LINEARIZATION OF NTC THERMISTOR CHARACTERISTIC USING OP-AMP BASED INVERTING AMPLIFIER

Thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF ELECTRICAL ENGINEERING

By

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2012

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We hereby recommend that the thesis prepared under our supervision and guidance by **Aloke Raj Sarkar** entitled **"LINEARIZATION OF NTC THERMISTOR CHARACTERISTIC USING OP-AMP BASED INVERTING AMPLIFIER"** be accepted in partial fulfillment of the requirements for the award of the degree of **"Master of Electrical Engineering"** at Jadavpur University. The project, in our opinion, is worthy of its acceptance.

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CERTIFICATE OF APPROVAL*

The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a satisfactory manner to warrant its acceptance as pre-requisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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DEDICATED

TO

MY PARENTS, MY YOUNGER BROTHERS AND SISTERS

AND

MY TEACHERS

ACKNOWLEDGEMENTS

Truly speaking I believe that just a mere “thank you” doesn’t do proper justice to peoples’ contribution towards most of the endeavors. But usually, that remains the only thing we can offer, not just to acknowledge their efforts but also to pacify our consciences.

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I am from a family, which always encourages for higher studies. My parents despite their modest formal education always give highest preference to my studies. I feel deep respect about my family. I am fortunate and proud to be a member of such a family.

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Kolkata: ………………………………..

May, 2012 **(**Aloke Raj Sarkar)

CONTENTS

INTRODUCTION

Calibration and linearization are two important topics that must always be considered to assure a measurement system's accuracy. The measurement of physical quantities by electrical transducers is frequently affected by offset, gain and nonlinear errors. These errors, which appear for example in temperature transducers, need compensation in order to improve transducer accuracy and sensitivity. Several methods can be found to linearise the transducer characteristics. A common solution for linearisation is based on dedicated electronic circuits, whose transfer function is the inverse of the characteristic to be linearised [1–10].

Signal conditioning arrangements for thermistors with negative temperature coefficient (NTC) have long been objects of inquest to engineers involved in research and developmental work related to transducers. The NTC thermistors, by virtue of their high sensitivity, find extensive usage in transducers for measurement and control of temperature and other physical variables (e.g. flow, humidity) and also as temperature compensating elements in electronic systems [11-14]. Further, the NTC thermistors have highly nonlinear (approximately exponential) resistance-temperature characteristics that make the devising of signal conditioning arrangements, a formidable task.

In the past, numerous signal conditioning circuits have been devised for NTC thermistors, aimed at obtaining an output that has a quasi-linear relation with the temperature being sensed. These linearising arrangements involved in the simplest form, passive components (resistances) either shunting the sensor or placed in series with it [15-17]. They were followed by logarithmic amplifier based systems [8, 10, 18, 19] and multivibrator circuits [20-24].

A parallel stream of developmental activities focused on software techniques, i.e. numerical methods and soft computing techniques for linearization [25-31].Recently, linearization circuit has been reported, that places the thermistor as one of the timing resistors for a 555 timer based circuit, with both analog and frequency outputs [32], and another that proposes a digital hardware based lineariser employing a dual slope analog to digital converter [33].

This thesis reports a low-cost linearising circuit for NTC thermistors, employing an op-amp based inverting amplifier, wherein, the thermistor is placed in series with the linearising resistance in the feed forward path. Unlike the usual practice, the value of the linearising resistance has been selected by defining a normalized deviation from linearity, and by numerically minimizing the sum-square value of this deviation considering several points across the intended working temperature. Experimental results show that the performance of the proposed scheme exhibit acceptable linearity which is comparable with the results obtained from other circuits reported in literatures [32]. However, the proposed circuit is somewhat simpler in configuration.

CHAPTER-1

LINEARIZATION TECHNIQUES FOR TRANSDUCERS

INTRODUCTION

All engineering industries have their ‘Control and Instrumentation (C and I)’ systems which enable them to operate in an efficient manner without violating the safety or operational constraints of the plants. The C and I systems cannot work without transducers. The function of a transducer is to convert a physical variable of one form into more convenient form, which for obvious reason, is an electrical signal in almost all cases. It is expected that a transducer should have a linear output versus input relation. However, the transducers have different types of errors in their output versus input characteristics. These errors can be corrected by linearization techniques or by compensation techniques that are extensions of the linearization methods.

In this chapter, the basics of transducer linearization, which provide the background knowledge for the present investigations, are discussed in brief.

1.1. LINEARIZATION

One of the important characteristics of an instrument or a measurement system is considered to be linearity. That is, the output is linearly related to the input. Seldom does a transducer, without the incorporation of additional arrangements, have a decent output versus input characteristics, i.e., ‘Transfer Characteristic’. The deviation from linearity is known as ‘Linearity Error’ or ‘Non-Linearity Error’. There are also other types of errors in the transfer curves. The process of reducing the ‘Linearity Error’ is called linearization. Often in the course of linearization, some of the other errors are also minimized.

It is desirable for most of the transducer systems to have a linear behavior. This is because the conversion from a scale reading to the corresponding measured value of input quantity is most convenient if one merely has to multiply by fixed constant rather than consult a non-linear calibration curve or compute from non-linear calibration equations. Also when the instrument is part of a large data or control system, linear behavior of the part often simplifies the design and analysis of the whole system.

1.2. STATIC ERRORS IN MEASUREMENT USING TRANSDUCER

An elementary discussion of these errors can be found in the text books [11, 34 and 35] A short overview is given here.

1.2.1. OFFSET ERROR

It is often found in case of measurement systems that the output is not zero even when the input is zero. This type of error is known as 'Offset Error'.

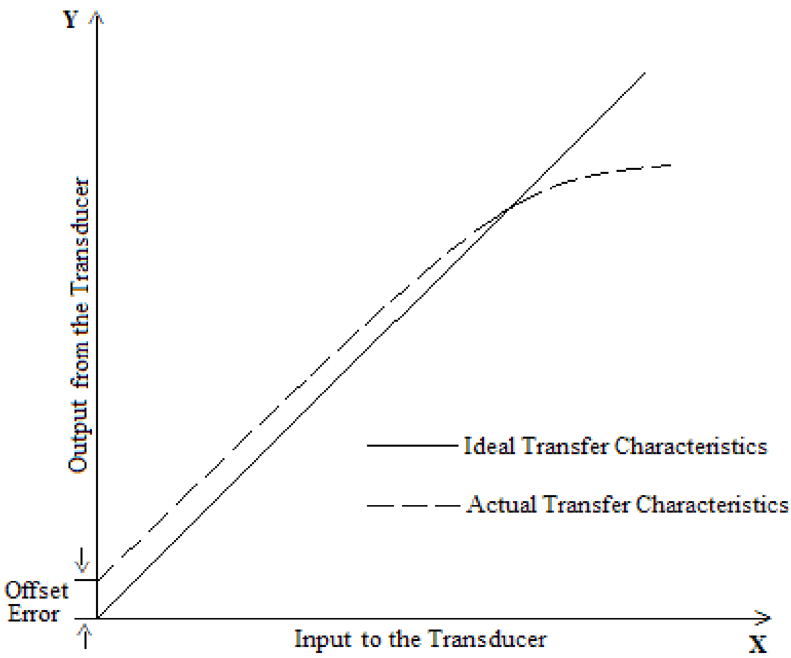

Fig.1.1 Offset Error

1.2.2. HYSTERESIS ERROR

The hysteresis error of a transducer is the output deviation at a certain input when that input is approached first in an increasing and then in a decreasing order.

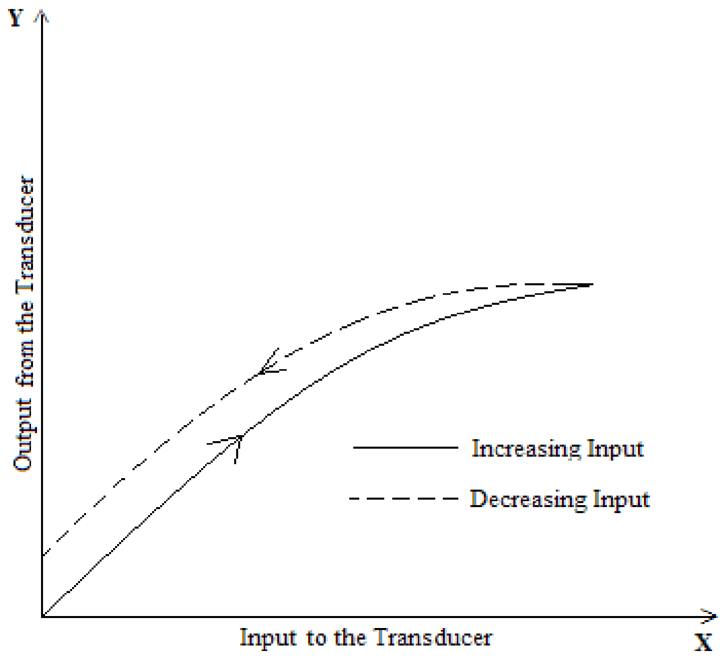

Fig.1.2 Hysteresis Error

1.2.3. GAIN ERROR

If the sensitivity or the transfer characteristics of any transducer differs from the desired sensitivity then it is known as ‘Gain Error’.

1.2.4. LINEARITY ERROR

As already mentioned, when the relationship between the output and the input of a transducer is not linear, the transducer has ‘Linearity Error’ or ‘Non-linearity’.

1.3. NECESSITY OF LINEARIZATION

Nonlinear transfer (output versus input) relations are undesirable due to following reasons,

(i) If the transducer output is used directly for analog display, the meter scale becomes non-uniform, which results in inconvenience in reading the scale.

(ii) As an alternative, if an analog meter with uniform scale, or a digital readout meter is used for measuring the transducer output, the conversion from the meter reading to the measurand value, requires referring to a nonlinear calibration curve. This is again an inconvenient thing to do.

(iii) In case of dynamic measurement, if the signal is fed to a recording instrument, the plot is a distorted version of the actual temporal variation of the measurand.

(iv) Digitization of a transducer output signal (uncorrected against nonlinearity) implies a very uneconomical utilization of the dynamic range of the ADC. Moreover, presence of a localized low sensitivity in the transfer curve lessens the number of ADC quantization levels available for a certain range of the input to the sensor.

(v) When the transducer is a part of a larger control system, its nonlinear output-input relation complicates the design and analysis of the whole. Presence of several such transducers in the system further aggravates the problem.

(vi) If the transducer forms part of a control loop, and if the transducer nonlinearity is not taken into account while designing the entire, the control system may exhibit certain abnormalities, one example is excessive oscillations.

1.4. MEASURE OF LINEARITY

There are many definitions of linearity that exist. However, linearity defined in terms of ‘Independent Linearity**’** is the most preferred, in many cases. The computation of ‘Independent Linearity’ is done with reference to a straight line representing the ideal relationship between output and input. This straight line is drawn by using the method of least squares from the given calibration data. This straight line is sometimes called an idealized straight line expressing the input-output relationship. The linearity is simply a measure of maximum deviation of any of the calibration point from this straight line.

The independent non-linearity or linearity error for any particular value of the input, may be defined as-

$$\text{NON-LINEARITY}=\frac{\text{Deviation of The Output From The Idealised Straight Line}}{\text{Actual Output}}\times 100 \qquad (1.1)$$

Or as

$$\text{NON-LINEARITY}=\frac{\text{Deviation of The Output From The Idealised Straight Line}}{\text{Full Scale Output}}\times 100 \qquad (1.2)$$

Equation (1.1) expresses the non linearity in terms of the percentage of the instrument reading and therefore recognizes the desirability of a constant percentage non-linearity. However, this expression cannot be used to quantify the zero-error. Therefore, we will be using the definition of non-linearity as given by equation (1.2). Equation (1.2) also can be rewritten as follows

$$\text{Linearity Error} = \frac{f(x)_{\text{actual}} - f(x)_{\text{ideal}}}{f(x_u)_{\text{actual}} - f(x_l)_{\text{actual}}}\times 100 \qquad (1.3)$$

The ideal (linear) transfer can be defined [35 and 37] in a number of alternative ways as shown in Fig.1.3. It is important to note that different definitions of ideal transfer may be well suited for different types of systems. As an instance, according to the standard load cell terminology of Scientific Apparatus Makers Association, Chicago, a straight line between no-load and full scale load outputs is considered as the ideal characteristic [11].

It is also worth noting that, with some transducers (example – resistive potentiometers), the linearity error [11] under loaded condition may be much worse than the specified (unloaded) value. In such cases, some form of buffer amplifier should be interposed between the transducer and the load.

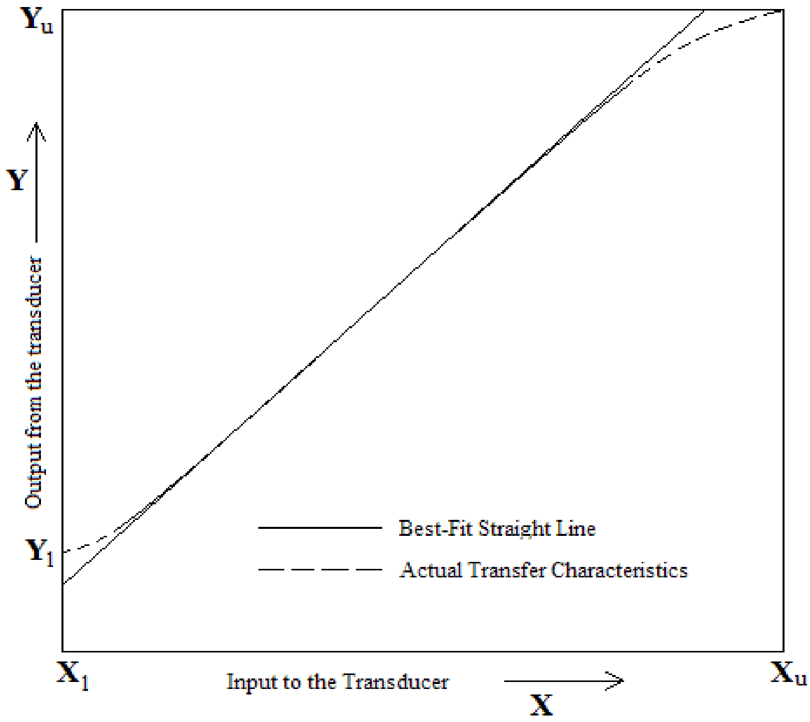

Fig.1.3. (a) Independent Linearity

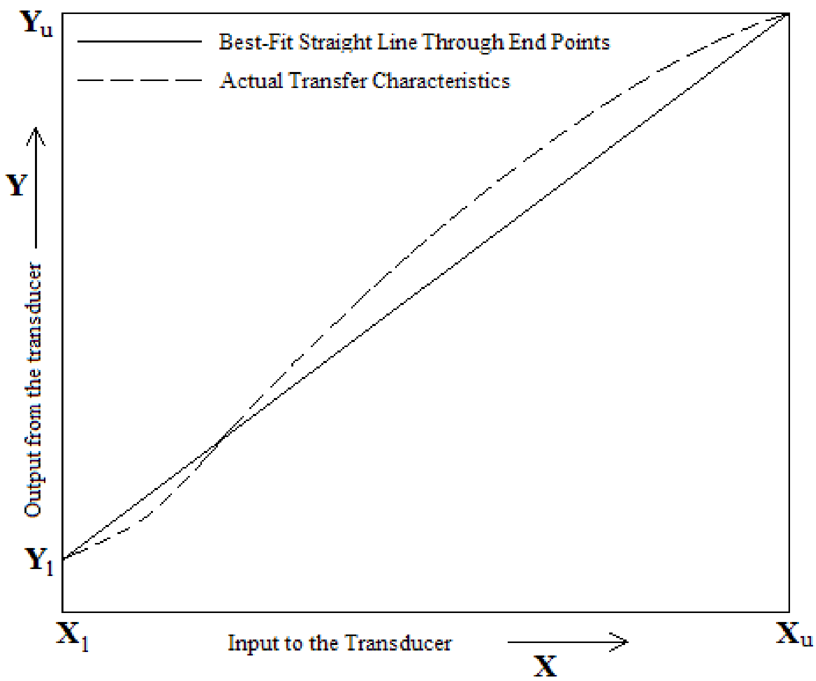

Fig.1.3. (b) Terminal Linearity

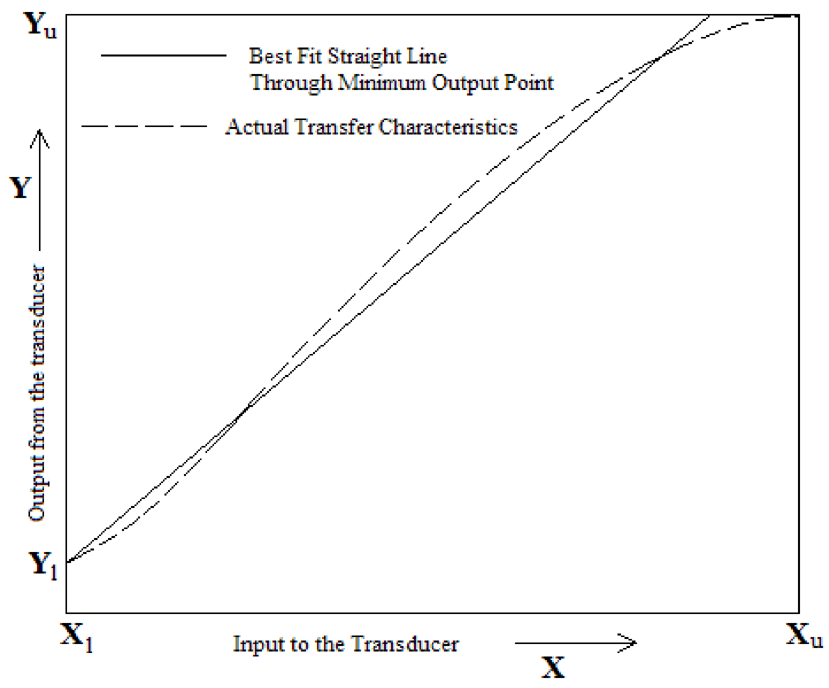

Fig.1.3. (c) Zero Based Linearity

Fig.1.3. Alternative Definitions of Ideal (Linear) Transfer Relation

1.5 LINEARIZATION – A SIMPLE APPROACH

Let $y = f(x)$ be the output signal of a transducer, where x is the physical variable being measured. If $f(x)$ is fed to a functional block as shown in Fig.1.4. such that the output $\varphi(y)$ of the block and $f(x)$ are opposite in their effect, the overall characteristic of the measurement system will be linear. The linearising functional block may be realised by hardware or by software. However, application of software method necessitates the use of a computer/processor-based system, wherein the signal is first digitized and then processed, using the relevant algorithm.

