NORTHERN ALBERTA INSTITUTE OF TECHNOLOGY
EDMONTON ALBERTA

ELECTRONICS DEPARTMENT

MAGNETIC AMPLIFIER

OBJECTIVES

To study the operation and input - output characteristics of various types of magnetic amplifier circuits.

MATERIALS REQUIRED

One Educational Magnetic Amplifier (type 5174) and associated parts
One VTVM
One Oscilloscope
One DC milliammeter
One AC ammeter
One variable dc power supply
Resistors One 25 watt 25 ohm
One 2 watt 22 ohm

INTRODUCTORY INFORMATION

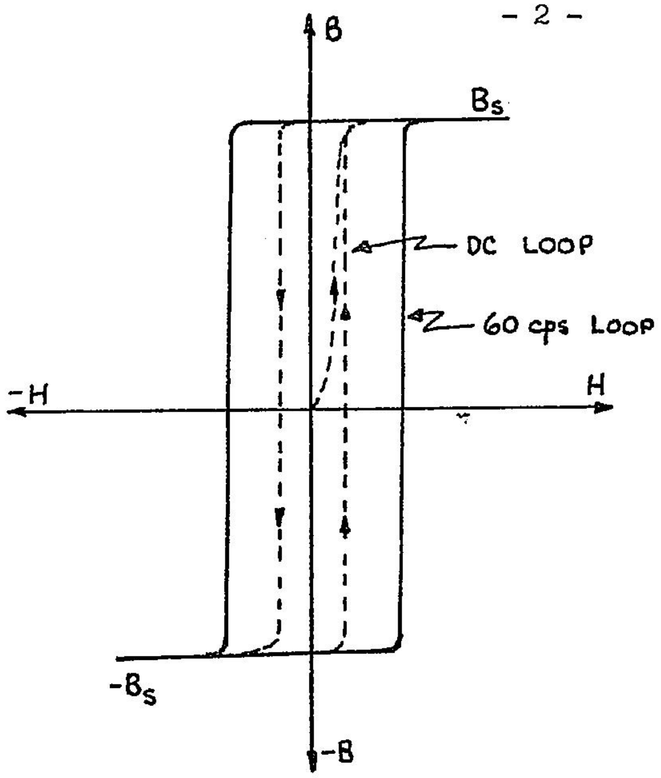
The heart of the magnetic amplifier and the source of its name is the magnetic core. Efficient magnetic amplifiers are dependent on a core constructed with a minimum of air gaps and from a "square loop" material having a sharply defined transition into its saturated condition and a narrow width to its B-H loop. The minimum gap condition is usually accomplished by constructing the core from a thin band of material wrapped to form a toroid.

Figure 1 illustrates the B-H loop of typical core material. Figure 2 illustrates the cross sectional view of a toroidally wound saturable reactor. Each core is wound with a gate winding (N_g) which acts as a variable inductance in the circuit controlling power. The remaining windings; the control (N_c), the bias (N_B), and the feedback (N_{FB}) are wound common to both cores.

SERIES CONNECTED SATURABLE REACTOR

Figure 3 illustrates a series connected saturable reactor having a common control winding. The gate windings are connected in series - opposing to prevent AC voltage from being induced into the control winding.

Consider first the operation of the device with zero control current.



$$B = \frac{\phi}{A_f} \qquad (1)$$

B = flux density, gauze
ϕ = flux, maxwell
A_f = core area, cm^2

$$H \propto \frac{NI}{\ell mp} \qquad (2)$$

H = coercive force, oersteds
N = turns
I = amperes
ℓmp = magnetic path length, cm

