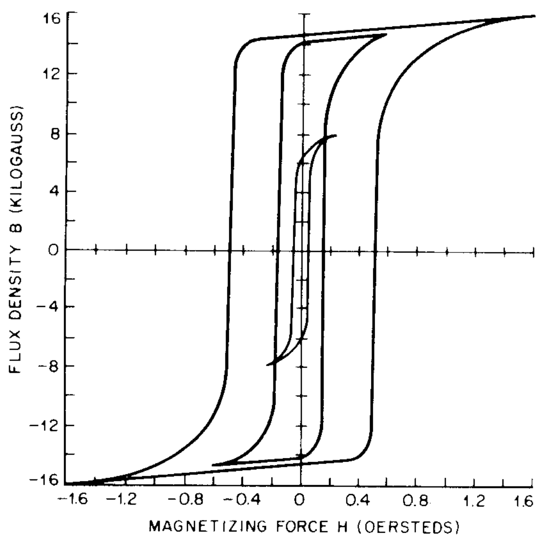

Fig. 2—Comparison of dc loops of three materials listed in Table 1.

Table 1—Materials and Applications.

Material Letter Code	Trade Name	Cost/Core* Relative to Material A	Principal Use
A	Square Orthonol, Hipernik V, Orthonik, 49 Square Mu, Deltamax	1.00	High-gain amplifiers, oscillators, integrators, timers, memory devices.
N	Round Orthonol	1.00	Amplifier applications with slightly less gain, but less liability to triggering instability, than material A.
H	48 Alloy, Carpenter 49	1.00	Material A and N applications with lower sensitivity, lower losses, and less triggering instability. High-quality transformers.
D	Square Permalloy 80, Square Mu 79, Super Square Mu 79, Hy Ra 80, 4-79 Permalloy, Square Permalloy	1.14	High-gain amplifiers at low signal levels and low losses, low-power-consumption inverters and converters.
R	Round Permalloy 80, Hy Mu 80	1.14	High-quality low-loss inductors and transformers.
F	Supermalloy	1.63	Material D and R applications in which the lowest possible exciting currents and losses are required.
K	Magnesil, Selectron, Microsil, Hypersil, Supersil	0.70	Power amplifiers requiring lower gain and lower cost than material A applications. High-quality power transformers.
S	Supermendur	3.4	Material A and K applications where minimum size and weight and maximum operating temperatures are required.

* Based on 2-mil tape-wound core of about 3-inch diameter.

signal. Further, note that at the end of the half-cycle, ϕ is at saturation. Thus the core must be reset to ϕ_0 in the second half-cycle. If a similar voltage is to be applied to the load in the second half-cycle, a second core must be included in the circuit. Such resetting and output problems are responsible for the variety of amplifier circuit configurations that have been used.

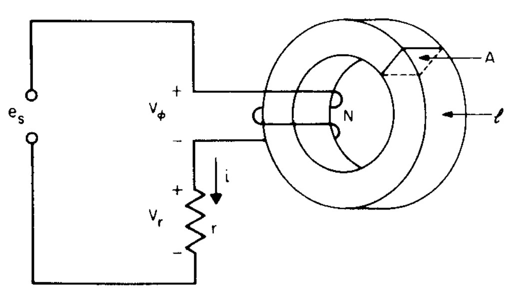

Fig. 3—Saturable reactor in series with a resistor.

