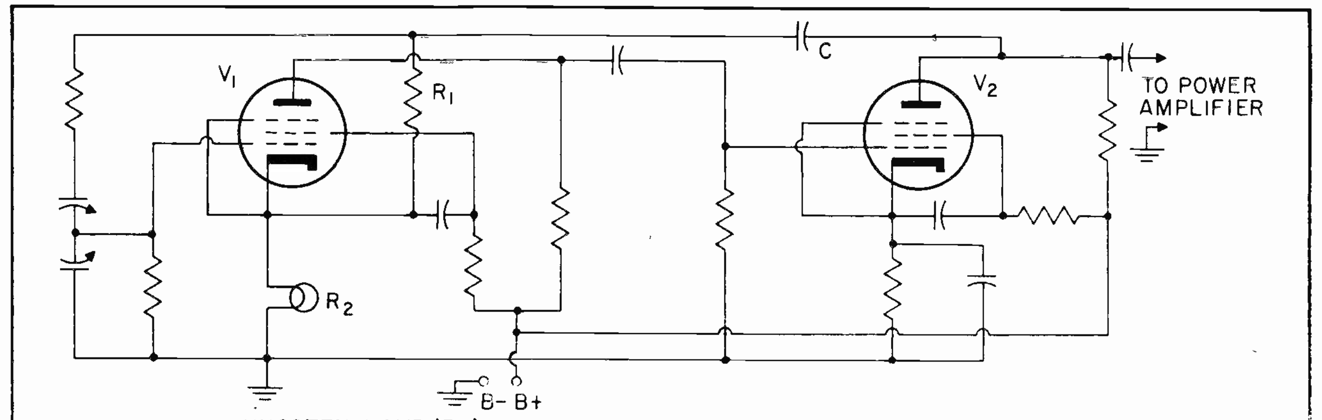
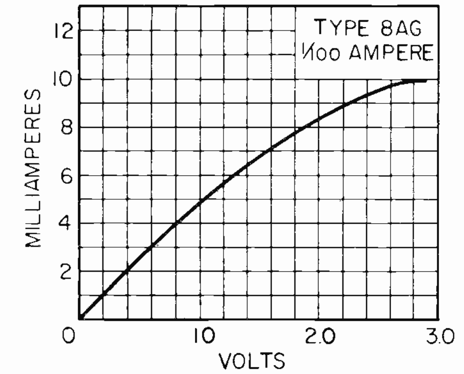


TUNGSTEN LAMP (R_2) AS STABILIZING RESISTOR IN AUDIO OSCILLATOR

FIGURE 9

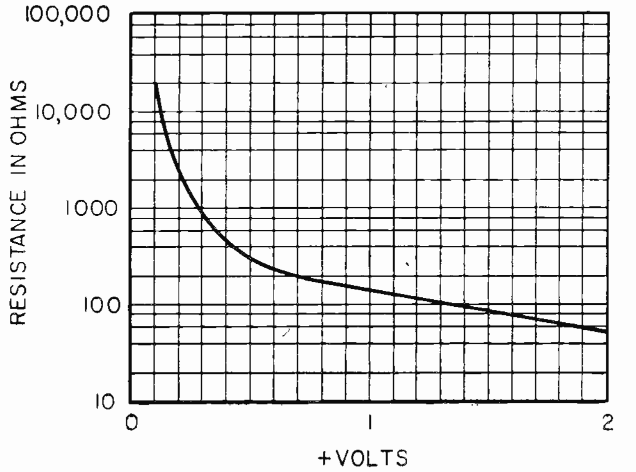
are relatively low-current devices, as compared with some other non-linear resistors.

Like the Thyrite resistor, the forward-conducting diode is capable of distorting an a. c. current waveform and occasionally is used to accentuate harmonics. The requirement is that the diode current magnitude be such as to operate the diode in its most non-linear region. Thus, the simple series connection of a diode in the plate or grid lead of an oscillator or amplifier can accentuate harmonic content of the current waveform when this type of operation is required. An example, is the distortion of waveform of a standard-frequency oscillator to produce high-order harmonics for calibration purposes.