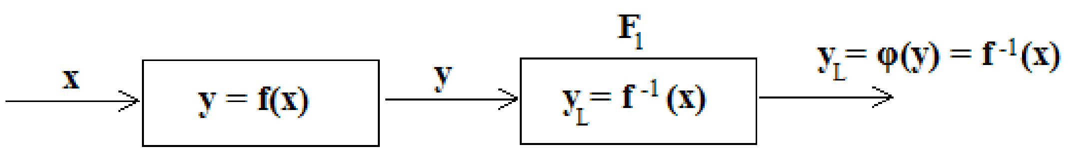

Fig.1.4. Block Diagram for a Transducer Linearization in a simple way

As an example, a sensor may have a logarithmic transfer characteristic, expressed as,

$$E(x) = K_0 + K_1 ln\ (\alpha + \beta x) \tag{1.4}$$

Where, K_0, K_1, α and β are sensor constants.

Such a characteristic can be easily linearised, for example, by utilizing the exponential relation between the base-emitter voltage and the collector current of a bipolar transistor shown in Fig.1.5. Hence, in an appropriately designed signal conditioning circuit, if voltage *E(x)* after proper scaling is applied across the base and the emitter of a bipolar transistor, the collector current becomes a linear function of *x.*

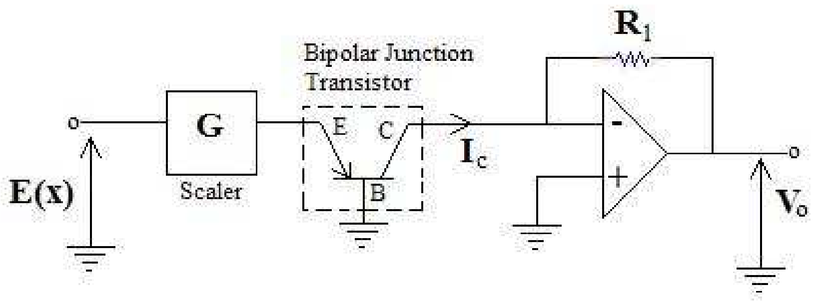

Fig.1.5. Linearization Using Bipolar Junction Transistor

In above circuit,

$$V_0 = -R_1 I_c \approx -R_1 I_{ES} \exp\ (V_{be} / U_T) \tag{1.5}$$

Where,

I_{ES} = A Transistor Parameter,

I_c = Collector Current,

V_{be} = Emitter-Base Voltage,

R_1 = Feedback Resistance,

and

$$U_T = \frac{kT_a}{q} \tag{1.6}$$

Where,

$k =$ Boltzmann Constant (1.38×10^{-23} J/K),

$T_a =$ Ambient Temperature,

$q =$ Charge of Electron (1.6×10^{-19} C)

By proper choice of G (in Fig.1.5)

$$V_0 = A\,(\alpha + \beta x) \tag{1.7}$$

Hence, the logarithmic transfer characteristic expressed in equation (1.4) becomes a linear transfer characteristic like equation (1.7).

The idea put forward is a simplified approach in the sense that transfer relations can never be exactly represented but can only be approximated by standard functions, and it is not always feasible to integrate the inverse function of the transducer characteristic either in electronic hardware or in software. Hence what is being referred to as linearization using the principle stated above, and also using the methods discussed in the subsequent sections, should be truly called *quasi-linearization*.

1.6 LINEARIZATION USING HARDWARE AND SOFTWARE

As already stated, the task of improving the linearity can be performed by signal processing, using electronic circuits (hardware) or by processing the digitized version of the transducer output using some software modules which essentially implement appropriate algorithms of some form or other. The electronic circuits that are used may be analog or digital in nature.

The hardware methods are in general inferior in accuracy to many of the software based linearizing techniques, due to the vastly improved numerical algorithms available now-a-days. However, the computational burdens of most of such algorithmic techniques result in unavoidable measurement time-delays, which must be accommodated. On the contrary, in the case of schemes employing hardware, barring few methods involving ADCs, the question of above mentioned time-delay does not arise [4].

Another point in favour of the electronic linearizing circuits is the fact that the software methods can only be employed in computer or processor based measurement systems; and in spite of the dwindling prices of the microprocessors and computers, it is still worthwhile to use electronic hardware for dedicated systems on the ground of cost-effectiveness.

1.7 LINEARIZATION USING ELECTRONIC HARDWARE

1.7.1 A GENERALISED THEORY OF LINEARIZATION

Let us consider a sensor (passive or active) placed in an appropriate linearising network, as shown in Fig. 1.6. The output signal of the network is $f(K,x)$, where x is the measurand, and K is a network parameter which is to be adjusted to an optimum value, to achieve maximum possible linearity of $f(K,x)$ versus x characteristic, over a range x_l (lower limit) to x_u (upper limit) of measurand. Let, x_m represent the midpoint of the range.

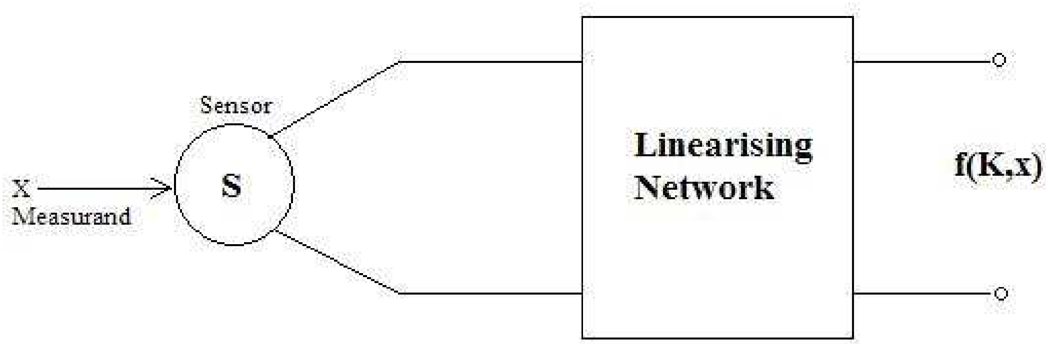

Fig.1.6. Pertaining To Generalized Theory of Linearization Using Hardware

Three commonly used methods for obtaining an optimum value of K are discussed below.

1.7.1.1 METHOD – I

To have perfect linearity, the following condition should be fulfilled.

$$f(K, x_m) - f(K, x_l) = f(K, x_u) - f(K, x_m)$$

that is

$$f(K, x_u) + f(K, x_l) = 2f(K, x_m) \tag{1.8}$$

The above equation yields an optimum value of ‘K’.

This approach is applicable only when the transfer relation of primary sensor does not deviate considerably from the ideal [38].

1.7.1.2 METHOD – II

If $f(K,x)$ is made to have a point of inflection at $x = x_r$, it is well known that $f(K,x)$ will be near-linear over a considerable span about $x = x_r$. Usually, the midpoint x_m of the range of interest is chosen as x_r [16].

Hence in this case, the condition that is to be imposed for obtaining an optimum K, is

$$\left.\frac{\partial^2 f(K,x)}{\partial x^2}\right|_{x=x_m} = 0 \tag{1.9}$$

1.7.1.3 METHOD – III

Let the normalized deviation of $f(K,x)$ from linearity, be defined for our purpose as

$$D(K,x) \;=\; \frac{f\left(K,x\right)-f_0}{f\left(K,x_u\right)-f_0} \;-\; \frac{x-x_l}{x_u-x_l} \qquad (1.10)$$

where, $\quad f_0 = f\left(K,x_l\right)$

The sum-square deviation is

$$S \;=\; \sum_{i\,=\,1}^{N} D^2\;(K,x_i) \qquad ;\;\; x_l \le x_i \le x_u$$

An optimum value of K can be evaluated by numerically minimizing the sum-square deviation S.

1.7.1.4 EXAMPLE

Fig. 1.7 depicts a thermistor temperature sensor in series with the linearising resistance r.

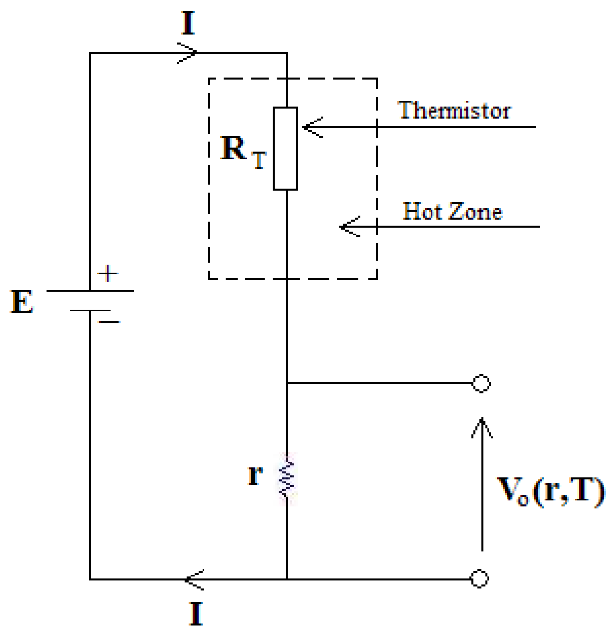

Fig.1.7. A Linearising Circuit For NTC Thermistor

The output voltage is

$$V_0\left(r,T\right) \;=\; V_i r \;/\; \left(r \;+\; R_T\right)$$

Where, T is the temperature (in Kelvin) under measurement.

The condition imposed is

$$\left.\frac{\partial^2 V_0(r,T)}{\partial T^2}\right|_{T=T_m} \;=\; 0$$

Considering the well known expression

$$R_T \;=\; R_{T_0} \exp\;\left[\beta\;\left(1/T \;-\; 1/T_0\right)\right]$$

the expression for the linearising resistance is obtained as,

$$r = R_{T_m}\left[\frac{\beta - 2T_m}{\beta + 2T_m}\right] \tag{1.11}$$

The independent linearity error pattern of modified transfer characteristic is shown in Fig.1.8.

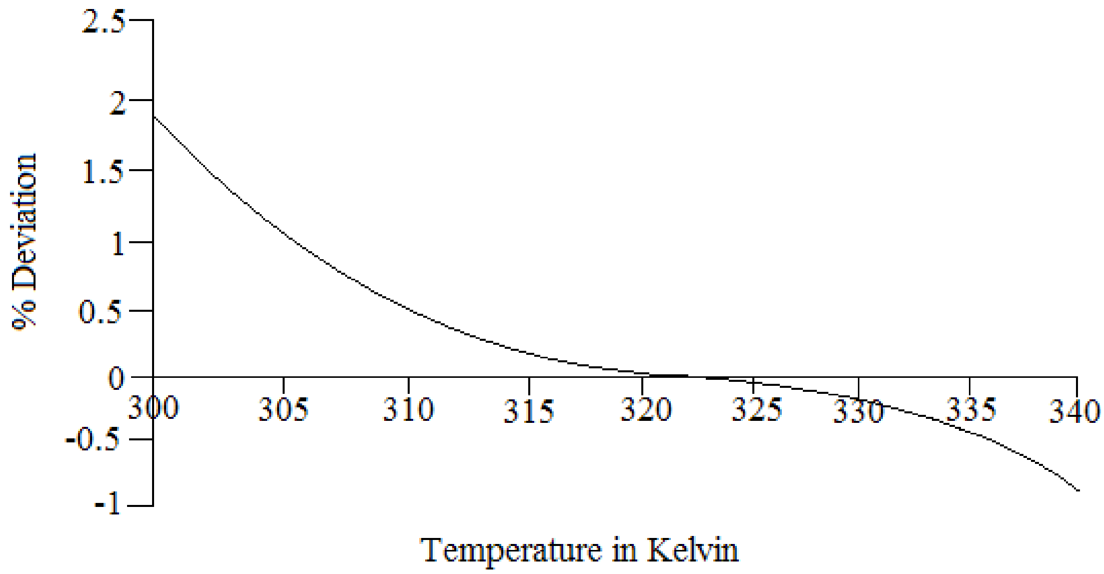

Fig.1.8. Deviation of normalized Output Voltage Versus Temperature Characteristic from linearity, for Series Resistance Linearization for Thermistor

1.8 SOFTWARE BASED LINEARIZATION TECHNIQUE

In the discussion to follow, normalised transducer transfers have been considered. By normalisation, the range under consideration [x_l, x_u] of the measured x is mapped on the range [-1, 1] for the normalised measurand $\overline{x}$. In a similar manner, the range [S_l, S_u] of the desired transducer output S should be mapped on the [-1, 1] range for the normalised output signal $\overline{S}$. Normalised input and output signals of the transducer are respectively,

$$\overline{x} = \frac{2x - x_u - x_l}{x_u - x_l} \qquad (1.12)$$

and

$$\overline{S} = \frac{2S - S_u - S_l}{S_u - S_l} \qquad (1.13)$$

Then, the normalised transfer characteristic of the transducer is,

$$\overline{y} = f(\overline{x})$$

Furthermore, let us assume that the desired normalised transfer $g(\overline{x})$ is a linear function of $\overline{x}$ with unity gain.

That is,

$$g\ (\overline{x})\ =\ \overline{x}$$

The point to note is that there is no previous knowledge about how to describe $f(\overline{x})$. However, several calibration measurements $f(\overline{x}_m)$ [$m = 1,.....,M$] are available, which can be used to determine an interpolation function which approximates the actual transfer function. The transfer characteristic of the transducer is to be linearized so that it approaches the ideal characteristic $g\ (\overline{x})$. The linearized transfer function $h\ (\overline{x})$ will therefore be derived from the transducer output $f(\overline{x})$, calibration measurements $f(\overline{x}_m)$ and corresponding ideal values $g(\overline{x}_m)$.

That is,

$$h\ (\overline{x}) = F[\,f(\overline{x}),\, f(\overline{x}_m), g(\overline{x}_m)] \tag{1.14}$$

1.8.1. LINEARIZATION USING LOOK-UP TABLE

The simplest and best known way of correcting the nonlinearity of any type of transducer transfer, is one which involves storing of the complete inverse function of the transfer in a look-up table (LUT) and to retrieve the corrected output value corresponding to the measured value of the transducer output signal [39-41]. A schematic and a graphical illustration explaining the method are given in Fig. 1.9 and Fig. 1.10 respectively.

An ADC is used to digitize the output signal of the transducer. Each quantization level of the ADC corresponds to an address of the location in the memory containing the LUT. Thus for any value $\bar{x}$ of the physical variable under the measurement, the digitized value *f[m]* of the transducer output serves as the address of the location in the look-up table containing the corresponding digital value for the measurand ,which can therefore be read out from the memory location. If necessary, the digital output can be converted into an analog signal using a DAC. It goes without saying that for better corrections, more and more values of the measurand should be kept stored in the table, which will call for increased memory size and consequently increased number of bits of an ADC.

The method of handling of look-up tables discussed above, requires a simple realization using digital hardware [40].

When the measurement system under consideration forms a part of a larger computer-based data acquisition system, the LUT is usually implemented using a reserved block of memory. In such a situation, the task of handling the LUT is taken over by software routine [39]. The table would begin at a start address and occupy, say, ‘M’ memory locations. To access the table, the program would add the ADC output *f[m]* to the starting address of the table, and fetch the content (that is the required value of the measurand) of the new address thus generated.

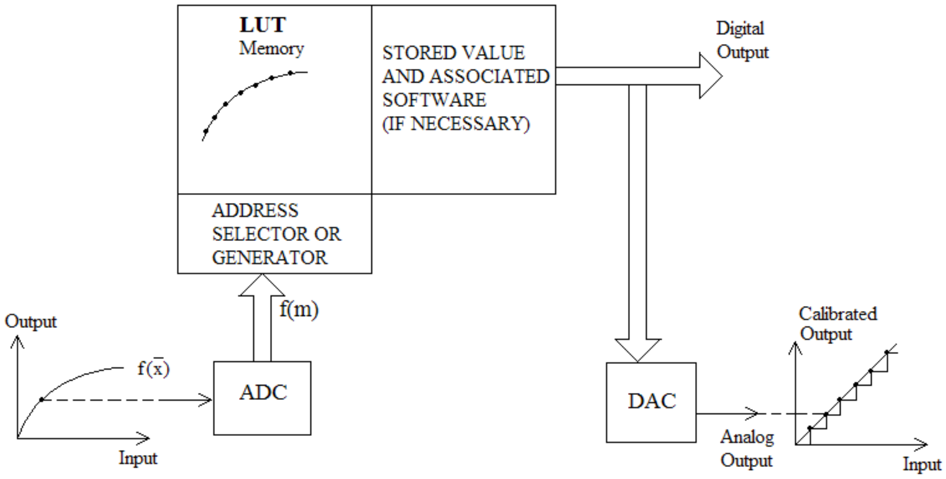

Fig.1.9. Schematic for Look-Up-Table Based Linearization

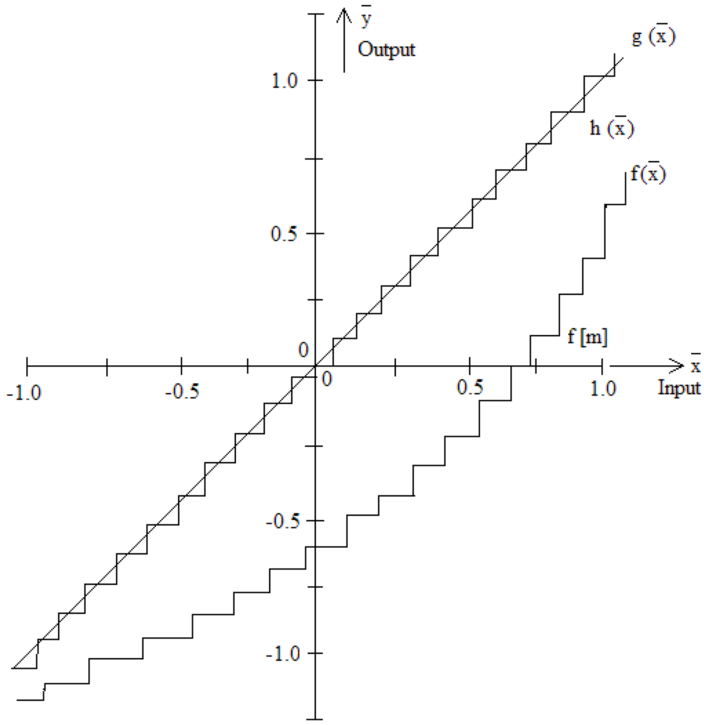

Fig.1.10. Graphs for Look-Up-Table Method

Since the disadvantage of the table look up method is that the LUTs consume much memory space, one compromise solution is to use a table occupying less memory space, which results in a coarse resolution and then to use a computation method to obtain a final accurate value of the measurand.

