INVESTIGATIONS IN TRANSISTOR BASED SENSING OF TEMPERATURE

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INVESTIGATIONS IN TRANSISTOR BASED SENSING OF TEMPERATURE

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By

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CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled "**Investigations In Transistor Based Sensing of Temperature**" *By SRI* SOURAV DESHMUKH (M4ELE22016)*, submitted to the Jadavpur University Kolkata, West Bengal for the award of Master of Electrical Engineering in Electrical Measurement and Instrumentation is a record of Bonafede research work carried out by him in the Department of Electrical Engineering, under my supervision. I believe that this thesis fulfils part of the requirements for the award of degree of Master of Electrical Engineering during the academic session 2020- 2022. The results embodied in the thesis have not been submitted for the award of any other degree elsewhere.*

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This foregoing thesis is hereby approved as a credible study of an engineering subject carried out and presented in a manner satisfactorily to warranty its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not endorse or approve any statement made or opinion expressed or conclusion drawn therein but approve the thesis only for purpose for which it has been submitted.

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I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of his **M.E. (ELECTRICAL ENGINEERING)** studies during academic session 2020-2022. All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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Sourav Deshmukh

CONTENTS

Chapter 5: Conclusion

Chapter 1: Introduction

1.1 Introduction

Temperature is one of the mostly measured physical parameters in modern world. Due to the increasing usage of automation and technology, temperature sensors are becoming more and more important for many temperature monitoring and controlling applications from big industries to small microchips. Back from 16^{th} century various methods have been adopted for sensing temperature. In the 1600s *Galileo* was able to construct a temperature sensitive device called thermoscope (air thermometer) but it was prone to be affected by the change of atmospheric pressure. In 1701 *Ole Christian Romer* made a practical thermometer using red wine as temperature indicator. In that the starting point used for temperature scale was represented by the temperature of a salt and ice mixture called as Romer's zero point. Later *Daniel Gabriel Fahrenheit* invented the mercury in-glass thermometer and alcohol thermometer. The mercury thermometer had greater precision than Romer's and its temperature scale was from Romer's zero point to human's body temperature. Alcohol thermometer was able to measure much low temperatures because of alcohol's very low freezing point (-113℃) compared to mercury (-39℃). In the most important year of history of temperature measurement 1821, *T J Seebeck* discovered the thermocouple effect and *Sir Humphrey Davy* discovered that platinum metal could be used as a temperature detector (RTD), later both became very important temperature sensors. Later bi-metallic temperature sensors in 19^{th} century and semiconductor devices in 20^{th} century such as thermistor, integrated circuit sensors and fibre optic temperature sensors evolved as the most recent discoveries in this field.

1.2 Motivation and Prior Work

Temperature sensor is basically a device that can measure temperature such as thermistors, thermocouples, RTDs (Resistance Temperature Detector) etc. However, temperature is a physical parameter that describes the typical kinetic energy of molecules; it does not itself measure energy, but it is the manifestation of the energy content of molecules in a material. As a result, it is impossible to detect the kinetic state of molecules directly [1]. Instead, thermal sensors use thermometric variables, which are various parameters that change in proportion to the kinetic state of molecules. For thermistors and RTDs, resistance is the thermometric variable. Thermistors are very good at temperature sensing due to its high resolution, high sensitivity, low cost and ruggedness. But the major drawback of a standard thermistor is its severely nonlinear resistance-temperature curve [2]. So, by using appropriate signal conditioning circuits the problem of nonlinearity can be tackled.

Various–signal conditioning circuits have been developed throughout the years with the goal of getting an output that has a roughly linear relationship with the temperature being detected. The simplest method among them involves linearizing certain portions of the thermistor's properties by connecting a passive element, such as a fixed resistance, in series or in shunt with the thermistor [3]. This method can be somewhat adjusted by inserting a thermistor into one of the Wheatstone bridge's arms and selecting the resistance values for the other three arms so that they have the same effect as the single resistance indicated above [2,4,5].

Utilizing linearizing arrangements with logarithmic amplifiers yields better linearity [6–9]. In order to realise a linear voltage/temperature relationship, Khan [7] employed a thermistor in a logarithmic network in which linearity was achieved over a large temperature range, from 20°C to 137°C, with an error of less than 0.9 percent.

Utilizing various multivibrator circuits is another well-known method of linearizing thermistor characteristics [10–18]. It is also popular to use temperature to frequency converters that employ an astable multivibrator [13–18].

Software techniques, such as numerical methods and soft computing techniques, are also used in addition to the above hardware linearization methods that can give better performance in terms of linearity. The usage of a "look up table" is one of the most common methods among these techniques [19]. An analog-to-digital converter or a specific ROM is employed for this. Also, piecewise linear interpolation, piecewise polynomial interpolation [20], Inverse curve fitting [21] are further software approaches.

1.3 Scope of Present Work

In this thesis, two transistor based active circuits for temperature sensing are presented in chapter 4. Each of them consists of an op-amp based log amplifier followed by an instrumentation amplifier and a summer amplifier. In the first circuit the **bipolar transistor** (BJT) present in the feedback path of the log amplifier acts as the temperature sensing element, and in the second one both the **BJT** and the **thermistor** present in forward path of the log amplifier act as temperature sensing elements. Experimental results show that only the log amplifier can act as linearizing circuit but its output voltage is very low (in millivolt range). So, the instrumentation amplifier and summer amplifier are used for further signal conditioning by adjusting gain to get a rising characteristic with higher sensitivity. The performances of the suggested schemes display respectable linearity, which is comparable to the outcomes from other schemes that have been published in literatures. Also, the cost effectiveness and optimal operating temperature range with acceptable linearity make this an effective signal conditioning circuit for temperature sensor.

Chapter 2: Temperature Sensing Elements: Bipolar Junction Transistor and Thermistor

2.1 Introduction

There can be three major components in any generalized measurement system: -

- Input device
- Processing or Signal conditioning device
- Output device

The input device is generally a *transducer* which receives the quantity of the measurand (generally a physical quantity to be measured) and delivers a proportional or analogous electrical signal to the processing device. Then this electrical signal is manipulated by the processing device which includes amplification, attenuation, filtering, adding offset etc. Finally, the modified signal is recorded or displayed by the output device.

Generally, an electrical transducer is a device which converts non-electrical quantity into electrical signal.

A sensor is basically a transducer that responds to an input signal and produces a signal which contains information about the input signal. Thermistors, gyroscope, proximity sensors, thermocouples are well known sensors. Also, a bipolar transistor (BJT) is temperature sensitive which can be used as temperature sensor.

In this chapter, the basics of BJT and thermistor are going to be discussed as a background of this investigation work.

2.2 Bipolar Junction Transistor (BJT)

2.2.1 Basics of BJT

A transistor is a small semiconductor device which can control voltage or current flow inside it. It is generally used as a switch or an amplifying device. But transistor is also sensitive to temperature change, with increase in temperature its minority carrier concentration increases and its base to emitter voltage decreases. With this property an approach is made to use a transistor as a temperature sensor.

Bipolar transistor is named so because both majority and minority carriers have contribution in controlled current. A single crystal of BJT consists of two junctions which are between N-type and P-type of semiconductor materials.

2.2.2 Types and Construction

A BJT consists of three layers or regions base(B), emitter(E) and collector(C). These three layers have different doping concentrations and areas. Emitter is highly doped with medium area; collector is moderately doped with largest area and base is lightly doped with thinnest area.

Based on doping impurities (such as phosphorus doping makes N-type where Boron doping makes P-type) the layer with extra electrons is called N-type and the layer with electrons removed or extra holes is called P-type. On this basis a bipolar transistor is generally divided into two categories.

1. NPN transistor

2. PNP transistor

In NPN type electrons can flow from emitter to collector whereas in PNP type electron flow direction is simply opposite.

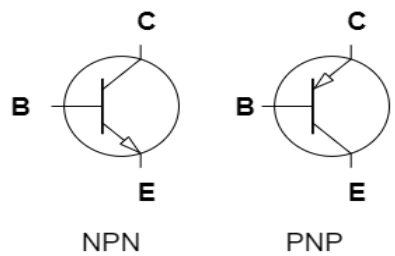
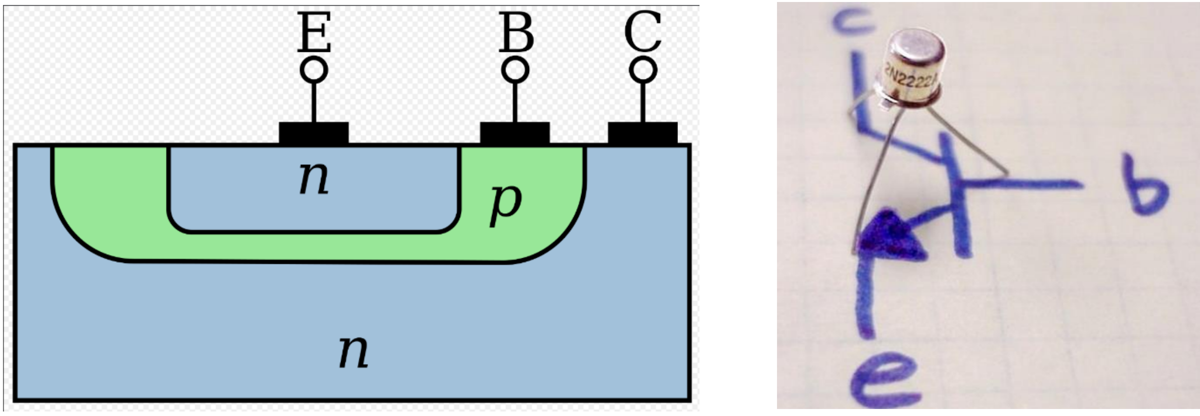


Fig 2.1: Symbols of NPN and PNP transistor

Base region is in between emitter and collector region where collector is surrounded by emitter so that carriers injected to base region can completely be collected by collector as shown in the below figure. Emitter is heavily doped so that carriers injected at emitter-base junction by emitter region are much more than that by base region.



(a) (b)

Fig 2.2: (a) Cross sectional view of layers of BJT; (b) Q2N2222 in metal package

In old days, transistors were made from germanium but in modern days those are generally made from silicon except some used for high-speed applications are made from gallium arsenide such as HBT (hetero-junction bipolar transistor).

2.2.3 Operating Function of Forward Active Mode

BJTs can work in three different configurations: -

- Common-base configuration (CB)
- Common-emitter configuration (CE)
- Common-collector configuration (CC)

For each configuration BJTs can operate in four modes of operation: -

- Forward active mode
- Reverse active mode
- Saturation mode
- Cut-off mode

For the sake of this thesis, only the forward active mode with CB configuration will be discussed.

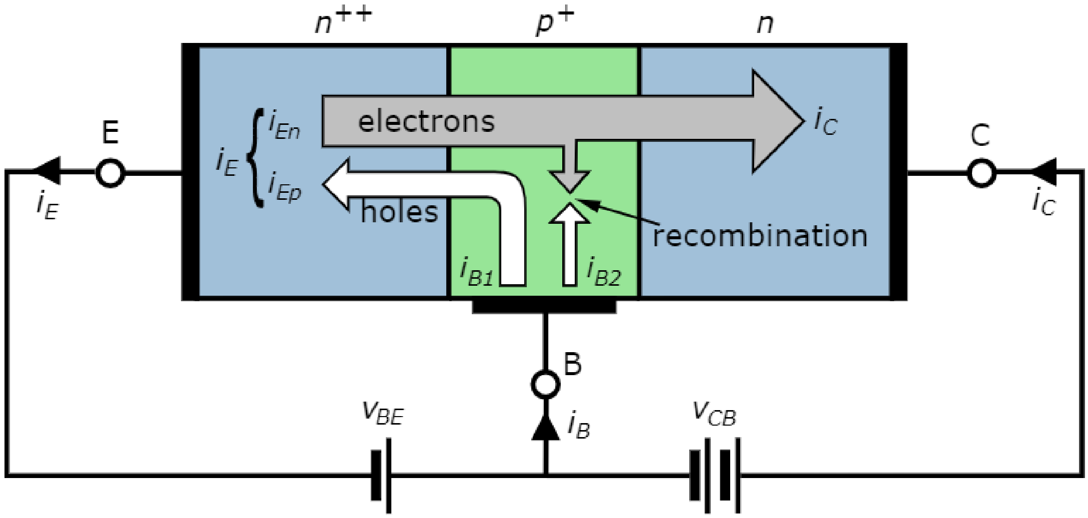


Fig 2.3: NPN transistor inactive mode with CB configuration

In forward active mode of operation, base-emitter junction is forward biased and collector-base junction is reverse biased. The equilibrium between the thermally produced electrons and the repulsive electric field of the n-doped emitter depletion area is disturbed when forward bias is given to the base-emitter junction. This allows thermally excited electrons (electrons in NPN and holes in PNP) to be injected from emitter region towards base region. From the area of high concentration near the emitter to the area of low concentration near the collector, these electrons diffuse through the base.