AMPLIFIER CONFIGURATIONS

The amplifier configuration is arranged with two considerations in mind. One is the method of control, and the other is the type of output desired. As seen from the discussion above, a core that is brought to saturation and is gating power to a load on a positive half-cycle must be reset to its initial state if it is to repeat this function on the next positive half-cycle. On the other hand it is usually desirable to deliver power to the load on both half-cycles. Thus a second core will be gating power to the load during the half-cycle in which

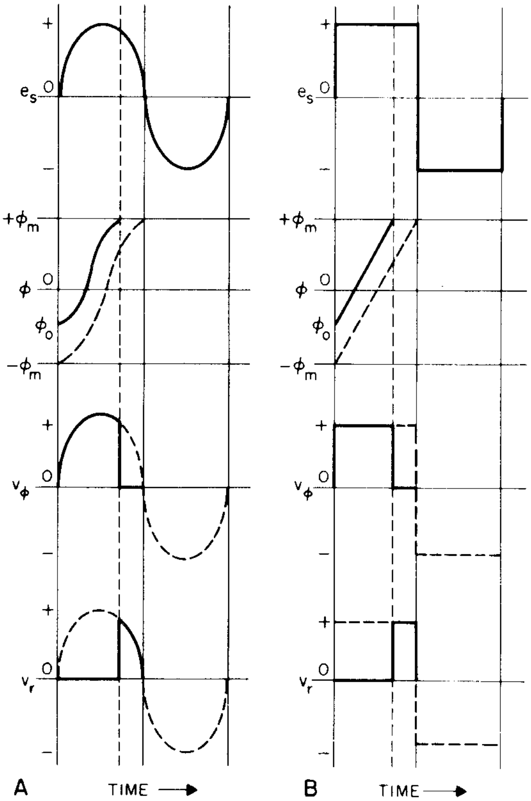

Fig. 4—Voltage and flux waveforms for the circuit of Fig. 3 for (A) sine-wave and (B) square-wave excitation.

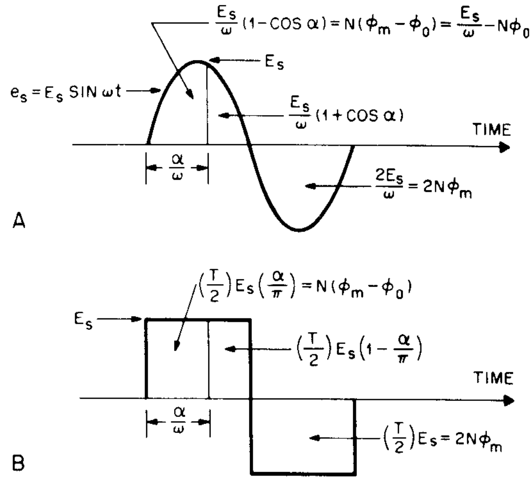

Fig. 5—Components of integrals of (A) sine-wave and (B) square-wave half-cycles.

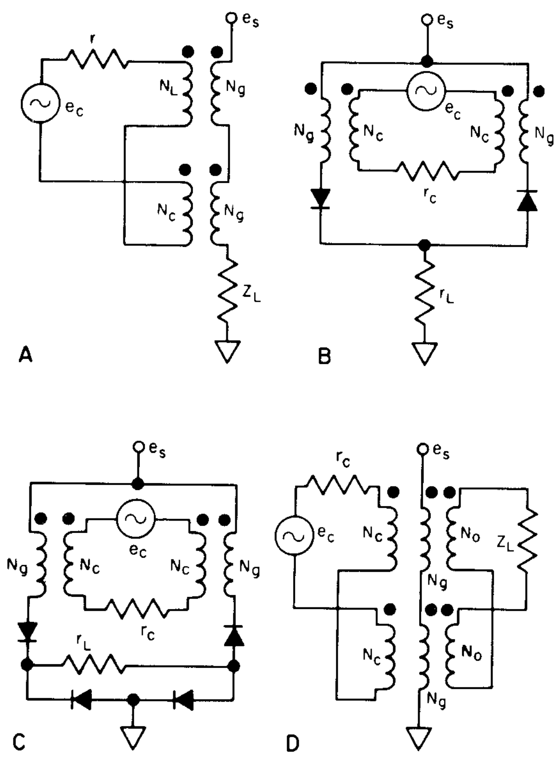

Fig. 6—Circuits for (A) the series-connected amplifier or transductor, (B) self-saturating amplifier with ac output, (C) self-saturating amplifier with dc output, and (D) second-harmonic modulator. N_c = control turns, N_g = gating turns, and N_o = output turns.

the first core is being reset. Since the increment in flux linkage in the two cores is equal in the steady state, the core driven from the power supply can be used to reset the second core by transformer action through the control circuit. In single-phase circuits the roles of the cores interchange during alternate half-cycles. The use of one core to reset the other is fundamental to most amplifier configurations.

