Modeling, Characterization and linearization of Negative Temperature Coefficient (NTC) Thermistor and Pressure Sensors

K. Narayana Swamy, Nandeesh M, Nagaraj Hediyal

Abstract: Industrial applications such as air-conditioning, microelectronic, automotive, food processing are automated using various sensor technologies. The sensor technologies could be temperature, pressure and others as well. The negative temperature coefficient (NTC) sensors are the preferred choice due to their stability over their counterpart positive temperature coefficient (PTC) sensors. These sensors are highly nonlinear and need special signal conditioning circuits to use them in all industrial applications. Pressure sensor does need a special treatment while measuring their values for industrial applications. This paper presents the method to model, characterize and linearize NTC and pressure sensors. A low-cost system was built to validate the presented method.

Index Terms: Temperature, NTC/PTC, Coefficient, Modeling, Characterization, Linearization, pressure sensor.

I. INTRODUCTION

Temperature measurements are very critical and essential in air-conditioning, food processing and other industrial applications. Generally, these industrial applications make use of negative or positive temperature (NTC/PTC) coefficient Thermistor as temperature detectors/sensors. NTC Thermistor are preferred choice even though less sensitive than their counterparts due to their stability. Thermistor possesses unique thermoelectric properties which makes them to be suitable for temperature detectors in many applications [1].

The accurate measurement of temperature is a challenge in aeronautical, food processing and other applications as these NTC sensors are highly nonlinear. Therefore, these sensors need special treatment to use them in various industries to detect temperature [2]. There are many technologies based on which NTC sensors are manufactured. Mainly the oxide concentration ratio defines the characteristics of these sensors. Metal oxide sensors have higher sensitivity compared to other sensors.

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K Narayan Swamy*, Associate Professor, School of EEE,REVA UNIVERSITY, Bengaluru, India. E-mail: knarayanswamy@reva.edu.in

Nandeesh M,M.Tech student,REVA UNIVERSITY Bengaluru, India

Nagaraj Hediyal,CEO,eNLiven Technologies,Bengaluru,India. E-mail: Nagaraj_hediyal@yahoo.com

The stability and reliability of these sensors are high [3].During the manufacturing process, the thermal treatment applied to coat either glass or epoxy to complete the sensor product. The coating material such as Aerosol Deposited NiMn2O4 plays an important role, while forming the leads of the sensor. The influence of this coating agent has the direct impact on the temperature detection and ageing [4]. The linearization method for these sensors is the major criteria due to their inherent characteristics of nonlinearity. An error evaluation associated with resistive linearization circuits has been proposed in [5]. The proposed method utilizes a resistive linearization technique using voltage source. The results of the proposed method were compared with other methods for analyses. The analysis shows that the results of practical implementation compared with those of thermotical have huge difference. Meaning the practical implementations does have error in results which need special attention [5].

A series and parallel resistive divider network along with two stage piecewise linear analog to digital converter (PWC ADC) has been presented to linearize the NTC Thermistor in [6]. Method was intended to improve the accuracy of NTC by reducing the nonlinearity. The accuracy of measurement completely relies on the resolution of the 1st stage ADC. The measurement error greatly reduces if and only if 1st stage ADC resolution is higher. Another way of linearizing the NTC sensors is by way of gain linearization and is presented in [7]. The simulation and experimental results were compared to validate the gain linearization method. The method was tested for the range of temperature between 3000°K to 3720°K. A full Wheatstone bridge with differential amplifier has been presented [8] to measure the low pressure for wireless biomedical applications. The paper presents the analysis of low magnitude signal conditioning and how the noise affects the pressure measurements if improper ADC selected for the purpose of pressure measurement. A frame work on Thermistor temperature transducer to ADC application has been presented in [9]. The application report deals with the measurement of low magnitude signal and the error issues. The paper presents the generic method of treating the low magnitude sensor signals while interfacing with the microcontrollers/processors. Generally, the low magnitude signals are dealt with ratio metric measurement methods where in the scope is extended to self-calibration [10]. The accuracy in most of the measurement systems is guaranteed by way of reference signal.

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These references will have changes based upon the quantity such as voltage, current to be measured [11]. It has been established that the reference voltage has an influence on the measurement accuracy that need to be taken care. The self-calibration is another way of assuring the accuracy of measurement of any sensor output signal [12]. The ratio metric measurements with self-calibration techniques play an important role in the measurement accuracy.

