A Linearized Thermometer Circuit Employing a Thermistor and a Diode as Probing Elements

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The development of a linearized thermistor-based thermometer circuit with a thermistor and a diode as the temperature probing elements is here reported. The circuit is effectively that of an op amp based logarithmic amplifier, which takes its input from another inverting op amp circuit having a thermistor in its feedback loop. The performance of the circuit is demonstrated experimentally and has been found to have a linearity error of less than 0.2%. The accuracy analysis of the circuit is also discussed.

INTRODUCTION

Temperature is probably the most measured and frequently controlled vaiable in the numerous industrial processes. This is because quite often, the processing or manufacturing of a desired product is possible only if temperatures are accurately measured and maintained. In addition, it forms an important governing parameter in thermodynamics, heat transfer and a number of reactions/operations. Of greater importance is human body temperature measurement since it is one of the oldest known indicator of the general well-being of a person.

Negative temperature coefficient (NTC) thermistors out perform all other temperature sensors in applications requiring temperature measurement from -50^{0}C to 150^{0}C. They have been widely used in the recent past for quick and precise measurement of temperature because of their small size, low price, low themal inertia, high sensitivity and reliability. They are also virtually unaffected by lead resistance (Khan and Sengupta 1984, www.selcoproducts.com, 2003). However the thermistor alone is seldom used because its resistance variation with temperature is highly non-linear. This inherent non-linearity in thermistor response is a big disadvantage for measurement and instrumentation applications. To obtain a linear response over a temperature range of interest, a linearizing circuit is inevitable.

Perhaps the simplest and probably one of the earliest attempts at linearizing the inherently non-linear dependence of current and voltage of an NTC thermistor was made by Beakley (Beakley, 1951, Hyde, 1971). In this approach, the current I(T) through a thermistor in series with a resistance is expanded in Taylor's series and the second derivative is made equal to zero by making $r = R_0(B - 2T_0)/(B + 2T_0)$. The approach gives a maximum error of 0.03^{0}C from 290K to 310K and 0.1^{0}C from 285K to 315K.

A more linear thermistor circuit, which is more recently reported in literature is the Temperature/Voltage Converte using thermistor in the logarithmic network (Khan and Sengupta, 1984). The circuit has a thermistor-resistor network operating in conjunction with a logarithmic amplifier. One of the similarities that this approach has with Beakley's is that the voltage function is experessed in a Taylor's series and the same approximation method is used. The approach is reported to have an error of less than 1.6% in the range -24^{0}C to 110^{0}C.

The approach being proposed here has some similarities with that reported by Khan and Sengupta (1984). It is a Temperature/Voltage Converter and a logarithmic network is used. However instead of the thermistor-resistor network, a sort of current source with an output that varies exponentially with temperature is used in conjnction with a logarithmic amplifier to give a better linearity.

THEORY OF PROPOSED LINEARIZATION TECHNIQUE

The basic linearizing circuit using this approach is illustrated in Fig. 1 where the output of the current source is a temperature-dependent current of the form

$$I(T) = a \exp \frac{b}{T} \qquad \text{--------------------(1)}$$

Where *a* and *b* are constants and *T* is the temperature in Kelvin.

The output of the logarithmic network may be expressed according to Khan and Sengupta (1984) as

$$V'_0 = A \log_{10} \frac{V_{IN}}{V_{REF}} \qquad \text{---------------------------} \quad (2)$$

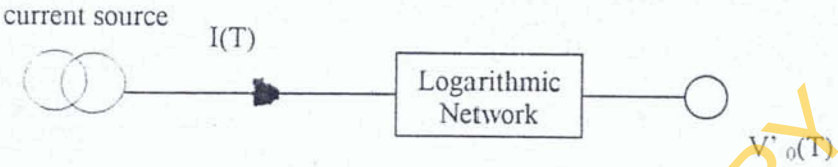

Fig. 1 – Proposed Basic Linearizing Circuit

Where V_{IN} is the input voltage to the network, V_{REF} the internally generated voltage in the network to which the voltage V_{in} is compared. A the sclae factor of the network. Equation 2 may be written as

$$V'_0(T) = C_1 T_1 \,\mathrm{In}\, \frac{V_{IN}}{V_{REF}} \qquad \text{-------------------} \quad (3)$$

where $C_1T_1 = \frac{A}{2.3}$, T_1 is the temperature around the network, and C_1 is a constant. The input voltage to the network is

$$V_{IN} = I(T).R_{OUT} \qquad \text{-------------------} \quad (4)$$

Where R_{OUT} is the output impedance of the source. Equation 3 may be re-written by substituting equation 1 and 4 and making $T_1 = T$

$$V'_0 = K_1 + K_2T \qquad \text{-------------------} \quad (5)$$

which is the required linear output response with $K_1 = C_1b$ and $K_2 = C_1 \left[\mathrm{In}\, a - \mathrm{In}\, \frac{V_{REF}}{R_{OUT}} \right]$

ANALYSIS AND IMPLEMENTATION OF THE LINEARIZATION CIRCUIT

Equation 5 shows that the output voltage V'_0 of the system of Fig. 1 has a perfectly linear relationship with temperature T. In this section we propose and analyse a circuit that implement the system in Fig. 1.