Several of the most common configurations are shown in Fig. 6. Figure 6A is the series-connected amplifier, sometimes called the transductor. It has been extensively analyzed [3, 9, 10] and is commonly used to measure large direct currents in electrochemical and power applications [11]. The details of the circuit operation are complicated but, in essence, at most one core is saturated at a time, gating power to the load. During this interval, the second (unsaturated) core, which has a very small coercive force, must therefore maintain the condition $N_L i_L - N_c i_c = F_c$, the dynamic coercive force of the unsaturated core. The control current i_c has the same waveform as the load current i_L

but has the same polarity on each half-cycle. Thus, the rectified average values of the load current and the control current, I_L and I_c, are related by the turns ratio.

$$I_L = (N_c/N_L)I_c + (1/N_L)F_c$$

a linear function with a constant offset as shown in Fig. 7A. In practice, the linearity of this function can be kept within about 0.1 percent, which makes it very useful for instrumentation.

The circuit in Fig. 6B is characterized by parallel-connected saturable reactors, so that the load current does not have to flow through an unsaturated core. Thus, since the resetting core is primarily transformer driven through the control circuit by the power-gating core, only the exciting current for the resetting core must be carried in the control circuit. In the steady state, the flux linkages coming from the winding on the gating core must equal the flux linkages delivered to the resetting core. With zero control voltage, the two flux linkages will differ by the integral of $i_c r_c$ over the half-cycle. The function of the control voltage is to offset this voltage drop to make the two flux linkages equal at the desired output level. The diodes decouple the cores from the power supply during their resetting half-cycles.

When the amplifier is delivering full output, there is essentially no flux excursion in the gating core. It therefore does not drive the resetting core. Since the resetting core must not be reset under these conditions, the control current must be just below the coercive direct current for the core. At zero output, the gating core drives the resetting core at normal power voltage, resulting in a control current equal to the normal power-frequency coercive current. Full control of the amplifier is obtained over a control-current range equal to the widening of the hysteresis loop from dc to the power-frequency loop, divided of course by the control-winding turns. The resulting control characteristic is shown in Fig. 7B, with reference to Fig. 1. Again, there is a minimum output corresponding to the exciting current for the gating core. Also, the control current and voltage are automatically rectified because of the half-cycle symmetry of the circuit as seen from the control terminals. The modification shown in Fig. 6C delivers dc to the load.

A fourth configuration (Fig. 6D) used for very-small-signal amplifiers and magnetometers [12, 13] takes advantage of transformer coupling of the output to eliminate the residual exciting-current component found in the other circuits. The fundamental component of the induced voltage is canceled out and, at input currents other than zero, there is a second-harmonic component in the output proportional to the input current. The

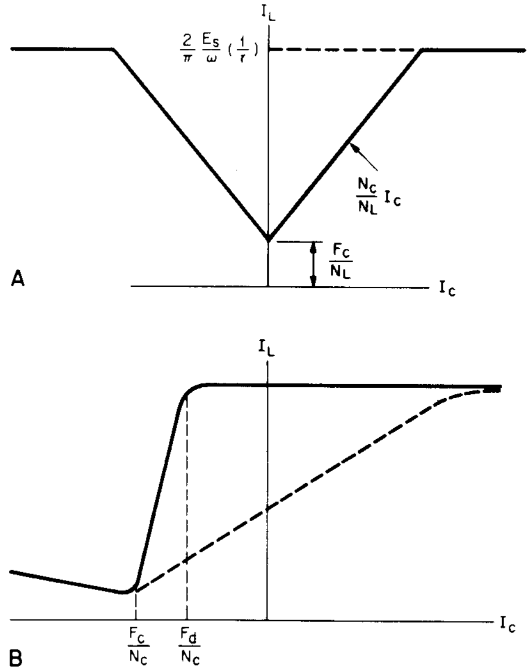

Fig. 7—Control characteristics for (A) the amplifier of Fig. 6A; and (B) for the amplifier of Fig. 6B and 6C. The dotted characteristic corresponds to nonsquare hysteresis loop, resistively shunted rectifiers, or negative feedback.