BJTs are categorised as minority-carrier devices because the majority of the collector current in a BJT is caused by the flow of charge carriers (electrons in NPN or holes in PNP) injected from a severely doped emitter into the base, where they are minority carriers (electrons are minority carriers in P-type base) and diffuse toward the collector. In between this diffusion process some of injected electrons (holes in PNP) are recombined with its counterpart (holes) at base region which decreases BJT efficiency. This is the reason why base region is kept thin so that injected minority carriers at the base get minimum recombination time which results in most of the carriers diffused into collector region.

By using KCL the below equation is observed:

$$I_E = I_B + I_C \Rightarrow I_E \approx I_C \quad \text{[As } I_B \text{ is very small]}$$

where I_B, I_C and I_E are the base, collector and emitter currents.

The BJT gain is reduced by both injection efficiency and recombination in the base.

$$\alpha = \frac{I_C}{I_E} \qquad \text{... (2.1)}$$

$$\beta = \frac{I_C}{I_B} \qquad \text{... (2.2)}$$

where α and β are common-base current gain and common-emitter current gain.

α value is very close to but less than 1 (0.98-0.99) due to recombination. β decides BJT efficiency which is ratio of carriers reach the collector to carriers injected at base.

2.2.4 Ebers–Moll model of BJT

In 1954 a mathematical model of BJT was introduced by Jewell James Ebers and John L. Moll [22]. In this model a BJT is represented as two P-N junction diodes as shown in following figure.

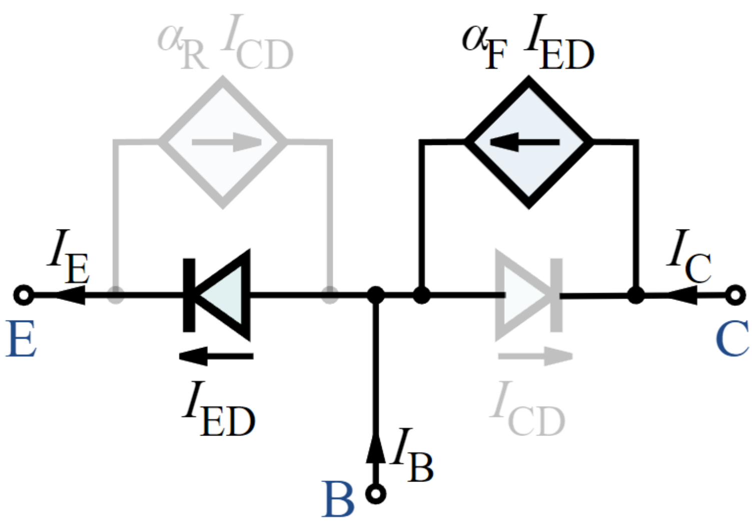


Fig 2.4: Approximated Ebers–Moll model of NPN transistor in active mode

where I_B, I_C and I_E are the base, collector and emitter currents,

I_{ED} and I_{CD} are emitter diode current and collector diode current respectively,

α_F is forward current gain of common base connection.

$$I_E \cong I_{ES}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)$$

$$I_C = \alpha_F . I_E$$

$$I_B = (1 - \alpha_F). I_E$$

Where V_{BE} is base to emitter voltage of the transistor,

V_T is thermal voltage.

The difference between this two-diode model of BJT and two separate diodes connected by wire is that in the later one minority carriers cannot move from one diode to another like the BJT model.

2.2.5 Applications of BJT

There are many different applications of BJT as following:

- Building block of electronic *amplifiers*.
- Used in electronic switching and automatic *switching applications*.
- As a *temperature sensor*.
- Used in logarithmic *converters*.
- Can be used in very high frequency applications such as radiofrequency circuits of wireless systems.

2.3 Thermistor

2.3.1 Basics of Thermistor

A thermistor (also called thermal resistor) is simply a resistor which is very highly sensitive to temperature. Pure metal resistors have linearly-increasing resistance to temperature characteristics but for thermistor its resistance to temperature characteristics is highly nonlinear. Generally, thermistors have negative temperature coefficient i.e., its resistance is decreasing with increasing temperature. However, there are also positive temperature coefficient thermistors available where its resistance is increasing with rise of temperature. A temperature measurement circuit with thermistor as its passive component can detect very small changes in temperature because of its high sensitivity with temperature. This property of thermistor usually gives it an advantage over other temperature sensors like thermocouples and RTDs. Resistance of thermistor can decrease up to 6% for 1℃ rise in temperature. This high sensitivity of thermistors make it well suited to precision temperature measurement, control and compensation. Therefore, thermistors are widely used for such applications, especially in lower temperature range of $-100℃$ to $300℃$ [23].

2.3.2 Types and Construction of Thermistors

Thermistors are broadly divided into two categories: -

1. NTC thermistors (Negative Temperature Coefficient)
2. PTC thermistors (Positive Temperature Coefficient)

Thermistors are made of semiconductor materials. They are composed of sintered mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. Their resistances range from 0.5Ω to $75M\Omega$ [24]. Because of very high base resistance of thermistors, lead resistance has practically very less or no effect on temperature reading.

Commercial PTC thermistors are of two types. First type is called “silistors” (silicon resistors) in which semiconductor material used is silicon and other type is switching type PTC thermistors which are made from doped polycrystalline ceramic (containing barium titanate ($BaTiO3$) and other compounds) [25]. Silistors are used because of its fairly linear resistance-temperature characteristics. Silicon PTC thermistors are typically rated up to 150°C, if used above this temperature they may exhibit a negative temperature coefficient [26]. Silicon-based PTC thermistors have a much smaller drift than an NTC thermistor. They are inherently stable devices which are hermetically sealed in an axial leaded glass encapsulated package [26]. Switching type PTC thermistors have a typical resistance-temperature characteristics, firstly with rising temperature it shows very low negative temperature coefficient until a transition or switching point named as 'Curie temperature' T_C is reached. After that it shows rising characteristics with very large slope. This happens due to changing dielectric constant of $BaTiO3$with temperature [25].

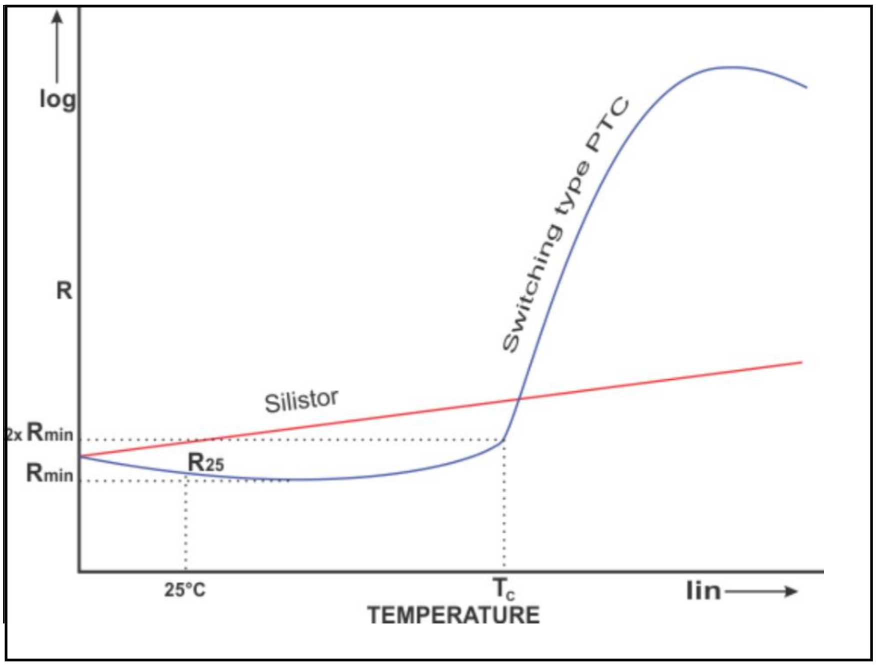


Fig 2.5: Resistance-Temperature characteristics of PTC Thermistor

NTC thermistors are generally composed of oxides of iron group of metals such as manganese, cobalt, nickel, copper, titanium etc [25]. Commercial NTC thermistors are broadly divided into two categories. First category consists of bead type thermistors which have platinum alloy lead wires which are directly sintered into the ceramic body [27]. Second category consists of discs, chips, rods, surface mounts types which have metalized surface contacts [27]. The smallest in size are bead types and most stable with highest accuracy are hermetically sealed thermistors. The nonlinearly decreasing resistance temperature characteristics is shown in the following figure.

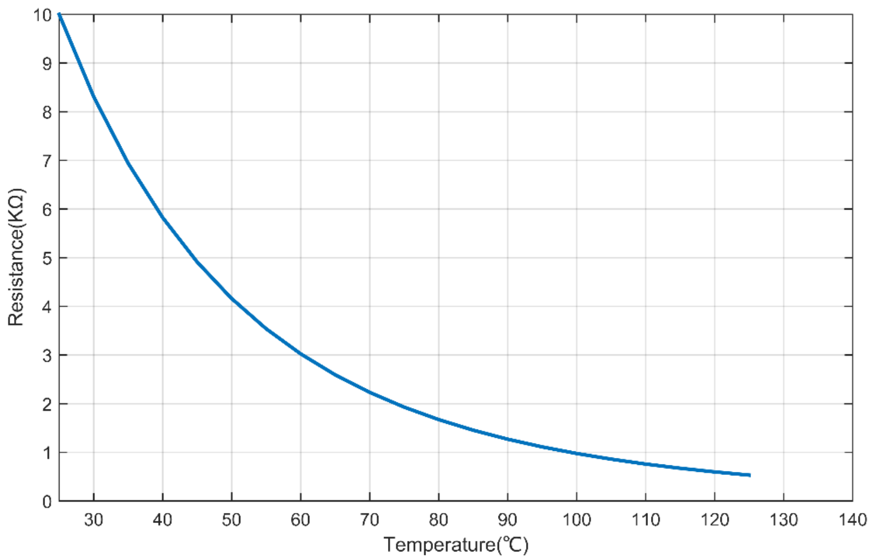


Fig 2.6: Resistance-Temperature characteristics of NTC 10K Thermistor

2.3.3 Mathematical Modelling of Thermistor

2.3.3.1 Linear Approximation

For small temperature range a nonlinear characteristic of thermistor can be approximated to a linear relationship. The first order approximation is

$$\Delta R = k\Delta T$$

where ΔR is the change in resistance,

k is the first order temperature coefficient of resistance,

ΔT is the change in temperature.

Here if k has positive sign then it is PTC thermistor and if k has negative sign then it is NTC thermistor. k decides the sensitivity of resistance-temperature characteristics of the thermistor.

2.3.3.2 Steinhart-Hart Equation

For high accuracy in temperature measurement by thermistor, curve fitting techniques are widely used to mathematically model the resistance (R) - temperature (T) relationship of the thermistor. As the linear approximation is only valid over a very small range, a third order approximation used for wide ranges are given by following Steinhart-hart equation: -

$$\frac{1}{T} = a + blnR + c(lnR)^3$$

Where a, b, c are curve fitting constants.

