THERMISTORS

In the conventional Ohm's law equation

$$v = R\,i \tag{1}$$

it is well known that the resistance value R corresponds to a specific temperature. Every two-terminal resistor invariably possesses a resistance–temperature (R–T) characteristic. Three typical shapes of such a characteristic are shown in Fig. 1 over a temperature range 0° to 100°C (273.15 to 373.15 K). In curve (a), the resistance is almost invariant with temperature, this property being exhibited by materials like manganin or constantan. Curve (b) corresponds to a material having a positive temperature coefficient of resistance. Examples of such materials are metals like platinum, copper, nickel, and others. A characteristic as in curve (c) is indicative of a large negative temperature coefficient of resistance and is encountered with resistors made out of semiconducting materials such as Mn_2O_3, Co_2O_3, and NiO (1–2). Thermistors belong to this class of resistors and derive their name from the phrase "thermally sensitive resistors." Their properties and applications are discussed in greater detail in the following sections.

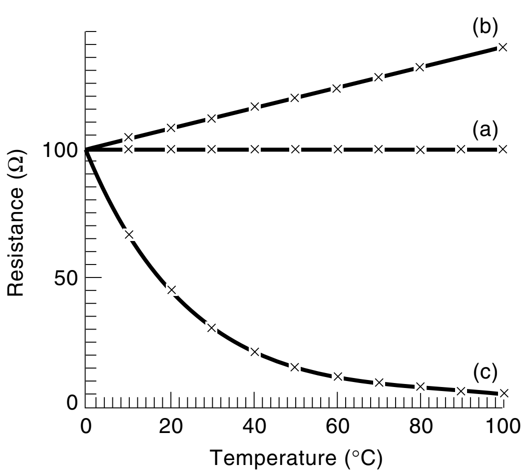

Figure 1. Typical shapes of R–T characteristics of resistors: (a) with negligible temperature coefficient of resistance, (b) with positive temperature coefficient of resistance, (c) with negative temperature coefficient of resistance.

TEMPERATURE-DEPENDENCE OF RESISTIVITY: METALS AND SEMICONDUCTORS (3)

The value of the resistance R referred to in Eq. (1) depends on the physical dimensions of the resistor and the resistivity ρ of the material used. The change in resistance with temperature is due mainly to the change in ρ or its reciprocal, the conductivity σ. The nature of the change is different for metals and semiconductors. A given solid is classified as a conductor if, in its atomic model, the energy gap between the valence and the conduction bands is absent, with the two bands overlapping. For semiconductors, however, there exists an energy gap ranging from 0.1 eV to 3 eV between the two bands. The value of σ depends on the number of charge carriers n_c available in the conduction band and the velocity with which these carriers move under the application of an electric field. The latter is directly related to the mobility μ of the charge carriers. In the case of metals, n_c does not vary appreciably with temperature. The contribution to the change in resistivity comes from a change in μ. As temperature is increased, the enhanced thermal agitation of the atoms in the crystal lattice decreases the mean free path of a charge carrier between two successive collisions. This causes a decrease in μ and a consequent increase in the resistivity ρ. For semiconductors, on the other hand, an increase in temperature causes a large number of charge carriers to move into the conduction band. The resultant increase in n_c more than offsets the effect of the decrease in μ. Semiconductors thus exhibit a negative temperature coefficient of resistance, whose magnitude is several orders higher than that observed in the case of metals. The temperature coefficient of resistance of a semiconductor would lie between -1 and -5% per K, compared with a value of around $+0.4\%$ per K for copper and platinum.

CONSTRUCTION OF THERMISTORS

It is only through special processing that germanium or silicon can be had in pure form. Such intrinsic semiconductors, no doubt, possess a large temperature coefficient of resistance. Their conductivity at ordinary temperatures is, however, too low for practical resistors to be made out of them. Commercial thermistors are therefore basically compound semiconductors, which are made of oxides of cobalt, copper, manganese, nickel, tin, titanium, and others. While the R–T variation of a compound semiconductor is similar to that of intrinsic germanium or silicon, the increase in number of