1.9 ADVANTAGES AND DISADVANTAGES OF HARDWARE AND SOFTWARE LINEARIZATION

Linearization is necessary for any kind of measurement using ‘Hardware’ or ‘Software’ method. These methods also have some advantages and disadvantages as stated below.

1.9.1 ADVANTAGES OF HARDWARE LINEARIZATION METHOD

(i) There is no measurement time delay almost in all type of hardware linearization method except a few (example – Analog to Digital Converter based method).

(ii) Hardware linearization method is still cost effective method compared to processor based method.

1.9.2 ADVANTAGES OF SOFTWARE LINEARIZATION METHOD

(i) In case of software linearization method improved numerical algorithms have resulted in vastly enhanced accuracy.

1.9.3 DISADVANTAGES OF HARDWARE LINEARIZATION METHOD

(i) In case of hardware linearization method accuracy is less than many software based linearization method.

(ii) To achieve the accuracy of a software linearization in hardware linearization the linearising circuit becomes much more complicated in compare with normal hardware linearization.

1.9.4 DISADVANTAGES OF SOFTWARE LINEARIZATION METHOD

(i) Software linearization is still expensive than their hardware counterparts.

(ii) Computational burdens results in unavoidable measurement time delay in this type of linearization.

(iii) Data loss will occur if nonlinear characteristic is directly used, as the resolution of ADC has some data loss.

CHAPTER-2

THERMISTOR AS TEMPERATURE SENSOR

INTRODUCTION

After time, temperature is the variable most frequently measured. The three most common types of contact electronic temperature sensors in use today are *thermocouples*, *resistance temperature detectors* (RTDs), and *thermistors*. Thermistors exhibit a very large resistance change for a small temperature change. This can be as large as 3 to 5% per °C (versus 0.4% per °C for RTDs) [42]. This makes them very sensitive to small temperature changes. They can be used to detect temperature changes as low as 0.1°C or smaller. A thermistor element is significantly smaller in size compared to RTD’s.

In this chapter the fundamentals of thermistor is discussed, as the background for the present investigations.

2.1. THERMISTORS

The term ‘Thermistor’ is used to describe a range of electronic semiconductor devices whose principle characteristic is that their electrical resistance changes in response to changes in their temperature. The word "Thermistor" originates from the description "thermally sensitive resistor". Thermistors are further classified as "Positive Temperature Coefficient" Thermistors (PTC Thermistors) or "Negative Temperature Coefficient" Thermistors (NTC Thermistors). In case of PTC thermistor, resistance increases as their temperature increases. For NTC thermistor, resistance decreases as their temperature increases.

The most important use of NTC thermistor is as a temperature sensor. It is manufactured from a mixture of metal oxides pressed into a bead, wafer or other shape. The bead is heated under pressure, at high temperatures, and then encapsulated with epoxy or glass.

2.2. THERMISTOR STANDARDS

At present, there are no standards applicable worldwide for thermistors (unlike the RTD). The base resistance (or nominal resistance) of NTC thermistors vary anywhere from 100

Ω to 10^6 Ω. The resistance versus temperature curves varies a lot as well. Each manufacturer and country uses different standards. Therefore, one must be careful not to use the wrong thermistor type. Base resistance values are typically measured at 25°C or 77°F (instead of 0°C for RTDs) [42], and are represented as R_{25}. For most applications, the R_{25} values are between 100 Ω and 100 kΩ [45]. Other R_{25} values as low as 10 Ω and as high as 40 MΩ can be produced, and resistance values at temperature points other than 25°C can be specified. The thermistor is limited to a small temperature range in which it maintains its accuracy. The numbers of applications for which the thermistor can effectively be used are limited. Currently, most are seen in medical equipment markets. Another area where thermistors are used, are for engine coolant, oil, and air temperature measurement in the transport industry.

2.3. THERMISTOR LEAD WIRE EFFECT

Lead wire used for the thermistor adds to the overall resistance of the thermistor (as with the RTD). However, the base resistance of the thermistor is usually so large (1000 Ω or more), that the added lead wire resistance has very little to almost no effect on the temperature reading. Thus, no resistance compensation is usually required for thermistors.

2.4. THERMISTOR MATERIALS AND CONFIGURATION

Commercial PTC thermistors are divided into two major categories. The first category consists of thermally sensitive silicon resistors, sometimes referred to as “silistors”. These devices exhibit a fairly uniform positive temperature coefficient (about +0.77% /°C) through most of their operational range, but can also exhibit a negative temperature coefficient region at temperatures in excess of 150°C [43]. These devices are most often used for temperature compensation of silicon semiconducting devices in the range of -60°C to +150°C [43]. The other major category is referred to as switching PTC thermistors. These devices are polycrystalline ceramic materials that are normally highly resistive but are made semiconductive by the addition of dopants. They are most often manufactured using compositions of barium, lead and strontium titanates with additives such as yttrium, manganese, tantalum and silica.

The NTC thermistors are composed of metal oxides. The most commonly used oxides are those of manganese, nickel, cobalt, iron, copper and titanium [44]. The fabrication of commercial NTC thermistors uses basic ceramic technology and continues today much as it has for decades. In the basic process, a mixture of two or more metal oxide powders are combined with suitable binders, are formed to a desired geometry, dried, and sintered at an elevated temperature. By varying the types of oxides used, their relative proportions, the sintering atmosphere, and the sintering temperature, a wide range of resistivities and temperature coefficient characteristics can be obtained. A thermistor's R/T characteristic and R_{25} value are determined by the particular formulation of oxides.

Of the thermistors, beads, discs, and chips are the most widely used for precise temperature measurement. Although each configuration is produced by a unique method, some general ceramic processing techniques apply to most thermistors formulation and preparation of the metal oxide powders; milling and blending with a binder; forming into a "green" body; heat-treating to produce a ceramic material; addition of electrical contacts (for discs and chips); and, for discrete components, assembly into a usable device with wire leads and a protective coating.

Bead thermistors, which have lead wires that are embedded in the ceramic material, are made by combining the metal oxide powders with a suitable binder to form a slurry. A small amount of slurry is applied to a pair of platinum alloy wires held parallel in a fixture. Several beads can be spaced evenly along the wires, depending on wire length. After the beads have been dried, the strand is fired in a furnace at 1100°C- 1400°C to initiate sintering. During sintering, the ceramic body becomes denser as the metal oxide particles bond together and shrink down around the platinum alloy leads to form an intimate physical and electrical bond. After sintering, the wires are cut to create individual devices. A glass coating is applied to provide strain relief to the lead-ceramic interface and to give the device a protective hermetic seal for long-term stability. Beads can be very small, less than 1 mm in size some cases. The result is a temperature sensing device that displays a very distinct non-linear resistance versus temperature relationship.

Disc thermistors are made by preparing the various metal oxide powders, blending them with a suitable binder, and then compressing small amounts of the mixture in a die under several tons of pressure. The discs are then fired at high temperatures to form solid ceramic bodies. A thick film electrode material, typically silver, is applied to the opposite sides of the disc to provide the contacts for the attachment of lead wires. A coating of epoxy, phenolic, or glass is applied to each device to provide protection from mechanical and environmental stresses.

Chip thermistors are manufactured by tape casting, a more recent technique borrowed from the ceramic chip capacitor and ceramic substrate industries. An oxide-binder slurry similar to that used in making bead thermistors is poured into a fixture that allows a very tightly controlled thickness of material to be cast onto a belt or movable carrier. The cast material is allowed to dry into a flexible ceramic tape, which is cut into smaller sections and sintered at high temperatures into wafers 0.01 in. to 0.03 in. (0.25 mm to 0.80 mm) thick. After a thick film electrode material is applied, the wafers are diced into chips. The chips can be used as surface mount devices or made into discrete units by attaching leads and applying a protective coating of epoxy, phenolic, or glass.

Washer-shaped thermistors are essentially a variation of the disc type except for having a hole in the middle, and are usually leadless for use as surface mount devices or as part of an assembly. Rod-shaped thermistors are made by extruding a viscous oxide-binder mixture through a die, heat-treating it to form a ceramic material, applying electrodes, and attaching leads. Rod thermistors are used primarily for applications requiring very high resistance and/or high power dissipation.

2.5. BASIC CONCEPTS RELATED TO THERMISTOR

To understand the applications of thermistors and the selection of thermistor components in the design of thermistor circuits it is necessary to be aware of some basic concepts and definitions. This section covers some of these topics.

2.5.1. SLOPE OF RESISTANCE VERSUS TEMPERATURE CURVE (RESISTANCE RATIO)

In considering the relationship between resistance and temperature of thermistors there are some important concepts. One such concept is slope, which is an indication of the rate of change of the resistance of the component with temperature.

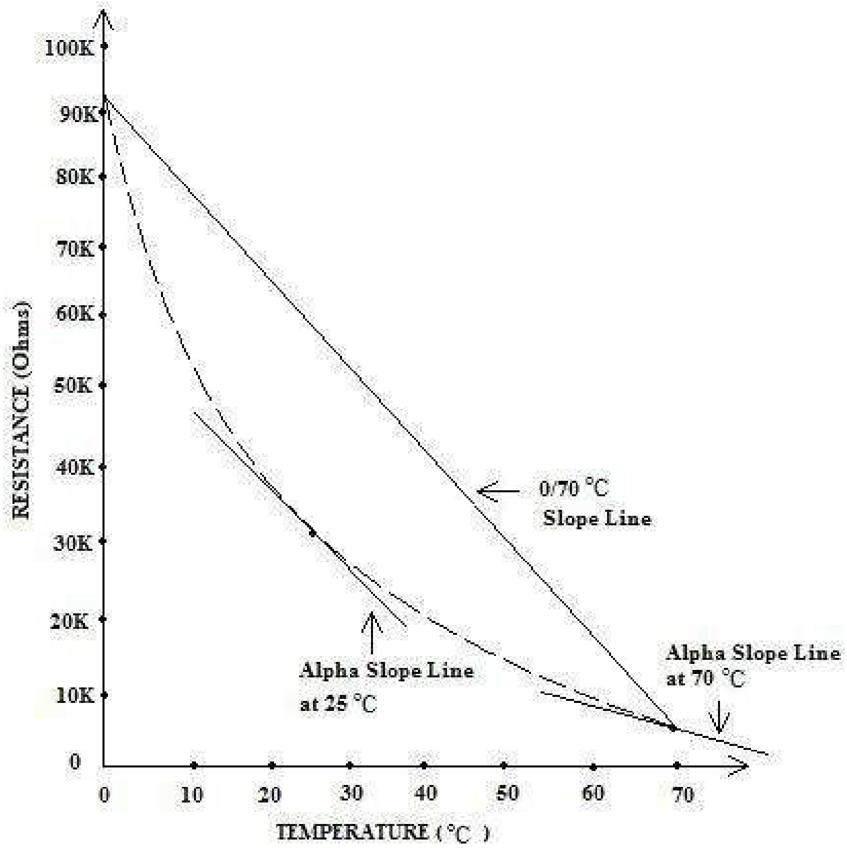

Fig.2.1. Relationship between Thermistor Resistance and Temperature

The slope or resistance ratio for thermistors is defined as the ratio of resistance at one temperature (usually 0^oC) to the resistance at a second and higher temperature (usually 70^oC) [46].

The concept of resistance / slope is demonstrated in Fig. 2.1, where the $0/70^oC$ slope line connects the resistance value at 0^oC to the resistance value at 70^oC. This provides an indication of the rate of change of resistance with temperature and the potential thermal sensitivity of the component.

Slope or resistance ratio provides an introduction to the concept of rate of change of resistance with temperature and the sensitivity of the resistance of thermistors to temperature change. This concept is developed further by considering the more general case of thermal sensitivity in terms of percentage resistance change of a component per degree centigrade increase in temperature.

2.5.2. TEMPERATURE COEFFICIENT ALPHA (α)

Alpha, a material characteristic, is defined as the percentage resistance change per degree Centigrade. Alpha is also referred to as the temperature coefficient. As an example, for Negative Temperature Coefficient (NTC) Thermistors, typical values of alpha are in the range -3%/^{o}C to -6%/^{o}C [46]. The temperature coefficient is a basic concept in thermistor calculations.

Because the resistance of NTC thermistors is a nonlinear function of temperature, the alpha value of a particular thermistor material is also nonlinear across the relevant temperature range, as illustrated in Fig. 2.1. The alpha value is a material constant and is independent of the resistance of the component at that temperature.

The relevance of alpha values to the Resistance versus Temperature curve of particular material is illustrated in Fig. 2.2. In this Fig. 2.2, a tangent line is drawn along the R-T curve at 25^{o}C. This line represents the gradient or "steepness" of the curve at 25^{o}C. From the definition of Alpha given above, it may be calculated as follows

$$\alpha = \frac{1}{R_T} \times \frac{dR_T}{dT} \times 100 \qquad (2.1)$$

Where

R_T is the resistance of the component at the relevant temperature T (^{o}C),

$\frac{dR_T}{dT}$ is the gradient of the Resistance versus Temperature curve at that temperature point,

and

α is expressed in units of "percentage change per degree Centigrade"

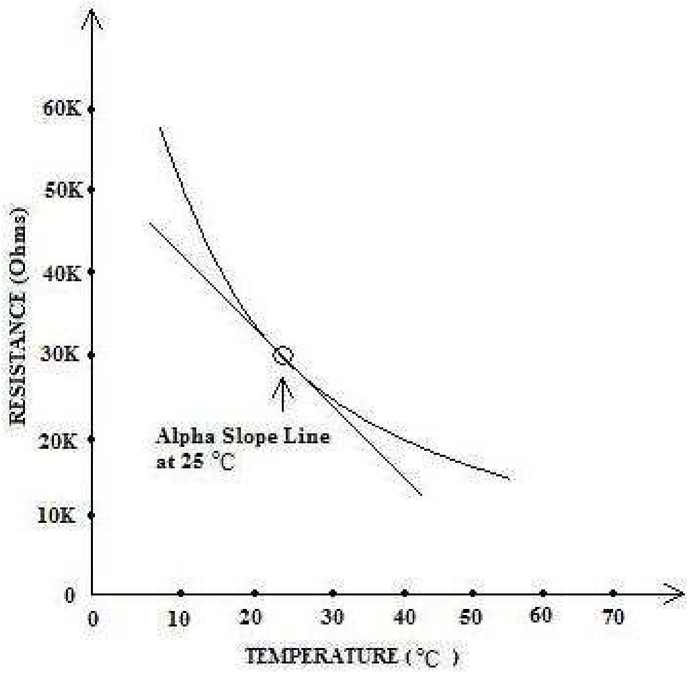

Fig.2.2. Alpha Slope Line of Thermistor at 25 ^{o}C

The purpose of the concepts that have been introduced and discussed so far is to enable some basic calculations to be performed. The most important calculations required in case of thermistors are those that relate the resistance of thermistor components to their temperature.

The approach of using temperature coefficient values is adequate provided that accurate alpha values and resistance values are available for a range of temperature points for the thermistor materials. Using some given alpha values in equation 2.1 is useful for initial selection of thermistors for applications. The method is somewhat slow and highlights the need for a mathematical model that can be used to relate the resistance and temperature of thermistors by a single equation.

The need for such a model is especially relevant to allow computation of R/T values using modern calculators, computers or microcontrollers.

2.5.3. EXPONENTIAL MODEL OF NTC THERMISTOR (BETA VALUE (β) OR SENSITIVITY INDEX)

Using principles of solid state physics [46] it is obtained that the Resistance (R) of a piece of material of resistivity ρ (ohm-cm) is proportional to this resistivity value. Hence,

$$R = \rho \times \frac{t}{A} \tag{2.2}$$

Where

R is the resistance in ohms,

t is thickness of the material (length of current path),

A is the cross-sectional area.

It follows that the expression for resistance as a function of temperature can be stated as

$$R_T \propto \exp\left(\frac{1}{T}\right) \tag{2.3}$$

Where,

R_T denotes Resistance in ohms at temperature T Kelvin.

As outlined above, a simple approximation for the relationship between Resistance and Temperature for an NTC thermistor assumes an exponential relationship between them. This approximation is based on simple curve fitting to experimental data and also on an intuitive feel for electrical behavior of semiconductor devices [46]. The exponential approximation is a mathematical model that applies an equation that can be expressed in the form

$$R_T = A \ \exp\left(\frac{\beta}{T}\right) \qquad (2.4)$$

Where

R_T is the Resistance in ohms at temperature T

T is the absolute Temperature in Kelvin

A is a linear factor

β is the exponential factor or sensitivity index of the thermistor material.

The β value is a very important parameter in the description and specification of thermistor materials and thermistor components. When the natural logarithm of both sides of the equation is taken, the relationship becomes

$$\ln\ (R_T)\ =\ C\ + \left(\frac{\beta}{T}\right) \qquad (2.5)$$

Where

C is a constant factor, (C = ln(A)) from the equation (2.4).

If *ln(*R_T*)* is plotted against 1/T, then the slope of the resulting curve will be equal to β**.** This equation provides a reasonable approximation to measured data, but the thermistor materials are not ideal materials. For the exponential model to apply over a large temperature range (greater than 50^{o}C), the beta value has to vary, therefore the β value is not constant over extensive ranges. In fact, the β value is also temperature dependent and it decreases with temperature. Although this simple exponential model for the relationship between the resistance and the temperature of a thermistor is limited to short temperature spans, concepts derived from it is import in the specification of NTC thermistors.

2.5.4. PRACTICAL APPLICATION OF THE BETA VALUE

It is common practice to specify thermistor materials in terms of beta value over a particular temperature.

For a temperature T_1 and thermistor resistance R_1 at this temperature T_1

$$R_1 = A \ \exp \ \left(\frac{\beta}{T_1}\right) \tag{2.6}$$

For a temperature T_2 and thermistor resistance R_2 at this temperature T_2

$$R_2 = A \ \exp \ \left(\frac{\beta}{T_2}\right) \tag{2.7}$$

Taking the ratio of R_1 and R_2

$$\frac{R_1}{R_2} = \ \exp \ \left[\beta \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{2.8}$$

The expression for β from equation (2.18) become

$$\beta \ = \ \frac{1}{\frac{1}{T_1} - \frac{1}{T_2}} \times ln\left(\frac{R_1}{R_2}\right) \tag{2.9}$$

In this form, β values can be used to calculate resistance or temperature values when other items in the equation are known. The β value can then be regarded a quantitative value of thermistor materials that is assigned as a material constant and that indicates the relationship of material resistivity to temperature. The general information on sensitivity of material resistivity to temperature that can be interpreted from the beta value. The beta value is derived from a mathematical approximation. For this mathematical approximation to apply over a large temperature range, beta has to vary with temperature. The variation is greater at the low Temperature.

