Simple Interface Circuit for High-Resolution, Multichannel, Smart Temperature Sensing based on NTC Thermistors

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***Abstract*—A simple interface circuit for high-resolution, multichannel smart temperature sensing based on NTC thermistors is described in this paper. The circuit is based on the Universal Sensors and Transducers Interface integrated circuit designed by authors, which supplies three different interfacing modes for thermistors and has three popular digital serial interfaces. Such approach lets considerably reduce a time-to-market for various thermistor based sensor systems.**

Keywords-thermistor; universal sensors and transducers interface; temperature sensing

I. INTRODUCTION

Temperature is one of the most widely measured physical quantities in industrial, consumer, and computer applications. Measurement of temperature is critical in various modern portable electronic devices as notebooks, tablets and smart phones to monitoring and control battery and CPU temperatures and compensate oscillator drift. Accurate temperature measurements are also necessary in many other measurement systems such as different instrumentation applications and process control [1, 2].

The modern forecast of *MarketsandMarkets* analysts reports that the market size of temperature sensors in the year 2010 was $3.27 billion and is expected to reach $4.51 billion by 2016, at an estimated CAGR of 5.6 %. In terms of volume, 2.02 billion temperature sensors were shipped in the year 2010 and the number is expected to reach 3.54 billion by 2016, at an estimated CAGR of 10 % from 2011 to 2016 [3]. Due to improved sensitivity, temperature sensors are used in loads of applications such as petrochemicals, automotive segments, consumer electronics, computer peripherals, space applications, and industrial segment. There is a rise in demand for consumer electronic devices, which use microprocessors such as smartphones, media players, cameras and gaming devices that make use of temperature sensors ICs to a greater extent [3].

The most common sensors for measuring temperature are thermocouple, thermistors and resistance temperature detectors (RTDs). Fiber-optic sensors, IR sensors, quartz thermometers and ultrasonic thermometers, while more specialized, are growing in popularity for temperature measurements [4].

Thermistors (THERMally sensitive resISTORS) have a considerably higher sensitivity than other temperature sensors [5]. Thermistors have either a negative temperature coefficient (NTC), that is their resistance value goes down with and increase in the temperature, or a positive temperature coefficient (PTC), their resistance value goes up with an increase in temperature. NTC thermistors are used mainly for temperature sensing applications because they are more stable, while PTC thermistors are typically used for circuit protection applications and as heating elements in small temperature-controlled ovens [6]. NTC thermistors have found a wide application in temperature measurement and control in chemical, food and automobile industries, in measurement instruments, and medicine [7].

A main advantage of thermistors for temperature measurements in comparison with other popular temperature sensors is their extremely high sensitivity [8], for example, sensitivity of $-100\ \Omega/^0C$ in comparison with $0.4\ \Omega/^0C$ for RTDs. It allows to detect miniature variations in temperature, which could not be observed with an RTD or thermocouple. Other advantages of thermistors are the following: low absolute error $\pm\ 0.05\ ^0C$; high resistance value from $30\ \Omega$ to $20\ M\Omega$ (at $25\ ^0C$); short response time due to low thermal mass; easier to wire (2-wire configuration); miniature size, and low cost [4, 8, 9].

The major tradeoff for these advantages is thermistor's highly nonlinear output and relatively limited operating range typically from $-55\ ^0C$ to $300\ ^0C$ depending on the type of thermistor. However, special high-temperature sensors, such as chromium oxide ceramic thermistors made by GE Sensing can operate up to $1000\ ^0C$ [5].

Typical, average comparative characteristics for common temperature sensors are shown in Table 1.

When thermistors are used in temperature sensing, they must be connected to a corresponding measuring circuit. Very often, the measurement circuits are voltage dividers or bridge circuits. However, due to strongly, exponential type of the thermistor characteristic, a linearization must be used to make their application much easier [7].

With the increasing availability of integrated circuits, the demand for high resolution temperature measurement is now greater than ever [10] .There is no limit to the resolution of thermistors. The limitations are till now in the electronics needed to measure to a specific resolution. They also exist in determining the accuracy of the measurement at a specified resolution [11].

Formerly, the nonlinear resistance vs. temperature characteristic was problematic in analog sensing circuits [12]. Today, however, with the advent of digital and quasi-digital electronic controls the linearization can be handled via equations in software or lookup tables. This paper is divided into four main parts. The first part contains state-of-the-art review of existing interfacing circuits for thermistors including integrated solutions, available on the modern market. The second part includes a design approach for thermistor sensing systems based on a Universal Sensors and Transducers Interface circuit (USTI). The third part devotes to experimental investigation of designed temperature multisensor system prototype based on the epoxy bead NTC thermistor S861 from EPCOS [13]. The last part of the paper provides conclusions and future research directions.