The error in the Steinhart–Hart equation is generally less than 0.02 °C in the measurement of temperature over a 200 °C range [28].

2.3.3.3 Exponential Model of NTC Thermistor

From the band gap theory of solid-state physics, it is assumed that charge carrier concentration (n_i) has an exponential dependence on absolute temperature (T in Kelvin) [10].

$$n_i \propto \exp\,(-1/2kT)$$

where k is the Boltzmann constant (1.38×10^{-23}) J/K.

Also, resistivity of a material (ρ) is inversely proportional to charge carrier concentration.

$$\rho \propto 1/n_i$$

$$\text{or,} \rho \propto \exp\,(1/2kT)$$

$$\text{or,} \;\; \rho \propto \exp\,(1/T)$$

Although NTC thermistor is a semiconductor material, but we can assume its resistance (R_T) to be proportional to its resistivity (ρ).

So, $$R_T \propto \exp\,(1/T)$$

At temperature T_1 thermistor resistance is $R_{T_1}\,\Omega$ and at temperature T_2 thermistor resistance is $R_{T_2}\Omega$.

So, we can write,

$$R_{T_1} = A\exp(\beta/T_1)$$

$$R_{T_2} = A\exp(\beta/T_2)$$

where A is proportional constant,

β is the sensitivity index of the thermistor material.

$$R_{T_1}/R_{T_2} = \exp\left[\beta\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

From the above equation we can calculate thermistor resistance at any temperature if thermistor resistance at any certain temperature and β parameter of the thermistor material is known.

2.3.4 Factors Affecting Thermistor Resistance Measurement

The following factors can affect the measured resistance values of thermistor which ultimately disturbs the accuracy of temperature measurement by the thermistor.

2.3.4.1 Self Heating effect

When thermistor is subjected to voltage across it, current flows through the thermistor. So certain power is dissipated in the thermistor. It generates heat which raises the temperature of the thermistor above the environment temperature. This is called self - heating effect of thermistor.

Power dissipated, $P_T = I_T \times V_T$watts

where I_T is current through the thermistor,

V_T is voltage across the thermistor.

Self-heating effect can introduce error in measurement of thermistor resistance. But to obtain accurate measurement the power levels must be kept at low level so that there is scope for thermal equilibrium to establish between the thermistor and its environment.

However self-heating effect of thermistor has some specific applications such as liquid-level detection, liquid-flow measurement and air-flow measurement where its body temperature is raised well above the ambient temperature so the sensor then detects even subtle changes in the thermal conductivity of the environment [25].

To minimize the effect of self-heating, some auxiliary heating elements are used to maintain thermistor stability at a given temperature.

2.3.4.2 Thermal Time Constant

In temperature monitoring applications, thermistors are subjected to continuous varying temperature. But due to the thermal mass of thermistor and heat transfer characteristics of the environment, thermistors need some time to change its body temperature. This property is quantified by the thermal time constant (T.C) of thermistor.

Thermal time constant is the time required for the thermistor to change its body temperature by 63.2% of a specific temperature span when the measurements are made under zero-power condition in thermally stable environments. As an example, a thermistor is placed in an oil bath at 25℃ and allowed to reach equilibrium temperature. The thermistor is then rapidly moved to an oil bath at 75℃. The T.C. is the time required for the thermistor to reach 56.6℃ (63.2% of the temperature span) [29].

2.3.4.3 Thermal Dissipation Constant

Due to the dependence of measured thermistor resistance on the power dissipated in the thermistor during measurement and on the thermal dynamics of the system being measured. These two factors lead to the concept of Thermal Dissipation Constant (D.C) of thermistor.

D.C of a thermistor is defined as the power required to raise the thermistor's body temperature by 1℃ in a particular measurement medium. It is measured in mW/℃ [29].

The change in resistance of a thermistor due to change in D.C. can be used to monitor levels or flow rates of liquids or gasses. For example, as flow rate increases, D.C. of a thermistor in a fluid path will increase and the resistance will change in a manner that can be correlated to flow rate [29].

These three properties of thermistor can easily influence the measurement of resistance. Therefore, it is very important to understand these properties for accurate measurement.

2.3.5 Advantages and Limitations of Thermistor

Thermistors have following advantages which makes it better than other temperature sensors like thermocouples and RTDs.

- Performance: Very high **sensitivity** and **accuracy** allows a thermistor to measure small changes in temperature. Also, it has good **stability** with ageing.
- *Structure*: **Rugged** and **flexible** construction allows variety of forms with small packages.
- *No lead wire resistance*: Negligible lead resistance allows a thermistor to be installed at a distance from measuring circuits.
- *Hermetic seal*: Glass encapsulation provides a hermetic package which eliminates failure of the sensor due to moisture.
- Wide ranges of thermistor with cost effectiveness.

Thermistors also have some limitations as follows:

- *Nonlinearity*: Due highly nonlinear resistance-temperature characteristics of thermistors, it has to installed with additional signal conditioning circuits to have a linear characteristic.
- *Self-heating*: Due to its self-heating property, thermistors are limited to low sensing current to avoid error in measurements.

2.3.6 Applications of Thermistor

- **Temperature Measurement:** As with increase in temperature NTC thermistor resistance (in KΩ range) decreases, so the current i (in mA range) in the below circuit is increases. This current is calibrated in terms of temperature to measure temperature.

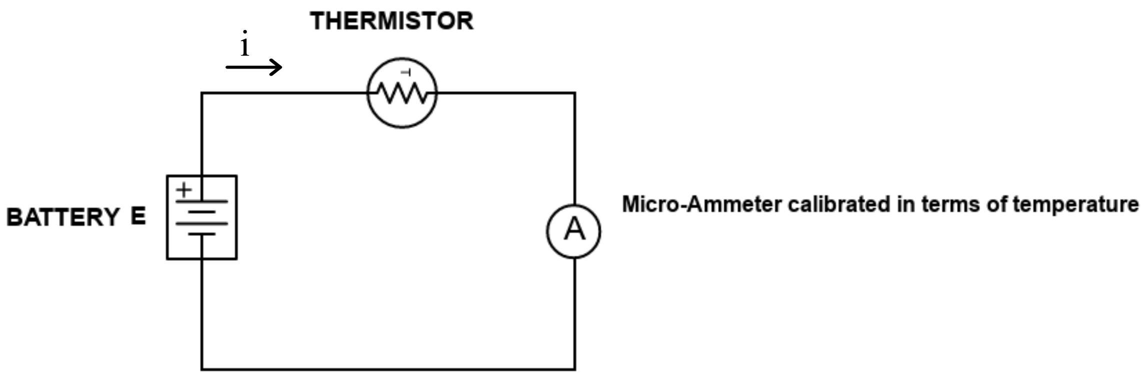


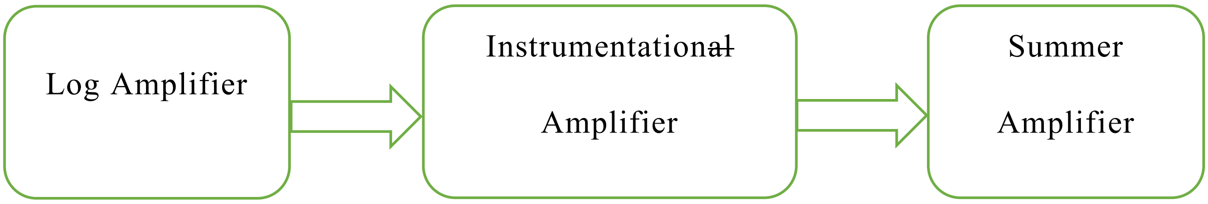
Fig 2.7: Simple circuit for temperature measurement

- **Temperature compensation:** NTC thermistors have negative temperature coefficient of resistance which is opposite to most of the electrical conductors (metals) with positive temperature coefficient of resistance. So, a thermistor with a parallel resistance can be used for temperature compensation of a metal conductor.
- As a circuit breaker in manufacturing industries.
- Precise monitoring of temperature in medical applications and food and beverage industry.

Chapter 3: Proposed Signal Conditioning Circuit and Its Mathematical Analysis

3.1 Introduction

The proposed signal conditioning circuit consists of a logarithmic circuit followed by an instrumentation amplifier and a summer amplifier.



The output voltage of the inverting log amplifier is negative and in mV range. Such low amplitude signals can be susceptible to noise which leads to inaccuracy of measurement. Therefore, an Instrumentation amplifier is used which is capable of noise cancellation as well as providing high gain. Also, the final output signal should be positive increasing function with temperature for the ease of measurement. The summer amplifier does this by adding required offset to its input signal.

Also, due to loading, voltage of the dc sources used in the log amplifier and the summer amplifier can be reduced which can make room for error. Therefore, the sources are supplied through buffer amplifier to reduce the loading effect on it.

Here, the mathematical analysis is done to establish linear relation between the output voltage of the temperature sensor and temperature. Before that we need to know the basics of the sub-circuits used in this scheme.

3.2 Log Amplifier

Log amplifier is an electronic circuit, output of which is simply proportional to the natural logarithmic of applied input. Generally, it consists of an operational amplifier with a diode or a transistor in its feedback path. It is sensitive to temperature mainly because of emitter saturation current of the transistor or reverse saturation current of the diode which varies significantly with change in temperature.

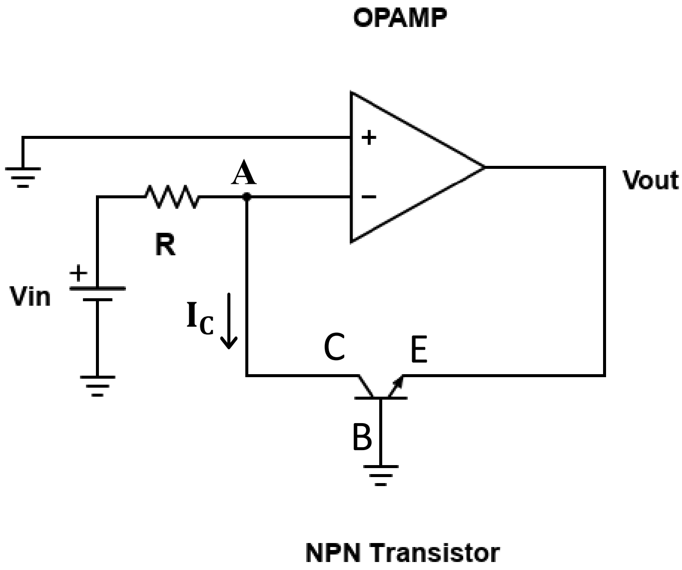


Fig.3.1. Log amplifier using NPN Transistor

From the above circuit,

$$V_{out} = -V_{BE} \quad \ldots (3.1)$$

where V_{BE} is base to emitter voltage of the transistor.

In this circuit as the collector voltage of a transistor V_C = 0, the collector current is given by Eqn. (3.2).

$$I_C \cong \alpha . I_{ES} (e^{\frac{V_{BE}}{V_T}} - 1) \quad \ldots (3.2)$$

where $\alpha$is the ratio of collector current and emitter current$(I_C/I_E) \approx 1$,

$V_T$is thermal voltage,

I_{ES} is reverse saturation current of the base emitter diode.

$$V_T = \frac{kT}{q} \quad \ldots (3.3)$$

where $k$is Boltzmann's constant (k =1.38 × 10^{-23} J/K),

T is ambient temperature in Kelvin,

$q$is magnitude of charge of electron ($q = 1.602 \times 10^{-19}$ C).

From **virtual short concept** of an ideal op-amp the inverting terminal voltage (V_{-}) is equal to the non-inverting terminal voltage (V_{+}).