Because the beta value is an indication of the relationship between the resistivity of thermistor material and temperature, it can also be used to calculate alpha (α) value (temperature coefficient) for a thermistor made from the same material. Recalling the definition of the alpha value as the percentage change in resistance per ^{o}C, given by equation (2.1), and expressing R as a function of T using the exponential model, it can be shown that a good approximation for the temperature coefficient or alpha value, at a temperature T Kelvin, in terms of beta is

$$\alpha = \frac{-\beta}{T^2} \times 100 \qquad (2.10)$$

Where

α is expressed in units of "percentage change per degree Centigrade".

The β value is a single expression that can be considered to represent a material constant. It depends on basic material properties, and beta values derived from measurements provide an indication of general thermistor material quality.

2.5.5. FURTHER MODELLING OF NTC THERMISTOR RESISTANCE VERSUS TEMPERATUR CHARACTERISTICS

The concepts introduced so far to relate the resistance of a thermistor to the temperature have been primarily based on the characterization and specification of materials and on the use of material parameters rather than on component parameters.

While the temperature coefficient or α value can be used to calculate the temperatures corresponding to various resistance values of a thermistor, the method is rather limited. A look-up table of Resistance versus Temperature values for the thermistor is required and details of α values at various points are needed also. It is very useful and relevant in certain situations.

The use of β values or sensitivity index, and the associated exponential model are useful for material specification, and for the comparison of the sensitivity of bulk materials. The method is somewhat limited for general use in relating the resistance of a thermistor to temperature over extensive ranges mainly because of the temperature dependence of the β Value itself.

In general applications, NTC thermistors are used to measure temperature, and this is accomplished by measuring the resistance of the thermistor and then using that resistance value to make an estimate of temperature. The various means of relating resistance of a thermistor to the temperature that have been discussed so far are not ideally suited to this, as outlined above. The requirement is for a single equation that can be used easily to relate resistance and temperature of thermistors. The requirement is all the more important to optimize the use of programmable calculators, computer spreadsheets and microcontrollers.

The method used for accurate mathematical modeling of the Resistance versus Temperature characteristic of a thermistor is to obtain accurate measurements of Resistance and Temperature of components and to apply curve fitting techniques to model the relationship between them.

The next section of this chapter describes the mathematical model, which is in general use, to give a single equation that relates the Resistance and Temperature of an NTC thermistor component. The equation is called the Steinhart-Hart Equation.

2.5.6. THE STEINHART-HART THERMISTOR EQUATION

The Steinhart-Hart thermistor equation is named for two oceanographers associated with Woods Hole Oceanographic Institute on Cape Cod, Massachusetts. The equation is derived from mathematical curve fitting techniques and examination of the Resistance versus Temperature characteristic of thermistor devices. In particular, using the plot of the natural logarithm of resistance value, *ln(R)* versus *(1/T)* for a thermistor component to consider (1/T) to be a polynomial in *ln*(R), an equation of the following form is developed

$$\frac{1}{T} = A_0 + A_1 \ln R + \ .... + A_N (\ln R)^N \qquad (2.11)$$

Where

T is the temperature in Kelvin,

and

$A_0....A_N$ are polynomial coefficients that are mathematical constants.

The order of the polynomial to be used to model the relationship between R and T depends on the accuracy of the model that is required and on the non-linearity of the relationship for a particular thermistor. It is generally accepted that use of a third order polynomial gives a very good correlation with measured data, and that the "squared" term is not significant. The equation then is reduced to a simpler form, and it is generally written as

$$\frac{1}{T} = A + B \ln R + C(\ln R)^3 \qquad (2.12)$$

where

A, B, and C are constant factors for the thermistor that is being modeled

T is the temperature in Kelvin

and

R is the resistance in ohms.

This equation (2.14) is the Steinhart-Hart equation, with Temperature as the main variable. The equation (2.14) is relevant for the complete useful temperature range of a thermistor. The coefficients A, B, and C are constants for the individual thermistors. Unlike Alpha and Beta they should not be regarded as material constants.

To yield resistance (R) as a function of temperature (T), equation (2.12) can be rearranged into

$$R = \exp\left[\left(x - \frac{y}{2}\right)^{1/3} - \left(x + \frac{y}{2}\right)^{1/3}\right] \tag{2.13}$$

Where

$$y = \frac{A - \frac{1}{T}}{C}$$

and

$$x = \sqrt{\left(\frac{B}{3C}\right)^3 + \frac{y^2}{4}}$$

The A, B, and C constants are established for individual thermistors in a particular temperature range as follows.

The equation (2.12) is considered for three temperature points in the range - usually at the low end, the middle and the high end of the range. This ensures best fit along the full range. (The smaller the temperature range, the better the calculations will match the measured data.) The temperature values are usually taken to be 0^oC, 25^oC and 70^oC . Therefore these values are used to illustrate the principle [46]. Precisely controlled measurements of temperature and associated resistance value of the thermistor are made in a temperature controlled medium at these three calibration points. These accurately measured values of Resistance and Temperature are inserted into the equation to form three simultaneous equations as follows with temperature (T) is considered as in Kelvin

$$\frac{1}{T_0} = \frac{1}{273.15} = A + B\ln R_0 \ + \ C(\ln R_0)^3 \tag{2.14}$$

$$\frac{1}{T_{25}} = \frac{1}{298.15} = A + B\ln R_{25} \ + \ C(\ln R_{25})^3 \tag{2.15}$$

$$\frac{1}{T_{70}} = \frac{1}{343.15} = A + B\ln R_{70} \ + \ C(\ln R_{70})^3 \tag{2.16}$$

Since the resistance values are measured numerical quantities, the equations are a system of three simultaneous equations in three unknowns namely A, B and C. The values for A, B and C can be found by standard mathematical techniques for solving simultaneous equations, or by use of analytical software tools. These A, B and C coefficients are sometimes referred to as the "Steinhart Coefficients" for a thermistor. For thermistors with higher resistance values, which are generally used at higher temperatures, the Steinhart-Hart coefficients should be derived usually at the low end, the middle and the high end of the temperature range.

It should be noted that the Steinhart-Hart equation produces a good approximation to the relationship between T and R for the complete range of a thermistor based on data from just three calibration points. The Steinhart-Hart equation is a very useful means of modeling the Resistance versus Temperature characteristics of a Thermistor but it should be remembered that it provides good correlation with actual measurements for a thermistor in ideal measurement conditions.

2.6. FACTORS AFFECTING MEASURED RESISTANCE VALUES OF THERMISTORS

In the following section factors that affect the measured resistance value of a thermistor is discussed. These factors are associated with thermistor properties or characteristics that are the basis of general thermistor applications. It is essential that developers of thermistor circuits have an understanding of these characteristics to exploit relevant thermistor properties in a particular application and to minimize the influence of other properties that could adversely affect thermistor performance in the application.

2.6.1. SELF HEATING EFFECT OF THERMISTORS

When a current flows through a thermistor, it will generate heat which will raise the temperature of the thermistor above that of its environment. If the thermistor is being used to measure the temperature of the environment, this electrical heating may introduce a significant error if a correction is not made. Alternatively, this effect itself can be exploited [47].

The electrical power input to the thermistor is just

$$P_E = IV \qquad (2.17)$$

Where

I is current through the thermistor

and

V is the voltage drop across the thermistor

This power P_E is dissipated in the component, and for a thermistor the power causes heating of the thermistor. The heating effect in turn causes the resistance of the thermistor to decrease. This power dissipation is known as self-heating of the thermistor. The rate of transfer of this power P_E is well described by Newton's law of cooling as stated below

$$P_T = K\left[T(R) - T_0\right] \qquad (2.18)$$

Where,

$T(R)$ is the temperature of the thermistor as a function of its resistance R,

T_0 is the temperature of the surroundings,

and

K is the dissipation constant, usually expressed in mW per °C .

At equilibrium, these two powers must be equal that is $P_E = P_T$.

The current and voltage across the thermistor will depend on the particular circuit configuration. As a simple example, if the voltage across the thermistor is held fixed, then by Ohm's Law we have I = V / R (where I is the current through the thermistor, V is the voltage drop across the thermistor and R is the corresponding temperature of the thermistor) and the equilibrium equation can be solved for the ambient temperature as a function of the measured resistance of the thermistor

$$T_0 = T(R) - \frac{V^2}{KR} \tag{2.19}$$

If the power levels are moderate (of the order of a few mW), the self-heating will not continue indefinitely, because the thermistor will reach thermal equilibrium with its environment. It should be noted that when this "steady" state is reached, the resistance of the thermistor will not accurately represent the temperature of its environment. Instead, the resistance of the thermistor will be lower than expected, because of the self heating effect. To obtain a resistance reading from the thermistor that accurately represents the temperature of its environment it is critical that the power levels (essentially the current levels) associated with the measurement are low enough not to cause appreciable self heating.

2.6.2. ZERO-POWER RESISTANCE CHARACTERISTIC

The *"zero-power resistance characteristic"* is a description of "ideal" conditions for resistance measurement. *The Zero-Power Resistance (R_o) at a specific temperature T, is defined as the measured DC (Direct Current) resistance when the power dissipation is negligible.* In practical terms, a thermistor is generally considered to be dissipating zero-power when the current through it is less than 100 µA [46].

Zero-power sensing refers to applications that use thermistors in such a way that the resistance of the thermistor will reflect the temperature of the medium.

2.6.3. THERMAL TIME CONSTANT (T.C.)

When a thermistor is being used to monitor the temperature of its environment, the accuracy of measurement of the resistance of the thermistor is critical. While the power dissipated in the thermistor is an important factor in this measurement, the thermal characteristics of the system and the thermistor are important as well. This is especially relevant in systems where the temperature is changing with time. The dynamic thermal response of the thermistor must be considered in these situations. To quantify this dynamic response, the concept of a Thermal Time Constant (T.C.) is used in the thermistor industry and it is defined below.

The Thermal Time Constant for a thermistor is the time required for a thermistor to change its body temperature by 63.2% of a specific temperature span, when the measurements are made under zero-power conditions in thermally stable environments.

2.6.4. THERMAL DISSIPATION CONSTANT (D.C.)

Since the measured resistance of a thermistor at a particular time depends on the power dissipated in the thermistor during measurement, and on the thermal dynamics of the system being measured, it is useful to quantify the combined effect of these two factors. This leads to the concept of Thermal Dissipation Constant (D.C.), which is defined below.

The Thermal Dissipation Constant of a thermistor is defined as the power required to raise the thermistor's body temperature by $1^{o}C$ in a particular measurement medium. The 'Thermal Dissipation Constant' is expressed in units of $mW/^{o}C$ (milliwatts per degree Centigrade).

The dissipation constant is a measure of the thermal connection (coupling) of the thermistor to its surroundings. Its value is generally provided for the thermistor in still air, and in well-stirred oil. If the temperature of the environment is known beforehand, then a thermistor may be used to measure the value of the dissipation constant.

The Thermal Dissipation Constant is an important factor in applications that are based on the self-heating effect of thermistors. *In particular, the resistance change of a thermistor due to change in Thermal Dissipation Constant can be used to monitor levels or flow rates of liquids or gasses.* For example as flow rate increases, Thermal Dissipation Constant of a thermistor in a fluid path will increase and the resistance will change in a manner that can be correlated to flow rate.

2.7. VOLTAGE-CURRENT CHARACTERISTICS

As stated previously in section 2.6.1 that, thermistors are devices that obey Ohm's law at temperature points within their useful range. Since Ohm's law relates Voltage and Current of a component, it is useful to consider the voltage versus current characteristics of thermistor components.

A typical voltage-current characteristic for thermistor is illustrated in Fig.2.3 below. When the amount of power dissipated in the thermistor is negligible, the voltage-current characteristic will be tangential to a line of constant resistance that is equal to the zero-power resistance of the device at the specified ambient temperature.

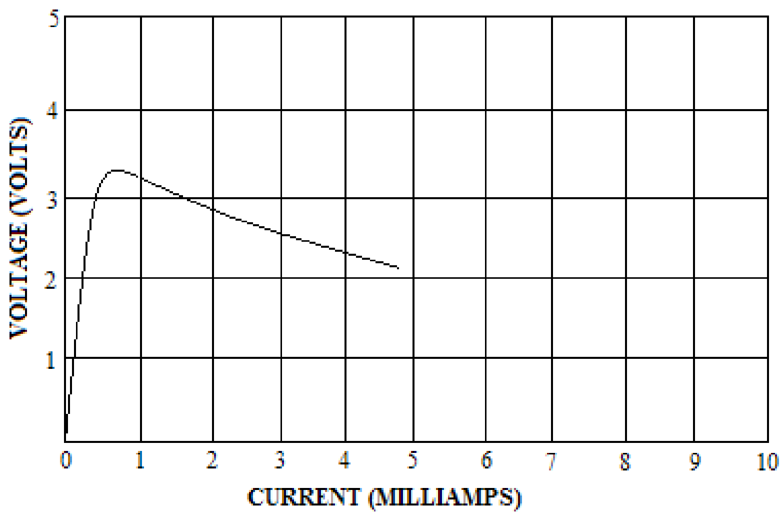

Fig.2.3. Typical Voltage Current Characteristic (Linear Scale)

As the current further increased, the effects of self-heating become more evident and the temperature of the thermistor rises with a resultant decrease in its resistance. For each subsequent incremental increase in current, there is a corresponding decrease in resistance. Hence, the slope of the voltage-current characteristic ($\Delta E/\Delta I$) decreases with increasing current. This continues until a current value (I_P) is reached for which the slope becomes zero and the voltage reaches a maximum value (E_P). As the current is increased above the value of (I_P), the slope of the characteristic continues to decrease and the thermistor exhibits a negative resistance characteristic.

2.8. CURRENT-OVER-TIME MODE

The current-over-time characteristic of a thermistor depends on the dissipation constant of the thermistor package, as well as on the element's heat capacity. As current is applied to a thermistor, the package will begin to get heated. If the current is continuous, the resistance of the thermistor will start reducing. The thermistor current- time characteristics can be used to slow down the affects of a high voltage spike, which could be for a short duration. In this manner, a time delay from the thermistor is used to prevent false triggering of relays.

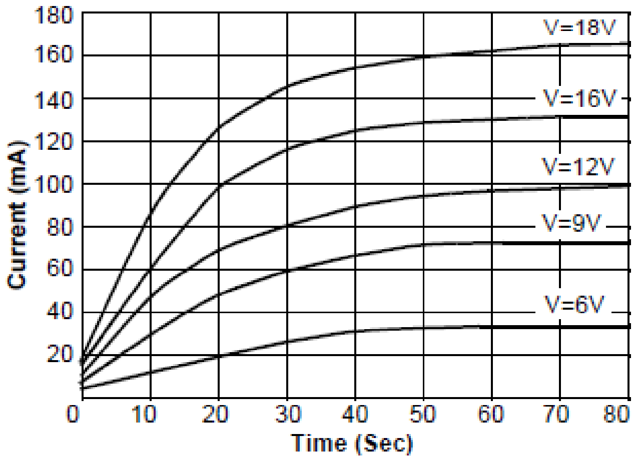

Fig.2.4. Typical Current Time Characteristics

The effect of the thermistor current-over-time delay is shown in Fig.2.4. This type of time response is relatively fast as compared to diodes or silicon based temperature sensors. The diode and silicon based sensors require several minutes to reach their steady state temperature. In contrast, thermocouples and RTDs are equally as fast as the thermistor, but they don't have the equivalent high level outputs. Applications based on current-over-time characteristics include time delay devices, sequential switching, surge suppression or inrush current limiting.

2.9. TOLERANCE OF THERMISTORS

Having considered some of the factors and conditions that affect the measured value of the resistance of a thermistor, it is important to consider inherent thermistor properties that affect the measured value of resistance of a thermistor at a particular temperature. In this respect, the concept of tolerance is essential in selecting and specifying thermistors for an application.

Tolerance for thermistors is the specified resistance percentage or temperature deviation from curve nominal values. Tolerance can be specified as a +/- percentage at a single temperature point or as a temperature value in °C over a particular temperature range.

2.10. APPLICATIONS OF THERMISTORS

(i) PTC thermistors can be used as current-limiting devices for circuit protection, as replacements for fuses. Current through the device causes a small amount of resistive heating. If the current is large enough to generate more heat than the device can lose to its surroundings, the device heats up, causing its resistance to increase, and therefore causing even more heating. This creates a self-reinforcing effect that drives the resistance upwards, reducing the current and voltage available to the device.

(ii) PTC thermistors are used as timers in the degaussing coil circuit of most CRT (cathode ray tube) displays and televisions. When the display unit is initially switched on, current flows through the thermistor and degaussing coil. The coil and thermistor are intentionally sized so that the current flow will heat the thermistor to the point that the degaussing coil shuts off in under a second. For effective degaussing, it is necessary that the magnitude of the alternating magnetic field produced by the degaussing coil decreases smoothly and continuously, rather than sharply switching off or decreasing in steps; the PTC (positive temperature coefficient) thermistor accomplishes this naturally, as it heats up. A degaussing circuit using a PTC thermistor is simple, reliable (for its simplicity), and inexpensive.

(iii) NTC thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K.

(iv) NTC thermistors can be used as inrush-current limiting devices in power supply circuits. They present a higher resistance initially, which prevents large currents from flowing at turn-on, and then heat up and assume much lower resistance value to allow higher current flow during normal operation. These thermistors are usually much larger than measuring type thermistors, and are specifically designed for this application.

(v) NTC thermistors are regularly used in automotive applications. For example, they monitor variables like coolant temperature and/or oil temperature inside the engine and provide data to the ECU and, indirectly, to the dashboard.

(vi) NTC thermistors can be also used to monitor the temperature of an incubator.

(vii) Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging.

CHAPTER-3

OVERVIEW OF LINEARIZATION ARRANGEMENTS FOR NTC THERMISTORS

INTRODUCTION

In this chapter, the linearization scheme for NTC type thermistor using different analog circuits is discussed. The analog circuits considered for this purpose are those involving shunt resistance, series resistance and log network.

3.1. PRINCIPLE FOR LINEARIZATION

Quasi-linear relationship of output versus input of an analog circuit configuration using thermistor is achieved following a principle stated below. In the linearizing network as shown in Fig.3.1, temperature (*T*) is the input and output signal *S(T)* is a function of the temperature.