STATIC D.C. CHARACTERISTIC OF MINIATURE FUSE

FIGURE 10



STATIC FORWARD RESISTANCE OF GERMANIUM DIODE

FIGURE 11

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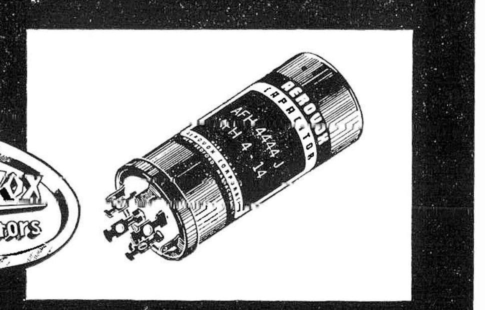

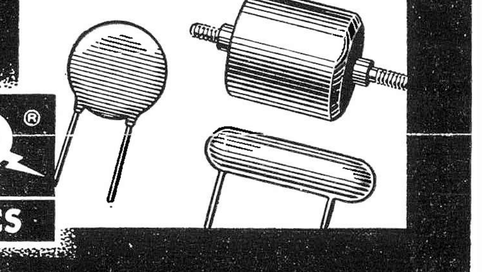

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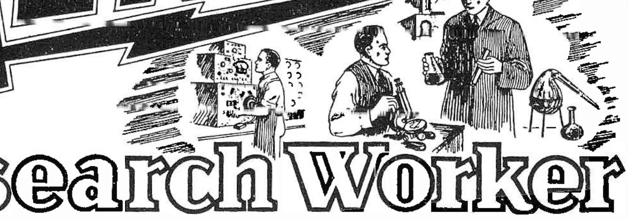

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Non-Linear Resistors

By the Engineering Department, Aerovox Corporation

A FEW electrical devices are distinguished by their non-linear current-vs-voltage characteristics of a magnitude sufficiently great to affect performance. Often this phenomenon is a characteristic. For example: non-linearity is observed in the plate characteristic of a vacuum tube under certain operating conditions, the extremity of a diode tube response, iron-cored inductors operated in the region of saturation, and in biased capacitors having special ceramic dielectrics (dielectric amplifiers). These are only a few examples. The non-linearity of certain 2-terminal devices such as resistor also may be employed to modify the operating characteristics of some circuits. These latter *non-linear resistors* do not obey the simple relationship R = EI of Ohm's Law.

Simple non-linear resistors are used in oscillators, wave shaping networks, voltage regulators, current regulators, constant-output potentiometers and voltage dividers, voltage-selective circuits, amplitude limiters, frequency multipliers, surge suppressors, etc. Their use in electronics is increasing as new requirements for non-linear current-voltage response arise.

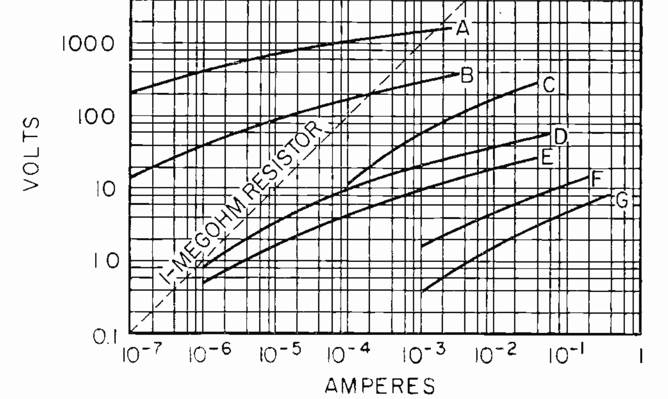
This article describes the general characteristics of some common 2-terminal non-linear resistors of several classes. In some instances, as will be seen, these devices have other prime uses and their application as non-linear resistors is secondary. Typical applications will be shown.