Figure 1

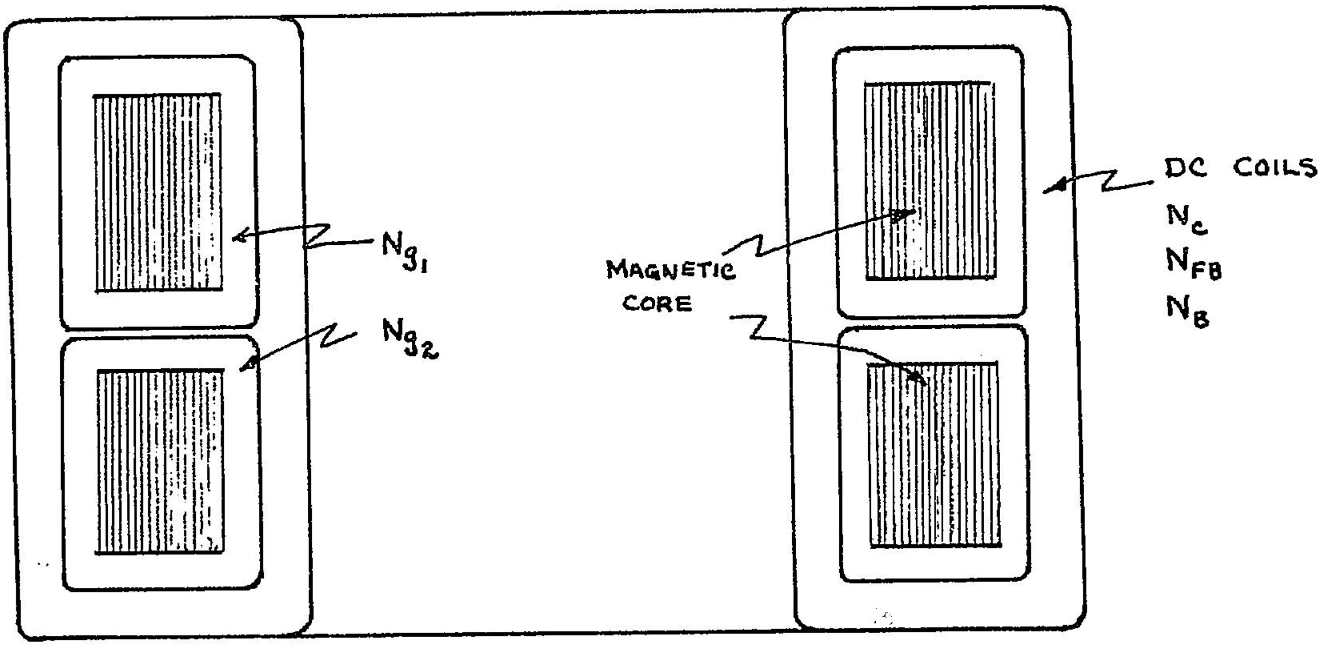


Figure 2

SERIES CONNECTED SATURABLE REACTOR

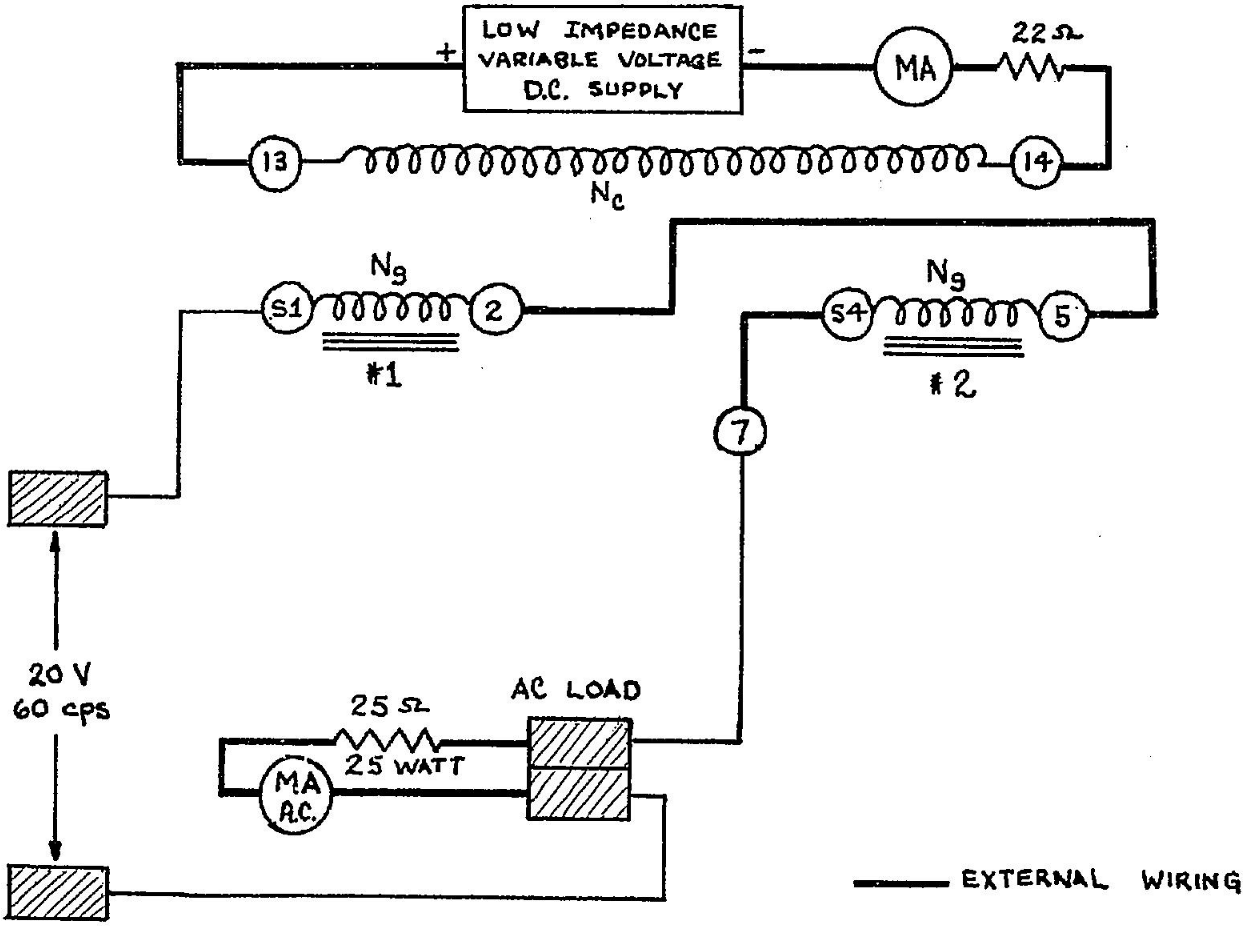


Figure 3

The AC supply voltage applied to the gate windings (N_g) sets up an AC flux in the cores which in turn generates a counter emf.

$$\frac{1}{2} e_g = N_g \frac{d\Phi}{dt} \tag{3}$$

where e_g = total voltage appearing across both gate windings.
N_g = number of turns of each gate winding.

If the magnetic permeability ($\mu = B/H$) is high, only a small load current (magnetization current) is required to maintain the flux necessary to produce the counter emf. As a result, the load voltage is approximately zero and the gate voltage is nearly equal to the supply voltage. Now if a control current (I_c) is passed through the control winding, it increases the magnetic intensity (H) in that core where the load current and control current are in phase and saturates it during some part of the ac cycle.

Assume core #1 saturates during some part of the positive going half cycle and core #2 saturates during some part of the negative going half cycle of the supply voltage, as shown in Figure 4. When core #1 saturates, the flux Φ_1 is constant and therefore $d\Phi/dt = 0$. Under this condition, reactor #1 cannot generate a counter emf and presents a short circuit on both its gate and its control windings. The control winding of reactor #2 is now connected across R_c and a very low impedance DC power supply, thus can be considered to be also short circuited. As a result the voltage across the control winding of reactor #2 is approximately zero and thus the flux in core #2 must be constant even though the reactor is not saturated and the counter emf of reactor #2 must be zero. The net result is that practically all the supply voltage is now connected across the load resistor and subsequently load current will flow.

Since reactor #2 is not saturated, the law of equal ampere - turns must be conserved and the control current and load current are related by the formula,

$$N_c I_c = N_g I_L \tag{4}$$

The current gain of a series connected saturable reactor is:

$$K_I = \frac{I_L}{I_c} = \frac{N_c}{N_g} \tag{5}$$

This equation expresses the current gain in terms of device parameters; since the supply voltage and resistance do not occur in the equation. The amplifier, therefore, acts as a controllable constant current device.