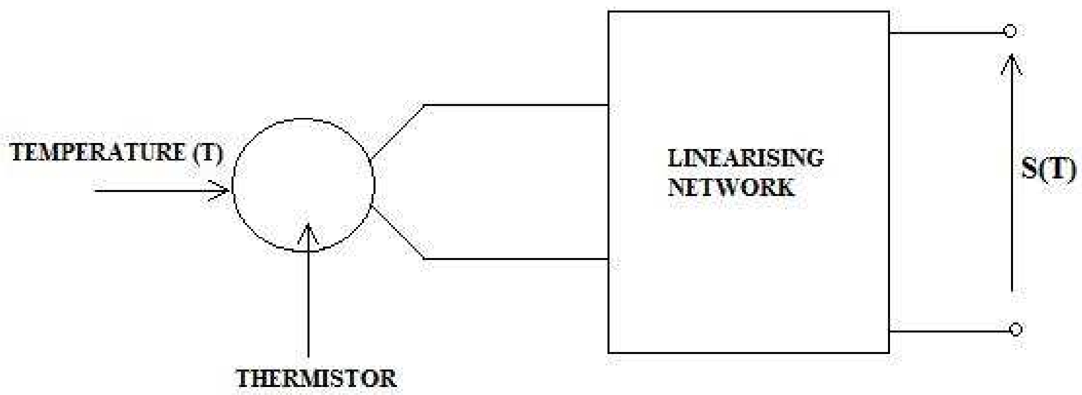

Fig.3.1. Linearizing Arrangement For Thermistor

It is desired that the relationship between output *S(T)* and input *T* (temperature) should be linear for a certain range of temperature which we want to measure in terms of voltage, current or frequency. To ascertain precisely how the output functionally depends upon the input, a fairly established method is to make use of Taylor's theorem [15].

According to Taylor's theorem, S(T) can be expanded into an infinite series, about a reference temperature T_r, as

$$S(T) = S(T_r)+hS'(T_r)+\frac{h^2}{2!}S''(T_r)+\frac{h^3}{3!}S'''(T_r)+...+\frac{h^n}{n!}S^n(T_r) \qquad (3.1)$$

Where,

$h = T \sim T_r$ is the increment or decrement in temperature about the reference temperature T_r.

$S'(T_r)$, $S''(T_r)$, $S'''(T_r)$ etc., are the first, second, third derivatives, respectively, of the output *S(T)* with respect to the temperature *T* at $T = T_r$.

From equation (3.1) it is to be noted that,

For above series to converge, the magnitude of the terms in increasing powers of 'h' should decrease rapidly with ascent of power 'h'.

For a practical system, it is found that it is sufficient to consider the terms containing h, h^2, and h^3.

Among all these three terms, the term involving h^2 is the only major term which introduces a considerable amount of nonlinearity in the input/output relation.

However, in a practical system, proper selection of circuit components allows one to set h^2 term, that is $S''(T_r)$ to zero. Under this setting, according to equation (3.1), *S(T)* may be assumed to be linearly related to the temperature *T* over an appreciably wide range, so long as the h^3 term remains negligibly small. Thus we can write

$$S(T) = S(T_r) + hS'(T_r)$$

Usually, it is desired to have a decent linearity over as wide a temperature span as possible, centered at the midpoint (T_m) of the temperature range of interest. Hence, the reference temperature T_r is so chosen that $T_r = T_m$.

$S''(T_m)$ is set to zero by selecting linearizing circuit parameter. Then $S(T)$ has an inflection at $T = T_m$. Thus quasi-linearization is achieved.

Different linearization schemes are stated subsequently.

3.2. SHUNT LINEARIZATION SCHEME

Linearization scheme for NTC thermistor using shunt or parallel resistance is shown in Fig.3.2. In this circuit, the linearizing resistance 'r' *made of some alloy with very low temperature coefficient of resistance (e.g., manganin)*, is connected in parallel with the thermistor of resistance R_T.

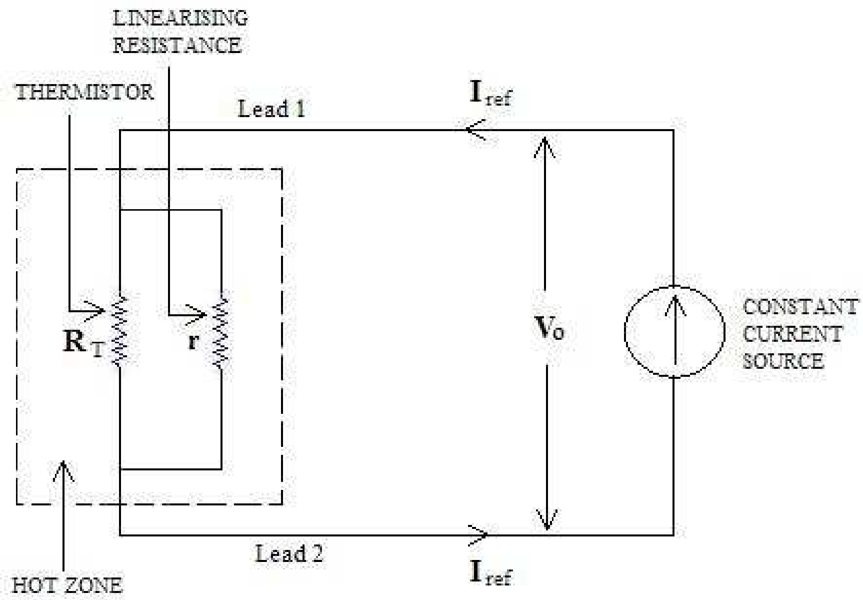

Fig.3.2. Linearizing Arrangements For NTC Thermistor Using Shunt Resistance

The output voltage of this arrangement is

$$V_0(T) = I_{ref} R_{eq}(T) \tag{3.2}$$

Where

$V_0(T)$ is the output voltage of the circuit with respect to temperature T

I_{ref} is the reference current flowing through the circuit

$R_{eq}(T)$ is the equivalent resistance of the linearizing resistance and thermistor resistance in parallel.

Now

$$R_{eq}(T) = \frac{r\ R_T}{r\ +\ R_T} \tag{3.3}$$

Substituting equation (3.3) into (3.2) we get

$$V_0(T)\ =\ I_{ref}\left(\frac{r\ R_T}{r\ +\ R_T}\right) \tag{3.4}$$

The aim of this linearizing arrangement is to make $V_0(T)$ versus T characteristic linear. This is equivalent to having a linear $R_{eq}(T)$ versus T characteristic. $R_{eq}(T)$ is a function of thermistor resistance R_T and linearizing resistance r, in which thermistor resistance R_T varies with change in temperature T, but linearizing resistance r remains fixed for individual thermistor. So the only way to make output versus input characteristic linear, is to set such a value of r, which will fulfill the target. Such a value of r can be obtained by the principle stated in section 3.1. Thus, we want to have

$$V_0''(T_m)=0$$

i.e.,

$$R_{eq}''(T_m)=0$$

Taking first order derivative of $R_{eq}(T)$ with respect to T we get

$$R_{eq}'(T) = \frac{rR_T'(r+R_T) - rR_T R_T'}{(r+R_T)^2} = \frac{r^2 R_T'}{(r+R_T)^2} \tag{3.5}$$

Taking second order derivative of $R_{eq}(T)$ with respect to T we get

$$R''_{eq}(T) = \frac{r^2 R''_T (r+R_T)^2 - 2r^2 R'^2_T (r+R_T)}{(r+R_T)^4}$$

Or

$$R''_{eq}(T) = \frac{r^3 R''_T + r^2 R_T R''_T - 2r^2 R'^2_T}{(r+R_T)^3}$$

Finally,

$$R''_{eq}(T) = \frac{r^2[rR''_T + R_T R''_T - 2R'^2_T]}{(r+R_T)^3} \qquad (3.6)$$

Hence, to have $R''_{eq}(T_m) = 0$, we should make

$$rR''_{T_m} = 2R'^2_{T_m} - R_{T_m} R''_{T_m}$$

From which we get

$$r = \frac{2R'^2_{T_m}}{R''_{T_m}} - R_{T_m} \qquad (3.7)$$

Now, the mathematical expression for the relationship between the resistance of a thermistor and absolute temperature of thermistor is

$$\mathrm{R_T} = \mathrm{R_{T_0}} \mathrm{e}^{\beta\left(\frac{1}{\mathrm{T}} - \frac{1}{\mathrm{T_0}}\right)} \qquad (3.8)$$

Where, the symbols have their usual meaning.

As, midpoint of the temperature range (T_m) is of interest hence equation (3.8) can be rewritten as

$$R_{T_m} = R_{T_0} e^{\beta\left(\frac{1}{T_m} - \frac{1}{T_0}\right)} \qquad (3.9)$$

Taking first order derivative of R_T with respect to T at T=T_m, we get

$$R'_{T_m} = R_{T_m}\left(-\frac{\beta}{T_m{}^2}\right) \quad (3.10)$$

Taking second order derivative of R_T with respect to T at T=T_m, we get

$$R''_{T_m} = R_{T_m}\left(\frac{\beta^2}{T_m{}^4}\right) + R_{T_m}\left(\frac{2\beta}{T_m{}^3}\right)$$

Or

$$R''_{T_m} = R_{T_m}\left(\frac{\beta}{T_m{}^3}\right)\left(2+\frac{\beta}{T_m}\right) \quad (3.11)$$

Now, substituting equation (3.10) and (3.11) into equation (3.7) we get

$$r = \frac{2R_{T_m}^2\left(\frac{\beta^2}{T_m{}^4}\right)}{R_{T_m}\left(\frac{\beta}{T_m^3}\right)\left(2+\frac{\beta}{T_m}\right)} - R_{T_m}$$

Finally we get

$$r = R_{T_m}\left(\frac{\beta - 2T_m}{\beta + 2T_m}\right) \quad (3.12)$$

Equation (3.12) helps to calculate a proper value of linearizing resistance ‘r’. Fig.3.3 shows a $V_0(T)$ versus T characteristic linearized by the above mentioned procedure.

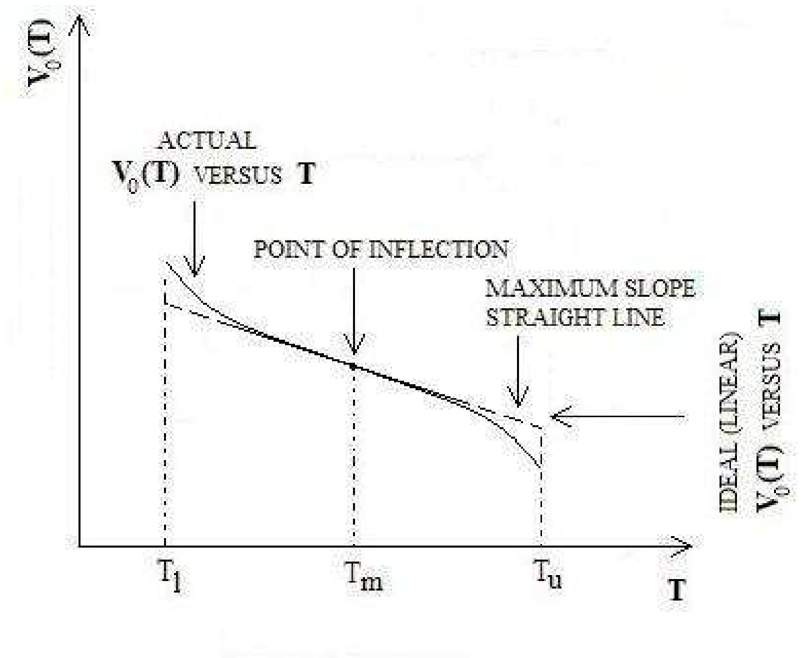

Fig.3.3 Quasi-linearized $V_0(T)$ versus T Characteristic Shunt Linearization Circuit

3.3. SERIES LINEARIZATION SCHEME

Linearization scheme for NTC thermistor using series resistance is shown in Fig.3.4. In this circuit the linearizing resistance 'r' is connected in series with the thermistor whose resistance is R_T.

From the circuit configuration the output voltage can be obtained as,

$$V_0(T) = E\left(\frac{r}{r+R_T}\right) \tag{3.13}$$

For midpoint of temperature range equation (3.13) becomes

$$V_0(T_m) = E\left(\frac{r}{r+R_{T_m}}\right) \tag{3.14}$$

Where,

$V_0(T_m)$ is the output voltage of the series linearizing arrangements

E is the stabilized D.C. input to the series linearizing arrangements

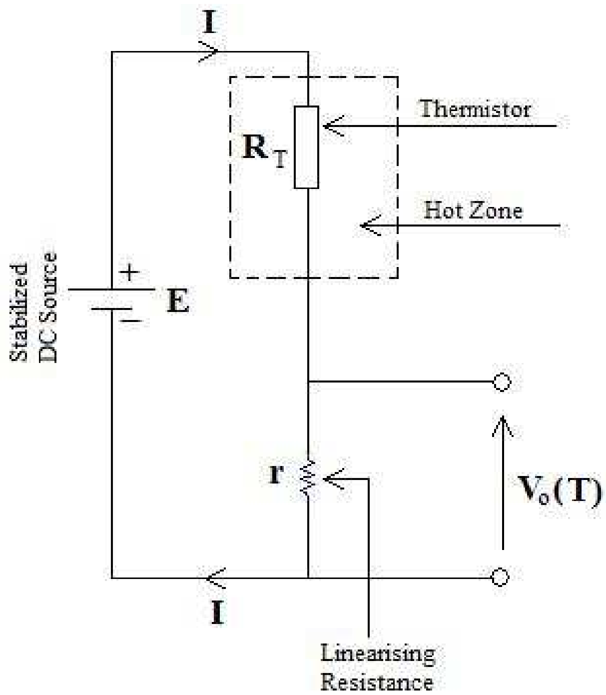

Fig.3.4. Linearizing Arrangements for NTC Thermistor Using Series Resistance

In this circuit configuration input voltage ‘E’ remains constant for entire range of temperature variation and the thermistor resistance R_T changes with the change of temperature. So, in this arrangement it also necessitates a proper selection of linearizing resistance ‘r’ to make $V_0(T)$ versus T characteristic linear. Hence, by means of the same principle as stated in section 3.1 we have to make

$$V_0''(T_m) = 0$$

Now, taking first order derivative of $V_0(T)$ with respect to T_m we get

$$V_0'(T_m) = -E \times r\left(\frac{R'_{T_m}}{(r+R_{T_m})^2}\right) \tag{3.15}$$

By taking second order derivative of $V_0(T)$ with respect to T at $T=T_m$ we get

$$V_0''(T_m) = -E \times r \left(\frac{R''_{T_m}(r+R_{T_m})^2 - 2R'^2_{T_m}(r+R_{T_m})}{(r+R_{T_m})^4} \right) \tag{3.16}$$

To have $V_0''(T_m)=0$ we should have

$$R''_{T_m}(r+R_{T_m})^2 = 2R'^2_{T_m}(r+R_{T_m})$$

Or

$$r = \frac{2R'^2_{T_m}}{R''_{T_m}} - R_{T_m} \tag{3.17}$$

Hence the required value of r may be obtained from

$$r = R_{T_m}\left(\frac{\beta - 2T_m}{\beta + 2T_m}\right) \tag{3.18}$$

This expression (3.18) is same as equation (3.12). In Fig.3.5, $V_0(T)$ versus T characteristic linearized by above mentioned procedure, is depicted.

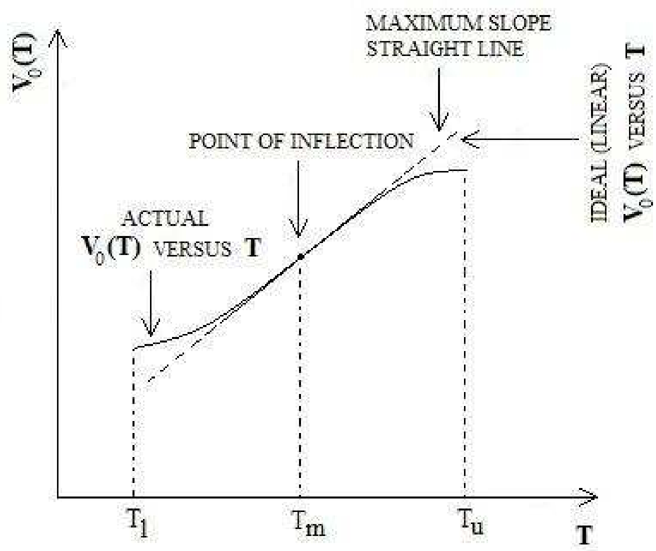

Fig.3.5. $V_0(T)$ versus T Characteristic Quasi-linearized By Series Linearization

3.4. LINEARIZATION USING LOGARITHMIC NETWORK

In an extension of the shunt linearization arrangement, the voltage across the thermistor-linearizing resistance combine is processed by a log network as shown in Fig.3.6. A constant current source feeds a current *I* to the thermistor-resistor network, thereby developing voltage V_i across it, being proportional to the equivalent network resistance R_{Teq}. This voltage V_i as shown in Fig.3.4, is an input to the logarithmic amplifier and thus the output voltage $V_0(T)$ becomes proportional to the logarithm of the voltage V_i . Analytically, we can write V_i and $V_0(T)$ as

$$V_i = IR_{Teq} \tag{3.19}$$

and

$$R_{Teq} = \frac{r \times R_T}{r + R_T} \tag{3.20}$$

where,

R_T is the thermistor resistance at absolute temperature T Kelvin.

'r' is the linearizing resistance connected in parallel with the thermistor.

and

$$V_0(T) = -K \; ln\left(\frac{V_i}{V_{ref}}\right) \tag{3.21}$$

Where,

K is the scale factor of the logarithmic network.

V_{ref} is the effective internally generated voltage in the log-network to which the voltage V_i is compared.