By considering the results of the various researchers' presentation introduced above, a ratio metric conversion-based approach has been considered in this paper to model, characterize and linearize temperature and pressures sensors. The rest of the paper is described section wise; section 2 describes the modeling of NTC and Pressure Sensors, 3rd section describes the proposed model & technique, 4th section describes the results and analysis and 5th section presents the conclusion.

II. MODELING OF NTC AND PRESSURE SENSORS

Since NTC sensors are thermally sensitive resistors with negative temperature coefficient, a best fitting model to determine change in resistance is proposed by Steinhart and Hart. The mathematical expression proposed by Steinhart and Hart is:

$$T = \frac{1}{A + B\ln(R) + C[\ln(R)]^3} \quad (1)$$

Where:

T is temperature in degrees Kelvin and ln (R) is the natural log of the measured resistance of the sensor; and A, B and C are constants (i.e., A=1.874E-03, B=2.3573E-04 and C=9.5052E-08).The values of coefficients A, B and C corresponding to TR141 series NTC sensors.

These values may vary depending on the type of the sensor considered for the application. Accuracy is the important factor in the acquisition of temperature of NTC sensors. The accuracy depends upon the method of excitation i.e, constant voltage or constant current source.

An NTC sensor of 5K@25°C (TR141 series) is considered for the experimental purpose. The temperature sensor TR141 is shown in Fig. 1.

Fig. 1. TR141 @ 25° C

The temperature verses resistance curve of the NTC sensor is shown in Fig. 2.

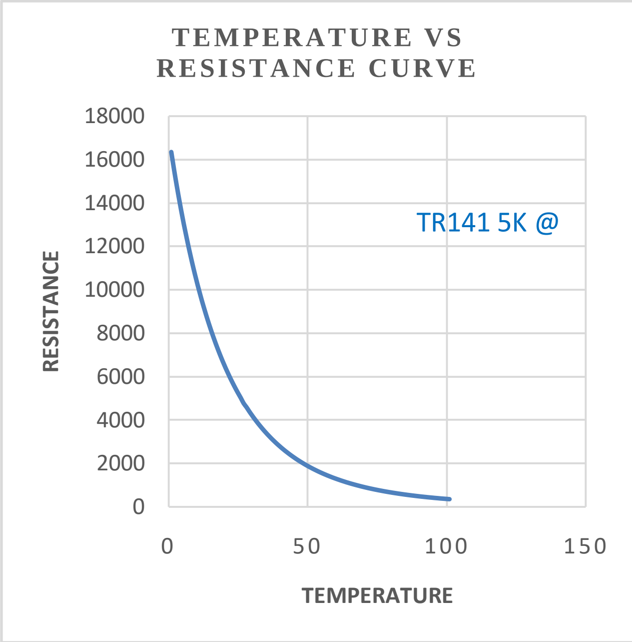

Fig. 2. Temperature Vs Resistance of NTC Sensor TR141 with 5K @ 25°C.

The NTC temperature sensor is highly non-linear as seen from Fig. 2. This need to be linearizes to acquire the temperature.

Proceeding further, industrial automation uses pressure sensors extensively. The range of pressure measured in air-conditioning applications is 0-10 bar or 0-40 bar. In industrial applications, the excitation voltage used for the pressure sensors is about 24V DC. This pressure sensor transmitter provides an analog signal proportional to the pressure applied to the sensor. The 0-10 bar pressure sensor from Danfoss MBS3000 series is considered and the variation of pressure verses signal is shown in Fig. 3 and Fig. 4.