phase of this output reverses with the input-current polarity. Other examples of high-sensitivity amplifiers can be found in the literature [14]. For many power applications, 3-phase amplifiers are preferred for the usual reasons. The output is much easier to filter when dc is required [15].

Examples of parametric amplifiers and microwave magnetic amplifiers can be found in the literature.

MULTISTAGE AMPLIFIERS

Because of the bilateral characteristics of magnetic amplifiers, multistage amplifiers are difficult to analyze. In addition, their properties as measured experimentally are technically unattractive and they are difficult to design even by empirical techniques except when the coupling-circuit impedance isolates the circuits. In this case, gain and frequency response are usually sacrificed. With the advent of a highly developed transistor technology, it is rarely necessary to design multistage amplifiers. Where it is necessary, the problem is treated as though the first stage were driving any other R–L or R–L–C isolated dc load. If this approach does not yield adequate performance, the designer must resort to less well documented techniques or initiate a new approach to solving the problem.

BIAS AND FEEDBACK

Bias and feedback windings look and act exactly like the control windings shown in Fig. 6. Problems in design arise because these windings couple induced voltages from the cores into the bias and feedback circuits. Thus, the circuits are not simply unilateral and passive [16]. If these circuits are isolated by suitable R–L networks, then the currents can be treated as though they were additive. In that case, the bias winding simply translates the origin of the control current in the direction of the bias.

The output current or voltage can be rectified and passed through simple R, R–L, or R–L–C networks and the derived current put into a feedback winding. In such a case, feedback is treated as it is in any other amplifier. It can linearize the amplifier successfully if the range of output is lowered. If the amplifier is used as a power device and its range of output is fixed by performance specifications, feedback is of no help unless compensating nonlinearity can be inserted in other amplifying stages. Feedback in such cases is useful primarily to lower output or impedance of the amplifier.

FREQUENCY RESPONSE

Analysis has shown that the voltage-gain bandwidth product [17] is

$$G_v \times (\mathrm{bw}) = 4f/N \quad \text{(series-connected amplifier, Fig. 6A)}$$

$$G_v \times (\mathrm{bw}) = 2f/N \quad \text{(self-saturating amplifier, Fig. 6B)}$$

where f is the frequency and N is the turns ratio N_c/N_g. These relations show again the advantage of high-frequency power supplies. They also suggest that if a design is adjusted to increase gain, the bandwidth (frequency response) will be reduced unless the turns ratios are adjusted to raise the gain–bandwidth product. High-gain amplifiers can be expected to have a bandwidth of about one-tenth the carrier frequency, which is frequently sufficient in instrumentation applications. In signal-processing applications, it is preferable to use several stages of low-gain wide-band amplification since the gains multiply and the bandwidths go down more or less additively. It is in this area that magnetic amplifiers have been largely replaced by semiconductor circuits.

CHOICE OF CORE MATERIALS

A variety of core materials can be chosen for magnetic amplifiers. They can be obtained in the form of tape-wound cores, laminations, and encapsulated tape cores cut into two mating C-shaped pieces. The latter configurations permit the use of simple inexpensive lathe-wound windings which can be assembled on the core. The cut-C core configuration maintains the rolling direction of the tape along the primary magnetic path. The laminations are stamped out of continuous strip such that part of the magnetic path is along the direction of rolling and part is perpendicular to it. Since most good-quality strip is anisotropic, the resulting characteristics of the cores are not as good as they would be in the tape-wound configuration, which has the best magnetic qualities. As a result, only the lower-cost lower-quality magnetic materials are widely used in other than the tape-wound configuration. In addition to differences in processing and in the cost of raw materials, the above manufacturing considerations significantly contribute to the economic basis for choosing core materials. Cost is the dominant consideration in most amplifier designs. There are, however, extreme cases where only the highest-quality material can meet the technical specifications.