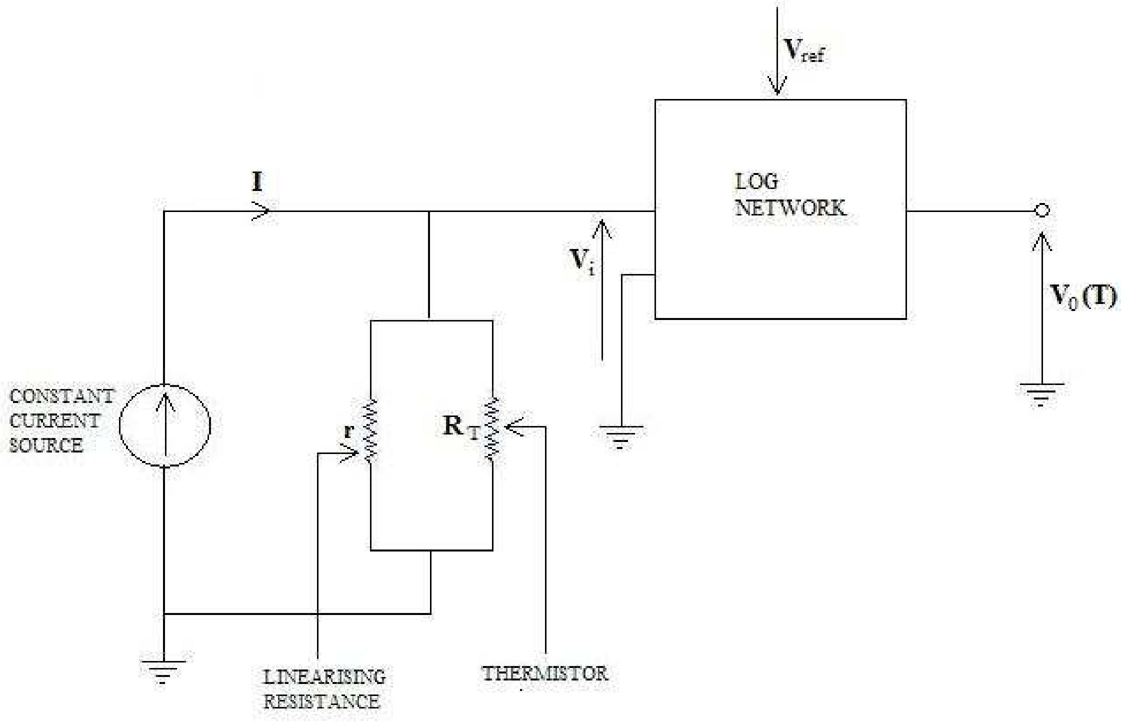

Fig.3.6. Linearizing Arrangement for NTC Thermistor Using Logarithmic Network

Now, using equation (3.19) and (3.20), equation (3.21) can be rewritten as

$$V_0(T) = -K \ \boldsymbol{ln}\left(\frac{I \times r \times R_T}{V_{ref}(r + R_T)}\right) \qquad (3.22)$$

Where,

$G = \dfrac{I}{V_{ref}}$ is a constant and midpoint of temperature range is of interest.

From the equation (3.22) it can be observed that to make output $V_0(T_m)$ versus measurand T (temperature in Kelvin) linear, proper selection of linearizing resistance is necessary. So, using the same principle stated in section 3.1 first we have to make $V_0''(T_m)=0$.

Taking first order derivative of $V_0(T)$ with respect to T at T= T_m, we get

$$V_0'(T_m) = -\frac{K \times r \times R_{T_m}'}{R_{T_m}\left(r + R_{T_m}\right)} \tag{3.23}$$

By taking the second order derivative of $V_0(T)$ with respect to T at T=T_m, we get

$$V_0''(T_m) = -\frac{K \times r}{R_{T_m}''(r + R_{T_m})^2}\left[R_{T_m}'' R_{T_m}(r + R_{T_m}) - R_{T_m}'^2(r + 2R_{T_m})\right] \tag{3.24}$$

Thus, for making $\mathrm{V}_0''(\mathrm{T}_\mathrm{m})=0$ the following condition to be fulfilled,

$$R_{T_m}'' R_{T_m}\left(r + R_{T_m}\right) = R_{T_m}'^2\left(r + 2R_{T_m}\right)$$

Or,

$$r = \frac{R_{T_m}(2R_{T_m}'^2 - R_{T_m}'' R_{T_m})}{R_{T_m}'' R_{T_m} - R_{T_m}'^2} \tag{3.25}$$

Substituting the expressions for R_{T_m}, R_{T_m}' and R_{T_m}'' from equations (3.9), (3.10) and (3.11), we obtain

$$\mathrm{r} = \frac{\mathrm{R}_{\mathrm{T}_\mathrm{m}}(\beta - 2\mathrm{T}_\mathrm{m})}{2\mathrm{T}_\mathrm{m}} \tag{3.26}$$

This expression helps to calculate a proper value of linearizing resistance 'r'.

3.5. IMPLEMENTATION OF LOGARITHMIC AMPLIFIER CIRCUIT

The fundamental log amplifier circuit includes a diode or grounded base NPN transistor in the feedback path. Such amplifier uses the non linear volt-amp relationship of the semiconductor device. Fig.3.7 represents the basic log-amplifier circuit. In this circuit diode 'D' protects transistor 'T' against excessive reverse base-emitter voltage.

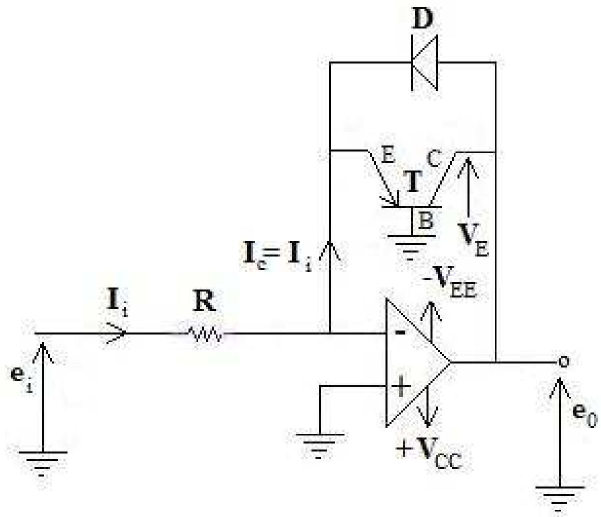

Fig.3.7. Logarithmic Amplifier Circuit

In this circuit, the collector current is equal to the input current and output voltage is equal to the emitter voltage that is

$$I_c = I_i = \frac{e_i}{R} \qquad (3.27)$$

where,

I_c is the collector current of the transistor T

I_i is the input current to the amplifier circuit

e_i is the input voltage to the amplifier circuit

and

$$e_0 = V_E \qquad (3.28)$$

where,

V_E is the emitter voltage of the transistor T

e_0 is the output voltage of the amplifier circuit

When a transistor is placed in a circuit such that the collector voltage $V_c = 0$, the collector current is given by

$$I_c \simeq \alpha \times I_{ES} \times \left[\exp\left(\frac{-q \times V_E}{K \times T_a} \right) - 1 \right] \qquad (3.29)$$

Where,

- α is the current transfer ratio between emitter and collector ($\alpha \simeq 1$)
- I_{ES} is the reverse saturation current of base emitter diode
- q is the magnitude of the charge of electron, 1.6×10^{-19} Coulomb
- K is the Boltzmann's constant, 1.38×10^{-23} Joules / Kelvin
- T_a is the ambient temperature in Kelvin

Typically, $I_{ES} \simeq 10^{-13} A$ and $\alpha \simeq 1$

So, $I_c \gg I_{ES}$ and equation (3.29) can be rewritten as follows

$$I_c \simeq I_{ES} \times \exp\left(\frac{-q \times V_E}{K \times T_a} \right) \qquad (3.30)$$

From equation (3.29) we get

$$-V_E \simeq \frac{K \times T_a}{q} ln\left(\frac{I_c}{I_{ES}} \right) \qquad (3.31)$$

Using equation (3.27), (3.28) and (3.31) we can obtain an expression for output voltage of the log-amplifier circuit as

$$e_0 = -\frac{K \times T_a}{q} ln\left(\frac{e_i}{I_{ES} \times R} \right)$$

Or

$$e_0 = -K_0 \, ln\left(\frac{e_i}{V_{ref}} \right) \qquad (3.32)$$

Where,

$$K_0 = \frac{K \times T_a}{q} \quad \text{and} \quad V_{ref} = I_{ES} \times R$$

A complete scheme for logarithmic amplifier is shown in Fig.3.8. In this configuration a buffer using op-amp A_1 in constant voltage D.C. source block, is introduced to remove loading effect.

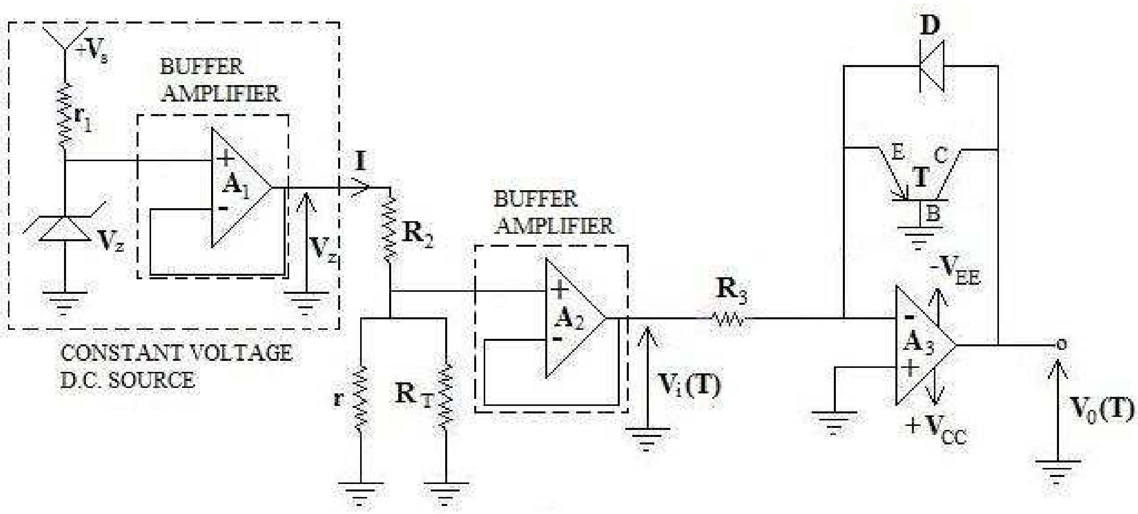

Fig.3.8. A Complete Circuit For Logarithmic Amplifier Based Linearizing Arrangement for Thermistor.

The current '*I*' generated by the constant voltage D.C. source is

$$I = \frac{V_z}{R_2 + \dfrac{r \times R_T}{r + R_T}} \qquad (3.33)$$

But, current '*I*' will depend on the resistance R_2, rather than depending on linearizing resistance '*r*' or thermistor resistance R_T. Hence the equation can be modified as,

$$\mathrm{I} \simeq \frac{\mathrm{V_z}}{\mathrm{R_2}} \qquad (3.34)$$

The collector current 'I_c' and output voltage 'V_0(T)' is as follows

$$I_c = \frac{V_i}{R_3} \tag{3.35}$$

and

$$V_0(T) = -\frac{K \times T_a}{q} ln\left(\frac{V_i(T)}{R_3 \times I_{ES}}\right) \tag{3.36}$$

One of the main consideration for log-amplifier circuit is that, $K_0 \propto T_a$ changes by 0.3% per ^oC in vicinity of 25 ^oC. Main temperature error using log amplifier based linearization is due to I_{ES}, which approximately doubles for every 10 ^oC change in temperature. To overcome this problem, temperature compensated 'Practical Log Amplifier' circuit which is shown in Fig.3.9 is used. In this circuit Q_1 and Q_2 are matched transistors.

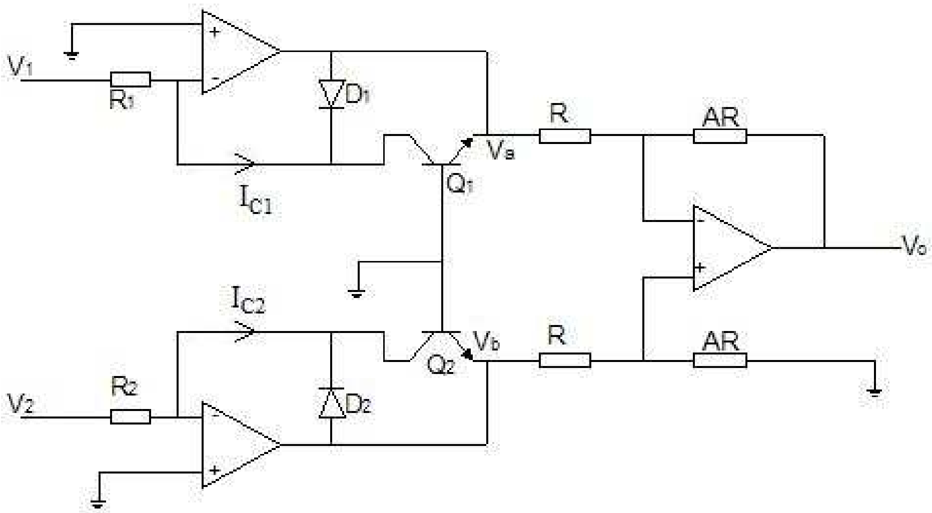

Fig.3.9. Practical Form of Logarithmic Amplifier

$$V_a = V_{E1} = -K_0 \ln\left(\frac{I_{c1}}{\alpha \times I_{ES1}}\right)$$

Or

$$V_a = -K_0\, ln\left(\frac{V_1}{\alpha \times R_1 \times I_{ES1}}\right) \tag{3.37}$$

and

$$V_b = V_{E2} = -K_0\, ln\left(\frac{I_{c2}}{\alpha \times I_{ES2}}\right)$$

Or

$$V_b = -K_0\, ln\left(\frac{V_2}{\alpha \times R_2 \times I_{ES2}}\right) \qquad (3.38)$$

Hence, output voltage V_0 is

$$V_0 = A(V_b - V_a)$$

Or

$$V_0 = AK_0\, ln\left(\frac{V_1}{\alpha \times R_1 \times I_{ES1}} \times \frac{\alpha \times R_2 \times I_{ES2}}{V_2}\right) \qquad (3.39)$$

If R_1 is made equal to R_2, and as V_0 is independent of I_{ES}, equation (3.39) becomes

$$V_0 = AK_0\, ln\left(\frac{V_1}{V_2}\right) \qquad (3.40)$$

As the term I_{ES} is eliminated from the output equation of log amplifier equation (3.40), the problem related to I_{ES} is removed. If $V_1 > V_2$, then V_0 becomes positive.

CHAPTER-4

LINEARIZATION OF NTC THERMISTOR CHARACTERISTIC USING INVERTING AMPLIFIER

INTRODUCTION

The linearizing circuit for NTC thermistors, employing an op-amp based inverting amplifier has been proposed to. Linearization of the highly nonlinear thermistor characteristic is achieved only through a proper choice of the value of a resistance placed in series with the thermistor, in the feedforward path of the inverting amplifier, depending on the thermistor parameters and the pre-specified working temperature range.

4.1. PROPOSED LINEARIZING CIRCUIT

This work puts forth a low cost and simple analog signal conditioning circuit for NTC thermistors depicted in Fig.4.1. The thermistor with resistance R_T is connected in series with linearizing resistance ‘r’. In this configuration, the buffer amplifier using an op-amp is introduced to get the desired excitation voltage, low enough to avoid self-heating of the thermistor.

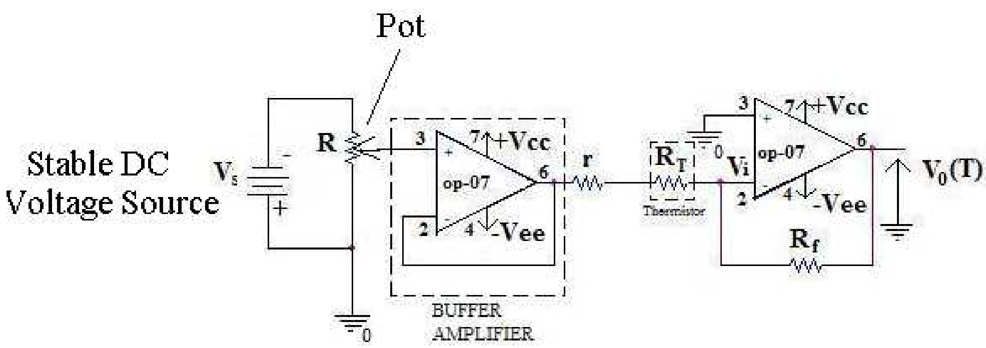

Fig.4.1. Block Diagram of Proposed Linearizing Scheme for NTC Thermistor

The output voltage signal of the circuit is

$$V_0(T) = -\frac{V_i R_f}{r + R_T} \qquad (4.1)$$

Where

$V_0(T)$ is the output voltage of the circuit with respect to temperature T in (K)

V_i is the input voltage to the linearizing arrangement

R_f is the feedback resistance

r is the linearizing resistance connected in series with the thermistor

R_T is the thermistor resistance at a temperature T in (K)

It can be easily seen that since the excitation voltage V_i is negative, $V_0(T)$ is always positive. Furthermore, if T increases, R_T will decrease and consequently $V_0(T)$ increases. It is desired that $V_0(T)$ should have a linear relation with the temperature T (K) to which the thermistor is exposed, over the temperature range of interest extending from T_L (K) to T_U (K). To achieve a linear output versus input characteristic a proper choice of linearizing resistance 'r' is necessary. The selection of this linearizing resistance 'r' is done by two different methods discussed in subsequent sections.

4.2. METHOD-I TO OBTAIN LINEARIZING RESISTANCE 'r'

For NTC thermistor based transducers, the widely accepted method of obtaining the linearizing resistance value is one that imposes the condition

$$\left.\frac{d^2V_0(T)}{dT^2}\right|_{T=T_m} = V_0''(T_m) = 0 \qquad (4.2)$$

Where, $T_m = \frac{T_l + T_u}{2}$ is the midpoint of the temperature range of interest.

