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Applications of Hall Effect and Magnetoresistance

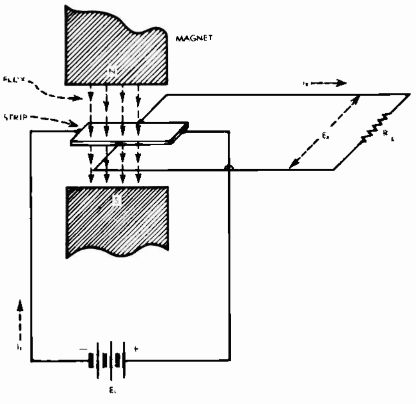

FIGURE 1. BASIC HALL-EFFECT CIRCUIT

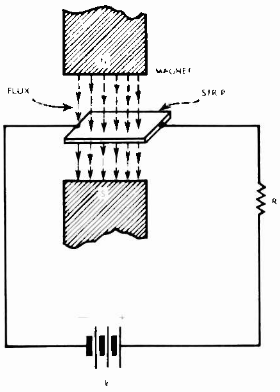

FIGURE 2. BASIC MAGNETORESISTANCE CIRCUIT

Until fairly recently, the *Hall effect* (discovered in 1879) and magnetoresistance were two very obscure phenomena. Both have to do with what happens to current or voltage in a solid material when an external magnetic field is applied. Neither effect has been fully exploited at this time.

Figure 1 illustrates a "Hall generator," which consists essentially of a thin strip or plate of suitable conducting material through which a current, I_1, is forced longitudinally by a d-c source, E_1. Contacts are attached to opposite edges of the strip at points a and b. When a magnetic field is applied perpendicular to the plane of the strip, as shown by the dotted arrows, a voltage, E_2, appears between points a and b and will force a current, I_2, through an external circuit containing a load device, R_L. (E_2 and I_2 are proportional to E_1, I_1, and the strength of the magnetic field.) With current I_1 flowing through the strip in the direction shown in Figure 1, and the magnetic flux applied in the direction shown, terminal a is positive for some metals, such as zinc, and is negative for others, such as aluminum.

Figure 2 shows the basic magnetoresistance circuit. Here, a strip or plate of suitable conducting material is connected in series with a voltage source (E) and load device (R_L). The current (I) in this circuit is limited by the resistance of the strip plus R_L. When a magnetic field is applied perpendicular to the plane of the strip, as shown by the dotted arrows, the resistance of the strip increases and the current in the circuit accordingly decreases. The change in resistance of the strip is proportional to the strength of the magnetic field.

In both devices, the output is subject to control by means of the input voltage and/or the magnetic flux. In accomplishing this action, however, neither device is efficient as a converter of energy, the ratio of control power to output power being low. But there has been great improvement: The original gold-leaf Hall generators required the application of a very intense magnetic field in order to obtain the tiniest output voltage; similarly, early observations of magnetoresistance (as in bismuth wire and bulk germanium) showed a scarcely discernible change in resistance in response to a powerful magnetic field. These shortcomings long kept both phenomena in the category of laboratory curiosities. Within the last few years, however, thin films of semiconductor material (notably indium antimonide or indium arsenide), instead of metal foil or strip, have been used both in Hall generators and in magnetoresistors and this has significantly boosted the sensitivity of these devices. The improved performance has given rise to a number of practical applications. This article describes some of the current applications of both devices.

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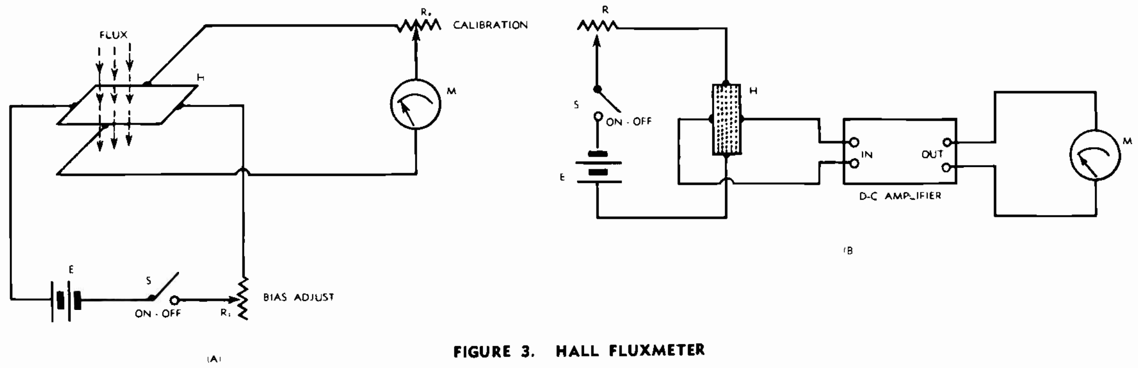