$V_{+}=V_{-} = 0$ … (3.4)

As input impedance of an ideal op-amp is infinite, currents entering both the terminals are zero.

$$I = \frac{V_{in}}{R} \quad \text{… (3.5)}$$

Therefore, by using KCL at node A,

$I = I_C$

$$\text{or, } \frac{V_{in}}{R} = I_{ES}\left(e^{\frac{V_{BE}}{V_T}} - 1\right) \quad \text{… (3.6)}$$

From Eqns. (3.1) & (3.3) and considering $e^{\frac{V_{BE}}{V_T}} \gg 1$

$$\frac{V_{in}}{R} = I_{ES} * e^{\frac{V_{BE}\,\cdot\,q}{kT}}$$

$$\text{or, } V_{out} = -\frac{kT}{q}\ln\frac{V_{in}}{R\,.\,I_{ES}} \quad \text{… (3.7)}$$

3.3 Instrumentation Amplifier

Low energy signals are vulnerable to noise which causes inaccurate measurement. Instrumentational amplifier is an Op-amp based differential amplifier, which comes in mind when we need to process low energy signals as it provides very high gain and high CMRR (common mode rejection ratio) i.e., ability of a device to reject a signal (such as noise) that is common in both the inputs of that device. Therefore, the output of this IC has minimal effect of noise.

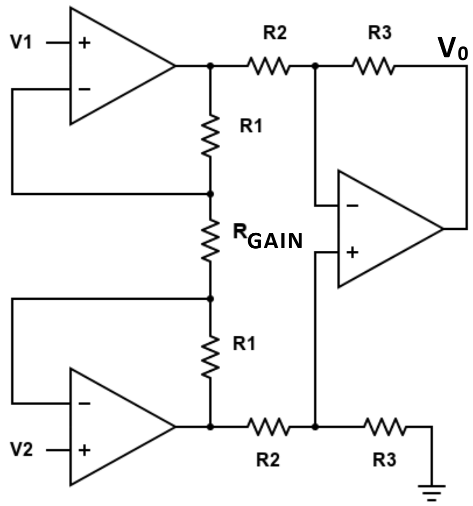


Fig. 3.2: Instrumentation Amplifier

Gain of the Instrumentation Amplifier,

$$A_V = \frac{V_0}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{GAIN}}\right)\frac{R_3}{R_2} \qquad \dots (3.8)$$

3.4 Summer Amplifier:

Summer amplifier is a type of Op-amp circuit configuration that is widely used to combine two or more signals. Also, it is useful in signal conditioning circuits to add offset to a signal. It has both the variety, inverting and non-inverting. Here inverting summer amplifier is used for the work.

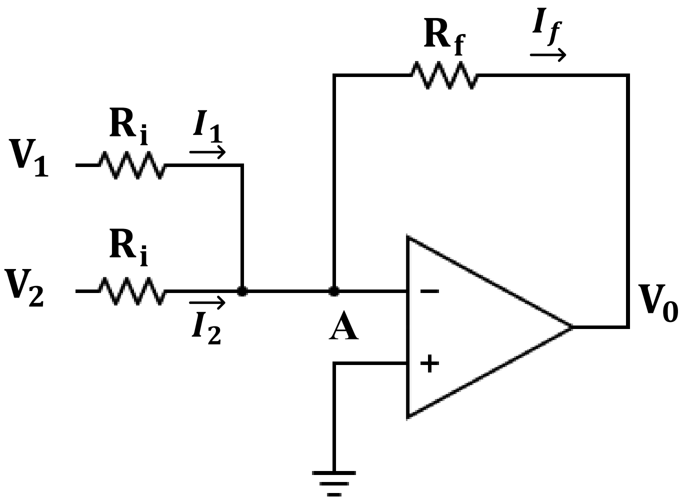


Fig 3.3: Non-inverting Summer Amplifier using 2 inputs

By virtual short concept of Op-amp voltage at node A is zero.

Considering ideal Op-amp currents entering both terminals are zero.

Using KCL at node A,

$$I_1 + I_2 = I_f$$

$$\text{or, } \frac{V_1}{R_i} + \frac{V_2}{R_i} = -\frac{V_0}{R_f}$$

$$\text{or, } V_0 = -\frac{R_f}{R_i}(V_1 + V_2) \qquad \ldots (3.9)$$

Output of summer amplifier is $-\frac{R_f}{R_i}$ times sum of voltage inputs. Therefore, it is also called voltage adder or summing inverter.

3.5 Buffer Amplifier

Buffer amplifier has unity gain with its output same as its input. But the main reason of using a buffer amplifier is its high input impedance and very low output impedance. Its input side is isolated from its output i.e., source present at input side is not loaded by the op-amp because input side current is very low due to high input impedance. Also, it is capable of driving high load (supply high current)as a perfect voltage source due to low output impedance.

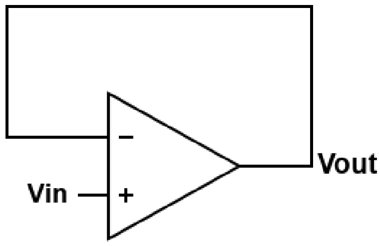


Fig 3.4: Op-amp based buffer amplifier or voltage follower

$$V_{in} = V_{out}$$

3.6 Proposed Circuits

There are two circuit diagrams Circuit1 and Circuit2 are proposed with a **constant resistance** (R) used in the log amplifier in Circuit1 replaced by a **thermistor** (Rt) in the Circuit2. Also, to get optimal output values gain adjustment is done by changing the resistance values of the summer amplifier from Circuit1 to Circuit2.

In Circuit1 only the transistor acts as temperature sensing element whereas in Circuit2 both of transistor and the thermistor act as temperature sensing element.

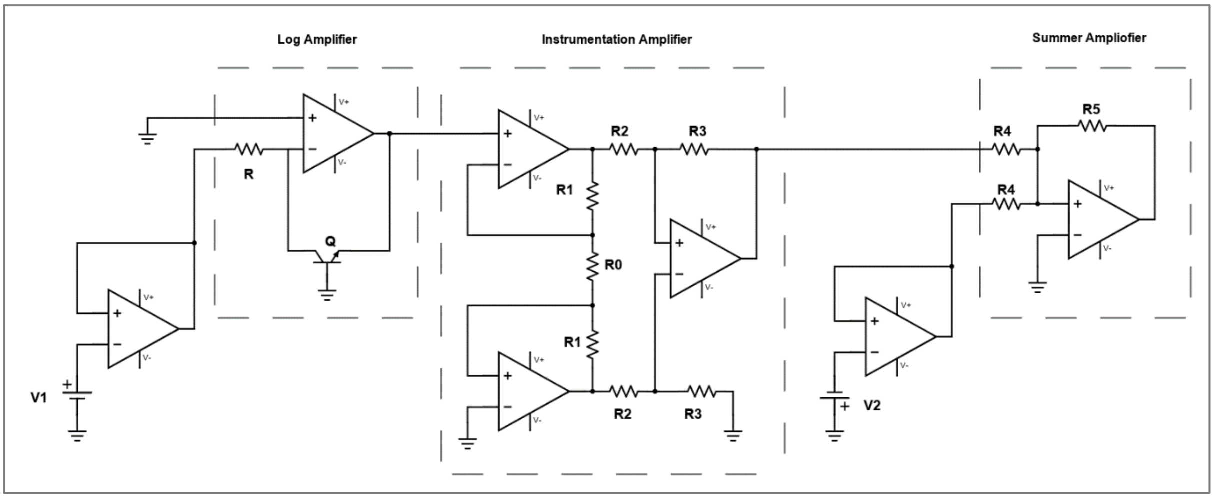


Fig 3.5: Circuit1 with transistor as sensor

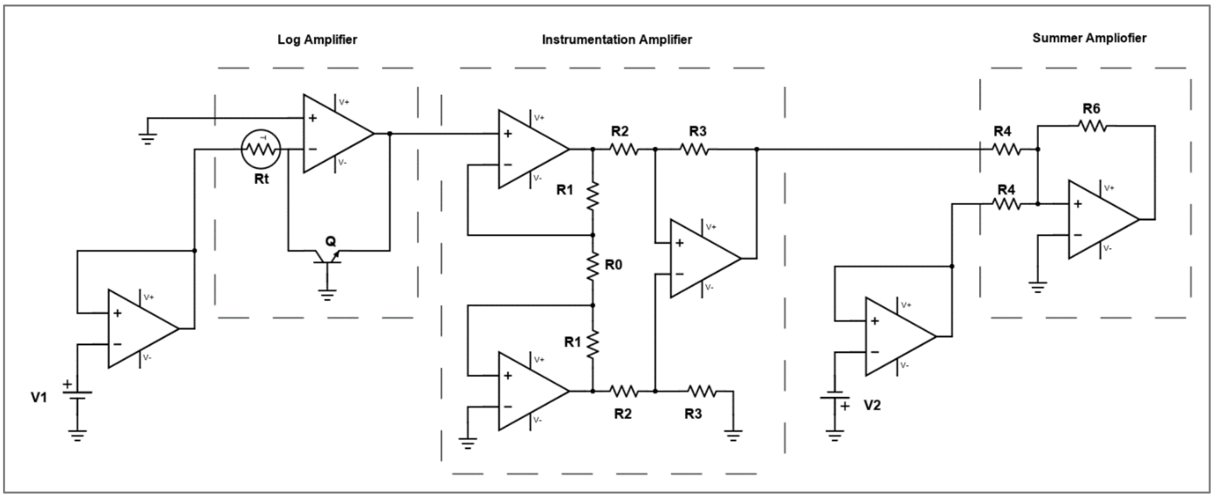


Fig 3.6: Circuit2 with both of transistor and thermistor as sensor

3.7 Mathematical expressions for the circuits proposed

As the gains of Instrumentation amplifier and summer amplifier are dependent only on fixed resistances values therefore its output voltages are not affected by temperature change. Therefore, linearity of output of the log amplifier with temperature is sufficient to prove overall circuit linearity with temperature. In the following a linear relation between the output and temperature is justified mathematically in Eqn. (3.20) & Eqn. (3.22) for Circuit1 and Circuit2 respectively.

<u>Circuit1:</u>

The output of the log amplifier in Circuit1 from Eq. (3.7) is:

$$V_{out} = -\frac{kT}{q}\ln\frac{V_{in}}{R\,.\,I_{ES}}$$

Here the only temperature dependent terms are T and I_{ES} .

I_{ES} is reverse saturation current due to diffusion of thermally generated minority carriers (holes in N-region and electrons in P-region) into the depletion layer when local electric field is applied.

A simplified expression for I_{ES} is [30]:

$$I_{ES} = e\left(\frac{n_{p0}D_n}{L_n} + \frac{p_{n0}D_p}{L_p}\right) \qquad \ldots (3.10)$$

where n_{p0} and $p_{n0}$are equilibrium concentration for electrons in P-region and holes in N-region respectively i.e., minority carriers,

D_n and D_p are diffusion co-efficient of electrons and holes respectively,

L_n and L_p are diffusion length of electrons and holes respectively.

According to mass action law for semiconductors at constant temperature,

$$n_{n0}.p_{n0} = p_{p0}.n_{p0} = {n_i}^2 \qquad \dots (3.11)$$

where n_{n0} and p_{p0} are equilibrium concentration for electrons in N-region and holes in P-region respectively i.e., majority carriers.

n_i is intrinsic carrier concentration (for both electrons and holes which is same).

$$I_{ES} = e\left(\frac{D_n}{n_{n0}.L_n} + \frac{D_p}{p_{p0}.L_p}\right){n_i}^2 \qquad \dots (3.12)$$

Now the following approximations are taken:

$n_{n0} = N_d$ for N-region

$p_{p0} = N_a$ for P-region

where $N_d$and N_a are donor and acceptor concentrations in N and P regions respectively.

$$I_{ES} = e\left(\frac{D_n}{N_d.L_n} + \frac{D_p}{N_a.L_p}\right){n_i}^2 \qquad \dots (3.13)$$

Now the diffusion term is very weakly temperature dependent which can be approximated [31] as

$$e\left(\frac{D_n}{N_d.L_n}+\frac{D_p}{N_a.L_p}\right) \approx B.T^{\gamma/2} \qquad \text{… (3.14)}$$

where γ is semiconductor material property.