Fig. 3. Pressure Transmitter

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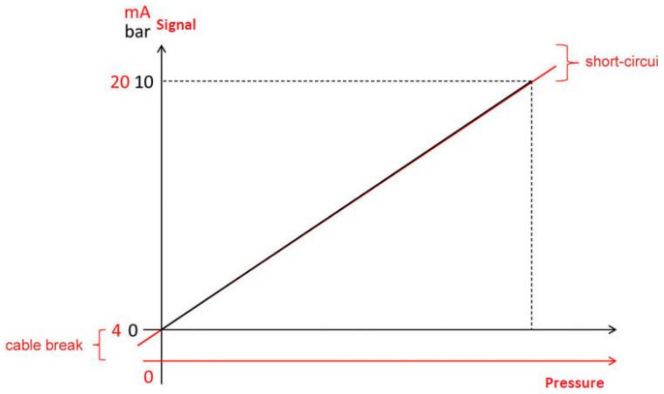

Fig. 4. Pressure verses signal (Bar/mA)

III. PROPOSED LINEARIZATION &CHARACTERIZATION TECHNIQUES FOR NTC TEMPERATURE AND PRESSURE SENSORS

A voltage divider circuit is generally preferred to linearize the NTC sensors and is presented in Fig. 5.

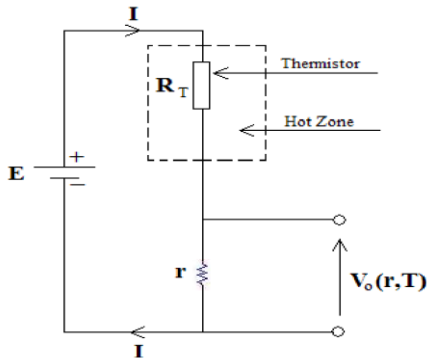

Fig. 5. Voltage divider circuit to linearize NTC

Resistor R_T is the NTC sensor and resistor 'r' is the series resistor across which voltage V_o corresponding to that resistance is obtained when the excitation voltage source 'E' is enabled [6]. This method has a major disadvantage of being nonlinear due to both parameters' variation in drop across series resistor 'r' and R_T. Therefore, a series and parallel voltage divider circuit is considered to improve the linearity and shown in Fig. 6.

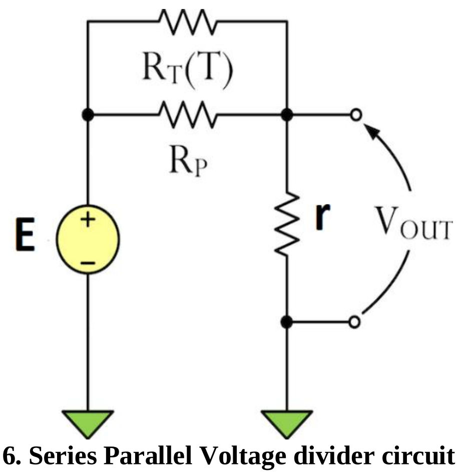

Fig. 6. Series Parallel Voltage divider circuit [6]

In this method also the excitation source is voltage source which eventually produces error in the measurement of resistance of NTC. This results in the temperature measurement error.

In this paper a constant current excitation method with series parallel resistive voltage divider circuit is proposed with certain considerations:

i) Desired range of temperature (0°C-100°C) with a sensor of TR141 @25°C.

ii) The value of R_P in parallel with R_T (NTC) is chosen such that the voltage drop developed across this parallel combination prevents saturation of the constant current source.

iii) The voltage drop developed across the parallel combination must be in accordance with the analog to digital converter (ADC) input range and the resolution requirement to ensure the accuracy of the measurement.

iv) The series resistance 'r' is selected based on the reference voltage required during measurement by a transducer circuit proposed in this paper.

v) The resistance of the NTC sensor at 0°C is 16330***Ω*** and 339.6 ***Ω*** at 100°C.

The proposed constant current source excitation series parallel resistive divider circuit is shown in Fig. 7.

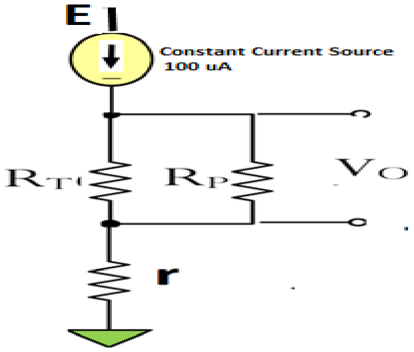

Fig. 7. Constant current source excitation for series parallel Voltage divider circuit

The constant current source of 100µA is used in the proposed linearization technique to avoid:

i) Self-heating of NTC sensor.

ii) Electromagnetic interference (EMI) problem.

iii) Noise problem and

iv) To limit the range of drop (across parallel combination of NTC and R_P) to the ADC reference voltage.