FIGURE 3. HALL FLUXMETER

Hall-Effect Devices

The electrical characteristics of Hall generators vary with make and model. The data sheet of the particular type employed should be consulted for performance figures. Typical performance: Open-circuit Hall d-c output voltage, 7.5 mv/kilogauss at 30 ma control current to 50 mv/kilogauss at 500 ma; zero-kilogauss input resistance, 1 to 600 ohms; zero-kilogauss output resistance, 0.5 to 300 ohms; maximum power level, 100 to 250 mw.

Fluxmeter. The natural response of the Hall generator to magnetic fields suits it to flux measurements. The d-c output of the generator is proportional to the magnetic field intensity. By holding the d-c bias constant, we standardize operation of the device.

Figure 3 shows two circuits for using this effect. In both circuits, d-c bias to the Hall generator, H, is supplied by battery E or an equivalent low-ripple, stabilized power supply. The bias current is preset to a standard level by means of a rheostat (R_1 in Figure 3A, R in 3B). In Figure 3(A), the d-c output of the Hall generator is applied directly to a d-c millivoltmeter or current meter, M. Here, resistor R_2 may serve either as a calibration control or (in groups of resistors) as flux range multiplier. In Figure 3(B), the d-c output of the Hall generator is stepped up by a d-c amplifier to deflect a higher-range meter M, or to actuate some load device. In this arrangement, the gain of the amplifier may be adjusted to change flux ranges.

Both circuits may be calibrated with the aid of several accurately known magnetic fields, and the meter scale may be graduated directly in gausses.

Current Probe. A circuit similar to the fluxmeter of Figure 3 (A) may be used as a current probe for measuring currents without breaking a lead to insert an ammeter. The arrangement is shown in Figure 4. Here, the magnetic field that surrounds the current-carrying conductor cuts Hall generator H which is held nearby for the measurement, and the d-c output to meter M is proportional to the field strength and thus to the unknown current. This probe has the utility of the well-known clamp-type meter, without requiring that a clamp surround the current-carrying conductor.

As in the fluxmeter circuit, rheostat R_2 serves to adjust the d-c bias to a standard level, and R_1 as either a calibration control or range multiplier. M is a d-c milliammeter, microammeter, or millivoltmeter, depending upon characteristics of the Hall generator employed. For a-c measurements, this meter must be an a-c type.

The scale of meter M may be calibrated directly in amperes on the basis of several accurately known values of current flowing in a conductor.

DC-AC Converter. Figure 5 shows a simple circuit for converting d-c voltage or current to equivalent ac. Here, the direct current to be converted (applied to the D-C INPUT terminals) supplies the bias for the Hall generator, H. The output terminals of the generator are connected directly to the A-C OUTPUT terminals of the circuit.

Supported close to the Hall generator is an electromagnet, L, to which is applied an a-c excitation signal at the desired frequency. This signal may be obtained from a suitable oscillator. The resulting alternating magnetic field switches the generator output terminals alternately between positive and negative, thereby producing an a-c voltage at the A-C OUTPUT terminals.

Chopper. The converter circuit shown in Figure 5 may be used also as a chopper for converting a d-c signal (such as the output of a thermocouple, strain gauge, photocell, or thermistor) to ac for amplification by a conventional amplifier.

Such a chopper has low-impedance input, an advantage when working out of a thermocouple or strain gauge. Additionally, it is simpler than many transistor and tube-type choppers.