MAGNETIC AMPLIFIER WITH POSITIVE FEEDBACK

Figure 5 shows a magnetic amplifier with 69% of positive feedback. The amount of feedback can be varied by choosing different feedback windings. The feedback windings are wound in the same fashion as the control windings, that is, the windings are common to both reactor cores. The load current is routed through them.

The equal ampere - turns relationship which exists in the simple reactor must hold in this case too. Therefore:

$$N_g I_L = N_c I_c + N_F I_L \tag{6}$$

Defining $\beta = \frac{N_F}{N_g}$ as the feedback ratio we may rewrite equation (6) as:

$$I_L = I_c \frac{N_c}{N_g} \frac{1}{1 - \beta} \tag{7}$$

The current gain becomes:

$$K_I = \frac{I_L}{I_c} = \frac{N_c}{N_g} \frac{1}{1 - \beta} \tag{8}$$

A typical I_c vs I_L curve for this circuit is shown in Figure 6.

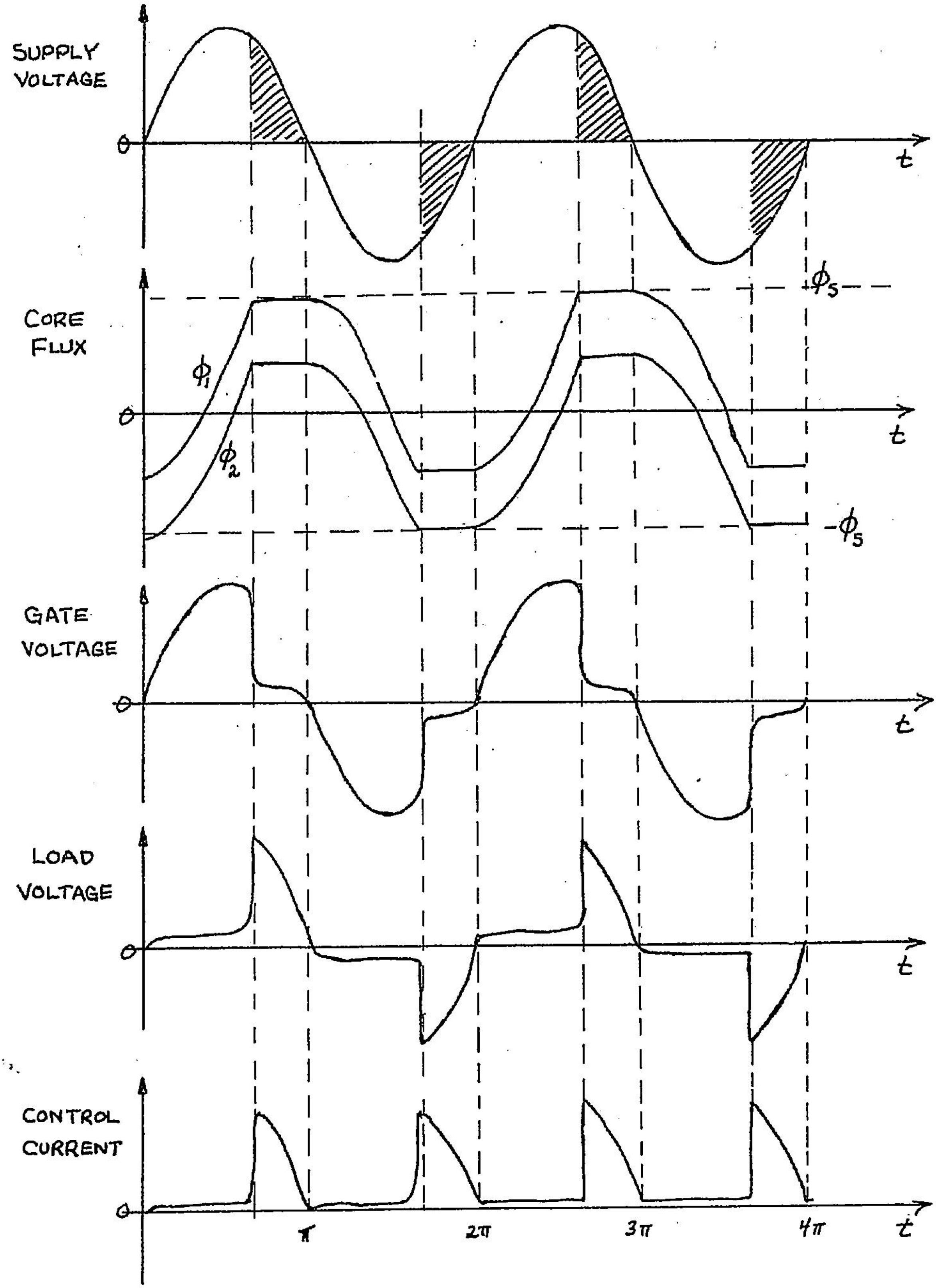