TABLE I. COMPARATIVE CHARACTERISTIS OF COMMON TEMPERATURE SENSORS

Characteristic	**Thermocouple**	**Resistance Temperature Device (RTD)**	**NTC Thermistor**	**Semiconductor Temperature Sensors**
Temperature range, ^{0}C	-184 ... +2 300	-200 ... +850	-55 ... +300	-55 ... + 150
Accuracy	< ± 2.2 ^{0}C or ± 0.75 %	< ± 1.9 %	Various, ± 0.05 ^{0}C to 5 ^{0}C	Various, ± 0.5 ^{0}C to 4 ^{0}C
Output Signal	µV	Ω	Ω	Analog (V), Digital (serial), Quasi-digital (frequency, period, PWM, duty-cycle)
Signal Conditioning	• Amplification • Filtering • Cold-Junction • Compensation	• Amplification • Filtering • Current Excitation	• Amplification • Filtering • Current Excitation	No necessary
Linearity	Fair	Excellent	Poor	Good
Precision	Fair	Excellent	Poor	Fair
Sensitivity	Low	Medium	Very High	High
Long-Term Stability	High	High	Low	Medium
Thermal Response Time	Medium to fast	Medium	Fast	Medium to fast
Self Heating	No	Low	High	High
Lead Effect	High	Medium	Low	Low
Cost	Low	High/Moderate	Low	Moderate
Size	Small to large	Medium to small	Small to medium	Small to medium

II. INTERFACING CIRCUITS FOR TERMISTORS: STATE-OF-THE-ART

The use of thermistors for temperature sensing requires some signal conditioning and interfacing hardware to produce an output for the further processing. Let consider main types of such interface circuits.

A. ADC based Thermistor Interfacing

The outputs of most linearizing circuits for thermistors are analog in nature and need to be converted to a digital form before being interfaced to digital instruments or DAQ systems. Digital processing capability (microcontrollers) is available now in many sensor systems at reasonable cost. In addition, such systems contain an excitation current or voltage source, amplifier, lowpass filter, analog multiplexer and high-resolution ADC [2, 14-18]. The temperature resolution in such systems, using tight tolerance thermistors and resistors can be in the order of ±0.01 ^{0}C [10, 14]. Nevertheless a high resolution and small absolute error ±0.3 ^{0}C [14] some such technical solutions are not suitable for multichannel temperature measurements [2, 14-16]; others - contain analog multiplexers [17], which introduce an additional error. In addition, such traditional analog design approach is not suitable for the further smart sensor system integration, especially for technological processes less than 100 nm [19, 20].

B. Temperature-to-Frequency (Period) Converter based Thermistor Interfacing

The use of both: PTC and NTC thermistors in resonant circuits to provide low frequency output is known from the end of 60's [21, 22]. The main advantage of a frequency output is that an ADC is not required. A frequency output is also useful in applications where the sensor conditioning circuitry is combined with a remote temperature sensor [23].

Thermistor interfacing linearization circuits with frequency output based on different kinds of multivibrators are described in [7, 24-26]. In these circuits, different degrees of linearity were obtained over limited ranges of temperatures (see Table 2). An improved converter based on an astable multivibrator with acceptable level of linearization over an increased temperature range 0-86 ^{0}C with sensitivity 21 Hz/ ^{0}C has been reported in [27].

A modified type of a relaxation-oscillator-based temperature-to-frequency converter has been implemented using a delay network and described in [28]. It exhibits linear input/output relation over the wide range -20 ... + 250 ^{0}C with a sensitivity of 14.7 Hz/ ^{0}C. The use of inverse exponential nature of the voltage-time relationship of a charging RC network based on a modified square wave pulse generator for thermistor characteristic linearization is reported in [29]. Although the experiment was done for a temperature range of 5 to 85 ^{0}C, the circuit has been designed for the extended temperature range of -100 to +225 ^{0}C with a sensitive of 9.6 Hz/^{0}C.

The linear temperature-to-frequency converters based on monostable multivibrator on the basis of integrated timer of 555 Series are described in [9, 30] for the temperature range of 270 to +370 ^{0}K with sensitivity of 10 Hz/^{0}K and 3 kHz output frequency corresponds to temperature of 300 ^{0}K [30]. In the circuit reported in [9], as the thermistor resistance varies from 198.3 to 551.2 kΩ, the period of the square wave varies from 22,542 to 61,671 µs.