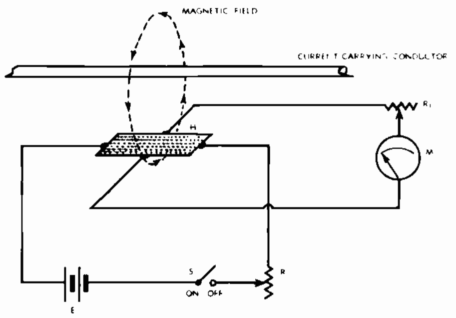

FIGURE 4. HALL CURRENT PROBE

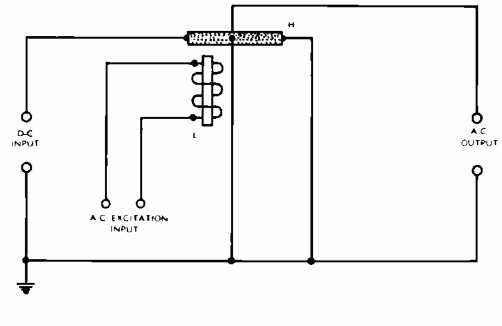

FIGURE 5. HALL DC-AC CONVERTER

Analog Multiplier. Figure 12 shows the basic circuit of an analog multiplier using magnetoresistors. This circuit is essentially a d-c bridge in which the four arms are the upper and lower parts of potentiometer R_1 and the two matched magnetoresistors, R_2 and R_3. Direct current I_1 supplies d-c bias to the magnetoresistors and is set to represent the multiplicand. Direct current I_2 energizes the coil of magnet M and is set to represent the multiplier. The output voltage, E, is equal to kI_1I_2, where k is a constant for the particular magnetoresistor employed. A d-c voltmeter used to read voltage E may accordingly be calibrated to read the product directly.

To multiply two numbers with the setup, first balance the circuit, by adjustment of R_1, with I_1, set to represent the multiplicand and I_2 set to zero. Balance is indicated by output voltage E=zero. Next, set current I_2 to represent the multiplier, and finally read the product directly from the scale of the calibrated voltmeter deflected by output voltage E.

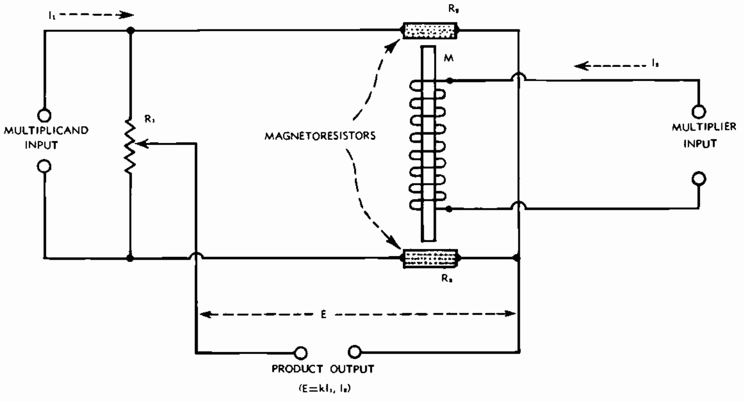

FIGURE 12. MAGNETORESISTOR ANALOG MULTIPLIER

Voltage Regulator. The magnetoresistor, acting as a flux-controlled variable resistor, may be used to regulate a d-c voltage. A typical circuit of an automatic regulator is shown in Figure 13.

In this arrangement, the magnetoresistor is connected in series with an unregulated d-c power supply and the load. Also connected to the power supply is the coil L wound on a core which is not a permanent magnet. The magnetic field set up by this core is applied to the magnetoresistor mounted close by, and its strength is adjusted by means of rheostat R_1.

When the input voltage rises, current through the coil increases. This increases the magnetic field strength which, in turn, increases the resistance of the magnetoresistor and reduces the output voltage. With proper preadjustment of rheostat R_1, the input-voltage variations will be smoothed out and the output voltage held to a constant value.

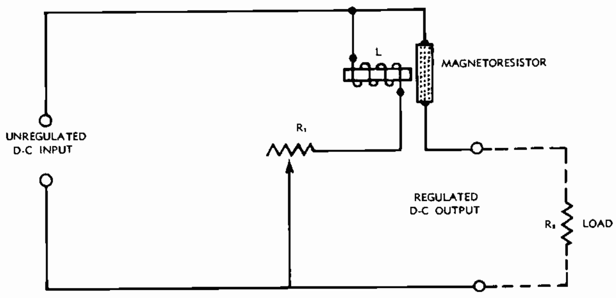

FIGURE 13. MAGNETORESISTOR VOLTAGE REGULATOR

Current Probe. Figure 14 shows the circuit of a probe for measuring currents without breaking a lead to insert an ammeter. Here, the magnetic field that surrounds the current-carrying conductor cuts magnetoresistor R_2, the resistance of which is increased thereby. The convenience of the familiar clamp-type meter is provided without the need for the clamp.