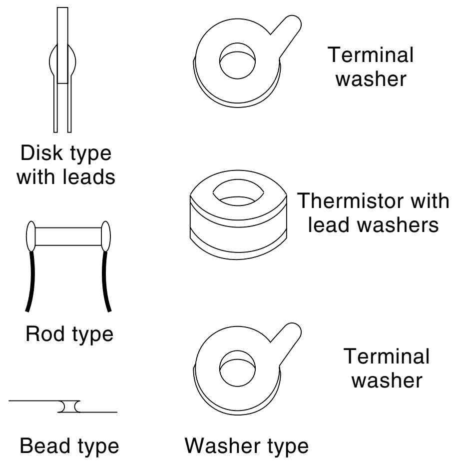

Figure 2. Various types of thermistors.

charge carriers is traceable in this case to a different phenomenon involving oxygen atoms (1).

Thermistors are manufactured in different shapes such as disk, rod, bead, and washer (1,4). A few sample shapes are illustrated in the sketches of Fig. 2. The various stages involved in the manufacture of thermistors are:

- Mixing of the various ingredients (metallic oxides) and grinding of the mixture to obtain a fine homogeneous powder.
- Binding of the powder by using a suitable organic chemical and shaping to the required form.
- Sintering at a controlled temperature. (Sintering is a process in which a powder mix of various ingredients is heated to a temperature below the melting point of the major constituent to achieve inter-particle bonding).
- Fixing of connecting leads and encapsulating in glass, epoxy, or a ceramic sheath.

The nominal resistance of the thermistor, its temperature sensitivity and other relevant properties depend on the proportions of the constituents, the size, and the sintering temperature.

A QUANTITATIVE RESISTANCE–TEMPERATURE RELATIONSHIP WITH SIMPLIFIED THEORY (1,5)

The charge carriers contributing to current in a semiconductor include both electrons and holes. The conductivity due to each type of charge carrier is proportional to the product of its concentration (number of charge-carriers per unit volume) and mobility. The charge-carrier concentration at any temperature is governed by the Fermi–Dirac distribution theory. Application of this theory to electrons would yield the following expression, known as the Boltzmann equation, for the electron-concentration n_e:

$$n_e = N e^{-E_g/2kT} \tag{2}$$

where N is the concentration in valence band, E_g is the energy gap between the conduction and valence band, k is the Boltzmann constant and T is the absolute temperature. A similar

Table 1. Typical Parameters for a Few Commercial Thermistors

Type of Thermistor	R_0	A	B
Siemens K 19	10 kΩ	9.754 mΩ	3440 K
Omega 44005	3 kΩ	5.586 mΩ	3934 K
YSI part No. 44033	2.25 kΩ	3.817 mΩ	3958 K

expression is valid for holes too. As mentioned in the previous section, the variation of μ with T can be ignored in semiconductors. The conductivity is thus directly proportional to the charge concentration and hence bears an exponential relation to temperature similar to Eq. (2). With such a relation inserted into the expression for the resistance R of the device, we would get

$$R = \frac{\ell}{a\sigma} = \frac{\ell}{a\sigma_\infty} \cdot e^{E_g/2kT} \tag{3}$$

In Eq. (3), ℓ and a are respectively the usual length and area of cross-section and σ_∞ is the conductivity at a very high temperature (ideally infinity), when all the valence electrons will have moved into the conduction band. Now, Eq. (3) can be rewritten in the form

$$R = R_\infty e^{B/T} \tag{4}$$

where R_∞ and B are constants associated with the thermistor made out of the semiconductor. R_∞ will be in ohms and $B = (E_g/2k)$ has dimensions of temperature. With E_g around 0.6 eV and $k = 8.625 \times 10^{-5}$ eV/K, we would get a B of about 3500 K for a typical thermistor. R_∞, which is theoretically the resistance at infinite temperature, can take values ranging from fractions of an ohm to several ohms, depending on the material and size of the thermistor. Equation (4) is normally written in the form

$$R = A e^{B/T} \tag{5}$$

A being equal to R_∞.

In Eq. (5), let us consider two temperatures T_0 and T. If the thermistor resistances at these two temperatures are R_0 and R, we would get

$$\frac{R}{R_0} = \frac{A e^{B/T}}{A e^{B/T_0}} = e^{(B/T - B/T_0)}$$

This leads to a commonly used R–T relationship, namely,

$$R = R_0 e^{B(1/T - 1/T_0)} \tag{6}$$

R_0 here is usually the thermistor resistance at a room temperature of 298 K (25°C). R_0 and B for a few thermistors are given in Table 1 (6,7).