Thyrite

Thyrite resistors were introduced by General Electric Company and were applied in the electric power field some number of years before entering electronics. Thyrite resistors are made of silicon carbide, bound with a filler, then pressed and fired at high temperature. They are fabricated in the form of pigtailed rods (identical to "radio resistors"), discs, washers, and stacks. Small units suitable for electronic applications are supplied up to 10 watts power rating (continuous).

The nin-linearity of the Thyrite resistor is expressed by $I = kE^n$, where I is the instantaneous alternating or direct current (amperes), E the instantaneous applied voltage, k a constant (amperes at 1 volt), and n an exponent between 3.5 and 7 governed by the manufacturing process. Figure 1 shows a set of typical Thyrite current-voltage curves for several types of G. E. Thyrite resistors. The curve for a conventional 1-megohm linear resistor is plotted for comparison. From these curves, it may be seen that large current changes result from small applied-voltage changes.

Figure 2 is a plot of resistance vs current for resistor B from Figure 1. Note in Figure 2 that a change of 10,000 to 1 in current flowing through this resistor changes the resistance of the latter approximately 375:1.



CURRENT-VOLTAGE CHARACTERISTICS OF THYRITE RESISTORS

FIGURE 1

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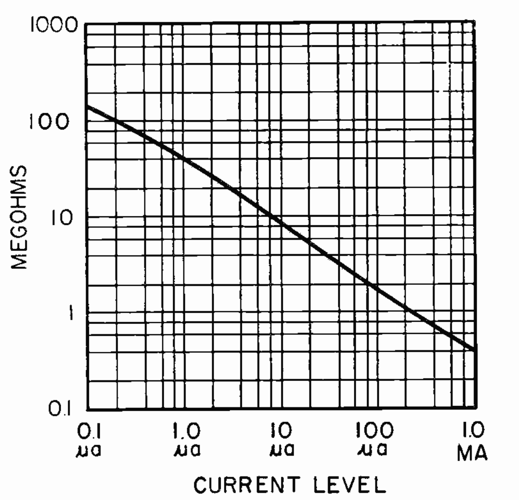
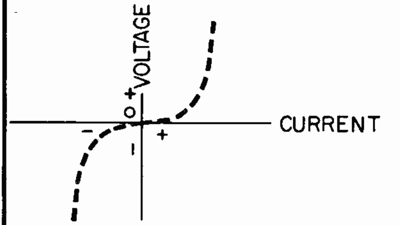


THYRITE RESISTANCE VS CURRENT LEVEL
(RESISTOR B FROM FIGURE I.)

FIGURE 2

Thyrite resistors have the advantage of operating in both a. c. and d. c. circuits. Any rectification effects are negligible. (Figure 3 shows a typical static positive-negative conduction curve). High-frequency a. c. operation of Thyrite is possible, the limiting factor appearing to be capacitance. It should be noted, however, that in a. c. operation the non-linearity of the Thyrite volt-ampere characteristic causes distortion of the current waveform. Figure 4 shows the distorted current wave accompanying a sine wave of applied voltage. Observe that odd-ordered harmonics are prevalent. This phenomenon is utilized in simple frequency multipliers and harmonic accentuators.



STATIC THYRITE
CONDUCTION CHARACTERISTIC

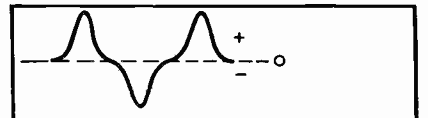
FIGURE 3

The temperature coefficient of Thyrite resistance is negative in sign and varies from −0.4 to −0.73 percent per degree Centigrade in the range 0 to 100°C.

Figure 5 shows several typical circuits utilizing the properties of Thyrite resistors.

Figure 5(A) is a simple voltage regulator or compressor for smoothing variations in supply voltage. The fluctuating input voltage produces fluctuating current which flows through the Thyrite resistor (T) and a linear limiting resistor (R) in series. Fluctuations in the resulting voltage drop across the Thyrite resistor are considerably lower in amplitude than those in the supply voltage, due to the non-linear E/I relationship in the Thyrite. It should be noted that a voltage reduction unavoidably occurs because of potentiometer action between R and T.