The circuit is a bridge in which the magnetoresistor is one of the four arms. The other arms are R_1 and the two parts of potentiometer R_3. This bridge allows the d-c microammeter, M, to be set initially to zero in the absence of a magnetic field. When the magnetoresistor subsequently is brought into a magnetic field, its resistance increases, the bridge unbalances, and the meter deflects in proportion to the field strength.

The meter scale may be calibrated to read directly in amperes on the basis of several accurately known currents flowing in the conductor. Current ranges may be provided by means of appropriate meter shunts.

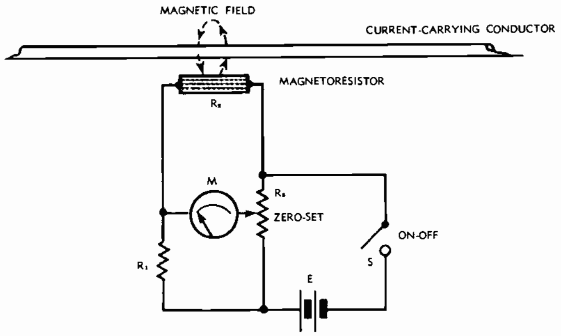

FIGURE 14. MAGNETORESISTOR CURRENT PROBE

Additional Applications

In this article, we have described those applications which seem to be in widest current use. A great many more applications have been investigated by solid-state engineers.

Some of the other devices employing Hall generators and/or magnetoresistors include the following: contactless magnetic switch, modulator, gyrator, isolator, motion transducer, function generator, wattmeter, phase shifter, phase meter, and tachometer.

The signal produces fluctuations in the magnetic flux, which in turn cause corresponding fluctuations in the resistance of the magnetoresistor. A fluctuating current accordingly flows from battery E through resistor R_2. The resulting fluctuating voltage drop across this resistor is coupled to the A-C SIGNAL OUTPUT terminals by capacitor C. Transformer-coupled output also may be used.

Since only a relatively small input signal is required to vary a high current through the magnetoresistor, good amplification may be obtained with this circuit. 30 to 40 db gain at room temperature has been reported, and 60 db at the temperature of liquid nitrogen.

DC-AC Converter. Figure 10 shows a simple circuit for converting dc to ac. The dc to be converted is applied to magnetoresistor in series with the primary winding of output transformer T. An alternating magnetic field from the nearby coil-and-core, L, fluctuates the resistance of the magnetoresistor in step with the coil excitation current obtained from a suitable oscillator. This changes the steady dc from the input into a pulsating current in the primary of the transformer, and an alternating voltage accordingly is set up at the A-C OUTPUT terminals.

If the core of coil L is an electromagnet, the resistance of the magnetoresistor will go through its full range of instantaneous values during each positive *and* negative half-cycle of magnetization, but the polarity of the pulsating current will remain constant. This results in a doubling of the excitation frequency in the output voltage. If, instead, the coil is wound on a permanent magnet, the magnetic bias thus provided will prevent this frequency multiplication. (The same result may be obtained by providing a dc-operated magnetic-bias winding on the temporary-magnet core, in addition to the excitation winding, L.)

A dpdt ON-OFF switch, S_1-S_2, is employed. By controlling both the d-c input and a-c excitation, this switch insures that pure dc will not be inadvertently applied to the A-C OUTPUT terminals.

Chopper. Figure 11 shows a simple chopper circuit for converting a d-c signal (such as the output of a thermocouple, strain gauge, photocell, accelerometer, or thermistor) to ac for amplification by a conventional amplifier. Like the Hall-effect chopper described above, this circuit is somewhat simpler than comparable transistor, tube-type, or electromechanical choppers.