In general, the large, heavy, power-control applications make use of the least expensive materials in the least expensive configuration. In one important sense, they are sometimes technically superior as well. First, because of low remanence of the core, using these materials in a self-saturating configuration (Fig. 6B, 6C) results in a control characteristic which crosses the control-current axis as shown dotted in Fig. 7B. This automatically biases the amplifier near the desired operating point. In addition, the lack of squareness also causes fairly slow switching at the firing time of the power-gating core. The result is much less noise than found in the more objectionable gas tubes, semiconductors, and square-loop core circuits.

Table 1 lists the core materials available in tape-wound cores from most of the core manufacturers, plus a guide to their principal applications. An approximate cost ratio is given for 2-mil tape in a core of about 3 inches in diameter. This indicates the economic advantage of using materials no better than necessary. In lamination form, the cost per pound of the material is lower by about a factor of 5.

TABLE 2—TECHNICAL PROPERTIES OF MATERIALS.

Material Letter Code	Flux Density (kilogauss)	Squareness (B_r/B_m) (400 Hz) ccfr*	Coercive Force (oersted) (dc)	Coercive Force (oersted) (400 Hz) ccfr*	Gain (kG/oe) (400 Hz) ccfr*	Curie Temp (°C)	Core Loss (mW/lb) (at +1 kG, 400 Hz)
A	14.2–15.8	0.94 up	0.1–0.2	0.45–0.65	310–715	500	56
N	14.0–15.6	0.85–0.95	0.07–0.17	0.10–0.20	260–500	500	42
H	11.5–14.0	0.80–0.92	0.05–0.15	0.08–0.15	280–550	500	19
D	6.6–8.2	0.80 up	0.02–0.04	0.022–0.044	550–1650	460	6.5
R	6.6–8.2	0.45–0.75	0.008–0.02	0.008–0.026	250–715	460	4.5
F	6.5–8.2	0.40–0.70	0.003–0.008	0.004–0.015	250–715	460	3.7
K	15.0–18.0	0.85 up	0.40–0.60	0.45–0.65	130–220	750	42
S	19.0–22.0	0.90 up	0.15–0.35	0.50–0.70	85–135	940	230

* The values are typical of cores with ID/OD ratio of about 0.80 and tape thickness of 0.002 in. Tests made are in accordance with AIEE Standards paper II-432. (ccfr = constant-current-flux reset.)

Table 2 summarizes the technical properties of these materials. Note that many of their properties are given in terms of the IEEE standard referenced in AIEE Standards paper II-432 [18]. The use of these standards in circuit design and component specification is highly recommended.

The control-current range for self-saturating amplifiers, as indicated in Fig. 7B, can be estimated by referring to the difference between the dc and 400-hertz coercive-force columns in Table 2. This value must be multiplied by about 0.8 times the mean magnetic path length of the core in centimeters to obtain control ampere-turns. The values are for 400 hertz and must be corrected experimentally for other frequencies. Studies of the properties of materials and their influence on circuits covering a wide range of frequencies, temperatures, and materials can be found in the published literature [19, 20].

For more-specific and detailed design information, the designer should use the referenced literature. Also, several core-materials manufacturers have prepared excellent booklets containing all the essential tables and nomograms for designing magnetic-core circuits.