This arrangement is next interfaced with a transducer block whose output is used to determine the NTC resistance at any point of time to determine temperature using a Steinhart & Hart equation presented in preceding sections. The block diagram of the transducer used in the proposed technique is shown in Fig. 8.

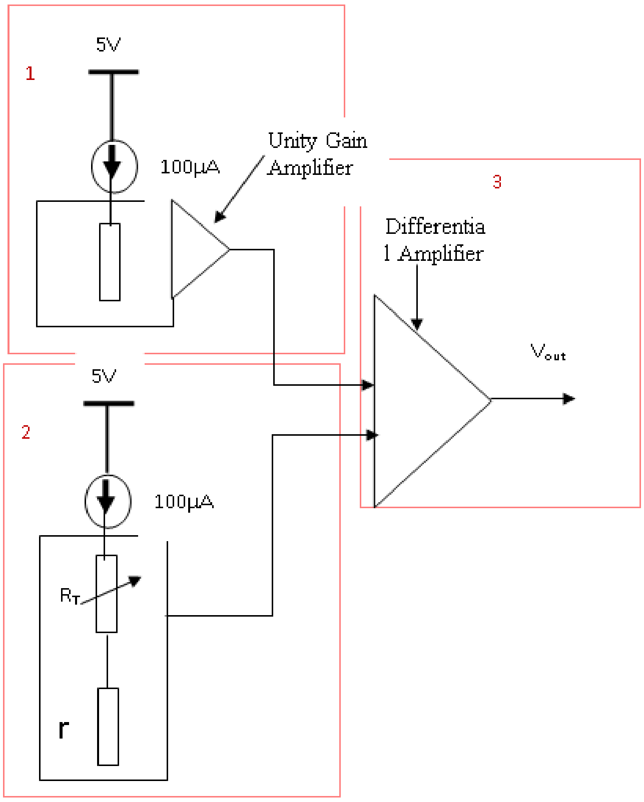

Fig. 8. Block Diagram of the proposed Technique

The block diagram has three sections; 1st section deals with the generation of reference voltage, where in another additional constant current source of 100µA (Mirror image of constant current source used for excitation of NTC sensor) has been used. This reference voltage plays an important role in the measurement of change in resistance of NTC sensor as the temperature changes. The reference voltage is created by using a reference resistor (R_F) in section 1 along with a constant current source as mentioned above. Thus, generated reference voltage is buffered using a unity gain amplifier to avoid the loading effect at the output of the transducer.

Section 1 has a linearization circuit built with series & parallel voltage divider circuit shown in Fig. 7. The series resistance 'r' is used to force the higher reference voltage to ease the measurement of voltage across the parallel combination of R_T and R_P by reducing the noise level. The output voltage V_O is passed through a low pass filter (Not shown in block diagram) to eliminate the local noise due to devices present within the circuitry.

Section 3 has a differential amplifier fed with the output from both section 1 and 2. This section also has a capacitor at the feedback circuit to eliminate the high frequency signals interfering with the temperature signal generated from section 2. Also, a low pass filter to eliminate local noise signal. The output signal V_{out} is then fed to the ADC of 10-bit resolution.

The gain of the differential amplifier designed within the section 3 of the transducer is given by:

$$G = \frac{V_{out,\max} - V_{out,\min}}{I_s(R_{T0} - R_{T100})} \quad (2)$$

Where:

G is gain of the differential amplifier, $Vout_{max}$ is maximum allowable voltage input to ADC, $Vout_{min}$ is minimum allowable voltage input to ADC, I_S is current fed to NTC sensor in µA, R_{T0} is resistance at 0°C and R_{T100} is resistance at 100°C.

As per the data sheet of NTC 5k @ 25°C, the resistance of the sensor considered in the proposed technique has: 16330**Ω** @ 0°C and 339.6**Ω** @ 100°C.

To linearize the NTC sensor, a parallel resistance R_P=16330**Ω** has been chosen according to the point number 2 in section 3i.e the maximum drop across the parallel combination $R_T || R_P$ has to be equal to reference voltage of the ADC. Hence, the gain of the differential amplifier of the proposed transducer is computed by using equation (2) as G=6.