SUPPLY VOLTAGE
CORE FLUX
GATE VOLTAGE
LOAD VOLTAGE
CONTROL CURRENT
0
t
ϕ_1
ϕ_2
ϕ_5
$-\phi_5$
π
2π
3π
4π

Figure 4

MAGNETIC AMPLIFIER WITH POSITIVE FEEDBACK

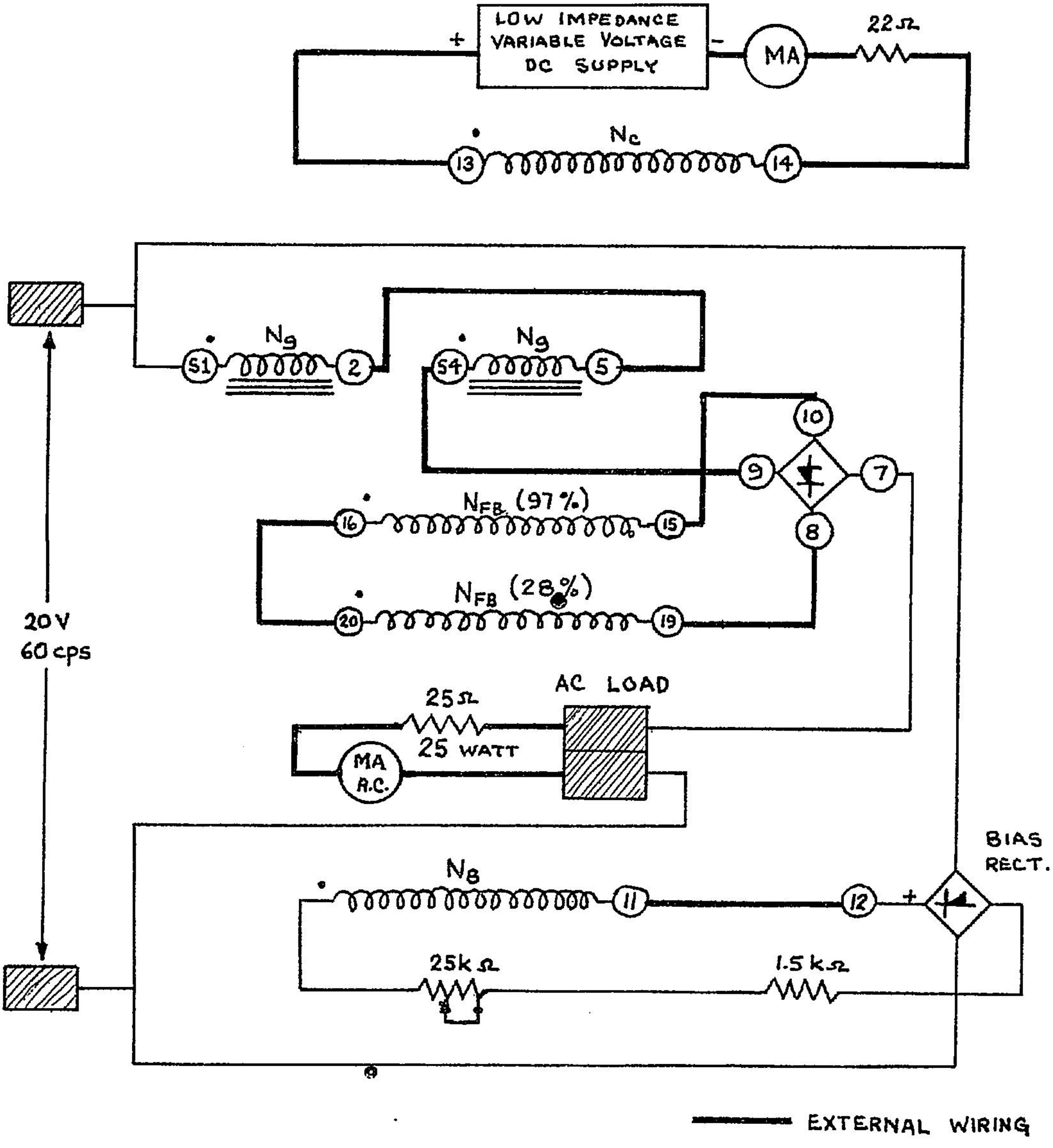


Figure 5

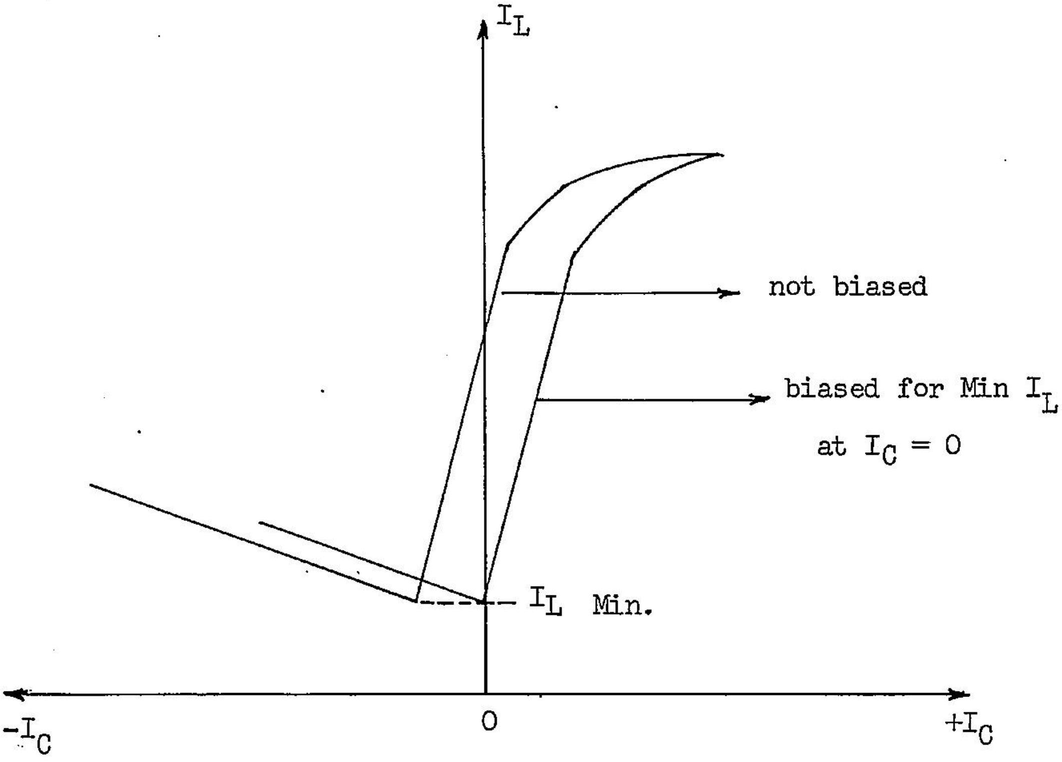


Figure 6

The reactors are no longer unsaturated with zero control current due to the Self-exciting effect of the feedback loops.

In order to have minimum load current when control current is zero, it is necessary to introduce some bias current which will shift the operating point to the said condition.

SELF-EXCITED MAGNETIC AMPLIFIER

Figure 7 shows a self-excited magnetic amplifier. The reactor cores are saturated with zero control current due to the self-exciting effect of the rectified load current. Again, in order to minimize load current when the control current is zero, it is necessary to introduce bias current.