A linear temperature-to-frequency converter using an integrable Colpitts oscillator is reported in [31] with sensitivity of 59 Hz /^{0}C and residual nonlinearity less than 2.85 % over the temperature range of -20 to +60 ^{0}C and frequency output approximately from 3.2 to 8 kHz.

TABLE II. Comparative Characteristis of Temperature-to-Frequency Converters

No	Temperature Range	Sensitivity, Hz/ ^{0}C	Non-linear Error, %	Frequency Range, Hz	Ref.
1.	0... +86 ^{0}C	21	n/a	380...1000	[27]
2.	0...+100 ^{0}C	10	n/a	3000 at 300 ^{0}K	[30]
3.	-20...+250 ^{0}C	14.7	< 0.12	n/a	[28]
4.	-20... +60 ^{0}C	59	2.85	3000...8000 6000 at 298 ^{0}K	[31]
5.	0...+80 ^{0}C	10	< 0.2	2730...3530 3230 at 323 ^{0}K	[26]
6.	-100...225 ^{0}C	9.6	n/a	2745...3514 at +5...+85 ^{0}C	[29]
7.	0...+120 ^{0}C	n/a	< 1	1500...7000	[7]

A temperature-to-frequency/time converter based on the voltage-to-frequency (or time) converter with linearity better then 0.1 % per decade is described in [32].

In comparison with the analog output, the frequency output has many well known advantages [20] including easy optical or pulse-transformer isolation. As rule, all described above temperature-to-frequency converters based on thermistors are well suitable for remote temperature sensing and telemetry. But the problem to convert frequency-to-digital with appropriate resolution and accuracy is still actual.

III. THERMISTOR SENSING SYSTEM DESIGN

The designed universal thermistor based temperature-to-digital converter is based on the novel Universal Sensors and Transducers Interfacing (USTI) integrated circuit [20, 33], in which a three-signal measurement ramp rate method is used for conversion [20, 34, 35]. There are three possible modes for interfacing of thermistors with the USTI IC: resistive measuring mode; resistive bridge measuring mode and frequency measuring mode. Let to consider these methods in details.

A. Resistive Measuring Mode

In this measuring mode the offset, reference and measurand values are converted into three time intervals by internal resistive-to-time converter base on the internal comparator. The unknown resistance of thermistor should be calculated according to the following equation:

$$R_T = \frac{N_T - N_{off}}{N_{ref} - N_{off}} \cdot R_c \qquad (1)$$

where N_T, N_{off} and N_{ref} are the numbers of reference frequency pulses counted during the measurand, offset cancelation and reference measurement stages respectively; R_c is the precision reference resistor. The interfacing circuit for this mode is shown in Fig.1. Design considerations concerning selection of external components (R_0, R_c and C) and charging time are described in details in [20, 34].

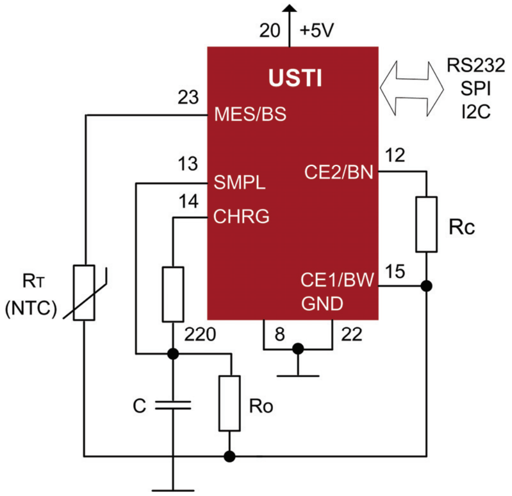

Figure 1. Thermistor interfacing in resistive measuring mode.

The USTI IC has three popular serial interfaces for connection to a master microcontroller, PC or DAQ system: RS232 (master and slave), SPI (slave) and I2C (slave). An example of commands for resistive measuring at SPI communication slave mode is shown in Fig.2.

```
<06><10>; Set up a resistance RT measurement mode
<0E><i><f>; Set the reference value Rc =3011 Ω*
<10><08>; Set the charging time 900 µs
<09>; Start measurement
<03>; Check result. This command returns “0” if the
      result is ready
<07>; Read conversion result in BCD format. Returns
      sign byte and 12 bytes of result in BCD code
```

* - command format:
<I5><I4><I3><I2><I1><I0><F0><F1><F2><F3><F4><F5>, where
<I5>…<I0> integer part of BCD number;
<F0>…<F5> fractional part of BCD number.

Figure 2. Commands for resistance conversion at I2C communication mode.