The reference voltage in section 1 is determined using:

$$G = \frac{V_{ref} - V_r - V_{out,\min}}{R_{T100} I_s} \quad (3)$$

Where:

V_{ref} is reference voltage of the unity gain amplifier in section 1 and V_r is drop across series resistance at section 2.

The reference voltage is determined using equation (3) with all the parameter values substituted as 0.499V.

The output of the transducer shown in Fig. 8 is fed to a 10-bit ADC of microcontroller to determine the resistance of the NTC sensor at various temperatures at different times. The results obtained from this proposed technique are presented in section 4 of this paper.

Next, the pressure sensor transmitter signal is 4-20mA. This signal is preferred to eliminate the noise, EMI issues and more importantly the drop of the cable used to transmit the data. The typical 4-20mA transceiver connectivity is as shown in Fig. 9.

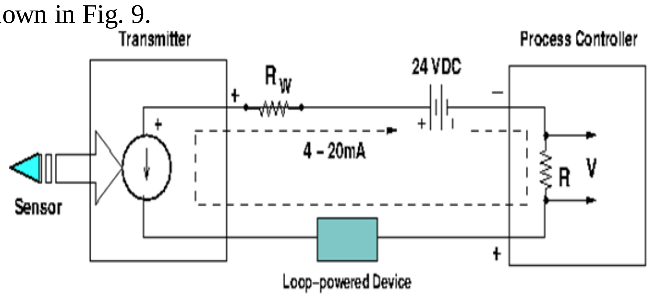

Fig. 9. 4-20mA Transceiver loop

According to the data sheet of the pressure sensor selected the supply voltage varies from 10-30V DC. Generally, in industry 24V DC supply is the preferred to excite the pressure sensor with 4-20mA loop.

Since the maximum load that can be connected to receive 4-20mA signal when the pressure sensor selected (Danfoss MBS3000) used for the application is given by:

$$R_L \leq \frac{V_s - 10}{0.02} \quad (4)$$

Where:

R_L is maximum allowable load resistance at the receiver and V_s is Supply voltage i.e., 24V DC

The R_L is computed as less than or equal to 700 **Ω** by using above equation

The proposed signal conditioning circuit block for the pressure sensor is shown in Fig. 10.

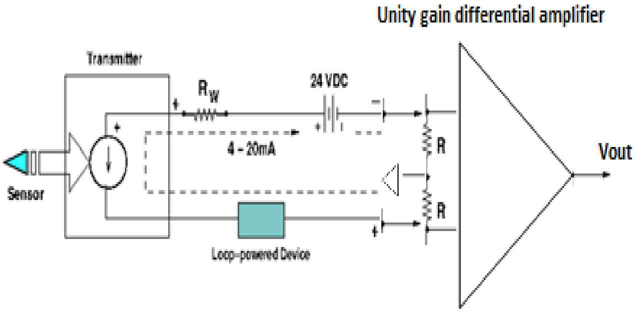

Fig. 10: Signal conditioning circuit for pressure sensor

Though the maximum allowable load resistance at the 4-20mA signal receiver is 700***Ω***, but practically the selection of this resistance depends upon the reference voltage of the corresponding ADC used to measure pressure. Since the ADC used is of 10-bit resolution with a maximum reference voltage of 5V, the load resistance has to be determined accordingly. The maximum current is 20mA and hence the upper limit of the load resistance to be used at the 4-20mA receiver input circuit computed as 250 ***Ω*** ($R_L = 5/(20x10^{-3})$)

Now, with this value of load resistance the minimum and maximum input voltage to the ADC are determined as 1V and 5V respectively.

In order to prevent the voltage becoming higher than the desired values at the ADC input, the load resistance is divided into two half sections with the intermediate point is connected to local ground as shown in Fig. 10.

As seen from the Fig. 4 in section 2, the pressure verses 4-20mA current signal or bar resembles a straight line as defined by an equation:

$$y = mx + c \quad (5)$$

Where:

This is a two-pint approximation technique used to determine the pressure with the signal conditioning circuit proposed in Fig. 10. Assuming the pressure along 'y' axis and current along 'x' axis, the slope 'm' and constant 'c' are determined by:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \quad (6)$$

And

$$c = y(x) - mx \quad (7)$$

Since the pressure to be measured is 0 to 10 bar and the corresponding currents are 4-20mA, the slope of the two-point approximation

Hence the pressure can be directly determined using the following relation:

$$y = 0.625x - 2.5 \quad (8)$$

Now with these proposed techniques, the temperature and pressure are acquired and the results are presented in section 4. The experimental model was designed and developed to validate the proposed techniques. The experimental set up is shown in Fig. 11 (a) & (b).