In other words, by proper choice of the resistance 'r', the output voltage versus temperature curve is forced to have an inflection at $T=T_m$. It is worth mentioning that the excitation voltage V_i and the value of the feedback resistance R_f do not influence the values of linearizing resistance 'r'. Only the sensitivity of the proposed circuit depends on V_i and on R_f. Hence, from equations (4.1) and (4.2) we get

$$f''(T_m) = 0 \tag{4.3}$$

Where,

$$f(T_m) = \frac{1}{r + R_{T_m}} \tag{4.4}$$

Now, taking first order derivative of $f(T_m)$ with respect to T_m we get

$$f'(T_m) = -\frac{R'_{T_m}}{(R_{T_m} + r)^2} \tag{4.5}$$

And, by taking second order derivative of $f(T_m)$ with respect to T_m we get

$$f''(T_m) = \frac{2R'^2_{T_m}(R_{T_m} + r) - R''_{T_m}(R_{T_m} + r)^2}{(R_{T_m} + r)^2} \tag{4.6}$$

To have $f''(T_m) = 0$ the condition that should be satisfied, is given by

$$R''_{T_m}(R_{T_m} + r)^2 = 2R'^2_{T_m}(R_{T_m} + r)$$

or,

$$r = \frac{2R'^2_{T_m}}{R''_{T_m}} - R_{T_m} \tag{4.7}$$

Although several expressions are in use to represent thermistors transfer curve, the most popular one is given by

$$R_T = R_{T_0} e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)} \tag{4.8}$$

Where,

R_T is the resistance of the thermistor at absolute temperature T (K)

R_{T_0} is the resistance of the thermistor at absolute temperature T_0 (K), known as nominal resistance

β is a constant depending upon the thermistor material (K)

The thermistor resistance at the midpoint of the temperature range (T_m) can be rewritten as

$$R_{T_m} = R_{T_0} e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)} \qquad (4.9)$$

Taking first order derivative of R_T with respect to T at T=T_m , we get

$$R'_{T_m} = R_{T_m}\left(-\frac{\beta}{T_m^2}\right) \qquad (4.10)$$

Taking second order derivative of R_{T_m} R_T with respect to T at T=T_m , we get

$$R''_{T_m} = R_{T_m}\left(\frac{\beta^2}{T_m^4}\right) + R_{T_m}\left(\frac{2\beta}{T_m^3}\right)$$

or,

$$R''_{T_m} = R_{T_m}\left(\frac{\beta}{T_m{}^3}\right)\left(2 + \frac{\beta}{T_m}\right) \qquad (4.11)$$

Now, substituting equation (4.10) and (4.11) into equation (4.7) we get

$$r = \frac{2R_{T_m}{}^2\left(\frac{\beta^2}{T_m{}^4}\right)}{R_{T_m}\left(\frac{\beta}{T_m{}^3}\right)\left(2+\frac{\beta}{T_m}\right)} - R_{T_m}$$

Finally we obtain

$$r = r_o = R_{T_m}\left(\frac{\beta - 2T_m}{\beta + 2T_m}\right) \qquad (4.12)$$

which is same as the expressions for linearizing resistance obtained for series and shunt linearizing schemes.

Equation (4.12) helps to calculate a proper value of linearizing resistance ‘r’. It involves the midpoint of the working temperature range, the resistance value of the sensor at this temperature, and the value of the β constant for the sensor.

4.3. METHOD-II FOR OBTAINING LINEARIZING RESISTANCE ‘r’

The required value of 'r' has been obtained in a different manner. To understand the principle involved, let us refer to Fig. 4.2. As a first approximation for obtaining r, it is considered that the relation between $V_o(T)$ and T is perfectly linear. We may then consider that

ΔV_1 is the change of $V_0(T)$ from T_l to T_m and is equal to $[V_0(T_m) - V_0(T_l)]$

and

ΔV_2 is the change of $V_0(T)$ from T_m to T_u and is equal to $[V_0(T_u) - V_0(T_m)]$

Now the condition to be fulfilled for the characteristic to be linear is

$$\Delta V_1 = \Delta V_2$$

That is

$$V_0(T_m) - V_0(T_l) = V_0(T_u) - V_0(T_m)$$

Or,

$$2V_0(T_m) = V_0(T_u) + V_0(T_l) \qquad (4.13)$$

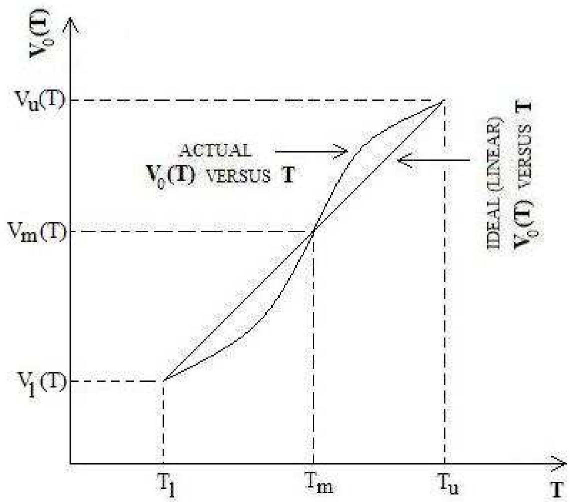

Fig.4.2. Output versus Input Characteristic For The Linearizing Arrangement

Now in the expression for output voltage given in equation (4.1), it can be easily seen that since the excitation voltage V_i is negative, $V_0(T)$ is always positive. Substituting equation (4.1) in (4.13) we get

$$\frac{2V_iR_f}{r+R_{T_m}}=\frac{V_iR_f}{r+R_{T_u}}+\frac{V_iR_f}{r+R_{T_l}}$$

Or

$$\frac{2}{r+R_{T_m}}=\frac{1}{r+R_{T_u}}+\frac{1}{r+R_{T_l}}$$

Or

$$r=\frac{R_{T_m}(R_{T_u}+R_{T_l})-2R_{T_u}R_{T_l}}{R_{T_u}+R_{T_l}-2R_{T_m}}$$

and finally,

$$r=r_1=\frac{R_{T_m}(R_{T_u}+R_{T_l})-2R_{T_u}R_{T_l}}{(R_{T_u}-R_{T_m})-(R_{T_m}-R_{T_l})} \qquad (4.14)$$

The normalized deviation from linearity at a temperature *T* (K) is defined as

$$D=\frac{V_o\left(T\right)-V_o\left(T_l\right)}{V_o\left(T_U\right)-V_o\left(T_l\right)}-\frac{T-T_l}{T_U-T_l} \qquad (4.15)$$

The sum-square value of *D* is obtained numerically by measuring the thermistor resistance at say N temperatures points, and is given by

$$S=\sum_{i=1}^{N}D^2\left(r,T_i\right) \qquad (4.16)$$

The optimum value of ‘r’ is obtained by minimizing the sum squared deviation S.

To start with, an approximate value r_l of ‘r’ is computed by introducing the condition for perfect linearity as stated in equation (4.13). The sum-squared error S given by equation (4.16) is then computed by varying ‘r’ over a range spanning from a suitable value less than r_1 to one greater than r_1, but necessarily including the value r_o obtained from equation (4.12).

It is worth mentioning that the excitation voltage V_i and the value of the feedback resistance R_f influence none of the values r_o and r_1, and not also the final value of ‘r’. It is also imperative that the sensitivity of the proposed circuit depends on V_i and on R_f. However, while V_i cannot be increased much in order due to avoid self-heating of the thermistor, one may play with the value of R_f to have a full scale output over a wide range.

CHAPTER-5

INVESTIGATIONS AND RESULTS

INTRODUCTON

The performance of the proposed analog signal conditioning arrangement has been tested with three separate NTC thermistors having different nominal resistances (R_{T0}) and β values. In this chapter, at first the mathematical calculations to obtain the values of nominal resistances (R_{T0}) and β values are discussed. Then the performance of the proposed signal conditioning circuit has been examined. The results obtained using computational studies are compared with the experimentally obtained results using actual hardware. The temperature range covered, extends from 30°C (that is T_l=303.15 K) to 120°C (that is T_U=393.15 K). Thus the midpoint of the range is 75°C (that is T_m= 348.15 K). The resistances for each thermistor have been obtained experimentally by measuring the resistance at 91 known temperature at intervals of 1°C. In this experimental study, a platinum resistance temperature sensor (Pt-100) has been used as the standard. Thermistors used for the measurement are of base resistance values of 100 Ω, 1 kΩ and 5 kΩ as given by the manufacturer. The base resistances of the thermistors are typically measured at ambient temperature of 25 °C (298.15 K).

5.1. DETERMINATION OF R_{T_0} AND β

As already discussed, the transfer relation of thermistor can be approximated by an exponential function. Hence, least square method can be used to calculate the unknowns R_{T_0} and β. For each thermistor, the measured values of resistance R_T obtained experimentally for the entire range of experiment are fitted to the exponential expression involving the β constant. Let us recall the expression

$$R_T = R_{T_0} e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Taking the natural logarithm of both sides of the above equation, we get

$$ln\ R_T = ln\ R_{T_0} + \beta\left(\frac{1}{T} - \frac{1}{T_0}\right)$$

Or

$$Y=a_o+a_1x \qquad (5.1)$$

Where,

$$Y = ln\ R_T$$
$$x = \left(\frac{1}{T} - \frac{1}{T_0}\right)$$
$$a_0 = ln\ R_{T_0}$$
$$a_1 = \beta$$

Equation (4.26) be the straight line where Y is linearly related to x, to be fitted to the given data. So, the sum of squared error S_o is

$$S_o = [y_1 - (a_0 + a_1 x_1)]^2 + [y_2 - (a_0 + a_1 x_2)]^2 + ... + [y_m - (a_0 + a_1 x_m)]^2 \qquad (5.2)$$

For S_o to be minimum, we have

$$\frac{\partial S_o}{\partial a_0} = 0 = -2[y_1 - (a_0 + a_1 x_1)] - 2[y_2 - (a_0 + a_1 x_2)] - ... - 2[y_m - (a_0 + a_1 x_m)] \qquad (5.3)$$

and

$$\frac{\partial S_o}{\partial a_1} = 0 = -2x_1[y_1 - (a_0 + a_1 x_1)] - 2x_2[y_2 - (a_0 + a_1 x_2)] - ... - 2x_m[y_m - (a_0 + a_1 x_m)] \qquad (5.4)$$

Simplifying equation (5.3) we get

$$ma_0 + a_1(x_1 + x_2 + ... + x_m) = y_1 + y_2 + ... + y_m \qquad (5.5)$$

and simplifying equation (5.4) we get

$$a_0(x_1 + x_2 + ... + x_m) + a_1(x_1^2 + x_2^2 + ... + x_m^2) = x_1 y_1 + x_2 y_2 + ... + x_m y_m \qquad (5.6)$$

More compact form of equation (5.5) is

$$\mathrm{ma}_0 + \mathrm{a}_1 \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{x}_\mathrm{i} = \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{y}_\mathrm{i} \qquad (5.7)$$

Same for equation (5.6) is

$$a_0 \sum_{i=1}^{m} x_i + a_1 \sum_{i=1}^{m} x_i^2 = \sum_{i=1}^{m} x_i y_i \qquad (5.8)$$

Since $\{x_i\}$ and $\{y_i\}$ are known quantities, equations (5.7) and (5.8), called the normal equations, can be solved for the two unknowns a_0 and $a_1=\beta$. Once a_0 is known, R_{T_0} can be obtained as $R_{T_0} = e^{a_0}$.

5.2. DETERMINATION OF EXCITATION VOLTAGE V_i AND

FEEDBACK RESISTANCE R_f

The sensitivity of the proposed linearizing circuit depends on both the excitation voltage V_i and the feedback resistance R_f of the amplifier circuit. One of the main obstacles in case of determination of input voltage is imposed by the phenomenon of self-heating of a thermistor. When an electric current flows through the thermistor, it causes ohmic heating of the sensor, which will raise the temperature of the thermistor above that of its environment. This electrical heating may introduce a significant error. Hence, to reduce the power input to the thermistor, the current through the thermistor should be restrained, which in turn puts a constraint on the excitation voltage. In this proposed linearizing circuit the input voltage is kept at 0.25 volt for experiments with the 1 kΩ and the 100 Ω thermistors, while, it has been selected as 1 V for the 5 kΩ thermistor circuit.

Feedback resistance R_f has been selected with the desire that the full-scale value of the output voltage (i.e. the output at 120 °C) should be 5 volt. The expression for the feedback resistance used for this purpose, is

$$R_f = -\frac{V_0}{V_i}(r + R_T) \tag{5.9}$$

where,

V_0 is the output voltage of the circuit

V_i is the input voltage to the linearizing arrangement

R_f is the feedback resistance

r is the linearizing resistance connected in series with the thermistor

R_T is the thermistor resistance at optimum temperature T in (K)

As already pointed out, an input voltage V_i with negative polarity has been selected, to yield a positive output voltage. So the value of the feedback resistance obtained from equation (5.1) is positive.

5.3. NON LINEARITY ERROR CALCUTION

There are many definitions of linearity that are used in practice. However, linearity defined in terms of **Independent Linearity** is the most preferred in many cases. The computation of independent linearity is done with reference to a straight line showing the relationship between output and input. This straight line is drawn by using the method of least squares from the given calibration data. This straight line is called the ideal straight line expressing the input-output relationship. The linearity is simply a measure of deviation of any of the calibration point from this straight line. The deviation from linearity, which in this case is known as the independent non-linearity error (in percentage), has been calculated for each temperature as

$$E(T)=\frac{\text{Actual } V_o(T)-\text{Ideal } V_o(T)}{\text{Full Scale } V_o}\times 100 \qquad (5.10)$$

5.4. PERFORMANCE OF THE LINEARIZING ARRANGEMENT

For the proposed linearizing arrangement, calculation of linearizing resistance '*r*' is based on two different methods as stated in chapter 4. It is quite natural to apprehend that the performance of this proposed circuit varies with the variation of linearizing resistance '*r*'. For this reason, the performance of this linearizing circuit is analyzed for the two different values of '*r*' obtained by the two different methods.

5.4.1. PERFORMANCE WITH *r* COMPUTED BY METHOD-I

The nominal resistance R_{T_0}, the value of β, the value of the linearizing resistance '*r*' calculated by method-I, the excitation voltages V_i and the value of the feedback resistance R_f are given in Table I.

TABLE I : DETAILS OF THERMISTORS AND LINEARIZING CIRCUIT PARAMETERS (Method –I)

Thermistors	**Measured** R_{T0} **(kΩ)**	**Measured** β **–Values (K)**	**Linearizing Resistance** r **(Ω)**	**Excitation Voltage** (V_i) **(V)**	**Feedback Resistance** R_f **(kΩ)**
Thermistor I (100 Ω)	0.11	2847.4	17.02	0.25	0.14
Thermistor II (1 kΩ)	1.34	3056.4	193.55	0.25	1.53
Thermistor III (5 kΩ)	4.86	3963.3	504.85	1.0	3.50

The Resistance versus Temperature characteristics of the three thermistors used for experimentation are shown in Fig.5.1.

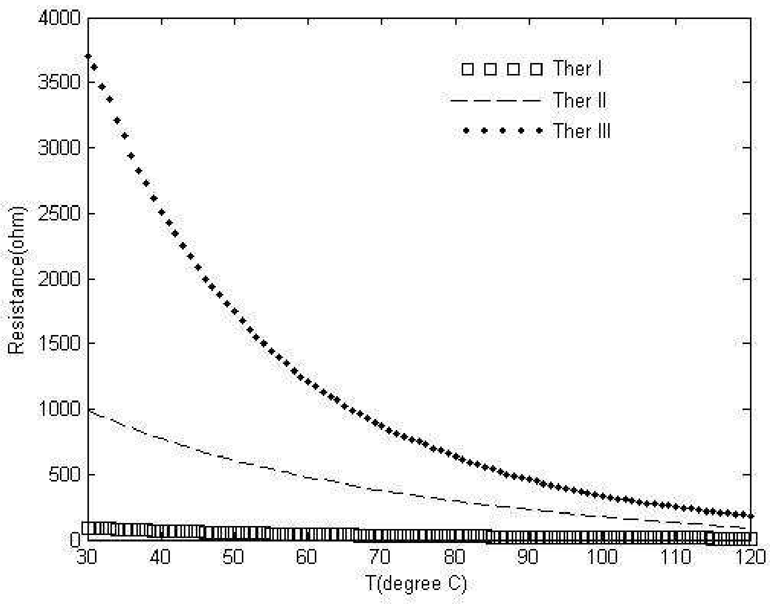

Fig.5.1. Resistance versus Temperature Characteristic of Thermistors used for Experimentation

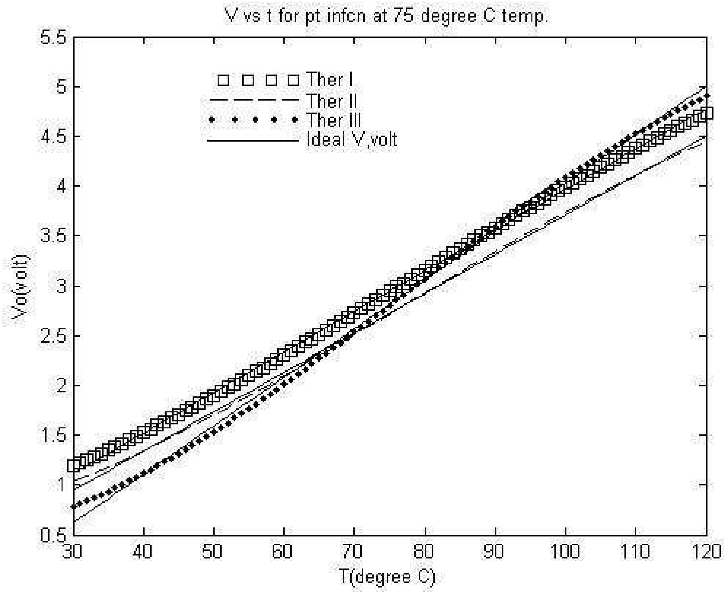

Fig.5.2. Output Voltage (V_0) versus Temperature (T) Characteristic of the Signal Conditioning Circuit

A measure of output voltage V_0(T) is carried out by experimentally obtained thermistor resistances. Substituting the values of linearizing resistance 'r' calculated by method-I, the excitation voltages V_i and the feedback resistance R_f from Table-I and experimentally obtained thermistor resistances R_T in equation (4.1) the output voltage V_0(T) is calculated for the entire temperature range for three thermistors. Fig.5.2 depicts the output voltage (V_0) versus temperature (T) characteristic of the signal conditioning circuit, for the thermistors under study. The curves have been generated by taking intervals of 1^oC. The actual temperature values have been obtained using the Pt-100 standard. In each case, the ideal characteristic is the best-fit least-square straight line for the experimental data.

It can be seen that, for thermistor I the nonlinearity error lies within ±1% for the temperature range of 34 ^oC to 120 ^oC, for thermistor II the nonlinearity error lies within ±1% for the temperature range of 35 ^oC to 119 ^oC and for thermistor III the nonlinearity error lies within approximately ±1% for the temperature range of 37 ^oC to 115 ^oC.

The linearity obtained by this method comparable with shunt or series linearization method as stated in chapter 3. The 'Percentage Error' versus Temperature curve for this measurement is shown in Fig.5.3.