APPLICATIONS OF THERMISTORS

General

The features of a thermistor that favor its use as a temperature sensing element are:

- high sensitivity
- availability in small sizes (beads as small as 0.7 mm in diameter), which facilitates measurement at a point and with fast response.
- wide range of resistance values
- possibility of covering a large temperature range from 120 K to 470 K and higher.

Because of these advantages, thermistors are extensively used for a variety of applications involving nonelectrical and electrical variables. The most common applications are in the measurement and control of temperature in process industries. Thermal conductivity, fluid flow, and gas composition are some of the other nonelectrical quantities for the measurement of which thermistors can be employed (1,6,8,9). One of the earliest known uses of the thermistor has been in the measurement of power in RF (radio frequency) and microwave circuits and devices (10). A problem frequently faced in the design of high-performance electronic circuits is the sensitivity of their response to ambient temperature variations. The thermistor with its high negative temperature coefficient comes in handy to minimize or nullify the above-mentioned undesirable effect. Millivoltmeters, biasing circuits of bipolar transistors, and log-antilog amplifiers (11) are typical examples where this property is used. Thermistors also serve as vital components in feedback systems used for the automatic control of amplifier gain and stabilization of output amplitude in electronic circuits.

Methods of Deriving a Temperature-Dependent Output (5,12)

A thermistor is essentially a passive transducer and hence requires energization by an external power source for deriving a temperature-dependent electrical output. The various techniques employed for this purpose are illustrated in simple forms in Fig. 3(a) to (d). In Fig. 3(a), the thermistor is excited by a constant voltage V_S and the resulting current indicated by the ammeter is a function of temperature. In Fig. 3(b), a constant current I_S is passed through the thermistor across which a temperature-dependent voltage is developed. The thermistor is used as one of the arms of a Wheatstone bridge in the circuit of Fig. 3(c). The bridge is initially in a balanced condition at a temperature, say, T_0. A change in temperature from this value causes an unbalanced voltage or current that can be detected by D and related to the change in temperature.

It is also possible to configure the thermistor in a circuit so that a temperature-dependent frequency or time-interval is obtained as an output. An output of this type is preferred, when temperature indication in digital form is desired or when the information is to be transmitted over long distances. An arrangement for realizing this is shown in the block-schematic of Fig. 3(d), where the thermistor (R_T) is used as a timing component of an oscillator or multivibrator.

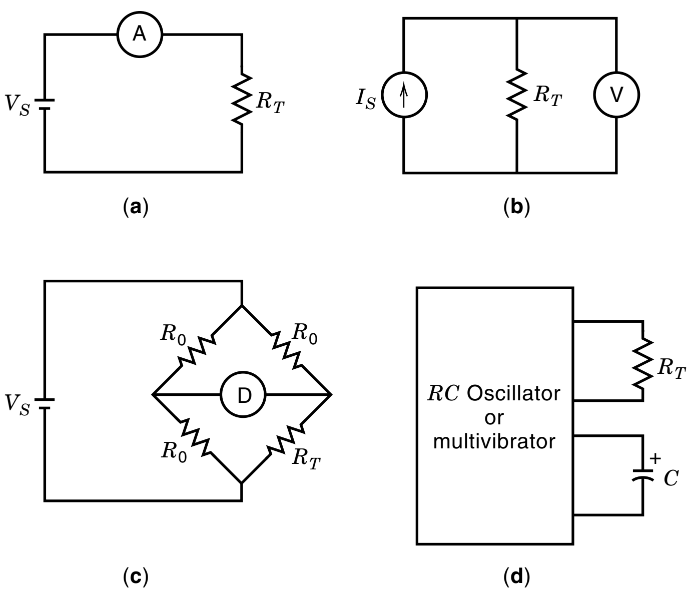

Figure 3. Thermistor converts temperature into an electrical output.