The further linearization can be handled via nonlinear equations in software (by a master microcontroller or PC) or lookup tables, containing the manufacturer's device characteristics. The custom designed USTI IC for temperature measurement based on thermistors (USTI-TEM) can make the linearization by itself.

B. Resistive Bridge Measuring Mode

Another method of interfacing thermistor to USTI IC is to use a Wheatstone bridge with the thermistor as one arm of the bridge (Fig.3), and the linearization can be made by three-point linearization technique. The selection of R1, R2 and R3 will determine the sensitivity of the circuit as well as the temperature range for which the circuit is best suited.

The resistive sensor bridge is considered as a resistor network with three inputs and one output [20, 35]. The resistance of each input to the output depends on the measurand. Using each input to turn to charge/discharge a capacitor connected to the bridge output yields three different time intervals. For a full bridge, the ratio between the difference between two time intervals and the third time interval yields the fractional resistance change. This change x for each bridge arm can be obtained by the following way:

$$x = \frac{t_1 - t_3}{t_2} \qquad (2)$$

Design considerations concerning selection of charging time, R and C external components are described in [20, 35].

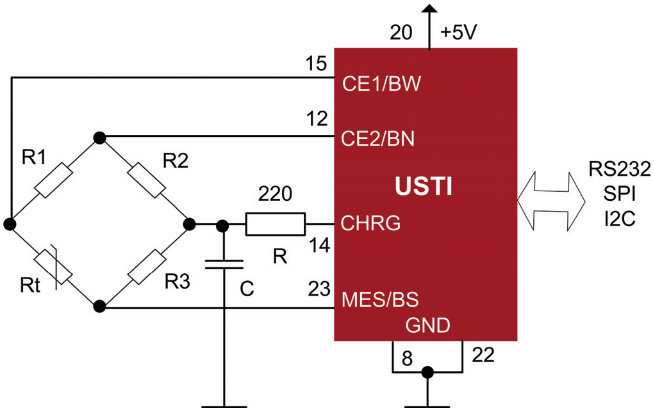

Figure 3. Thermistor interfacing in resistive bridge measuring mode.

An example of USTI's commands for resistance-bridge – to – digital conversion (I2C serial interface, slave mode) is shown in Fig. 4.

```
<06><12>; Set up a resistance-bridge Bx mode
<10><13>; Set the charging time, for example, 20 ms
<09>; Start measurement
<03>; Check result. This command returns "0" if the
      result is ready
<07>; Read conversion result in BCD format. Returns
      sign byte and 12 bytes of result in BCD code
```

Figure 4. Commands for resistive bridge conversion at I2C communication mode.

C. *Frequency Measuring Mode*

The designed universal thermistor based temperature-to-digital converter can work with any known thermistor based temperature–to–frequency (period) converters, described, for example, in [7, 9, 21-32]. In addition to thermistor or resistive bridge interfacing, two such converters can be connected directly to one USTI IC at the same time. The linearization can be made by a thermistor based temperature-to-frequency converter. A three-channel thermistors-based temperature sensing system is shown in Fig.5. Appropriate commands for frequency measurements are shown in Fig.6.

The number of channels can be easily increased by two ways: a time-division channeling method and space-division channeling method. The first one means the use of a digital multiplexer on one of the USTI's frequency input. The second one can be used in SPI and I2C slave communication modes, when appropriate number of USTI ICs is connected to a master microcontroller's bus.

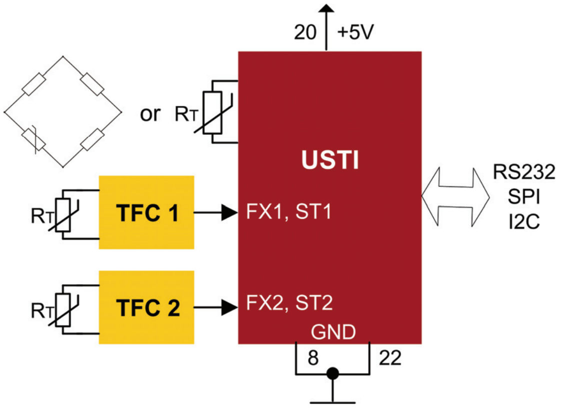

Figure 5. Thermistors interfacing frequency (period) measuring mode
(2 channels plus direct thermistor intefacing). TFC - thermistor based temperature-to-frequency converter.

```
<06><00>; Set up frequency mode in the 1st channel
<02><09>; Set up the relative error, 0.001 %
<09>; Start measurement
<03>; Check result. This command returns "0" if the
      result is ready
<07>; Read conversion result in BCD format
```

Figure 6. Commands for frequency measuremet at I2C communication mode.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A thermistor-based temperature sensing systems consist of the USTI IC and miniature, epoxy resin encapsulated, bead-type thermistor S861 from EPCOS (Fig. 7). Such thermistor is available with the following tolerances: ± 1 %, ± 3 % and ± 5 %, and is suitable for different applications including heating systems, industrial and automotive electronics in -55 ^{0}C to +155 ^{0}C temperature range. It has a nominal resistance R_{25}= 10 kΩ.