OTHER DESIGN CONSIDERATIONS

The basic design calculations, as discussed above, pick the core size and number of turns to fit the frequency and voltage. For a given magnetic material, a larger core requires fewer turns to support a given voltage at a given frequency. The number of turns varies as the inverse of the cross-section. From this fact alone, exciting current rises linearly with cross-section. There is also a linear relation between the exciting current and the mean magnetic path length for a fixed H. Thus, the exciting current is proportional to the volume of the core, as indicated by the energy dissipated in the material.

As the frequency rises, it is possible to use a smaller core for a fixed voltage. Comparing a 400-hertz design with a 60-hertz design, for example, the cores in the 400-hertz unit would be smaller by about a factor of 7. Since this is true for transformers and inductors as well, high-frequency power supplies are commonly found on aircraft where space and weight are important. The higher supply frequency also puts the carrier farther above the modulation-signal frequency spectrum, making it easier to recover the signal.

Since in many small-signal applications it is not necessary to have a large supply voltage, it is common to change available dc signals to square-wave ac voltages in the range from 5 to 25 kHz and higher. This means very small cores and very compact, sensitive amplifiers, a combination that often yields better performance in low-noise low-signal applications than semiconductor circuits.

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1.5. NONLINEAR MAGNETICS

Occasional anomalies in circuit behavior serve as rude reminders that magnetic linearity is a limited as well as arbitrary assumption. Fuses and transistors burn out when the rated bounds of voltage, frequency, or pulse width are exceeded. The resonant frequency of an *LC* circuit which includes a transformer primary exhibits variations attributable to the nonlinearity of L_P (thus providing a minor illustration of the important phenomenon known as *ferroresonance*). In addition, transformer ratios do not vary linearly with voltage amplitude except within a narrow range and do not remain constant when frequency or temperature changes.

Early in the genesis of audio circuits, telephone engineers became aware of the harmonics and the cross-modulation distortion caused by magnetic cores in audio transformers. They recognized that μ varied not only at the knee of the *B-H* curve but also at low flux densities. The idealized Fig. 1.2*d*, which shows a linear range of μ, does not provide a picture sufficiently accurate for estimating harmonic distortion. When a minimum of nonlinear behavior is called for, sophisticated circuit compensation techniques and fastidious design procedures must be employed.

Even before the development of an electronics industry, creative engineers were able to make a virtue of the "evil" of nonlinearity and exploit the nonlinearity of the magnetic medium. The magnetic amplifier, introduced into American radio broadcasting in 1916 by E. F. W. Alexanderson, uses the saturable reactor (or saturable transformer) in a circuit which amplifies power. This was followed by an increasing number of patent applications for devices exploiting nonlinear core behavior. In the mid-1940s, when rectangular-loop magnetic cores became commercially available, applications of nonlinear circuits increased dramatically.

The rectangular or square loop (*B-H* characteristic) shown in Fig. 1.3*a* is only approximately rectangular, and its squareness is defined as the quotient of residual flux density B_r and saturation flux density B_s. In soft (easily magnetized) core materials, a value of B_r/B_s close to 1 indicates high retentivity and an abrupt transition to staturation. Retentivity B_r ignored in Fig. 1.2*d*, serves in switching and logic circuits to produce the *memory* feature. For this reason, simplifications of the hysteresis loop (and thus, of its mathematical analysis) preserve the B_r characteristic shown in Fig. 1.3*d* and *f*.