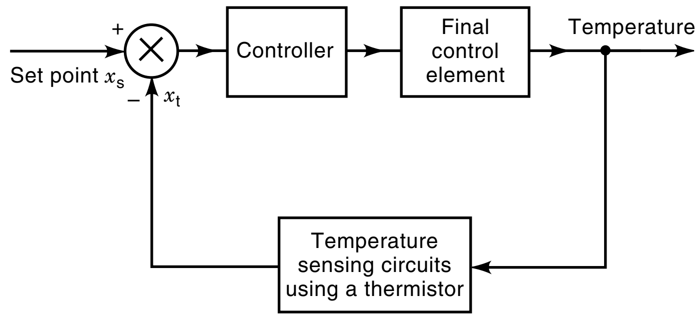

Figure 4. Thermistor in feedback path controls the temperature of a process.

Control of Temperature

It may often happen that the control of temperature in a process is also desired in addition to its measurement. In this case, a temperature-dependent signal is obtained using any one of the basic schemes described above. This signal, say x_T, is compared with a "set-point" (x_S) and the resulting error signal is used to control the heating or cooling of the process. The block diagram of Fig. 4 serves to explain the principle.

Measurement of Fluid Flow (1,8)

The use of the thermistor here is similar to that of the hot-wire anemometer with the thermistor taking the place of the Wollaston wire. The thermistor probe, energized electrically to attain a sufficiently high temperature, is placed in the fluid. Fluid flow causes a decrease in temperature of the probe, because of the heat transfer from the probe to the surrounding fluid. This decrease in temperature is accompanied by an increase in resistance of the thermistor. Additional heat input into the thermistor is needed to bring its resistance and temperature to the earlier value. To this end, the current through the thermistor is increased to a new level, which is then a measure of the fluid velocity. This mode of operation is called constant temperature or constant resistance mode. A bridge-configuration similar to Fig. 3(c) with the thermistor forming one of the arms is often preferred. The advantage of using a thermistor in place of a hot-wire lies in overall compactness, higher temperature sensitivity, and less risk of probe burn-out.

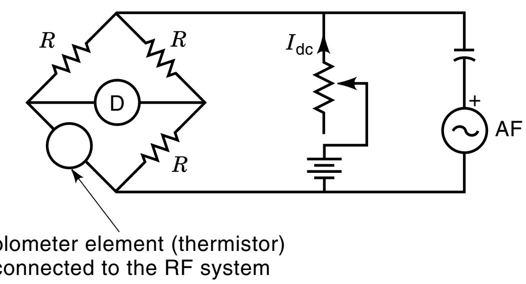

Figure 5. Thermistor helps RF power measurement through AF.

If, instead of a moving fluid, we have a static medium surrounding the thermistor, an arrangement similar to that already described can be used to measure any quantity of the medium which affects the heat transfer. In this manner, we can build thermistor-based instruments to measure variables such as thermal conductivity, gas composition, pressure of gas, and so on.

Measurement of Power in Radio Frequency Circuits

The earliest known application of a thermistor is in the measurement of RF and microwave power. The power-measuring instrument here is called *bolometer* (10), with the thermistor being known as the bolometer element. As is the case with most other applications, the thermistor is used as one arm of a simple bridge configuration shown in Fig. 5.

The thermistor suitably mounted in an RF/microwave system absorbs the high frequency power under measurement and is consequently heated. Simultaneously, it is energized by two other sources—a dc and a low-frequency ac [usually AF (audiofrequency)]. The dc current is adjustable and serves to set the thermistor resistance to a value that would be required for impedance matching on the RF side. The bridge is initially balanced with the thermistor receiving power from all the three sources, the AF power being minimal. The RF/microwave power is then turned off and without disturbing the dc, the AF power is increased to restore the bridge balance. Since the bridge is once again in balance, the thermistor resistance and hence the total input power to the bolometer element is the same under both conditions. The increase in AF power should therefore be equal to the unknown RF power. The accuracy of measurement will be enhanced if the initial AF voltage fed to the bolometer is as near zero as possible. A recent method employing two self-balancing thermistor bridges for RF power measurement is given in section 1.4.6 of Ref. 13.