In the expander circuit in Figure 5(B), the opposite action is secured. Small fluctuations in applied voltage produce large fluctuations in current through Thyrite resistor T. These current fluctuations in turn produce a fluctuating output-voltage drop across R. Since the resistance of R must be small with respect to that of T, voltage divider action between the Thyrite and linear resistance legs of the circuit produces a drop in voltage level. Several TR sections may be cascaded, as shown in Figure 5(C), to secure additional expander action, at the expense of course of further voltage division in each section.



Current resulting from sine-wave of applied voltage

A.C. DISTORTION DUE TO THYRITE

FIGURE 4

Figure 5(D) shows a potentiometer or voltage divider with Thyrite sections. The non-linear E/I characteristic of the Thyrite sections yields a nearly constant output voltage at each tap, although supply and load currents are variable.

For efficient operation of the circuits shown in Figures 5(A) and (D), the Thyrite current must be high with respect to the output load current. In Figures 5(B) and (C), current in resistor R must be high with respect to output load current.

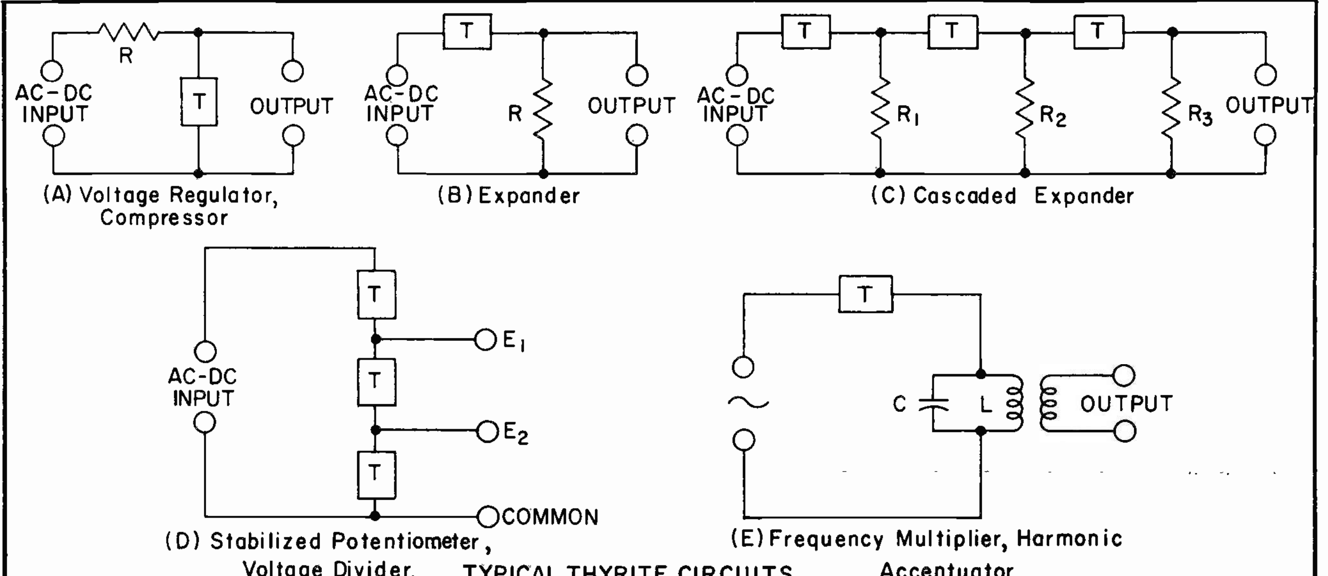
Figure 5(E) shows how a Thyrite resistor can be connected into a circuit to accentuate harmonics and act as a simple frequency multiplier. Alternating current is fed into the circuit and undergoes distortion in passing through the Thyrite. The tuned circuit, LC, is adjusted to the desired multiple frequency. It has been shown already in Figure 4 that odd harmonics are favored by this type of operation. The Thyrite frequency multiplier thus is most practical for tripling, quintupling, etc. The Thyrite resistor is a dissipative element, however, and its insertion into a circuit in the manner shown in Figure 5(E) results in some power loss. In applications where a considerable amount of power is available, the relative simplicity of the Thyrite frequency multiplier can offset its unavoidable power absorption.