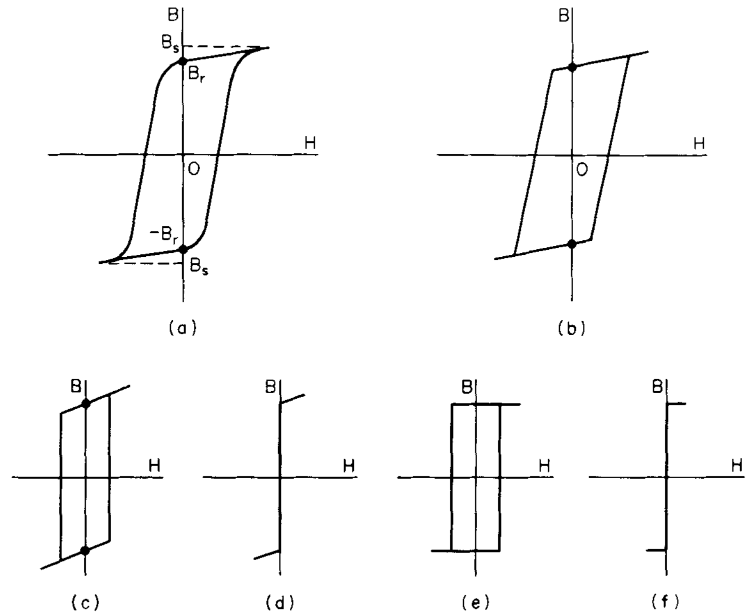

Fig. 1.3 *B-H* rectangular-loop curves. (*a*) Actual characteristic. Approximations: (*b*) tilted straight lines; (*c*) perpendicular sides with hysteresis, $B_r \neq B_s$; (*d*) perpendicular sides, no hysteresis, $B_r \neq B_s$; (*e*) perfect rectangle, $B_r = B_s$; (*f*) ideal characteristic with no hysteresis, $B_r = B_s$.

Transformers for Electronic Circuits.

Nathan R. Grossner. 1983

In general, nonlinear magnetic circuits combine building blocks to accomplish a novel function[8], i.e., a function other than the transformation of voltage, current, and impedance levels. Novel functions include (1) *stabilization,* (2) *wave-shape conversion,* (3) *modulation,* (4) *frequency conversion* (multiplication or division), (5) *detection* of voltage or current thresholds, (6) *amplification,* (7) *switching,* (8) *logic,* and (9) *digital storage.*