Compensation and Stabilization

We are aware that the thermistor basically possesses a negative temperature coefficient of resistance. It can therefore be used to counteract the effect of the positive temperature coefficient of some other element on the response of a device or a circuit, when ambient temperature changes. Take for example a moving coil millivoltmeter, where the coil is of copper having a temperature coefficient of about +0.4%. By choosing a thermistor or a thermistor-resistor combination for the series multiplier, it is possible to make the millivoltmeter reading insensitive to ambient temperature changes.

Another application of a thermistor as a compensating element is in logarithmic amplifiers (11). In this circuit (Fig. 6), the A_1–R_1–D_1 combination constitutes the basic logarithmic amplifier. Its output voltage is

$$v_1 = -V_\mathrm{T} \ln \frac{v_i}{I_o R_1} \tag{7}$$

where I_o is the reverse saturation current of D_1 and $V_\mathrm{T} = kT/q$ is the voltage equivalent of thermal energy. I_o and V_T in Eq. (7) make v_1 highly dependent on ambient temperature. If diode D_2 matches with D_1, it would, along with the current source I_S, compensate for changes in I_o with temperature. The voltage at the noninverting pin of A_2 is

$$v_2 = -V_\mathrm{T} \ln \frac{v_\mathrm{i}}{I_\mathrm{S} R_1}$$

The output voltage of the complete logarithmic amplifier circuit becomes

$$\begin{aligned} v_\mathrm{o} &= (1 + R_\mathrm{T}/R_2) \cdot v_2 \\ &= -(1 + R_\mathrm{T}/R_2) \cdot V_\mathrm{T} \ln \frac{v_\mathrm{i}}{I_\mathrm{S} R_1} \end{aligned} \tag{8}$$

A suitable thermistor can be chosen for R_T so that changes in the values of R_T and V_T due to variations in ambient temperature will have equal and opposite effects on the output voltage v_o.

Amplitude Stabilization in Oscillators (11)

We often use a thermistor as a nonlinear feedback element in amplifiers and oscillators to achieve an output of constant amplitude. Let us consider the Wien-bridge oscillator of Fig.

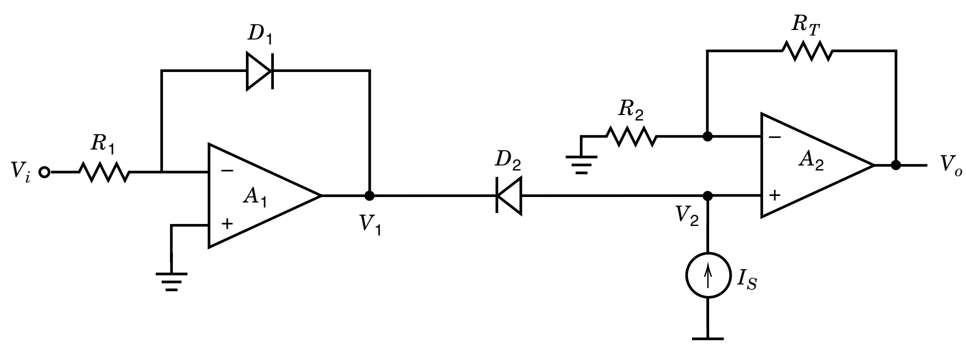

Figure 6. Thermistor R_T helps to reduce the temperature dependence of v_o.

7, built using an op-amp. Here negative feedback is provided by the R_3–R_4 potential divider connected across the output. R_4 is usually a thermistor. When there is a tendency for the amplitude of the output voltage v_o to increase, the current through the thermistor increases. This, in turn, causes a decrease in R_4 due to additional self-heating. The voltage across R_3 increases, resulting in more negative feedback, which tends to reduce the output and therefore maintain it at a constant value. We can also view the action of the thermistor here as an automatic control mechanism that alters the gain of an amplifier to achieve output amplitude stability. In principle, we can, with an appropriate arrangement, exploit the negative slope of the thermistor R–T characteristic to stabilize other electrical quantities as well.

LINEARIZATION OF THERMISTOR RESPONSE (14–19)

Whereas high sensitivity and fast response are the major plus points for a thermistor, the nonlinearity of its R–T characteristic stands as a stumbling block for its use in several applications in which we need an output varying linearly with temperature. The technique of achieving this is broadly known as "linearization."