SELF - EXCITED MAGNETIC AMPLIFIER

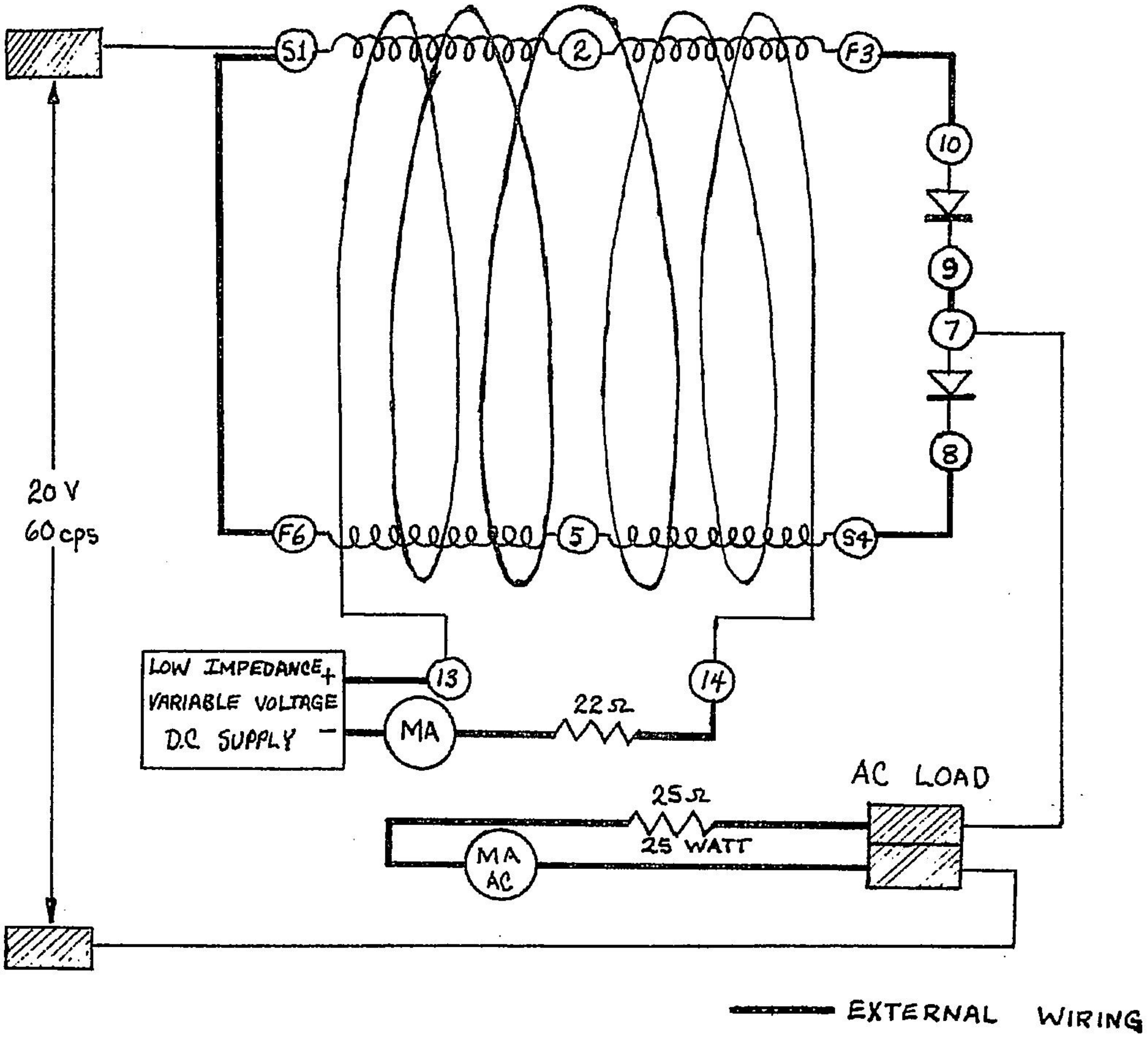


Figure 7

PROCEDURE

Part 1. Series Connected Saturable Reactor

1. Connect the unit as shown in figure 3 and supply with 20 VAC.
2. Vary the input control current between 0 and 100 ma and record the corresponding values of load current.
3. Plot the input - output curve for this saturable reactor from the data obtained in Step 2.
4. Set the output load current to approximately its mid range (300 ma). Observe and record the input and output current waveforms.
5. With load current at approximately midrange, change the load resistance from 25 to 15 ohms and record the change in I_L.

Part 2. Magnetic Amplifier with Positive Feedback

1. Connect the unit as shown in figure 5 and supply with 20 V AC.
2. Open the bias circuit.
3. Vary the input control current between +100 and -100 ma and record the corresponding load current.
4. Connect the bias circuit and adjust the bias potentiometer (RV1) for minimum load current when the control current is zero.
5. Repeat step 3.
6. Plot the input - output curves for data obtained in steps 3 and 5.

Part 3. Self-Excited Magnetic Amplifier

1. Connect the unit as shown in Figure 7 and supply with 20 V AC.
2. Adjust bias potentiometer so that the load current is minimum when the signal control current is zero.
3. Vary the input control current between +100 and -100 ma and record the corresponding load current.
4. Plot the input - output curve for data obtained in Step 3.

QUESTIONS

1. What are the current gains for each circuit you tested?
2. What is the minimum output current? Why? Explain.
3. Why does the graph have a flat top?
4. Why is it necessary to have bias current when the circuit has positive feedback or is self-excited?
5. Explain what happened to the load current when the load resistance was varied. Why?

GENERAL SPECIFICATIONS

SUPPLY .... 20 volts 60 c/s A.C.