The non-linear behaviour of an NTC thermistor resistance to temperature change is expressed as (Hyde, 1971, Khan and Sengupta, 1984).

$$R_T = R_0 \exp \left[\frac{1}{T} - \frac{1}{T_0} \right] \qquad \text{---------------------} \quad (6)$$

Where,

T_0 = reference temperature in Kelvin
R_0 = thermistor resistance at the reference temperature, T_0
T = thermistor temperature in Kelvin
B = a constant depending on the material of the thermistor

When the feedback resistor, R_f of an inverting operational amplifier circuit is replaced with a thermistor, the output V_0 of the amplifier is made temperature-dependent since the resistance of the thermistor varies exponentially with temperature. Thus, the output voltage is expressed as:

$$V_0 = |V_1| \frac{R}{R_1} \exp B \left[\frac{1}{T} - \frac{1}{T_0} \right] \qquad \text{---------------------} \quad (7)$$

Where V_1 is the input voltage and R_1 the resistor at the input of the amplifier. By connecting the output of this amplifier stage to the input of a logarithmic amplifier, a linearizing circuit being proposed is obtained as shown in Fig. 2. The temperature-dependent current $I(T)$ is given as:

$$I(T) = \frac{V_0}{R_2} \qquad \text{---------- (8)}$$

which, using equation 7 is expressed as

$$I(T) = \frac{|V_1|\, R_0}{R_1\, R_2} \exp B\left[\frac{1}{T} - \frac{1}{T_0}\right] \qquad \text{---------- (9)}$$

Since V_1, R_0, R_1, R_2, T_0 and B are constants, equation 9 is similar to equation 1 with

$$\left.\begin{aligned} a &= \frac{V_1 \quad R_0}{R_1 \quad R_2} \exp - \frac{B}{T_0} \\ b &= B \end{aligned}\right\} \qquad \text{----------(10)}$$

The amplifier A_1 in conjection with R_1 therefore acts as a current source $I(T)$ the output of which depends on the temperature of the thermistor. If the diode D_1 is kept at the same temperature as the thermistor, the output voltage V'_0 is obtainable as

$$V'_0 = \frac{-KT}{q} (\text{In} \;\; I(T) - In\, I_0) \qquad \text{------------(11)}$$

Where k = Boltzmann's constant = 1.38×10^{-23} J/K
q = electronic charge = 1.6×10^{-19} Coulomb
I_0 = reverse saturation current

And substituting equation 9 into 11, we have

$$V'_0 = \frac{kB}{q} - \frac{kT}{q}\left[\text{In}\frac{|V_1|R_0}{I_0R_1R_2} - \frac{B}{T_0}\right] \qquad \text{-------------(12)}$$

The reverse saturation current I_0 of a semiconductor diode may expressed (Ohte and Yamagata 1977, Tyagi 1991, Shur 1996) as

$$I_0 = A_0T^3 \exp \frac{-E_{g0}}{kT} \qquad \text{---------(13)}$$

where A_0 = a constant which depends on diode parameters
E_{g0} = energy gap in electron-volts at 0 K = 1.263 for silicon.

Substituting equation 13 in 12, we obtain

$$V'_0 = -\frac{kB + E_{g0}}{q} - \frac{kT}{q}\left[\text{In}\frac{|V_1|R_0}{A_0R_1R_2} - 3\;\text{In}\, T - \frac{B}{T_0}\right] \qquad \text{----------(14)}$$

If $3InT$ is assumed to be approximately constant and represented by K_C within the temperature range of interest, equation 14 is similar to equations 5 with

$$\left.\begin{aligned} K_1 &= -\frac{Kb + E_{g0}}{q} \\ k_2 &= -\frac{k}{q}\left[\mathrm{In}\frac{|V_1|\, R_0}{A_0R_1R_2} - k_c - \frac{B}{T_0}\right] \end{aligned}\right\} \qquad \text{-----------(15)}$$

ACCURACY ANALYSIS

Since the circuit of Fig. 2 is functionally a linearizing one, it s accuracy is necessarily expressed in terms of the deviation of its response from linearity. Though, equation 14 demonstrates a linear relationship between V'0 and T, there may be a slight error due to the assumptions made. The sources of error are:

Op Amp Non-Ideality

In this work, op amps are assumed to exhibit their ideal properties. Practical op amps deviate slightly from these properties thus introducing a slight error. By using FET-input op amps, the error is made negligible.