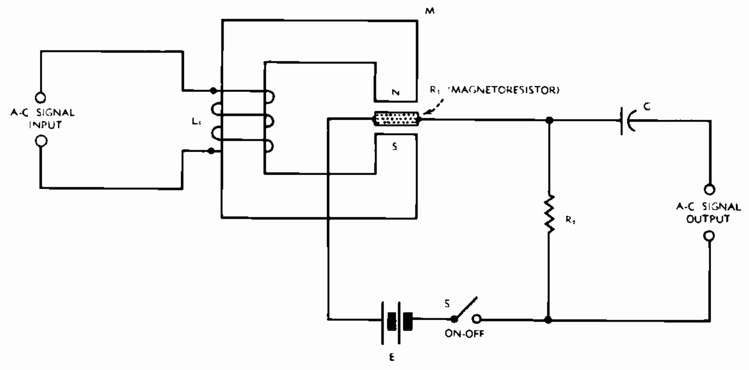

FIGURE 9. MAGNETORESISTOR AMPLIFIER

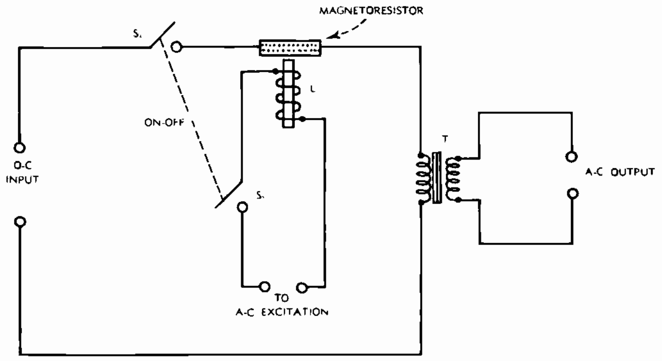

FIGURE 10. MAGNETORESISTOR DC-AC CONVERTER

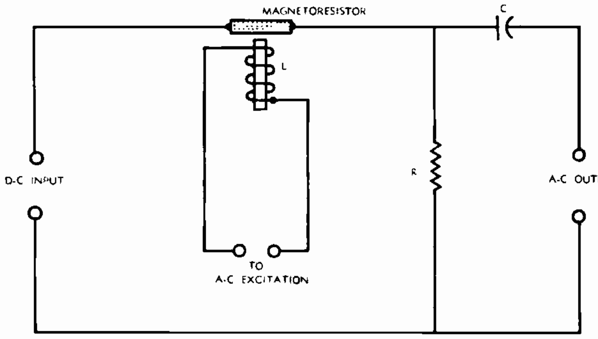

FIGURE 11. MAGNETORESISTOR CHOPPER

In this arrangement, the d-c signal to be converted is applied to the magnetoresistor and load resistor R in series. An alternating magnetic field from the nearby coil-core, L, fluctuates the resistance of the magnetoresistor in step with the coil excitation current obtained from a suitable oscillator. This converts the pure d-c input into a pulsating dc which flows through resistor R. The voltage drop across this resistor likewise is pulsating. Capacitor C transmits the a-c component of this voltage to the A-C OUTPUT terminals. (An output coupling transformer might also be used.)

The a-c output signal has twice the frequency of the excitation current when the core of L is not a permanent magnet, and has the same frequency when the core is a permanent magnet. If desired, an additional dc-operated magnetic-bias winding may be wound on the core with coil L, to obviate using a permanent magnet.

Frequency Doubler. Either the converter circuit (Figure 10) or the chopper circuit (Figure 11) may be used as a frequency doubler when the core of the excitation coil is not a permanent magnet, since under those conditions the output ripple frequency is twice the excitation frequency.

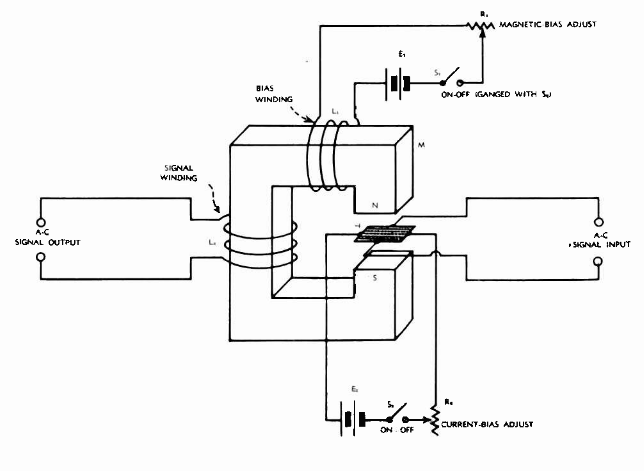

FIGURE 6. HALL AMPLIFIER

Amplifier. In Figure 6, a Hall generator, H, is placed between the closely spaced poles of a magnet, M. The latter is magnetized by means of current from battery E_1 flowing through the magnetic-bias winding, L_1. (If a permanent magnet is employed, neither L_1, E_1, S_1, nor R_1 will be needed.) An a-c input signal, applied to the signal winding, L_2, produces fluctuations in the strength of the magnetic field between the N and S poles, and this causes corresponding alternations in the output voltage of the Hall generator.

When the d-c bias is supplied to the Hall generator after being adjusted, by means of rheostat R_2, to the correct level for a given generator, the a-c signal output will be a multiple of the a-c signal input. In this way, amplification may be obtained at audio and supersonic frequencies.