Also, according to C. Kittel [32]:

$${n_i}^2 = CT^3\exp\left[-\frac{E_g(T)}{k.T}\right] \qquad \text{… (3.15)}$$

where $E_g(T)$ is the energy band gap between valence band and conduction band of the semiconductor material which also depends on temperature.

$E_g(T)$hasapproximately linear relation with temperature at high temperatures above 200K(for Si) and above 250K(for Ge) [33].

$$E_g(T) = E_g(0) - \alpha T \qquad \text{… (3.16)}$$

where $E_g(0)$ is linear extrapolation of$E_g(T)$to zero Kelvin.

$$I_{ES}(T) = BC.T^{(3+\gamma/2)}\exp\left[-\frac{E_g(0)-\alpha T}{k.T}\right] \qquad \text{… (3.17)}$$

By putting the value of $I_{ES}(T)$ from Eqn. (3.17) in Eqn. (3.7),

$$V_{out} = -\frac{kT}{q}\left[\ln\frac{V_{in}}{R} - \ln\left(BC.T^{(3+\gamma/2)}\exp\left[-\frac{E_g(0)}{k.T}+\frac{\alpha}{k}\right]\right)\right]$$

or, $V_{out} = -\frac{kT}{q}\left[\left(\ln\frac{V_{in}}{R.BC} - \frac{\alpha}{k}\right) - (3+\gamma/2)\ln T + \frac{E_g(0)}{k.T}\right]$

$$\text{or, } V_{out} = \left(\frac{\alpha}{k} - \ln\frac{V_{in}}{R.BC}\right)\frac{kT}{q} - \frac{E_g(0)}{q} + \frac{kT}{q}(3+\gamma/2)\ln T \qquad \dots (3.18)$$

In above equation, the term $(3+\gamma/2)\ln T$ is negligible [34].

Also $\frac{k}{q}$ is in range 10^{-4} and T is in range of 10^2. So overall $\frac{kT}{q}$ is in range of 10^{-2}.

So, $\frac{kT}{q}(3+\gamma/2)\ln T$ term can be neglected.

Now the equation (3.18) becomes as following:

$$V_{out} = \left(\frac{\alpha}{k} - \ln\frac{V_{in}}{R.BC}\right)\frac{kT}{q} - \frac{E_g(0)}{q} \qquad \dots (3.19)$$

$$\text{or, } V_{out} = c.T - \frac{E_g(0)}{q} \qquad \dots (3.20)$$

where c is a constant.

For Circuit1, Eq. (3.20) proves a linear relationship of output voltage (V_{out}) with ambient temperature (T), with positive slope c and negative intercept $\frac{E_g(0)}{q}$.

.

Circuit2:

In the previous calculation from Eqn. (3.18), replacing R by R_T using the exponential equation of thermistor $R_T = R_0 \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$ … (3.21)

$$V_{out} = \frac{kT}{q}\left(\frac{\alpha}{k} - \ln\frac{V_{in}}{BC} + \ln R_T\right) - \frac{E_g(0)}{q}$$

$$\text{or, } V_{out} = \frac{kT}{q}\left(\frac{\alpha}{k} - \ln\frac{V_{in}}{BC} + \ln R_0 + \frac{\beta}{T} - \frac{\beta}{T_0}\right) - \frac{E_g(0)}{q}$$

$$\text{or, } V_{out} = \left(\frac{\alpha}{k} - \ln\frac{V_{in}}{BC} + \ln R_0 - \frac{\beta}{T_0}\right)\frac{kT}{q} - \left(\frac{E_g(0)}{q} - \frac{k\beta}{q}\right)$$

or, $$V_{out} = b.T - \frac{E_g(0) - k\beta}{q} \qquad \text{… (3.22)}$$

For Circuit2, Eq. (3.22) proves a linear relationship of output voltage (V_{out}) with ambient temperature (T) with positive slope b and negative intercept $\frac{E_g(0)-k\beta}{q}$.

Chapter 4: Results and Discussion

4.1 Introduction

The performance analysis of the proposed circuits is done through both simulation and hardware-based experiment. Results are compared with its respective best fit straight line (BSL) using least square method and percentage errors of outputs from BSL are generated in MATLAB.

BSL is represented as:

$$V = a \times T + b$$

where V is output voltage,

T is ambient temperature,

a & b are coefficients of BSL.

4.2 Simulation results

The proposed signal conditioning circuits named 'Circuit1' and 'Circuit2' are simulated in temperature range of 35℃ to 125℃ with a step of 5℃ in PSPICE app.

For circuit1 simulation is carried out by sweeping temperature over the range between 35℃ and 125℃. In this case, out of all the components present in the entire circuit, only the transistor is subjected to such change in temperature. The results obtained in terms of output vs. temperature and percentage deviation of output from BSL are shown in Fig. 4.1 and Fig. 4.2, respectively.

During the simulation of circuit2 temperature of the transistor is changed using the option of temperature sweep in the simulation environment, similar to the case of circuit1. As the resistance associated with the log amplifier is nothing but the thermistor in present case, its value has to be altered in accordance with the operating temperature. This has been implemented by altering its value manually as per the data sheet of the thermistor in every run of simulation. At this the effect of varying temperature is finally realized on the transistor as well as on the thermistor used. The used data sheet is shown in TABLE I. The results obtained in terms of output vs.

temperature and percentage deviation of output from BSL are shown in Fig. 4.3 and Fig. 4.4, respectively.

Also, the main characteristics of the proposed circuits basically depend on the output of the log-amplifier present in each circuit. So, to compare the behaviour of the two circuits proposed herewith, the characteristics of output from log amplifier vs. the sweeping temperature are shown in Fig. 4.5.