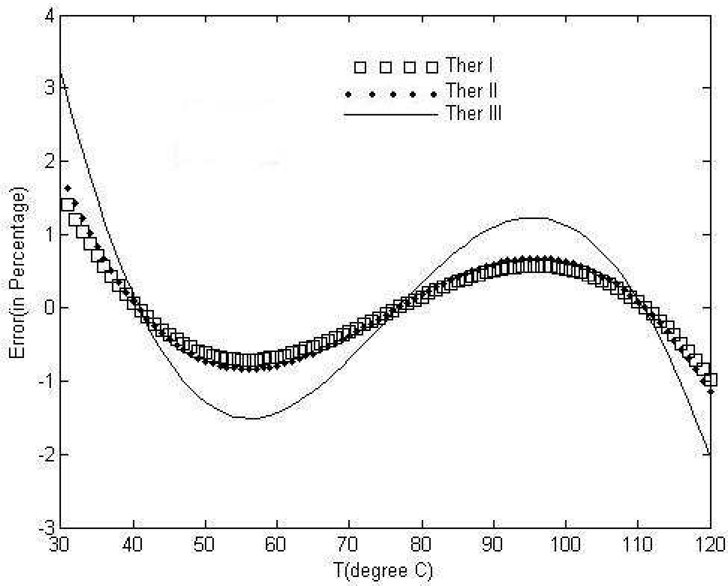

Fig.5.3. Percentage Error versus Temperature (^{o}C) for full span of experiment

5.5. PERFORMANCE OF LINEARIZING ARRANGEMENT USING METHOD-II

The values of the nominal resistance R_{T_0} and material constant β remain same with that obtained by method I, as evident from the discussions made in chapter 4. However, these two methods differ from each other in the procedure of calculating the linearizing resistance '*r*'. Hence, there are differences between the values of '*r*' as well as the feedback resistances obtained by these two methods. The nominal resistance R_{T_0} , the value of *β*, the value of the linearizing resistance '*r*' calculated by method-II, the excitation voltages V_i and the value of the feedback resistance R_f are given in Table II.

TABLE II DETAILS OF THERMISTORS AND LINEARIZING CIRCUIT PARAMETERS (Method-II)

Thermistors	Measured R_{T0} (kΩ)	Measured β –Values (K)	Linearizing Resistance r (Ω)	Excitation Voltage (V_i) (V)	Feedback Resistance R_f (kΩ)
Thermistor I (100 Ω)	0.11	2847.4	30.0	1.0	0.19
Thermistor II (1 kΩ)	1.34	3056.4	519.0	1.0	2.99
Thermistor III (5 kΩ)	4.86	3963.3	642.0	1.0	4.12

A measure of output voltage $V_0(T)$ is carried out by experimentally obtained same thermistor resistances. Fig.5.4 depicts the output voltage (V_0) versus temperature (T) characteristic of the signal conditioning circuit, for the thermistors under study. In this case the curves have also been generated by taking intervals of 1^{o}C. The actual temperature values have been obtained using the Pt-100 standard. In each case, the ideal characteristic is the best-fit least-square straight line for the experimental data.

It can be seen that, for thermistor I the nonlinearity error lies within ±1% for the temperature range of 30 ^{o}C to 120 ^{o}C, for thermistor II the nonlinearity error lies within ±1% for the temperature range of 30 ^{o}C to 120 ^{o}C and for thermistor III the nonlinearity error lies within approximately ±1% for the temperature range of 33 ^{o}C to 115 ^{o}C. Moreover, for thermistors I and II the linearity varies within ±0.5% approximately between the range 30 ^{o}C to 120 ^{o}C and 88^{o}C to 106^{o}C respectively. For thermistor III the nonlinearity error lies within ±0.5% between the range 65 ^{o}C to 81 ^{o}C.

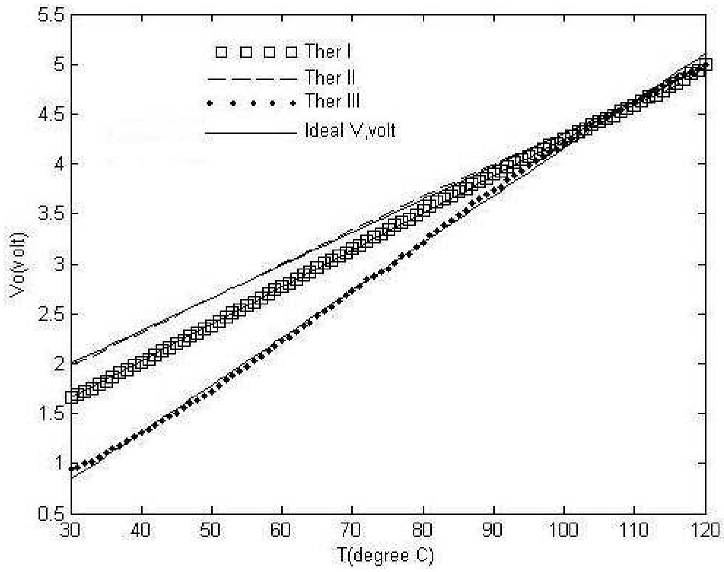

Fig.5.4. Output Voltage (V_0) versus Temperature (T) Characteristic of the Signal Conditioning Circuit

The 'Percentage Error' versus Temperature curve for this measurement is shown in Fig.5.5.

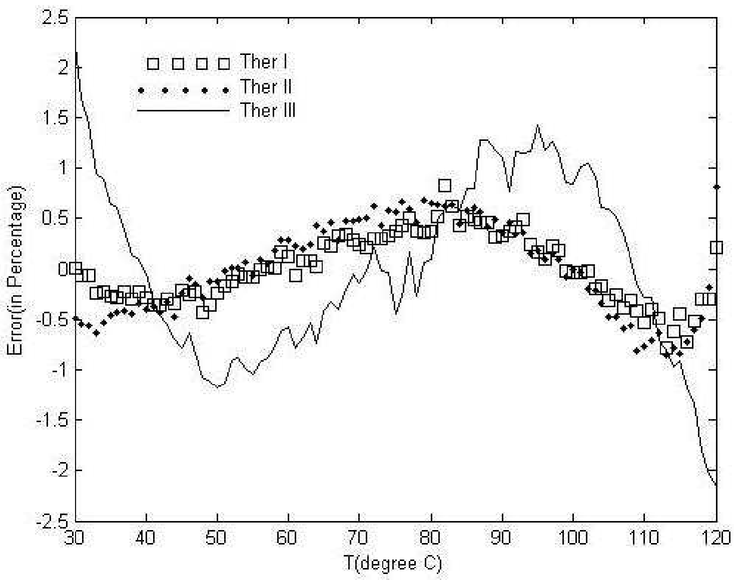

Fig.5.5. Percentage Error versus Temperature (^{o}C) for full span of experiment (30 ^{o}C to 120 ^{o}C)

5.6. HARDWARE IMPLEMENTATION AND RESULTS OF THE PROPOSED LINEARIZING ARRANGEMENTS

Comparing the results of above mentioned two methods, it is clear that better results can be achieved by second method of calculation of linearizing resistance '*r*'. Hence, in case of hardware implementation the values of the circuit parameters are taken from the Table-II. While checking the hardware results, for thermistors I and II, the results were different from the computed output. The reason behind this mismatch is the self heating effect of the thermistors which was removed by reducing the excitation voltage V_i from 1 volt to 0.25 volt. The photograph of the hardware setup is given in Fig.5.6.

Fig.5.6. Photograph of the Experimental Setup

The deviations from linearity have been plotted against temperature, in Fig.5.7, Fig.5.8 and Fig.5.9.

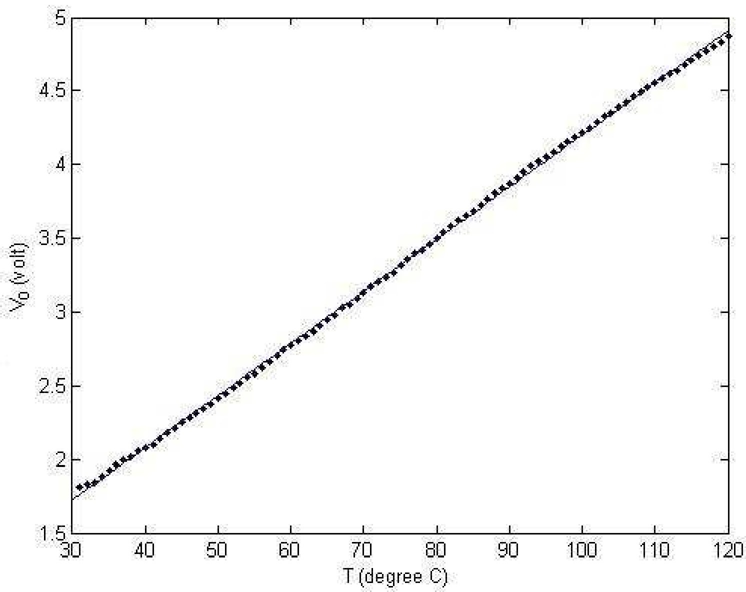

Fig.5.7. Output Voltage (V_0) versus Temperature (T) characteristic of the signal conditioning circuit for Thermistor-I

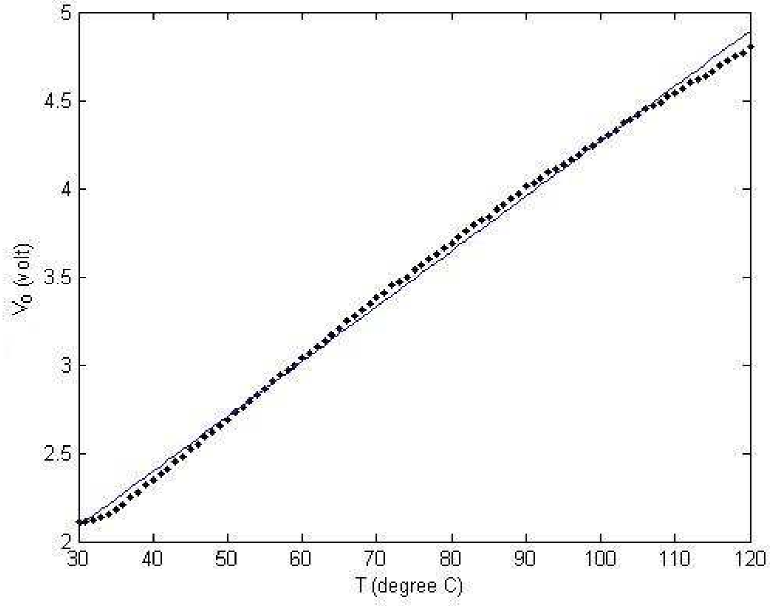

Fig.5.8. Output Voltage (V_0) versus Temperature (T) characteristic of the signal conditioning circuit for Thermistor-II

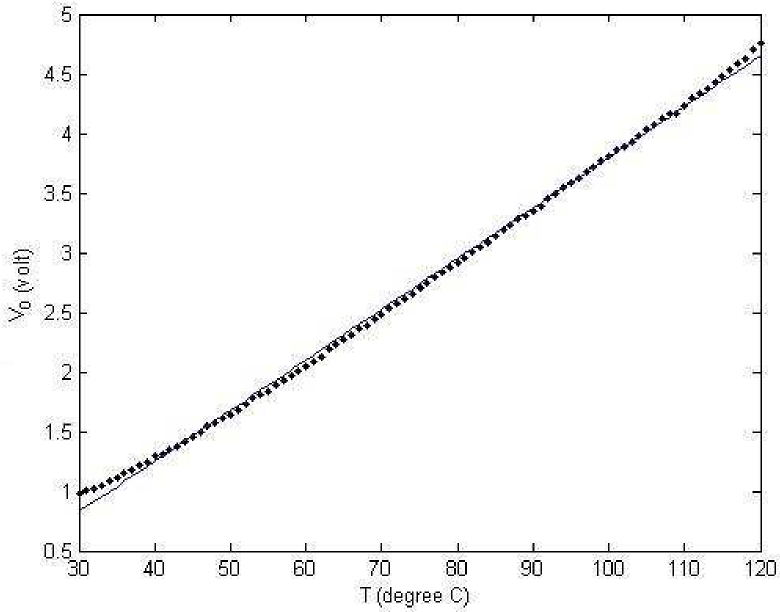

Fig.5.9. Output Voltage (V_0) versus Temperature (T) characteristic of the signal conditioning circuit for Thermistor-III

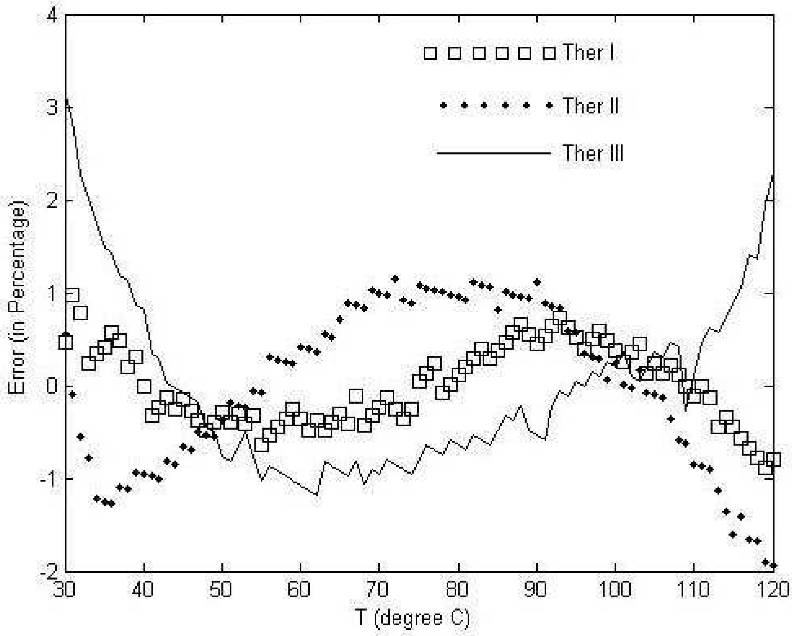

Fig.5.10 Percentage Error versus Temperature (°C) for full span of experiment

It can be seen that for thermistors I and II the nonlinearity error lies within approximately ±1% for the temperature range of 30 °C to 120 °C. Moreover, for thermistors I and II the linearity varies within ±0.5% between the range 33 °C to 115 °C and 96°C to 107°C respectively. For thermistors III the nonlinearity error lies within ±1% for the temperature range of 38 °C to 115 °C and within ±0.5% between the range 85 °C to 111 °C. Hence, the proposed scheme gives acceptable linearity for the thermistors with different nominal resistances (R_{T0}) and β values employing a somewhat simple circuit arrangement compared to [32,33]. The Percentage Error versus Temperature (°C) for full span of experiment (30 °C to 120 °C) is shown in Fig.5.10.

CONCLUSION

Thermistors have been widely used for quick and precise measurement of temperature because of their small size, low thermal inertia, good sensitivity and reliability, and thus overall improved performance. However, the thermistor is rarely used in conventional ordinary-purpose measurement circuits because its resistance variation with temperature is highly nonlinear. Hence, over the temperature range of interest, it does not yield a linear input/output relation for the measuring circuit in which it is placed, unless some remedial measures are taken. In a bid to overcome this shortcoming, simply a resistor connected either in series or in parallel with the thermistor sensor can be employed to yield an extended range of response linearity. There are other sophistications like log-amplifier based circuits to give enhanced performance over wider ranges of temperature. All of these thermistor-resistor networks are generally used in the system such that the output, namely, voltage, current, or frequency, is either directly or inversely proportional to a temperature-dependent parameter of the network.

A low-cost linearizing circuit has been developed for the NTC thermistor employing inverting amplifier circuit using operational amplifier. The experimental studies on the system developed, revealed the following points;

1) Good linearity could be achieved, somewhat better than those reported by other investigators, while the simplicity of the proposed arrangement compared to the reported ones.

2) The gain (sensitivity) of the system can be adjusted by using a resistive pot, without affecting the linearity of the transducer transfer curve.

Where microcontroller or computer based data acquisition system is used, the analog circuit introduced in this work may serve as the first-stage linearizer. The linearity may be further improved by software methods, that may be as simple as ROM –based look-up table (LUT) method, coupled with linear interpolation, if necessary.

APPENDIX

RTD Resistances

Temperature (^oC)	Resistance (Ω)
0.0	100.00
1.0	100.39
2.0	100.78
3.0	101.17
4.0	101.56
5.0	101.95
6.0	102.34
7.0	102.73
8.0	103.12
9.0	103.51
10.0	103.90
11.0	104.29
12.0	104.68
13.0	105.07
14.0	105.46
15.0	105.85
16.0	106.24
17.0	106.63
18.0	107.02
19.0	107.40
20.0	107.79
21.0	108.18
22.0	108.57
23.0	108.96
24.0	109.35
25.0	109.73
26.0	110.12
27.0	110.51
28.0	110.90
29.0	111.29
30.0	111.67
31.0	112.06
32.0	112.45

33.0	112.83
34.0	113.22
35.0	113.61
36.0	114.00
37.0	114.38
38.0	114.77
39.0	115.15
40.0	115.54
41.0	115.93
42.0	116.31
43.0	116.70
44.0	117.08
45.0	117.47
46.0	117.86
47.0	118.24
48.0	118.63
49.0	119.01
50.0	119.40
51.0	119.78
52.0	120.17
53.0	120.55
54.0	120.94
55.0	121.32
56.0	121.71
57.0	122.09
58.0	122.47
59.0	122.86
60.0	123.24
61.0	123.63
62.0	124.01
63.0	124.39
64.0	124.78
65.0	125.16
66.0	125.54
67.0	125.93
68.0	126.31
69.0	126.69
70.0	127.08
71.0	127.46
72.0	127.84

73.0	128.22
74.0	128.61
75.0	128.99
76.0	129.37
77.0	129.75
78.0	130.13
79.0	130.52
80.0	130.90
81.0	131.28
82.0	131.66
83.0	132.04
84.0	132.42
85.0	132.80
86.0	133.18
87.0	133.57
88.0	133.95
89.0	134.33
90.0	134.71
91.0	135.09
92.0	135.47
93.0	135.85
94.0	136.23
95.0	136.61
96.0	136.99
97.0	137.37
98.0	137.75
99.0	138.13
100.0	138.51
101.0	138.88
102.0	139.26
103.0	139.64
104.0	140.02
105.0	140.40
106.0	140.78
107.0	141.16
108.0	141.54
109.0	141.91
110.0	142.29
111.0	142.67
112.0	143.05

113.0	143.43
114.0	143.80
115.0	144.18
116.0	144.56
117.0	144.94
118.0	145.31
119.0	145.69
120.0	146.07

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