MAXIMUM OUTPUT FOR ...... into 25 ohms load resistance

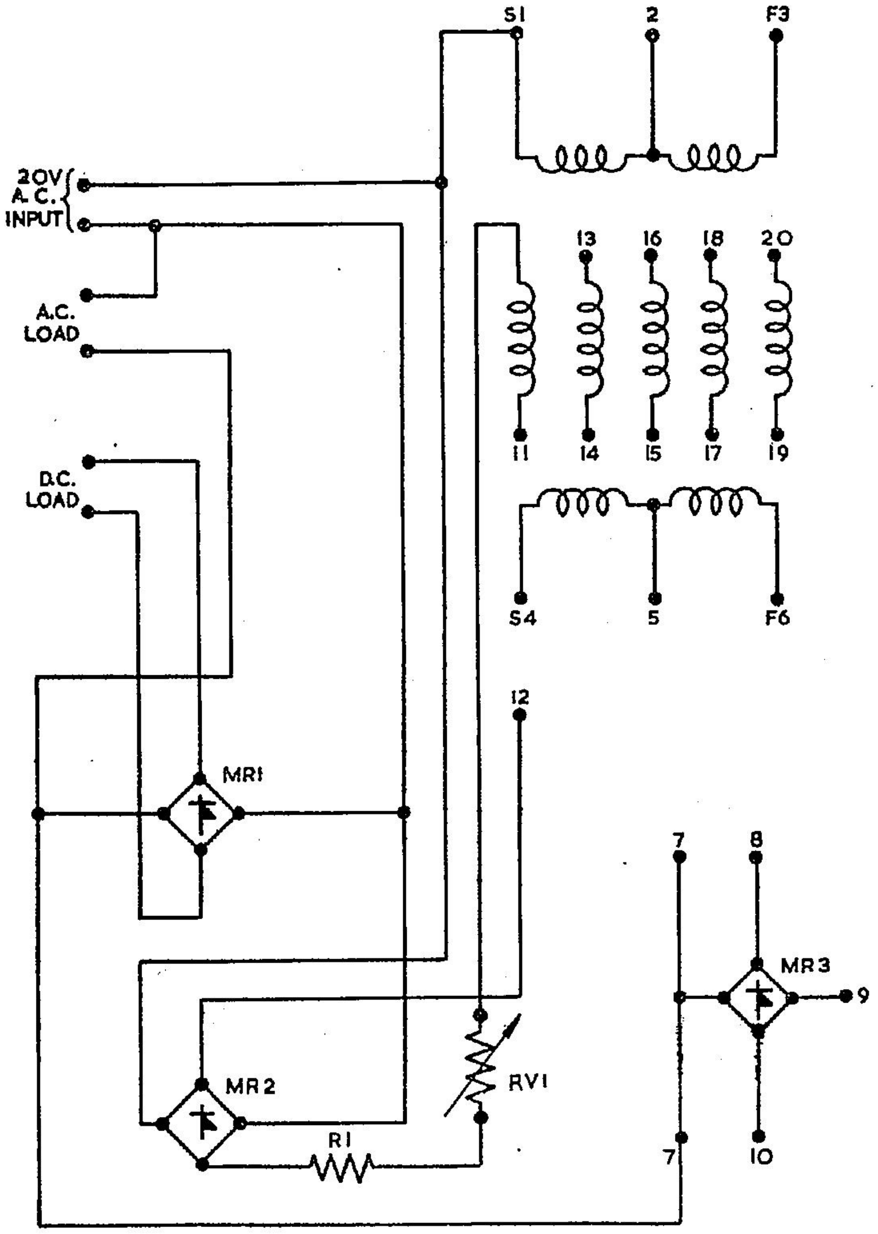
1. Saturable Reactor connection
   900 ma approximately
2. Series excited connection
   650 ma approximately
3. Auto self excited connection
   700 ma approximately

CORES .... Two toroids wound from 0.13" grain oriented silicon iron ribbon. Dimensions $5\frac{1}{4} \times 3\frac{1}{2}" \times 1$. Cross sectional area 0.875 square inch. Each core wound with 134 turns. $N_g = 67$ turns. Approximate resistance of total winding 0.43 ohms.

D.C. WINDINGS .... These are wound over both cores as shown in the diagram Figure 2.

1. Signal (N_c) 670 turns. Approximate winding resistance 19.6 ohms.
2. 97% Self-Excitation (N_F) 65 turns. Approximate winding resistance 0.37 ohms.
3. 57 Self-Excitation (N_F) turns. Approximate winding resistance 0.055 ohms.
4. 28% Self-Excitation (N_F) 20 turns. Approximate winding resistance 0.12 ohms.
5. Bias (N_B) 670 turns. Approximate winding resistance 20.6 ohms.

RECTIFIERS	1. For Self-Excitation. Selenium type consisting of two voltage doubler types assembled on one spindle and suitable for bridge connection when required. Each plate rated for an input of 0.66 amps at 28 volts, one plate per arm.
	2. For Bias Circuit. Selenium type bridge connected. Input rated at 0.133 amps, 56 volts full wave. Two plates per arm.
	3. For d.c. Output. Selenium type bridge connected. Input rated 1.33 amps at 28 volts full wave. One plate per arm.
BIAS CIRCUIT RESISTORS ..	Fixed resistor 1.5 k ohms 1 watt. Adjustable potentiometer 25 k ohms 3 watts.



S1-2-F3	A.C. WINDING ON ONE TOROIDAL CORE
S4-5-F6	A.C. WINDING ON SECOND TOROIDAL CORE
RV1-11	BIAS WINDING
13-14	SIGNAL WINDING
15-16	97% SELF EXCITATION WINDING
17-18	5% SELF-EXCITATION WINDING
19-20	28% SELF-EXCITATION WINDING
MR1	LOAD RECTIFIER
MR2	BIAS RECTIFIER
MR 3	SELF-EXCITATION & AUTO SELF-EXCITATION RECTIFIER
RV1.	BIAS POTENTIOMETER

CIRCUIT DIAGRAM EDUCATIONAL MAGNETIC AMPLIFIER

Figure 8

WHO NEEDS ELECTRONICS?

K.T. Wilson explores the all too frequently ignored and misunderstood field of Magnetic Amplifiers.

THINK OF AMPLIFICATION, and you automatically think of transistors. Perhaps if you're a bit longer in the tooth you remember valves. Have you ever thought of large amounts of power gain being obtained without using either transistors or valves? It's power gain we're talking about, too, not just voltage gain. A transformer will give voltage gain, up to 100 times, but at the expense of current, so that the power out is never quite as much as the power in. There's no *power* gain there, but a device called the magnetic amplifier, which looks very like a transformer, can give very large values of power gain, can control AC power into a load very smoothly, and is used in the sort of applications where thyristors would be a natural choice for many.