4.2.1 Results associated with the simulation of Circuit1

TABLE 4.1: **VALUES OF COEFFICIENTS OBTAINED FROM THE BSL OF OUTPUT VOLTAGE VS. TEMPERATURE**

Constant coefficients of BSL	Value
a	0.037179
b	1.2667

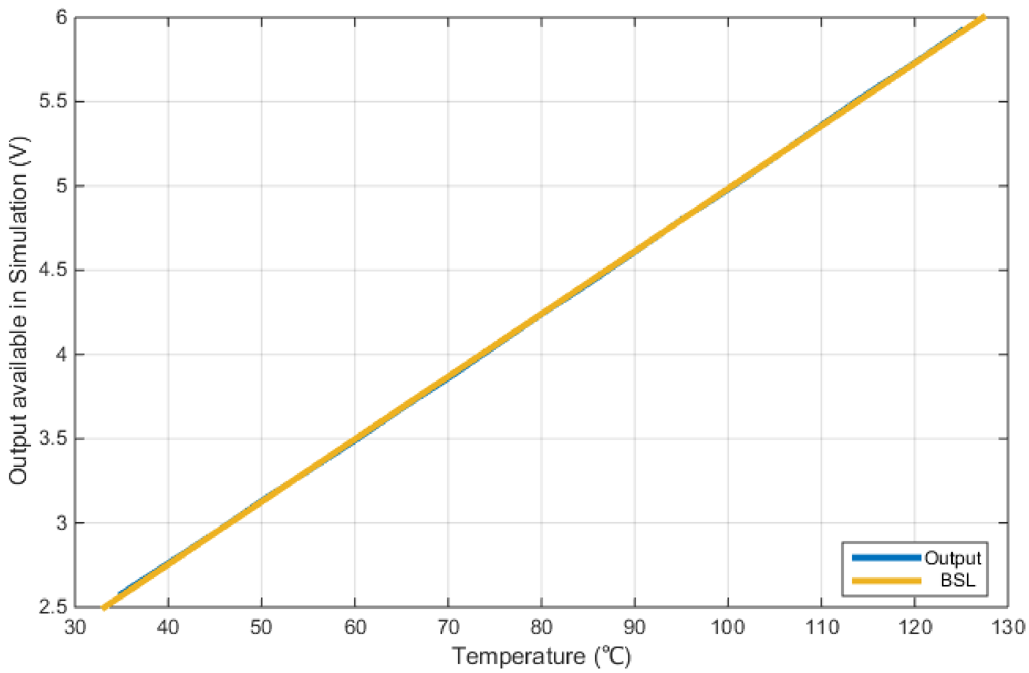


Fig. 4.1: Output Voltage from Simulation vs Temperature

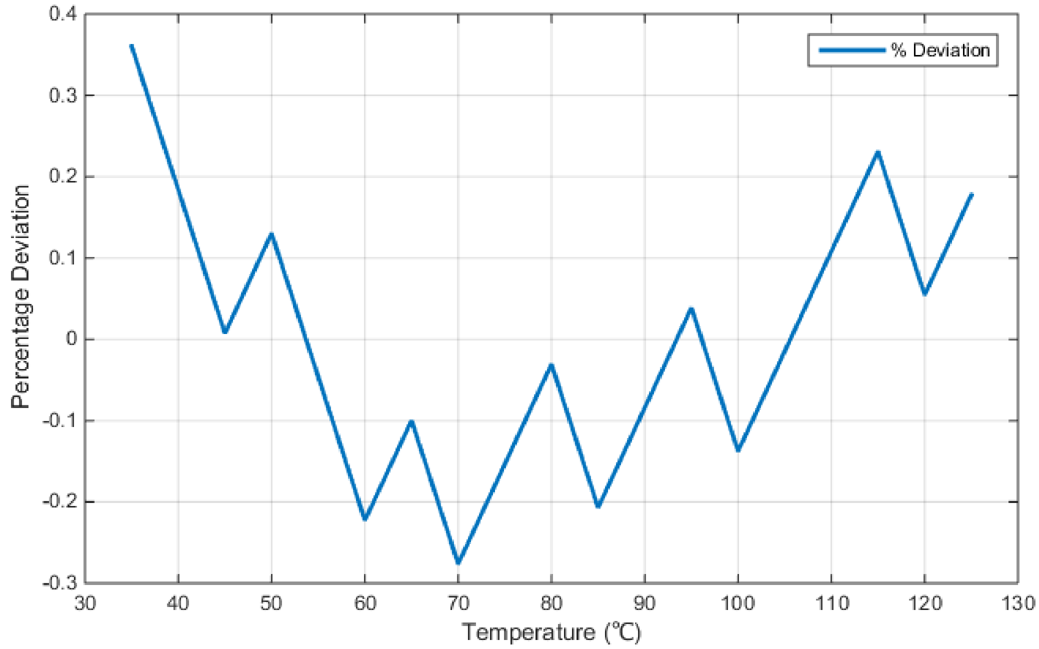


Fig. 4.2: Percentage deviation of Output Voltage from BSL in terms of span

4.2.2 Results associated with the simulation of Circuit2

TABLE 4.2: VALUES OF COEFFICIENTS OBTAINED FROM THE BSL OF OUTPUT VOLTAGE VS. TEMPERATURE

Constant coefficients of BSL	Value
a	0.045621
b	-1.4737

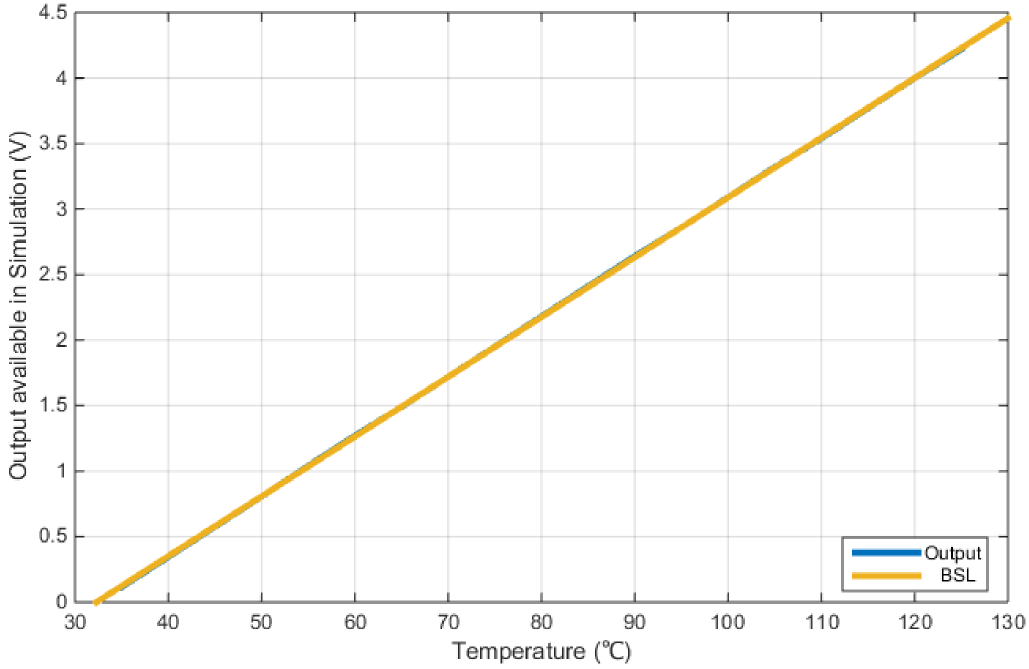


Fig. 4.3: Output Voltage vs Temperature

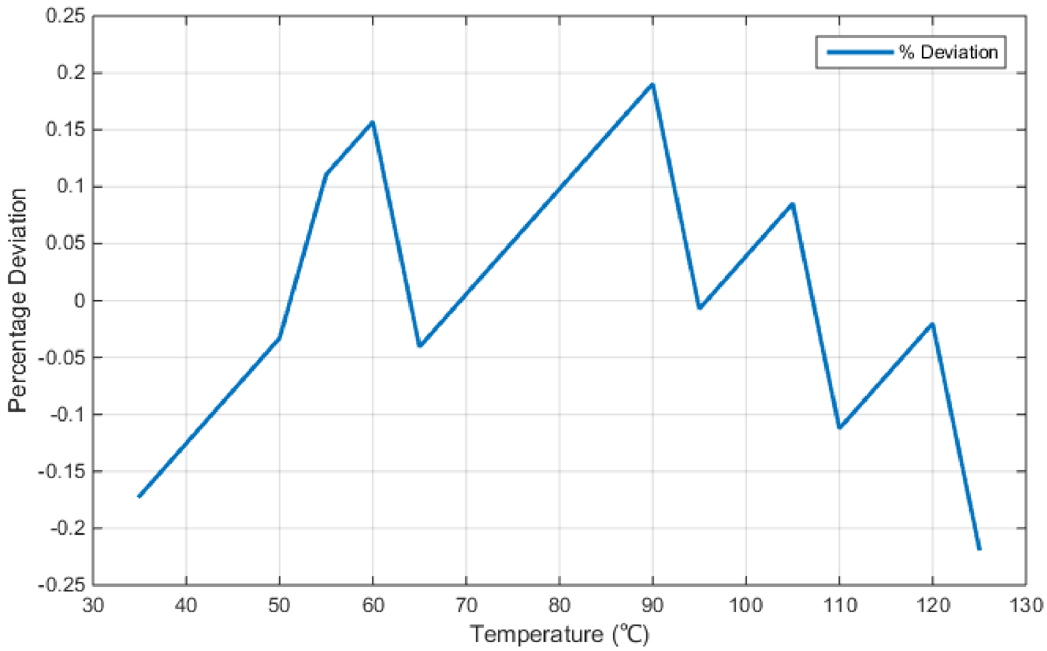


Fig. 4.4: Percentage deviation of Output Voltage from BSL in terms of span

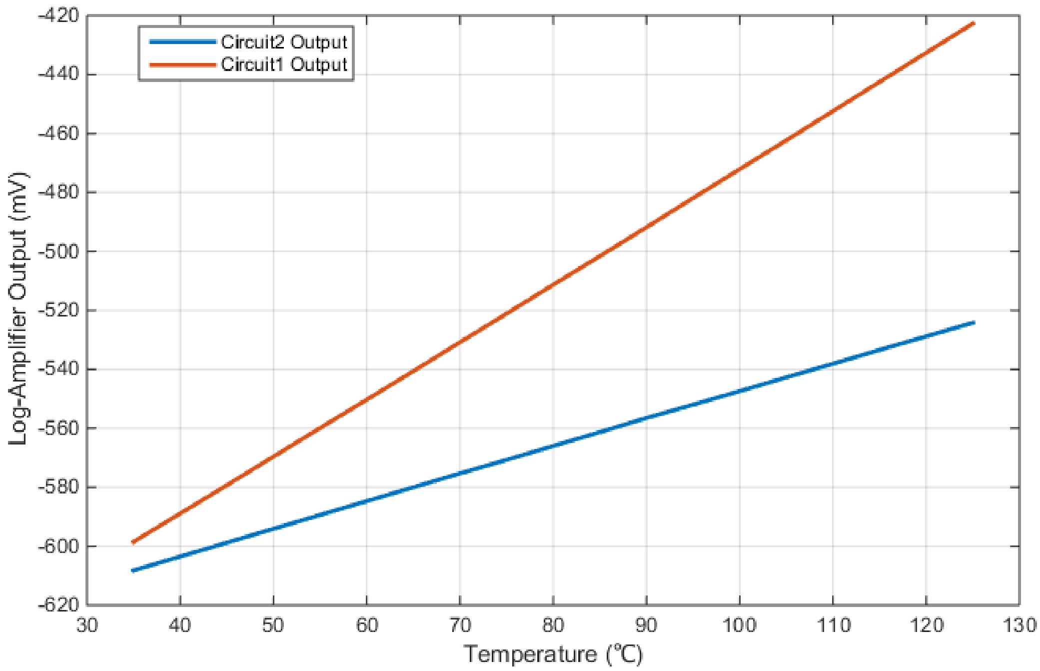


Fig. 4.5: Output of Log Amplifier vs Temperature

4.3 Experimental Results

In laboratory two experiments have been conducted for the two circuits separately, named Circuit1 and Circuit2, respectively. A breadboard has been used to fabricate them. In the experimental arrangement, an oil tank has been placed over an induction oven. The oven acts as heater and the oil tank acts as a temperature bath. A motorised stirrer is inserted in the temperature bath. When the heater is switched on, the temperature of the oil varies. The stirrer is used to distribute the generated heat uniformly along the volume of the oil in all directions. In the first run of the experiment only the transistor acts as the temperature sensor and is, therefore, inserted the temperature bath. In the second run, both of the transistor and the thermistor act as the set of sensors and, therefore, are submerged in the bath. The set-up for the experiment is shown in Fig. 4.6. The temperature of the bath was measured in terms of the resistance of a standard Pt100 RTD immersed in the bath. The RTD has linear and well defined Resistance-Temperature characteristic, shown in Fig 4.7.

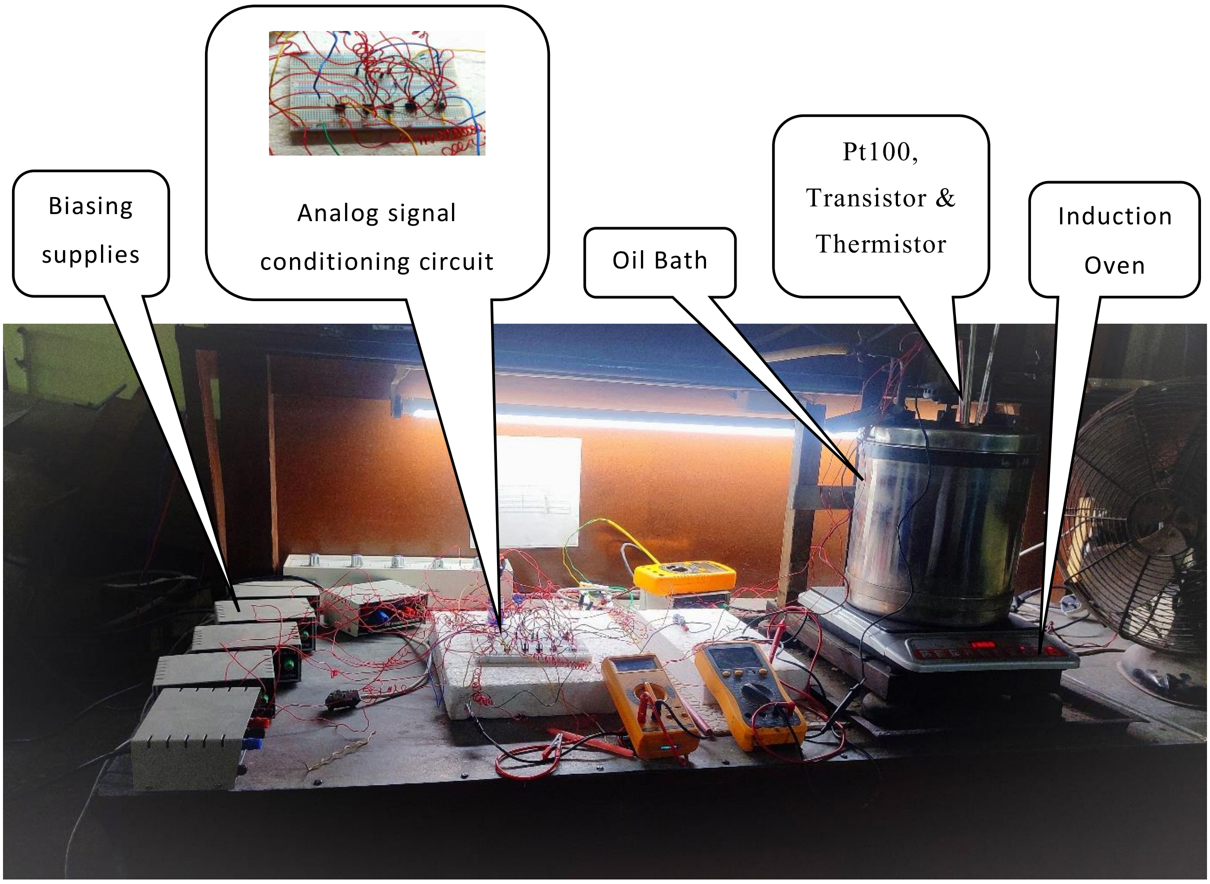


Fig. 4.6: Experimental Set-up

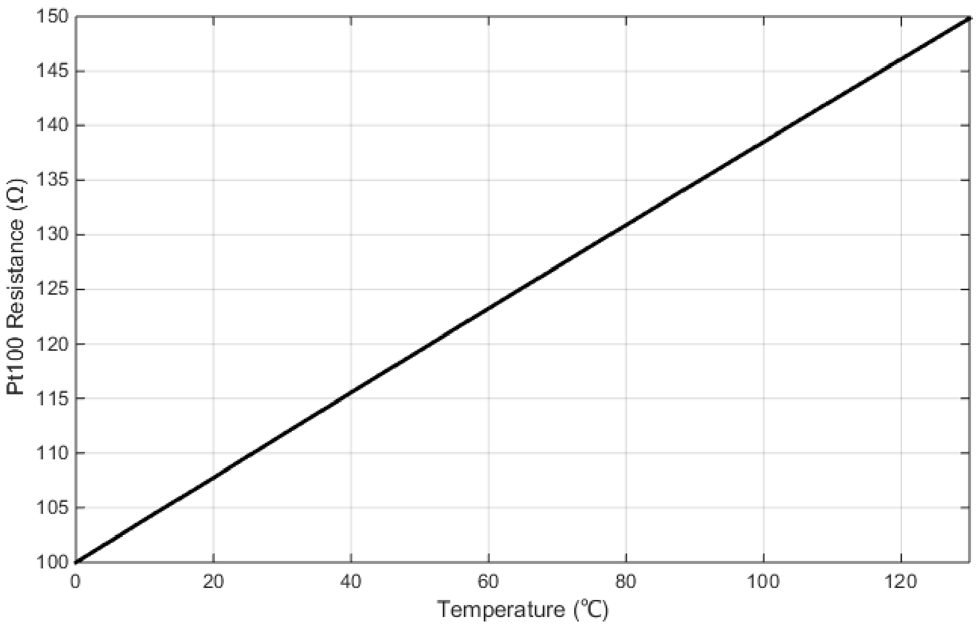


Fig. 4.7: Resistance-Temperature characteristic of a Standard Pt100

First, temperature is increased by heating the oil tank up to the upper limit of the working range of temperature, i.e., 125℃ for Circuit1 and 120℃ for Circuit2. As the heater is switched off, the oil in the bath starts cooling soon and the temperature begins to fall. During its cooling phase, data is recorded for every 0.5℃ interval up to the normal ambient temperature (almost 35℃). For recording the data, two digital multimeters are used where one is connected to the final output terminals and another is connected to the Pt100 RTD. During the cooling phase, with decreasing temperature, resistance of Pt100 also decreases. So, at every instant of occurrence of Pt100 resistance available in the TABLE I, output voltage is noted down. Thus, for the whole span of working temperature with step of 0.5℃, output voltages of both Circuit1 and Circuit2 with respective temperature are recorded.