Shaping of *R–T* Characteristic

The simplest method for achieving linearization is to use a linear resistor in series or in parallel with the thermistor and obtain a terminal resistance that varies more linearly with temperature (14). Consider, for example, a typical circuit as in Fig. 8, where R_T is an Omega 44034 thermistor and R_p is a 2 kΩ resistor connected in parallel with it. The curves on the figure clearly show the effect of adding R_p to get an R–T characteristic with improved linearity over a temperature range of 30°–50°C. The sensitivity however falls considerably (from 107 Ω/K to nearly at 19.7 Ω/K, at 40°C). If we pass a constant current through the R_p–R_T combination, the resulting voltage would vary linearly with temperature. The temperature range over which this technique is applicable is quite narrow.

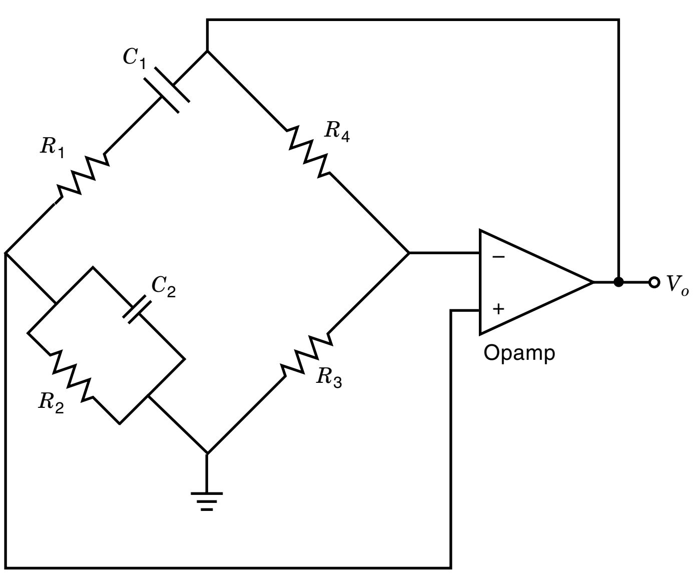

Figure 7. Thermistor (R_4) stabilizes oscillation amplitude.

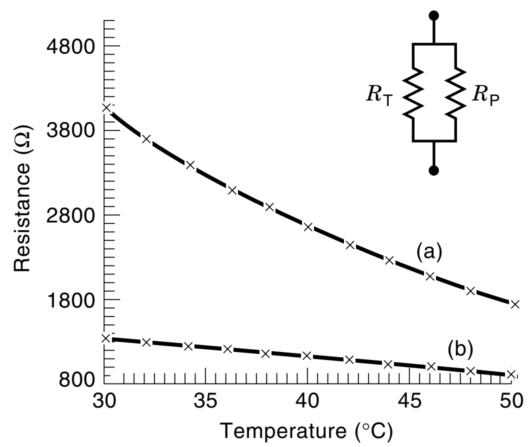

Figure 8. R–T characteristic (a) before (b) after the connection of a 2 kΩ resistor in parallel with Omega 44034 thermistor.

A Technique for Linear *T*-to-*f* Conversion

With thermistors that closely obey the two-constant law $R = A\,e^{B/T}$ over a specific temperature range, it is possible to obtain, using electronic circuits, an output in the form of a frequency which is proportional to temperature.

Refer to the schematic diagram of the T-to-f converter shown in Fig. 9. This circuit functions essentially as a relaxation oscillator (15). A reference voltage V_r energizes the network N containing the thermistor, and also a series R–C circuit. Let at $t = 0$, the output of the monostable multivibrator be low and the switch S open. The capacitor C starts to get charged and its voltage rises according to the relation

$$v_c = V_r(1 - e^{-t/RC}) \tag{9}$$

The network N provides a temperature-dependent voltage

$$v_T = V_r\left(1 - \frac{k}{A}\,e^{-B/T}\right) \tag{10}$$

where k depends on the parameter values of certain elements in N. Let v_c reach the level v_T at $t = t_0$. From Eqs. (9) and (10), we then obtain

$$t_o = \frac{BRC}{T} - RC\ln\frac{k}{A} \tag{11}$$

At this instant, the comparator output is lowered, triggering the monoshot. The output of the monostable increases; the switch S gets closed and discharges the capacitor. The monostable remains in the high state for its period τ at the end of which it returns to low state, initiating another cycle of operation. The period of the relaxation oscillator, namely, $t_o + \tau$ will be BRC/T, if τ is adjusted to be equal to RC ln (k/A). We thus get a frequency of oscillation

$$f = \frac{1}{t_0 + \tau} = \frac{T}{BRC}$$

which varies linearly with the absolute temperature T. The circuit achieves perfect linearization if the two-constant law is strictly valid for the thermistor used. Any nonlinearity in the output is due mainly to the departure of the thermistor behavior from the assumed law.