Thermistors

The thermistor, a product of research by Bell Telephone Laboratories and manufactured by Western Electric Company, is another interesting non-linear resistance device. Its action results from internal heating effects in special materials.

Thermistors basically are thermally-sensitive resistance devices. They are manufactured in the shape of rods, discs, beads, wafers, and flakes and are made of various semiconductor materials. Like Thyrite, the thermistor can be used with either a. c. or d. c.

Figures 6 and 7 show two important response curves describing thermistor action. From Figure 6, it is seen that the voltage drop across the thermistor increases non-linearly and rapidly with current flow up to a point beyond which the rate of increase falls. Finally, a peak is reached and beyond this latter point, the voltage drop decreases with increasing current, displaying *negative resistance*. An interesting side observation is that this negative-resistance property has been utilized to obtain low-frequency tubeless oscillation and amplification with thermistors.



(A) Voltage Regulator, Compressor

(B) Expander

(C) Cascaded Expander

(D) Stabilized Potentiometer, Voltage Divider.

(E) Frequency Multiplier, Harmonic Accentuator

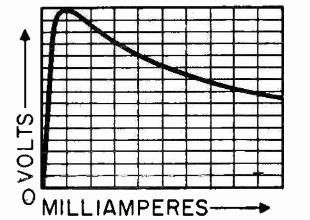
TYPICAL THYRITE CIRCUITS

FIGURE 5

In Figure 7, the plot shows how at a particular applied voltage internal heating causes the magnitude of thermistor current to vary as a function of time. This property has been utilized in various simple time-delay devices.

Figure 8 shows several simple circuits employing thermistors. In all except Figure 8(A), a small current-limiting resistor, r, is indicated. Figure 8(A) is a time-delay d. c. relay based upon the action illustrated by the curve in Figure 7. Some seconds after the switch, S, is closed, the circuit current rises to a value high enough to close the relay. The delay interval depends upon thermistor characteristics and supply voltage level, and can be adjusted to some extent by means of linear series resistance.

Figure 8(B) is the circuit of a regulator for supply-voltage variations and is somewhat similar to the Thyrite voltage regulator. Its operation is based upon the non-linearity of the thermistor which results in smaller variations in thermistor voltage drop than the fluctuations occurring is suply voltage and current.



STATIC DC. CHARACTERISTIC
OF THERMISTOR

FIGURE 6

Action of the limiter circuit, shown in Figure 8(C), is similar to that of the voltage regulator, amplitude excursions in the input signal being reduced in the output without clipping or slicing action.

Operation of the thermistor expander circuit, Figure 8(D), is the opposite of that of the limiter. The thermistor and load resistor are interchanged in position, output being taken across the resistor. A small signal-voltage change produces a large thermistor current change and a large voltage *change* across the output resistor.

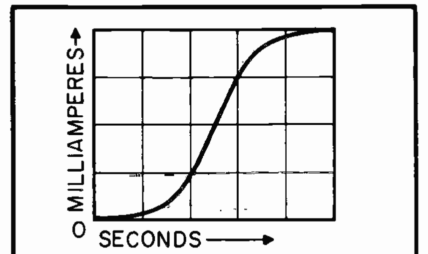
A voltage division takes place in the circuits shown in Figures 8(B), (C), and (D), as the result of potentiometer action between the thermistor and the linear series resistor. Because of this action, the absolute level of the applied voltage is reduced in the output.