Output voltage (V) vs temperature (T) graph is plotted for every 1℃ change in temperature from 35 ℃ to upper temperature limit. For better understanding of error, percentage deviation of output voltage from BSL vs temperature characteristic needs to be plotted for that values of temperature which are different from the values of temperature used to plot V vs. T graph. Therefore, percentage deviation of output voltage from BSL vs temperature characteristic is plotted for every 1℃ change in temperature from 35.5 ℃ up to 125.5℃ for Circuit1 and up to 120.5℃ for Circuit2.

4.3.1 Experimental Results associated with Circuit1

TABLE 4.3: VALUES OF COEFFICIENTS OBTAINED FROM THE BSL OF OUTPUT VOLTAGE VS. TEMPERATURE

Constant coefficients of BSL	Value
a	0.041391
b	1.8294

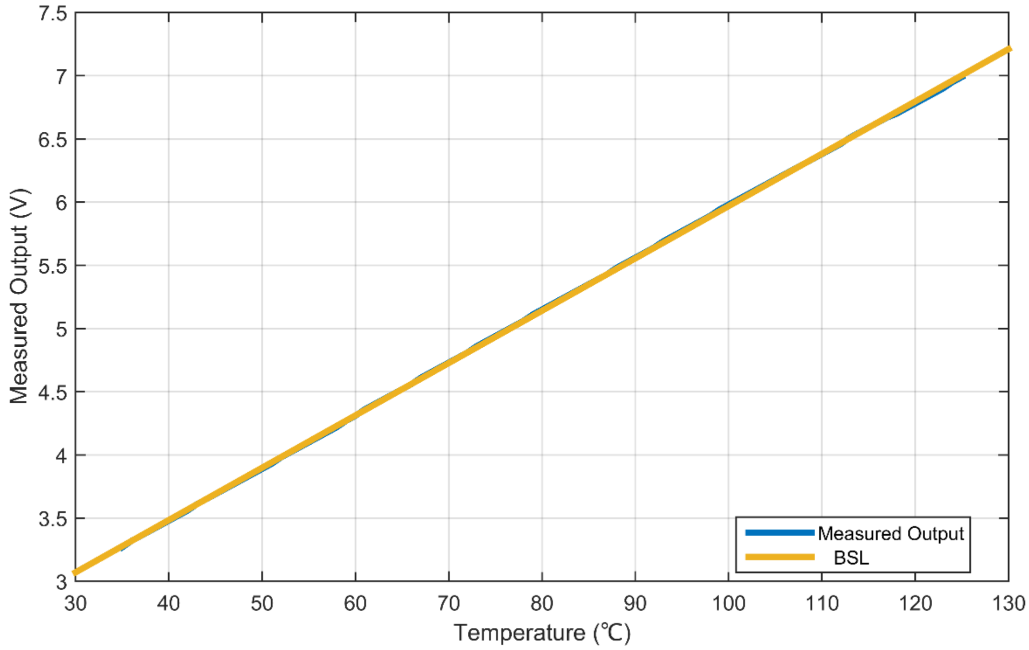


Fig. 4.8: Output Voltage vs Temperature

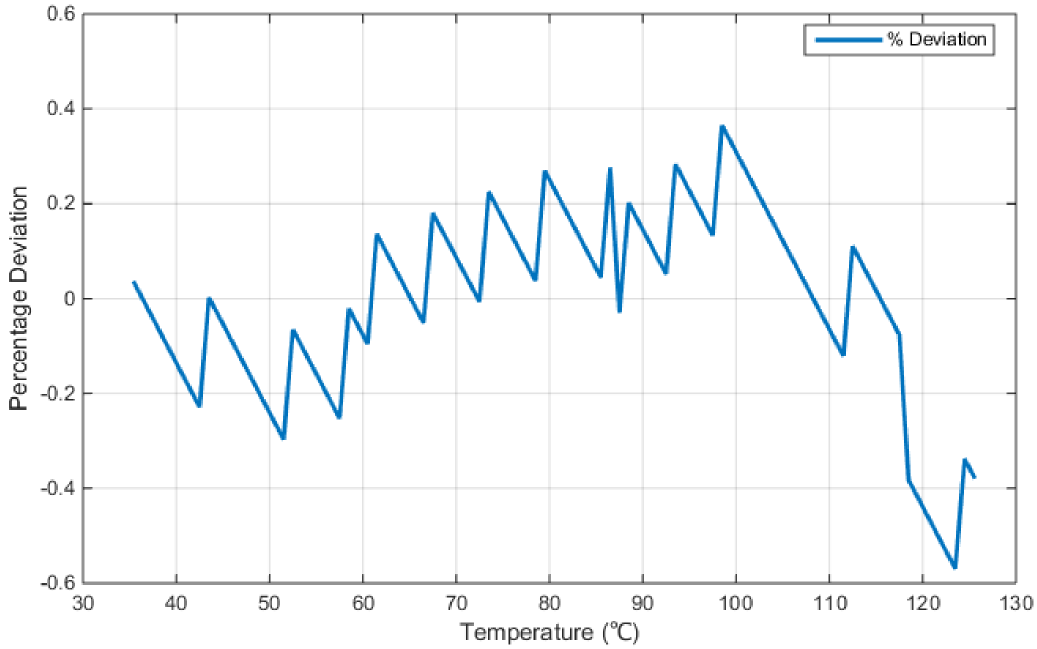


Fig. 4.9: Percentage deviation of Output vs Temperature from BSL in terms of span

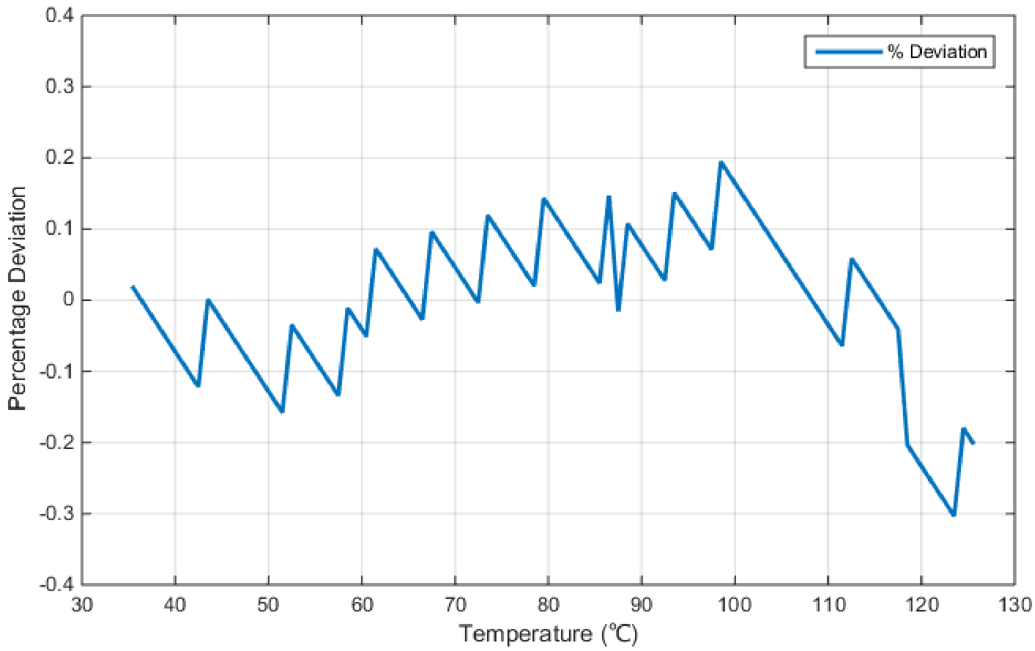


Fig. 4.10: Percentage deviation of Final Output from BSL vs Temperature in terms of full scale

4.3.2 Experimental Results associated with Circuit2

TABLE 4.4: **VALUES OF COEFFICIENTS OBTAINED FROM THE BSL OF OUTPUT VOLTAGE VS. TEMPERATURE**

Constant coefficients of BSL	Value
a	0.038141
b	1.0635

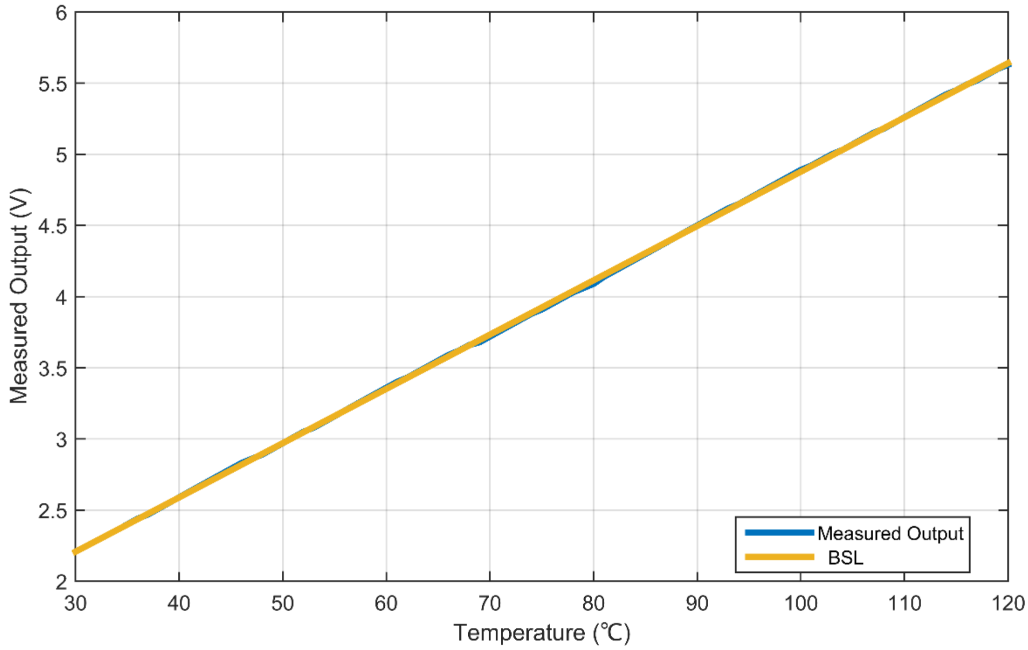


Fig. 4.11: Output Voltage vs Temperature

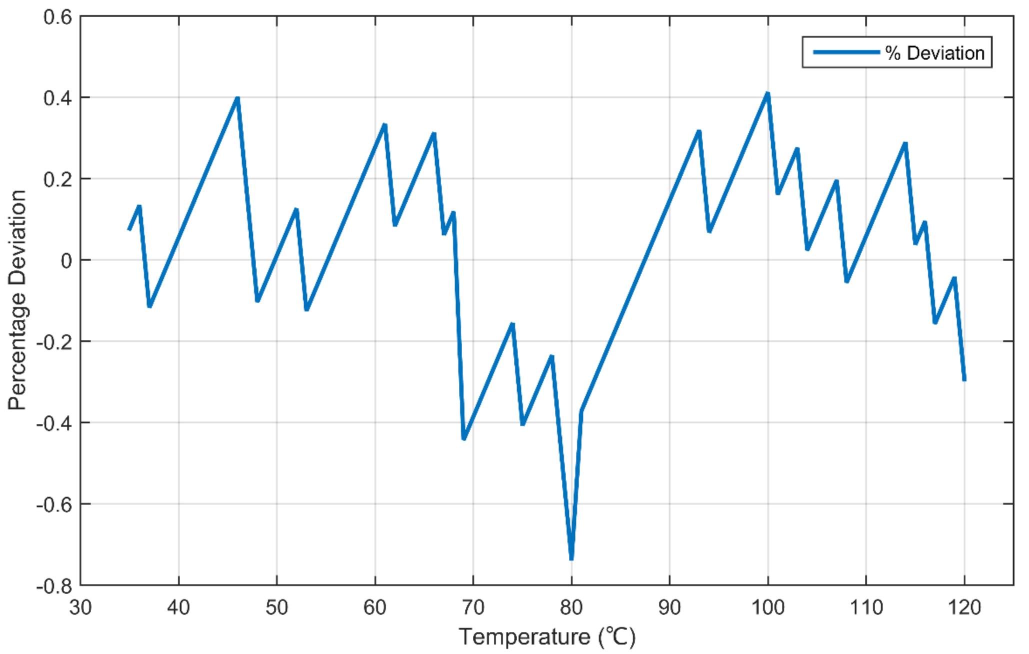


Fig. 4.12: Percentage deviation of Final Output vs Temperature from BSL in terms of span