Analog Multiplier. Because the Hall output voltage is proportional to the magnetic field strength and to the d-c bias current, it may be used conveniently to indicate the product of these two quantities over a useful range. Figure 7 shows the circuit of such an electronic multiplier. This is only the basic configuration; the final computing circuit would contain appropriate meters for measuring currents and rheostats or potentiometers for setting current levels.

In this circuit, the multiplicand is represented by direct current I_1 which, flowing through magnet coil L, determines the magnetic component. Similarly, the multiplier is represented by direct current I_2 which constitutes the d-c input of the Hall generator, H. The d-c output voltage, E, of the circuit is proportional to these two currents: $E = kI_1I_2$, where k is a constant for the particular Hall generator employed, and dependent upon its characteristics.

A suitable d-c voltmeter-millivoltmeter (or in some cases, a current meter) may be calibrated to read the product directly. In this way, currents I_1 and I_2 may be set to represent the multiplicand and multiplier, respectively, and the product read directly from the output meter.

Magnetoresistor Devices

As with Hall generators, the characteristics of magnetoresistors vary with make and model. The data sheet of the particular type employed should be consulted for specific figures. Nominal zero-kilogauss resistance varies from 1 to 5000 ohms at 25°C. Typical performance: Resistance change $(\Delta R/R_0)$, 0.06/kilogauss.

Fluxmeter. A fluxmeter based upon the magnetoresistor is somewhat simpler than one employing a Hall generator. Figure 8 shows a typical circuit. M is a d-c milliammeter or microammeter which usually reads directly in gausses.

In this arrangement, the magnetoresistor (R_1), mounted at the tip of an exploring probe, is one arm of a 4-arm bridge comprised by R_1, R_2, R_3, and R_4. M is a d-c microammeter or milliammeter which serves both as a bridge null indicator and flux indicator. The bridge is powered by a battery (E) or comparable low-ripple, stabilized power supply. The bridge is balanced initially (meter zeroed) by adjusting rheostat R_4 when no magnetic field is applied to the magnetoresistor. When a magnetic field subsequently is applied, the resistance of the magnetoresistor increases in proportion to the field strength, the bridge unbalances accordingly, and the meter deflects.

Since the deflection is proportional to the magnetic field strength, the scale of meter M may be calibrated (with the aid of several accurately known fields) to read directly in gausses. When such standard fields are not available, an approximate calibration may be obtained by replacing the magnetoresistor successively with fixed resistors whose resistances equal the values the magnetoresistor would have at selected field strengths (based on the $\Delta R/R_0$ figure for the particular magnetoresistor employed) and noting the corresponding meter reading.

Amplifier. An a-f amplifier similar to the Hall-effect amplifier, but somewhat simpler, uses the input signal to vary the resistance of a magnetoresistor connected in series with a d-c source and the load. Figure 9 shows the basic circuit.

In this arrangement, the magnetoresistor (R_1) is mounted between the closely spaced poles of a magnet, and connected in series with battery E (or a comparable low-ripple, stabilized power supply) and load resistor $(R_2$. The a-c input signal is applied to coil L_1 wound on the yoke of the magnet.

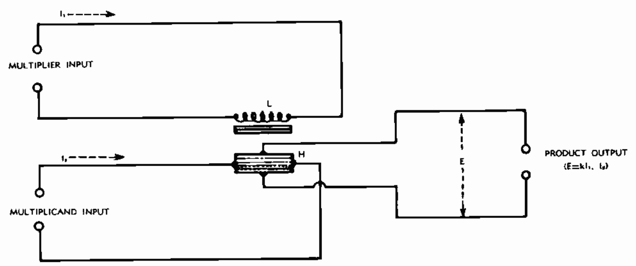

FIGURE 7. HALL ANALOG MULTIPLIER

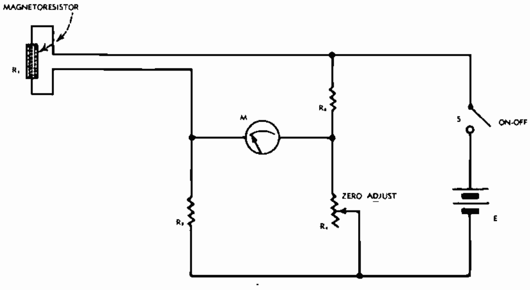

FIGURE 8. MAGNETORESISTOR FLUX METER

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