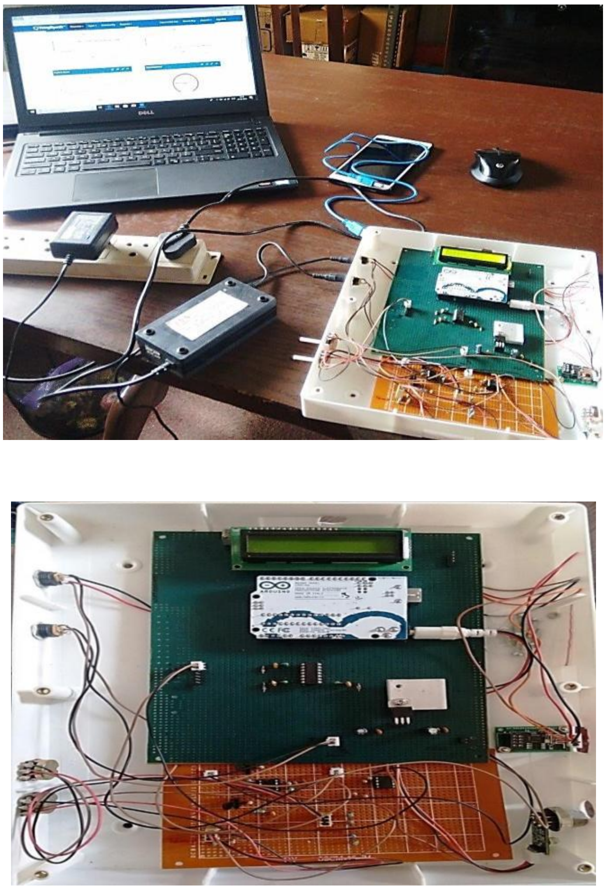

Fig. 11 (a & b). Experimental setup

IV. RESULTS AND ANALYSIS

Experimental results obtained for NTC sensor are shown in Fig. 12 where the variation of resistance verses temperature with and without linearization resistance are plotted.

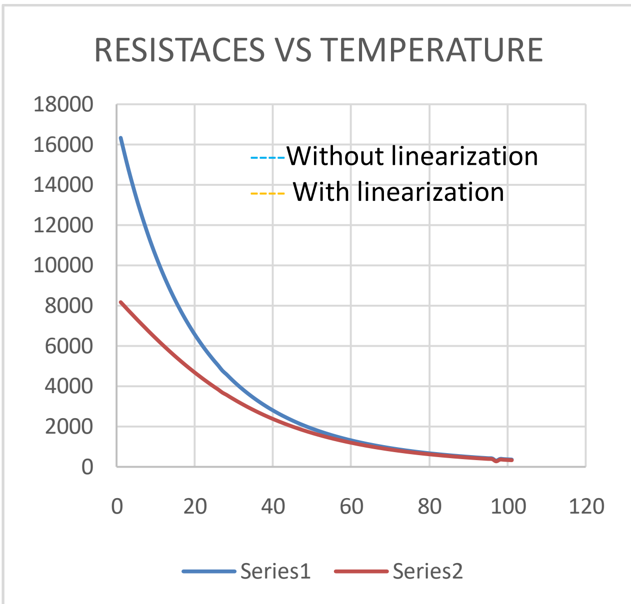

Figure 12: Resistance verses Temperature (with and without linearization resistance)

From the Fig. 12 it is clear that the proposed technique linearize the NTC sensor to a greater extent compared to without linearization resistance. The curve resistance verses temperature with parallel resistance is much linear than that without it. The experimental results of temperature acquisition using Steinhart & hart equation with the proposed transducer have been tabulated in Table I.