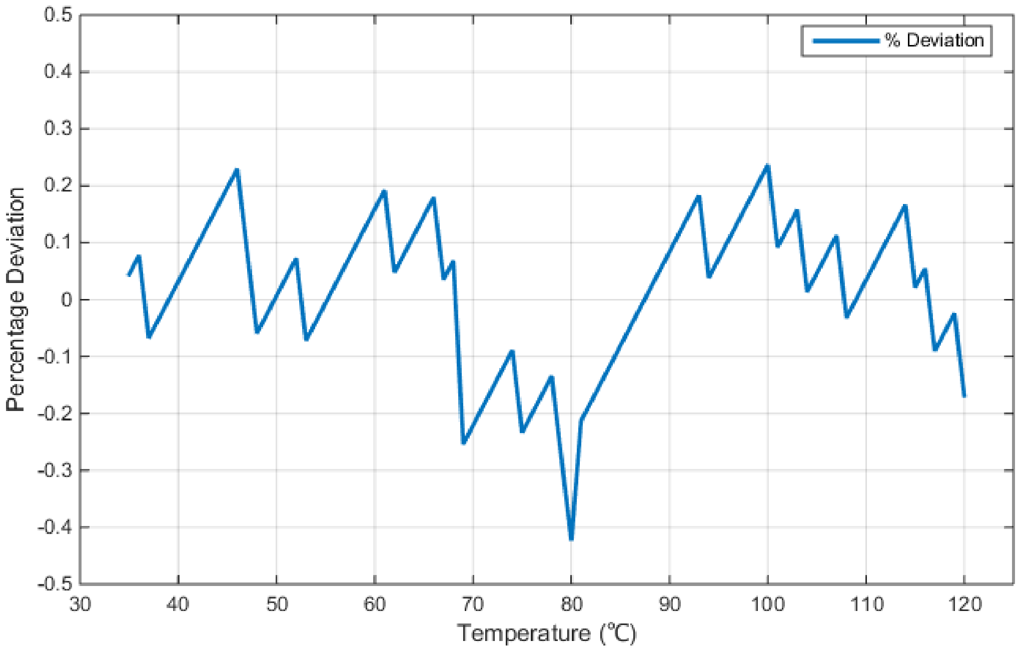


Fig. 4.13: Percentage deviation of Final Output vs Temperature from BSL in terms of full scale

4.4 Discussion

Referring to Fig. 4.9 and Fig. 4.12 percent deviations of output voltage of Circuit1 and Circuit2 from corresponding BSL lie approximately within ±0.57% and ±0.74% respectively when deviation is calculated in terms of output voltage span. When it is calculated considering full scale output voltage referring to Fig. 4.10 and Fig. 4.13, above deviations lie approximately within ±0.3% and ±0.43% respectively for Circuit1 and Circuit2. The experimental results are well validated by the simulation results obtained in PSPICE as shown in Fig. 4.2 and Fig. 4.4.

By inspecting Fig. 4.5, it is clear that inherent temperature sensitivity of Circuit1 is much higher than Circuit2. Therefore, to get optimal output range, comparably higher gains are used in instrumentation amplifier and summer amplifier for Circuit2 than Circuit1.

Chapter 5: Conclusion

5.1 Conclusion

Two affordable and flexible temperature sensing circuits employing transistor-based log amplifier have been presented in this thesis. This scheme is very simple and easy to implement using analog circuit components. This scheme utilizes the logarithmic output of log amplifier with exponential behaviour of NTC thermistor as well as bipolar transistor to get a linear relationship with temperature. The performance of the proposed circuits has been examined over 35℃ to 125℃ for Circuit1 and over 35℃ to 120℃ for Circuit2. Experiment results show that a decent linearity with an error within 0.8% can be achieved over a range of 90℃.

This scheme can be used in several applications requiring wide range of temperature sensing with good linearity. Both circuits are very flexible in terms of getting desired output sensitivity by manipulating the resistor values and the offset voltage of summer amplifier. However, this scheme is limited to RTD temperature sensors with exponential resistance-temperature characteristics.

5.2 Future Scope

Even though these temperature sensors with analog signal conditioning circuits are capable of providing very good linearity with cost effectiveness and flexibility, there are still certain variables that can be taken into account to enhance the scheme's performance.

- Although in this thesis, log amplifier with transistor (BJT) gives good result in terms of linearity and sensitivity, BJT can be a promising temperature sensor with different signal conditioning arrangements. Therefore, more research should be conducted in this area.
- A wider temperature range may be taken into consideration, and the performance of the plan for that temperature range may be examined.
- Additionally, to improve the results regarding linearity, it is possible to combine this hardware strategy with more sophisticated software techniques like polynomial and linear interpolation.

Appendix

TABLE I: CALIBRATION TABLE

Temperature (℃)	Pt100 RTD Resistance(Ω)	Thermistor Resistance (k Ω)
25	109.73	10
25.5	109.93	
26.0	110.12	
26.5	110.32	
27.0	110.51	
27.5	110.7	
28.0	110.9	
28.5	111.09	
29.0	111.29	
29.5	111.48	
30.0	111.67	8.309
30.5	111.87	
31.0	112.06	
31.5	112.25	
32.0	112.45	
32.5	112.64	
33.0	112.83	
33.5	113.03	
34.0	113.22	
34.5	113.41	
35.0	113.61	6.939
35.5	113.8	
36.0	114.0	
36.5	114.19	
37.0	114.38	
37.5	114.57	
38.0	114.77	
38.5	114.96	
39.0	115.15	

39.5	115.35	
40.0	115.54	5.824
40.5	115.73	
41.0	115.93	
41.5	116.12	
42.0	116.31	
42.5	116.51	
43.0	116.7	
43.5	116.89	
44.0	117.08	
44.5	117.28	
45.0	117.47	4.911
45.5	117.66	
46.0	117.86	
46.5	118.05	
47.0	118.24	
47.5	118.43	
48.0	118.63	
48.5	118.82	
49.0	119.01	
49.5	119.2	
50.0	119.4	4.16
50.5	119.59	
51.0	119.78	
51.5	119.97	
52.0	120.17	
52.5	120.36	
53.0	120.55	
53.5	120.74	
54.0	120.94	
54.5	121.13	
55.0	121.32	3.539
55.5	121.51	
56.0	121.71	

56.5	121.9	
57.0	122.09	
57.5	122.28	
58.0	122.47	
58.5	122.67	
59.0	122.86	
59.5	123.05	
60.0	123.24	3.024
60.5	123.43	
61.0	123.63	
61.5	123.82	
62.0	124.01	
62.5	124.2	
63.0	124.39	
63.5	124.58	
64.0	124.78	
64.5	124.97	
65.0	125.16	2.586
65.5	125.35	
66.0	125.54	
66.5	125.73	
67.0	125.93	
67.5	126.12	
68.0	126.31	
68.5	126.5	
69.0	126.69	
69.5	126.88	
70.0	127.08	2.233
70.5	127.27	
71.0	127.46	
71.5	127.65	
72.0	127.84	
72.5	128.03	
73.0	128.22	

73.5	128.41	
74.0	128.61	
74.5	128.8	
75.0	128.99	1.929
75.5	129.18	
76.0	129.37	
76.5	129.56	
77.0	129.75	
77.5	129.94	
78.0	130.13	
78.5	130.32	
79.0	130.52	
79.5	130.71	
80.0	130.9	1.673
80.5	131.09	
81.0	131.28	
81.5	131.47	
82.0	131.66	
82.5	131.85	
83.0	132.04	
83.5	132.23	
84.0	132.42	
84.5	132.61	
85.0	132.8	1.455
85.5	132.99	
86.0	133.18	
86.5	133.37	
87.0	133.57	
87.5	133.76	
88.0	133.95	
88.5	134.14	
89.0	134.33	
89.5	134.52	
90.0	134.71	1.27

90.5	134.9	
91.0	135.09	
91.5	135.28	
92.0	135.47	
92.5	135.66	
93.0	135.85	
93.5	136.04	
94.0	136.23	
94.5	136.42	
95.0	136.61	1.112
95.5	136.8	
96.0	136.99	
96.5	137.18	
97.0	137.37	
97.5	137.56	
98.0	137.75	
98.5	137.94	
99.0	138.13	
99.5	138.32	
100.0	138.51	0.976
100.5	138.7	
101.0	138.88	
101.5	139.07	
102.0	139.26	
102.5	139.45	
103.0	139.64	
103.5	139.83	
104.0	140.02	
104.5	140.21	
105.0	140.4	0.86
105.5	140.59	
106.0	140.78	
106.5	140.97	
107.0	141.16	

107.5	141.35	
108.0	141.54	
108.5	141.73	
109.0	141.91	
109.5	142.1	
110.0	142.29	0.759
110.5	142.48	
111.0	142.67	
111.5	142.86	
112.0	143.05	
112.5	143.24	
113.0	143.43	
113.5	143.62	
114.0	143.8	
114.5	143.99	
115.0	144.18	0.673
115.5	144.37	
116.0	144.56	
116.5	144.75	
117.0	144.94	
117.5	145.13	
118.0	145.31	
118.5	145.5	
119.0	145.69	
119.5	145.88	
120.0	146.07	0.596
120.5	146.26	
121.0	146.44	
121.5	146.63	
122.0	146.82	
122.5	147.01	
123.0	147.2	
123.5	147.39	
124.0	147.57	

124.5 125.0 125.5	147.76 147.95 148.14	0.532

TABLE II: SPECIFICATIONS OF THE PARAMETERS OF THE PROPOSED LINEARIZATION SCHEME IN CIRCUIT1

Parameter symbol	Parameter Specifications
R	10KΩ Resistance
R0	1.5KΩ Resistance
R1	2.2KΩ Resistance
R2	1KΩ Resistance
R3	2.2KΩ Resistance
R4	1KΩ Resistance
R5	2.2KΩ Resistance
V1	2.9V Battery Source
V2	6.35V Battery Source
V+	12V Source
V-	-12V Source
Q	Q2N2222 Transistor

TABLE III: SPECIFICATIONS OF THE PARAMETERS OF THE PROPOSED LINEARIZATION SCHEME IN CIRCUIT2

Parameter symbol	Parameter Specifications
Rt	10KΩ Thermistor
R0	1KΩ Resistance
R1	4.7KΩ Resistance
R2	1KΩ Resistance
R3	1KΩ Resistance
R4	1KΩ Resistance
R6	4.7KΩ Resistance
V1	2.9V Battery Source
V2	6.35V Battery Source
V+	12V Source
V-	-12V Source
Q	Q2N2222 Transistor

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