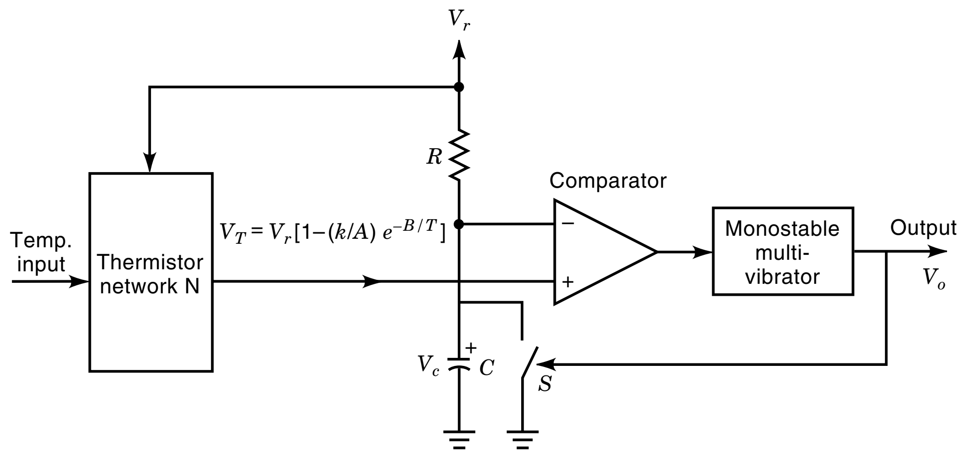

Figure 9. Linear T-to-f converter.

There are available in the literature a large number of linearizing circuits, producing an output in the form of a voltage, frequency, or time interval linearly related to temperature. In most of these circuits, linearization is achieved by expressing the output as a function of temperature in Taylor-series form and adjusting the circuit elements, to nullify the second-order term (16,17,18). The range of temperature over which these techniques will be useful is generally limited.

Wide-Range Linearization

The linearization methods discussed in the previous sections are basically hardware techniques, which would exhibit larger error as the temperature range is increased. As mentioned earlier, the major reason for the errors is the deviation of the R–T characteristic from the $A\ e^{B/T}$-law. This is because some of the assumptions such as invariance of carrier mobility with temperature, used in the derivation of that law, are not valid over a wide temperature range. One approach to reducing the linearity error would be to add suitable resistors in series and/or parallel to the physical thermistor, so as to obtain a terminal resistance which closely obeys the $A\ e^{B/T}$-law over a wide range (19). Other methods use empirical relationships involving three constants, to approximate the actual R–T characteristic of the thermistor better than the two-constant law. Under this category (1,7), we have:

$R = A\ T^{-c}\ e^{B/T}$, called the Becker–Green–Pearson (BGP) law

$R = A\ e^{B/(T+\theta)}$, Bosson's law

$1/T = A + B \ln R + C (\ln R)^3$, Steinhart–Hart equation

For an Omega 44034 thermistor (7), the above three approximations would respectively give rise to a maximum fit error of 0.065 K, 0.037 K, and 0.018 K over the temperature range 0 to 100°C. This value would be -0.533 K if the two-constant law is used. It is true that the three-constant laws fit better than the conventional $A\ e^{B/T}$-law, but they do not lend themselves to easy hardware linearization. The availability of computing power in the form of microprocessors and personal computers has made software-based linearization possible using these equations. A straightforward method would be to obtain an analog voltage proportional to the thermistor resistance, convert it to digital form using an analog-to-digital converter (ADC) and compute the temperature using the chosen three-constant equation.