TABLE I
COMPARISON TABLE OF NTC SENSOR

R1	R PARALLEL	R EQIVALENT	R Steinhart & Hart	%Error
16330	16330	8165	8162	0.03
9951	16330	6183.167688	6184.1	0.009323123
7857	16330	5304.701286	5306.01	0.013087142
6247	16330	4518.470567	4521.2	0.027294326
5000	16330	3827.941866	3831.78	0.038381341
4029	16330	3231.670023	3238.65	0.069799769
3266	16330	2721.666667	2723.13	0.014633333
2663	16330	2289.621966	2293.02	0.03398034
2184	16330	1926.364913	1927.98	0.01615087
1801	16330	1622.101925	1689.01	0.669080751
1493	16330	1367.93413	1360.54	0.073941301
1244	16330	1155.941732	1158.34	0.023982679
1041	16330	978.6155086	990.05	0.114344914
875.7	16330	831.1304393	831.12	0.000104393
740	16330	707.9203281	702.89	0.050303281
628.1	16330	604.836214	608.08	0.03243786
535.4	16330	518.4034769	521.04	0.026365231
458.2	16330	445.6943568	448.28	0.025856432
393.7	16330	384.4317346	388.31	0.038782654
339.6	16330	332.6815281	334.87	0.021884719

From Table I it is clear that the percentage of error in measurement of change in NTC sensor resistance due to change in temperature is very minimal. Hence the proposed method can be used in various industrial applications.

Similarly, the experimental results of the pressure sensor are tabulated in Table II.

TABLE II
PRESSURE MEASUREMENT RESULTS

x	c	y=0.625 * x -2.5	Measured (y)
4	-2.5	0	0
5	-2.5	0.625	0.61
6	-2.5	1.25	1.3
7	-2.5	1.875	1.7
8	-2.5	2.5	2.6
10	-2.5	3.75	3.55
15	-2.5	6.875	6.98
20	-2.5	10	10.01

From Table II it is clear that the two point approximation technique can be used to determine the pressure from a 4-20mA loop. The last column of the table 2 shows the pressure measured using microcontroller with ADC of 10-bit resolution and has a values approximately same as those obtained using mathematical model.

V. CONCLUSION

Modeling, characterization and linearization of both NTC and Pressure sensors have been presented in this paper. The experimental and mathematical model values of both sensors approximately close enough to indicate that the proposed techniques are indeed produce better results. The experimental setup has been designed and developed to verify the values obtained using mathematical models with those of experimental values and are in close agreement with each other. The hardware model was very compact and the technique can still be improved with linearization improvement. The percentage of error in determining the change in resistance of NTC sensor using series and parallel voltage divider circuit excited by constant current source is the better solution as it results in less percentage of error as shown in Table I.

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AUTHOR PROFILE

K.Narayana Swamy received the B.E. degree in Electrical Power from Mysore, India in 1986 and received the M.E. degree in Power Systems from Bangalore, India in 1994 and perusing Ph.D degree in Power Electronics from Kuvempu University, India. He worked as Lecture and Senior lecturer in the Electronics and Communication Engineering department of S.J.C. Institute of Technology, Chickballapur, India from 1987-2001. He later joined Sri Venkateshwara College of Engineering, Bangalore, India as Assistant Professor from 2001-2008. Then he joined REVA ITM, Bangalore, India as Professor in 2009 and presently working as Associate Professor in REVA University. He is pursuing his Ph.D in the area of multilevel inverter.

Nandeesh M. received the B.E. degree in Electrical and Electronics Engineering from Bangalore, India in 2017 and received the M.Tech. degree in Power Electronics from Bangalore

Nagaraj Hediyal received his BE (Electrical Engineering), and M.Tech (Computer Applications in Industrial Drives) from UVCE and MSRIT Bangalore. Currently he is perusing PhD in Reva University Bangalore. He is a founder and Chief Executive Officer of M/s eNLiven Technologies, Bangalore. He has over 30 years of experience in Research and Development in the field of Cryptography, Embedded, VLSI, Communication, HVAC controllers, Power Electronics and Renewable Energy. He has authored and co-authored more than 38 proprietary encryption algorithms and successfully implemented them in the defense network. He is actively involved in designing, creating and managing specialized systems in the area of secure communications, Avionics, Industrial Electronics, Renewable Energy sectors. He is also actively involved in academics, teaching advanced subjects such as FPGA design Methodologies, Embedded System Design, Digital Signal Processing, Microprocessors & Microcontrollers for M.Tech, and M Sc (Electronics).