The magnetic amplifier has been used in industrial control for decades, yet has never really caused any stir of interest anywhere else. Perhaps it's because it's always a ready-made item, but then so is an IC amplifier, and everyone seems to make use of those. Perhaps it's just because so very few people outside the ranks of professional engineers know just what a magnetic amplifier is. Let's remedy that!

Induced Knowledge

To start with, we need a pretty clear idea of what happens inside an inductor. A simple inductor has a winding which consists of insulated wire wound round a core of a soft magnetic material. Soft doesn't mean that you can spread it on your bread, but that the material magnetises easily, and *de*magnetises just as easily. Take a piece of this material, hold a magnet near it, and it's magnetised. Take a magnet away and it's demagnetised. This material we use for the cores of inductors, transformers, electric motors, relays etc.

An inductor makes use of this 'soft' magnetism. The winding has an alternating current flowing in it. This alternating current (changing smoothly from a peak in one direction to a peak in the opposite direction and back) causes the core of the inductor to magnetise. The magnetism isn't steady like a bar magnet, but alternating, which is the point of using soft magnetic material. a graph of the magnetism (called flux density) of the core plotted against time would, ideally, have exactly the same shape as that of the waveform of the AC applied.

So far so good — it's an alternating magnet. But we've known for about 150 years (or someone has) that wherever there's an alternating magnetic field, any piece of wire or other metal will have an alternating voltage induced.

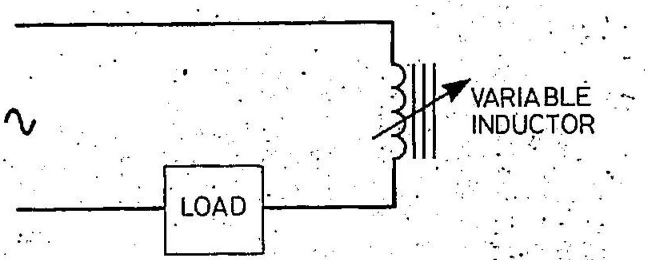


Fig. 1. Control of a load using a variable inductor, this configuration has very little power lost as heat, unlike a resistive controller.

Stick a piece of wire near your alternating magnet and you'll find an alternating voltage across the ends of the wire. The voltage is small if you use just a few centimetres of straight wire, but if you wrap several metres or wire round the core, so that all the magnetism of the core is at the centre of the coil of wire, then you find quite a respectable amount of AC. Recognise it?, a transformer.

Laying Down the Laws

The laws of Electricity are very consistent, though, *Any* coil of wire around a core that has an alternating magnetic field will have an AC voltage induced. That means that if we have only one coil, and we send AC through to generate the magnetism, it will *also* have an AC voltage induced in it. This voltage which the text books call a "back EMF", opposes the current which causes the magnetism which causes the voltage.

Result?

It's a darn sight more difficult to pass AC through an inductor than it is to pass DC!.

When we use an inductor in a DC circuit, then apart from some effects at the moments of switch-on and switch-off the thing behaves like a resistance, good old Ohm's Law and all the rest, and a fairly low value of resistance at that.

Now you might think that it should pass the same amount of current for AC as for DC, but it doesn't.

Imagine that the resistance is 2R, so that 10 V DC passes 5 A. Apply 10 V AC and the current's nothing like 5 A. It's not because Ohm's law stops working, it's because of the induced voltage. We're trying to push AC ▶

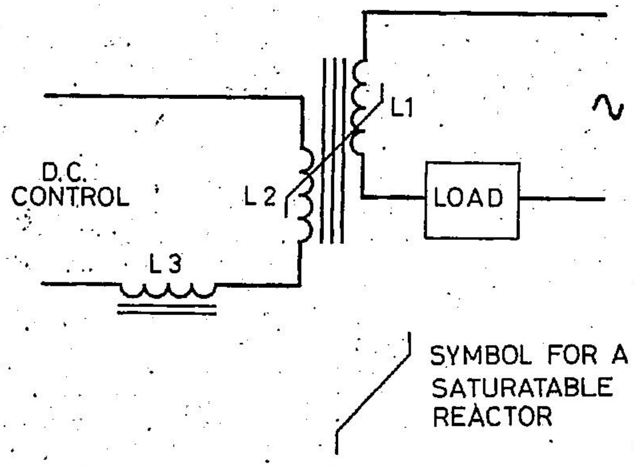


Fig. 2. Simple magnetic amplifier circuit, showing DC control winding.

through with one voltage, and the induced voltage is opposing our efforts. It's only the difference between the two voltages that has any effect at all.

Impedance Impediment

Suppose for example, that with 10 V AC applied, the induced voltage is 9V9. This makes the difference equal to 0V1, and the current is

$$\frac{0.1}{2} = 0.05 \text{ A, (by Ohm's Law)}$$

Now these are calculations we seldom bother to make. Instead we measure a quantity called the self-inductance, L, of the coil and use this quantity and the resistance value to calculate impedance, which is the ratio

$$\frac{\text{AC voltage}}{\text{AC current}}$$

for the coil. In our example, 10 V causes 0.05 A to flow, making the impedence 10/.05=200 R, not a particularly large impedance, but much greater than the *resistance* of 2 R.

The useful thing about an impedance is that there's practically no loss of power in it. Pass a current through a 200 R resistor, and you lose energy in the form of heat the amount of heat lost per second is $200 \times (\text{current})^2$ joules for a 200 R resistor. The same current through the inductor in our example doesn't look anything like this — only its resistance loses heat, and that's only $2 \times (\text{current})^2$ joules, because the resistance is only 2 R.

We can therefore use an inductor to control the flow of AC in a circuit (see Fig. 1) with none of the power loss that a resistor would cause. Now if we could just have a variable inductor, we could be very neatly control the flow of current in that circuit. Of course, we could use an inductor with tapped turns and slide contacts, built like a potentiometer, and we make use of just such a device, the familiar Variac. It's possible though, to control the inductance of a winding with no mechanical movement at all, and what makes it possible is the effect called saturation.

Control-A-Coil!

When we send a current, AC or DC, through a coil of wire which is wound round a magnetic core, we can't pass as much current as we like and expect the magnetism to keep pace. At some stage in the game the core saturates, which means that it's as magnetised as it's ever going to be, no matter *how* much current is used. Now when a core is saturated like this, a change of current doesn't cause a change in the magnetism, so there's no more induced voltage. In other words, the inductance is no more and the impedance is practically zero.