CERTAIN PARAMETERS OF IMPORTANCE (1,4)

Self-Heating Error

In the applications which involve temperature measurement, we have tacitly assumed that the temperature of the thermistor is the same as that of the surroundings. This assumption is valid provided the thermistor has been long enough at the location of measurement and is not electrically energized. Passage of current through the thermistor for obtaining an electrical output is bound to heat the thermistor to a temperature higher than the surroundings. Since the measurement schemes senses only the thermistor temperature, an error arises which is termed a self-heating error. To keep it small, the thermistor current must be sufficiently low, taking into account the environmental conditions and the heat dissipation capability of the thermistor.

Dissipation Constant

To help the user estimate the error due to self-heating, manufacturers often specify for each thermistor a parameter called the dissipation constant. This constant is defined as the power required to raise the temperature of the thermistor by 1 K above its ambient, and is usually expressed in mW/K. This parameter depends on the nature of the thermistor environment and also on how the sensor is mounted. For example, a commercial tiny bead type thermistor could have a dissipation constant much less than 1 mW/K in still air. Its value for a disk type device mounted on a chassis may be as high as 60 mW/K (3,7).

Response Time

Response time of a thermistor is of importance when monitoring of rapid changes in temperature is required. Since the dynamic behavior of a thermistor is that of a first order system, the response time is specified by the term time-constant. It is the time taken by the thermistor to undergo a resistance change equal to $(1 - e^{-1})$ times the total final change in resistance that would be caused by a given step temperature change. The time-constant and the response time depend on the thermal mass, specific heat, and dissipation constant of the thermistor. Very small-size bead thermistors having time-constants less than 0.5 s are commercially available.

Limitations

Along with their numerous advantages, thermistors have a few limitations too. A rather serious one is the problem of interchangeability. Even thermistors fabricated by the same technique with strict control of the manufacturing process exhibit a spread in their R–T characteristics. Another shortcoming is lack of stability, since the resistance of the thermistor drifts with aging and continued use. Bead type thermistors are generally more stable than their disk counterparts. At high temperatures, changes in composition might occur in the device and the sensor will then have to be recalibrated for further use. This places an upper limit (about 590 K) on the operating temperature of the thermistor. A lower limit for its use is imposed by the largest resistance value beyond which measurement becomes difficult. This lower limit lies around 120 K.

POSISTORS (5,6,7)

The thermistor sensors discussed in the preceding sections are basically ones having a negative temperature coefficient of resistance. Strictly speaking, they should be called NTC thermistors, since there is another class of thermally sensitive resistors which exhibit a large positive temperature coefficient over a small temperature range. These devices are known as PTC thermistors or posistors. The R–T characteristic of a typical posistor is shown in Fig. 10.

It is seen that, as the temperature is increased, the device exhibits an NTC characteristic with a gradually decreasing resistance-temperature coefficient up to a certain temperature. A transition now occurs and the resistance, instead of decreasing, steeply increases with temperature. This phenomenon is noticed in devices made of certain ferroelectric materials such as barium titanate doped with strontium or lead. The PTC is traceable to the sudden decrease in the dielectric constant above the Curie point, which results in an increase in the activation energy (E_g) and an associated increase in the resistivity of the material. The steep R–T characteristic in the transition phase of the posistor makes it ideally suited for applications such as low-cost self-regulating heaters, electronic switches, and overcurrent protectors (6,9).

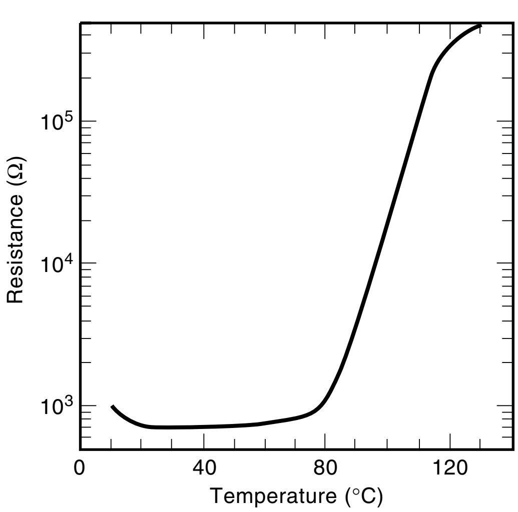

Figure 10. Typical R–T characteristic of a PTC thermistor.

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