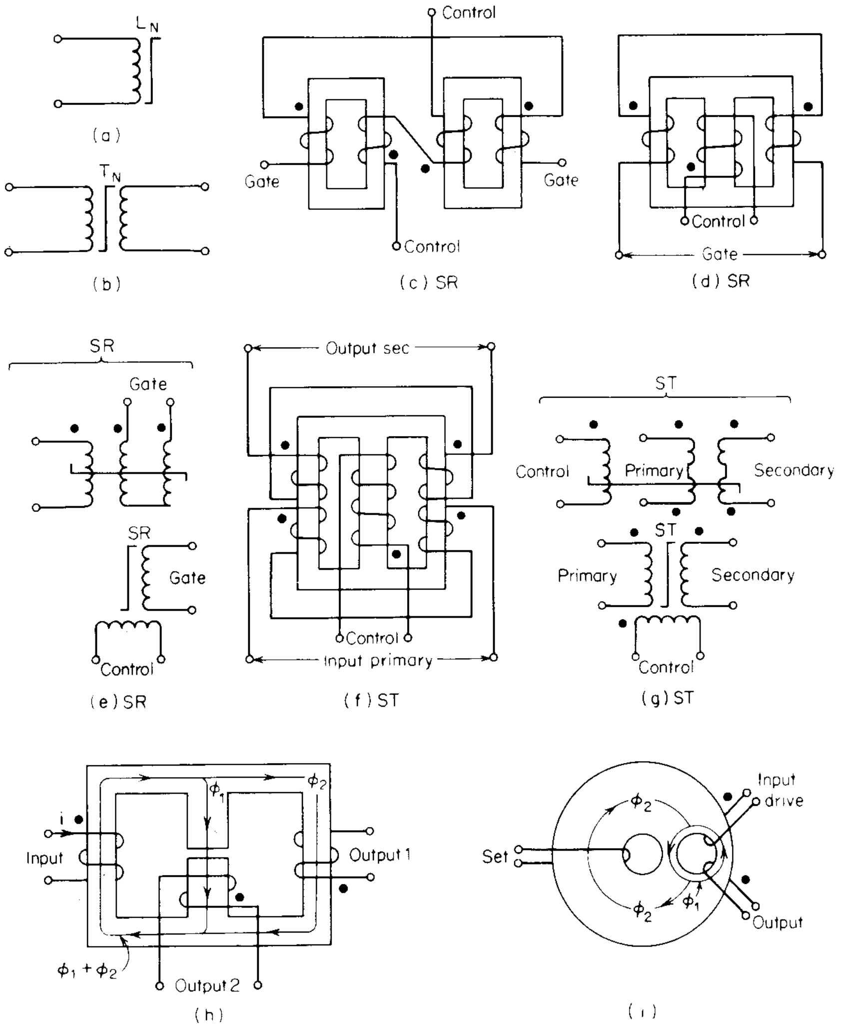

Fig. 1.4 Basic nonlinear magnetic components. (*a*) Nonlinear inductor L_N. (*b*) Nonlinear saturating transformer T_N. (*c*) Two-core saturable reactor *SR*. (*d*) Single-core *SR*. (*e*) Alternative schematics of the *SR* of (*c*) or (*d*). (*f*) Single-core saturable transformer *ST*. (*g*) Alternative schematics of the *ST* of (*f*). (*h*) Multiple flux-path magnetic network: path ϕ_1 may have different core material and μ than path ϕ_2. (*i*) Multiaperture device, MAD, or transfluxor: additional holes may be added for other local flux paths.

The building blocks may be linear or nonlinear. Linear building blocks include the capacitor (C), the linear inductor (L), and the linear transformer (T). *Nonlinear noninductive* building blocks include the nonlinear varistor (R_N) and semiconductors such as the Zener, tunnel, and varactor diodes. The *nonlinear inductive* building blocks include the nonlinear inductor (L_N), the cross-field inductor,[9,10] the nonlinear transformer (T_N), the saturable reactor (SR), the saturable transformer (ST), and the multiaperture core device (MAD). The various nonlinear inductive building blocks are shown schematically in Fig. 1.4.

Some nonlinear building blocks, components, and devices were known to the engineering world before World War II. In this group are the SR, ST, magnetic amplifier (MA), the flux valve (or flux gate) compass, and the two-path flux network.[2] The last named (Fig. 1.4*h*) is the basis for the voltage-stabilizer transformer and the peaking transformer. The magnetic modulator and the static magnetic switch (static relay), among others, came into use later. An interesting application of nonlinear network theory[11,12] is the *rotator,* a circuit which rotates the *B-H* saturation curve counterclockwise to produce the more desirable steep slope of Fig. 1.3*c*.

By the creative combination of building blocks into more complicated circuits, engineers have evolved such devices as the frequency multiplier, which uses saturable transformers, and the magnetic pulse generator. The dc inverter transformer (a successor to the vibrator transformer) converts dc into square-wave ac in an oscillator circuit which uses transistors and a readily saturable core material. In the light of new memory and logic applications, the multiaperture core device, such as the transfluxor (Fig. 1.4*i*), is of particular interest. A special case of the multipath[1] magnetic network [which may have both saturable and nonsaturable flux paths (Fig. 1.4*h*)] is important because of its nondestructible memory. More complicated logic devices include the magnetic shift register and the magnetic bubble memory.* The field of nonlinear magnetics continues to grow. The magnetic amplifier[13,14] is now a subject in itself, and the application of digital magnetic devices is another growing area.[15,16]

In general, although the principal function of nonlinear inductive circuits is not transformation, *basic transformer behavior, magnetic induction, is evident during part of the periodic cycle to which the circuit is subjected.* Too, the physical structure and thermal characteristics of nonlinear magnetic components are the same as those encountered in conventional transformer design and construction. For these reasons the practical as well as analytic techniques of the mature transformer field are often enlisted for the design of nonlinear magnetic circuits.

* Magnetic bubble memory can be fabricated on the scale of a chip. In such a device, microscopic bubbles, which are magnetic domains in a thin magnetic film, are sandwiched between two permanent-bias magnets.