Figure 8(E) shows a lockout-type switching circuit employing thermistors. In each leg of the circuit, r is a load resistor or represents some device, such as a relay, which is to be actuated by current flowing through the associated thermistor. The supply voltage and the value of linear series resistor R are chosen such that this resistor will support the current of only one leg before its voltage drop becomes excessive. When one switch (say, S_1) is closed, the associated thermistor "breaks down" allowing current to flow through and operate the associated device, r_1. This lowers the voltage at the inside of R, so that no other thermistor can "fire." Only after S_1 is opened, can either of the other circuit legs be operated. Operation of any one thermistor leg thus locks out all of the other legs. An arrangement of this type would enable a number of devices having similar volt-ampere characteristics to be connected across a single voltage pair, but with only one device operable at a time.

Filamentary Devices

The tungsten-filament incandescent lamp is fairly well known as a non-linear resistor in which current change lags a corresponding change in applied voltage. Up to the point at which heating effects begin to evidence, the filament volt-ampere characteristic is linear, or very nearly so. The non-linear region of lamp-filament resistance has been utilized in voltage-stabilization bridges, simple regulators, and allied devices.

In a common application, the lamp-type resistor is used as an automatic regulator of degeneration voltage in low-distortion, RC-tuned oscillators. A typical circuit is shown in Figure 9.



TIME-DELAY ACTION
OF THERMISTOR

FIGURE 7

In Figure 9, the lamp (R_2) is the cathode resistor of the first pentode, V_1. Feedback current from the output of V_2 flows through capacitor C to the frequency-selective RC network in the grid circuit of V_1. A portion of this current also flows through resistor R_1 and the lamp, R_2, establishing a negative feedback voltage across the latter. The lamp resistance is low when the feedback current is small, and is high when this current is large. Thus; strong oscillations result in large amounts of inverse feedback voltage across R_2, and this degeneration in turn reduces the amplitude. The opposite also is true; at weak oscillation amplitudes; there are lesser amounts of degeneration, and gain through the two-tube circuit automatically rises. The net result is uniform amplitude of oscillation.

Thermistors also are used occasionally in some RC-tuned oscillator circuits to stabilize oscillation amplitude.

Small filamentary, low-current fuses exhibit a type of non-linearity somewhat similar to that of the tungsten filament. Figure 10 shows the static d. c. volt-ampere characteristic of a sample Type 8AG 10-milliampere Littelfuse. In this instance, response is linear from zero up to the 0.8 v., 4 ma. point. Beyond this, the non-linearity is apparent.

When d. c. -biased to a point within the square-law region of their non-linearity, such fuses often are used as bolometer-type detectors in microwave work. This provides an extremely simple and inexpensive demodulator at frequencies up to many hundreds of megacycles.