Self Heating

The steady state equation relating the electrical to thermal power in a thermistor is given (Hyde, 1971) as

$$P = IV = K\,(T - T_a) \qquad \text{-----------(16)}$$

Where,

P = power dissipated in the thermistor (mW)
I = current through the thermistor (A)
V = voltage across the thermistor (V)
T = internal temperature of the thermistor (K)
T_a = ambient temperature (K)
K = dissipation constant of the thermistor (mW/K)

For accurate temperature measurement, the two temperature components in equation 16 must be at equilibrium, which occurs at $P = 0$. This is not exactly possible since some current, however small, must flow across the thermistor in circuit. A reasonable accuracy may still be obtained by making P as close to zero as possible (Khan and Sengupta, 1982, www.selcoproducts.com, 2003). This "zero power" sensing can be achieved here by making R_1 in Fig. 2 as large as possible.

Change in InT with T

Though ***InT***, which is assumed constant in equation 14 actually changes by ***0.31*** over the range of interest i.e. ***273K to 373K***, the magnitude of $K_C = 3InT$ is small compared to other terms. This change therefore has a very negligible effect on V'_0.

RESULTS

The circuit in Fig. 2 was as experimental circuit. Two sets of tests were carried out, the first using thermistor alone as the probe and the second using both the thermistor and the diode. The thermistor is ***RS*** bead thermistor with $R_0 = 4.7k$ at 25^0C and $B = 3977$. The diode is *IN4148* and is of silicon. The tests were carried out at convenient intervals in the range 0^0C to 100^0C and the corresponding output voltage V'0 was measured using a digital voltmeter with a resolution of 1mV. The results are shown in Figures 3 and 4.

The result in figure 3 shows a large deviation from linearity since only the thermistor is used as the probing element. A result with a maximum linearity error of 0.2% and a sensitivity of 4Mv/°C is shown in Figure 4 with both the thermistor and the diode as probing elements.

CONCLUSION

We have proposed a linearized temperature to voltage converter with a thermistor and a semiconductor diode as probing elements. The circuit, which is usable as a thermometer is basically a logarithmic network taking its input from a temperature-dependent current source. The circuit will however need to be calibrated for direct temperature measurement by adding another amplifier stage.

Notes:

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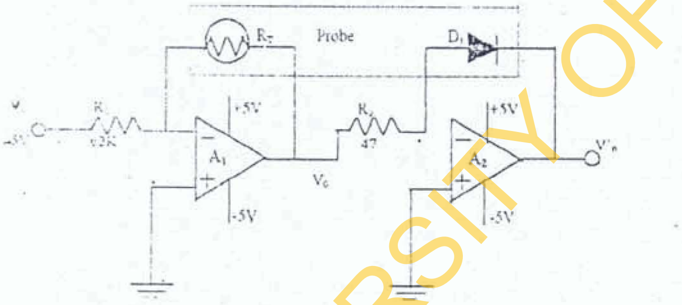

Fig 2-Circuit Implementation of the linearized thermometer circuit

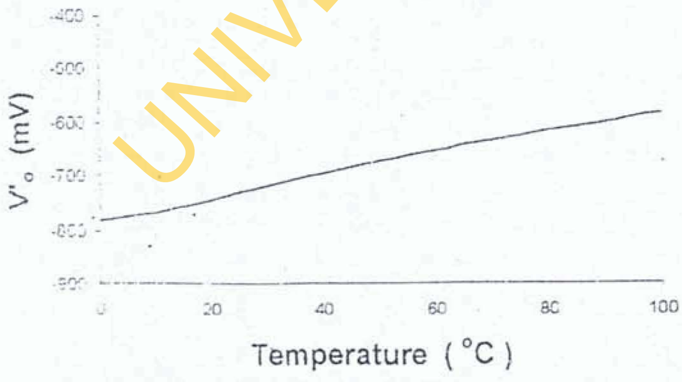

Fig. 3 - V'_o Versus Temperature With Only Thermistor as probing Element

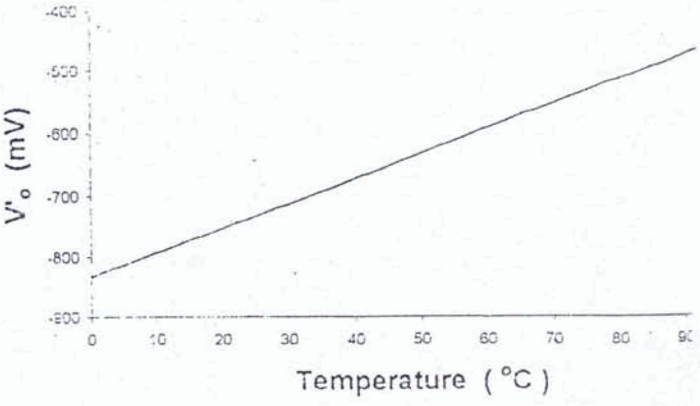

Fig. 4 - V'_o Versus Temperature With Thermistor and Diode 1N4148 as probing Element