Let the AC flow to it's load through an inductor whose core we can cause to saturate. How? By passing DC through another winding, by making the core of material which saturates easily, and the making the core continuous with no air gap.

That's our recipe for a magnetic amplifier.

Amps For Amps

Figure 2 shows a simple magnetic amplifier circuit. The inductor L1 has a large inductance when the core is not saturated, because of that, its impedance is very large, enough to make the current in the circuit very small. Now let DC flow through the second winding L2, and the core saturates.

If we can keep the core saturated for the whole of the AC cycle, then the inductance of L1 is almost zero, and the full amount of AC current flows through the load.

We don't of course, have to switch between saturation and no-saturation. We can adjust the control current so that the core saturates only on half of the AC cycle, or in peaks so that the average current through the lead is controlled.

Self Satisfied

Even such a simple magnetic amplifier has a lot of advantages, such as low power dissipation and high power gain, but better results are possible by using what is called a self-saturating design. Self-saturation is a form of positive feedback, using some of the signal current to assist the DC control current. Fig 3 shows a half-wave self-saturating circuit. The rectifier D1 ensures that only one direction of current flows through the coil L1 and the rated load current will cause the core to be close to saturation. The DC control current in winding L2 need only be quite small to cause the core to saturate on peaks, so that less power is needed to control the load current, and power gain is much higher.

Only half cycles are passing into the load, however, so that a full wave version is more desirable.

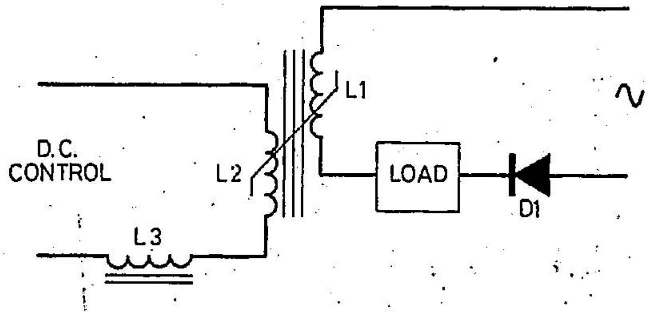


Fig. 3. Half-wave control using self-saturation.

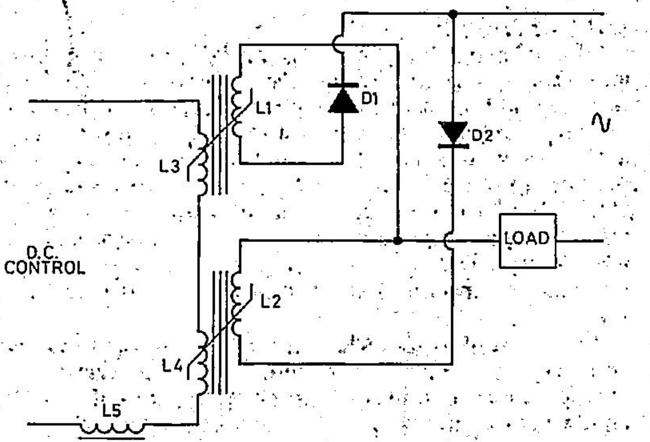


Fig. 4. Full-wave amplification with self saturation, by positive feedback.

A full-wave self-saturating magnetic amplifier is shown in Fig 4. Two sets of windings are used, each handling half of the wave, with rectifiers ensuring that the AC wave is split into its two halves.

In all these circuits, an additional inductor is used in the DC control line to prevent AC appearing in the control circuit because of transformer action.

Going Straight

DC amplification? Simple enough, just rectify the output of the magnetic amplifier — the self-saturating full wave type already has two rectifiers included in the circuit and only two more are needed. More sensitivity? Add another winding to pass DC bias current, and the sensitivity increases because the bias can be set so that the core is very close to saturation.

Nothing could be *that* perfect, there has to be a snag somewhere, and response time is it for magnetic amplifiers. Being slow beasts a sudden change of control signal may not cause much change in the output current until several cycles of AC have passed through. Nevertheless for stabilising AC supplies, for control of large AC loads and for high power gains magnetic amplifiers are not so easily displaced by electronics. There's not much to go wrong, they can be built to order, and they can be repaired.

Ever tried to put a new junction into a thyristor? **ETI**

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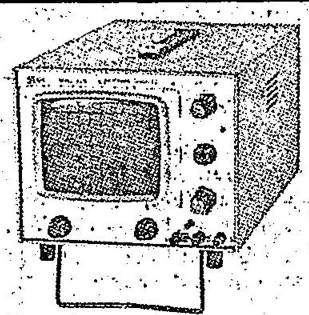

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Price ea per	Quantity prices 10	100	500	1,000
AC128	0.230	0.200	0.180	0.150
AD149	0.750	0.650	0.550	0.490
AD161	0.380	0.330	0.290	0.250
AD162	0.380	0.330	0.290	0.250
BC107	0.100	0.085	0.075	0.065
BC109	0.110	0.095	0.080	0.070
BC109C	0.120	0.100	0.085	0.075
BC114	0.080	0.065	0.050	0.040
BC132	0.080	0.065	0.050	0.040
BC153	0.085	0.070	0.055	0.045
BC172	0.075	0.060	0.050	0.040
BC173	0.075	0.060	0.050	0.040
BC205	0.070	0.055	0.040	0.035
BC208C	0.075	0.060	0.050	0.040
BC209	0.075	0.060	0.050	0.040
BD181	0.800	0.500	0.440	0.400
BD182	0.700	0.600	0.500	0.440
BF181	0.240	0.200	0.185	0.160
BFY50	0.180	0.160	0.140	0.125
BFY51	0.180	0.160	0.140	0.125
BFY64	0.220	0.195	0.175	0.150
BFY90	0.750	0.680	0.630	0.550
BU205	1.000	0.900	0.800	0.750
BU208	1.250	1.100	1.000	0.950
BY127	0.110	0.090	0.075	0.065
CA3085	0.440	0.385	0.350	0.300
LM311H	0.700	0.600	0.550	0.500
TBA625BX5	0.680	0.600	0.550	0.500

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