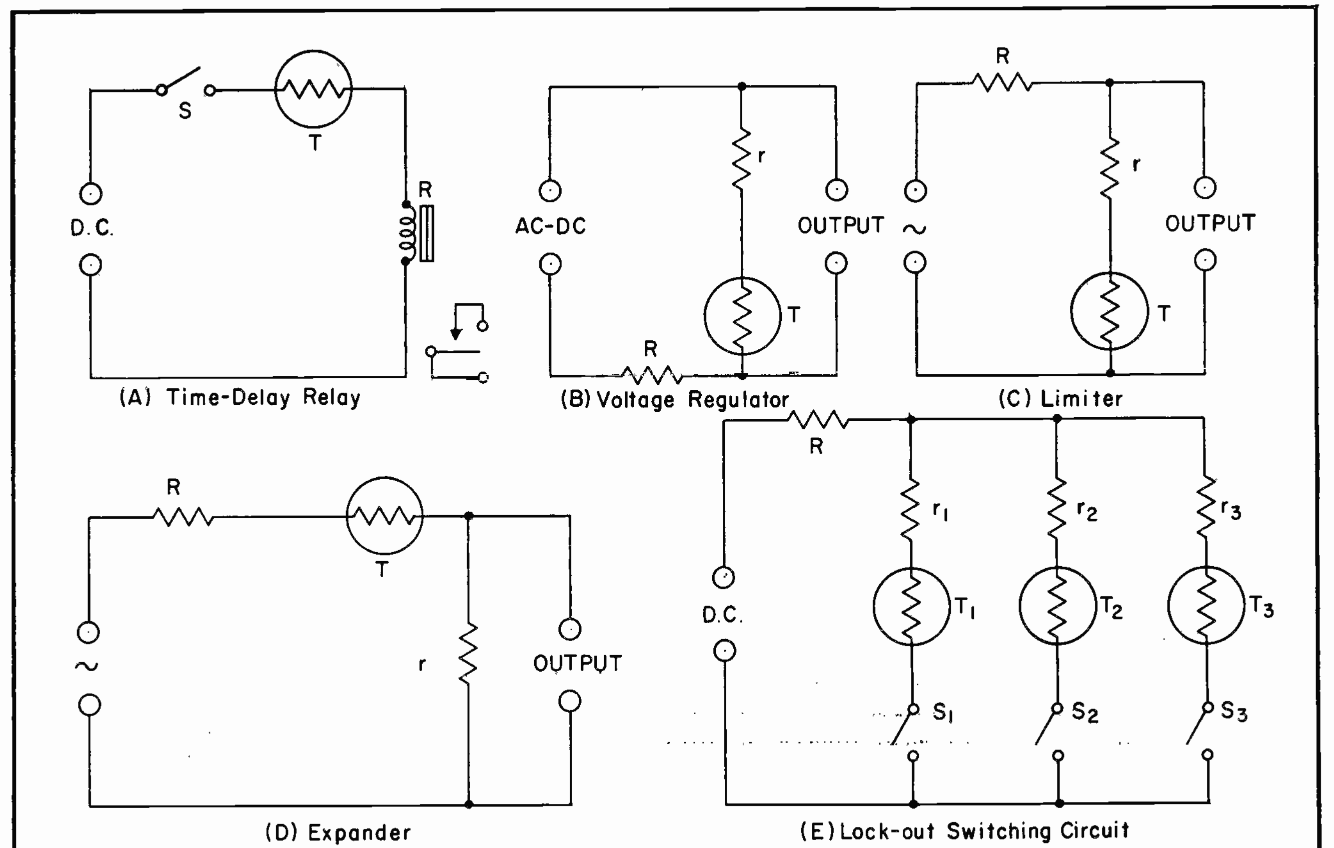
Diode-Type Resistor

Non-linearity in the forward conduction characteristic of the germanium diode suits this simple component to use as a non-linear resistor in applications within its current capabilities. While the reverse-conduction (back-current) characteristic of the diode also is non-linear, it does not in general offer the same possibilities of application that are available with the front conduction.

Figure 11 shows a plot of forward resistance vs applied voltage for a high-conduction-type germanium diode. Here, the polarity of the applied voltage is such that the anode of the diode is positive. Diodes may be connected in series, parallel, series-parallel, and parallel-series to obtain many attractive non-linear resistance effects.

Various portions of the forward volt-ampere characteristic of the germanium diode exhibit square law, logarithmic, and finally approximately linear relationships between E and I. By operating the diode in a desired one of these regions, the particular corresponding portion of the curve can be utilized to correct or modify the E/I characteristic of another circuit. For example, a linear microammeter may be converted into a square-law instrument by using the forward resistance of the diode as the meter series resistance (multiplier).

Diodes suffer somewhat in comparison with other 2-terminal non-linear resistors because the diode is a rectifier. This limits application in some cases to direct-current use only. However, small a. c. signals may be superimposed upon a d. c. forward bias current applied to the diode, the two currents being so proportioned that the net diode voltage never becomes zero or negative. Diodes also



(A) Time-Delay Relay

(B) Voltage Regulator

(C) Limiter

(D) Expander

(E) Lock-out Switching Circuit

TYPICAL THERMISTOR CIRCUITS

FIGURE 8