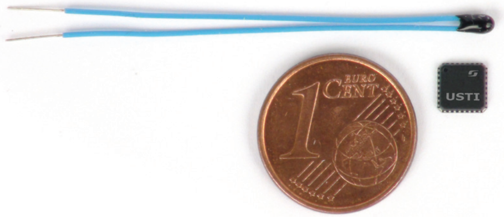

Figure 7. Thermistos S861 (EPCOS) and USTI IC in 5×5 mm MLF package - main components of temperature sensing systems.

The USTI has been preliminary calibrated in laboratory conditions at +23 ^{0}C temperature and 38 % relative humidity with the help of the Universal Counter 53132 A (Agilent). The calibration constant was Δ = 10002491.7979. The following nominals for external components have been selected based on design considerations, described in [33]: R_c= 3011 Ω, R_0=609.86 Ω and C_c = 434.62 nF. The thermistor's and external components' nominals have been measured by the precise LCR meter Instek LCR-819 with basic accuracy ±0.05 % or better. The real temperature was measured by the true-rms multimeter Fluke 187. Charging time constant was T=956.2 μs, which corresponds to the selected 1 ms time.

The time diagrams on the CHRG USTI's input at +23 ^{0}C temperature measurement are shown in Fig. 8.

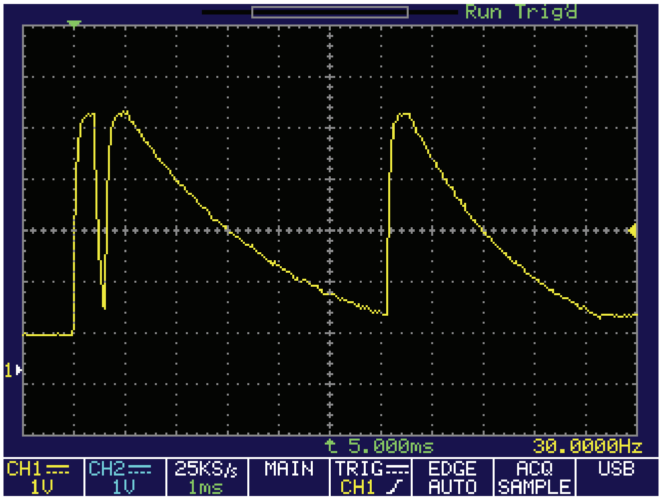

Figure 8. Oscillograms on the USTI's CHRG pin.

The measuring results and calculations based on the R/T thermistor's characteristics are shown in Table 3.

TABLE III. MEASURING AND CALCULATIONS RESULTS

T, ^{0}C	R_{nom}, Ω	R_{min}, Ω	R_{max}, Ω	Error, %	ΔT, ^{0}C	Rx aver, Ω
22	11418	11282	11553	1.2	0.3	-
23	10921	10797	11046	1.1	0.3	10713.84
24	10449	10335	10563	1.1	0.2	-

R_{nom}, R_{min}, R_{max}, Error % and ΔT are calculated parameters for NDT thermistor S861 (EPCOS); $R_{x\ aver}$ is the result of measurement at +23 ^{0}C.

The average resistance of thermistor was 10713.84 Ω, which corresponds to +23 ^{0}C ± 0.3 ^{0}C. It means, that the USTI does not introduce any additional error in the measuring channel, which necessary take into account.

When current flows through a thermistor, it generates heat, which raises the temperature of the thermistor above that of its environment. This of course will cause addition so-called self-heating error in measurement. Typically, the smaller the thermistor, the lower the amount of current needed to self-heat. Certain operating conditions can significantly increase such error, for example, a big number of serial measurements for the further statistical averaging. The increasing of thermistor's resistance due to self-heating effect during 100 serial measurements is shown in Fig. 9. This effect is more pronounced in still air. If the thermistor is located in moving air, liquids or solids, the self-heating error is much lower.

The USTI's error at thermistor's resistance-to-digital conversion has four components: the reference error ~10^{-4} % and three components for appropriate time interval measurements (Fig.8): 1) Time interval for offset cancellation stage; 2) Time interval for resistance reference measurement, and 3) Time interval for thermistor's resistance measurement. Taking into account that USTI measures time intervals with minimum possible relative error:

$$\delta_q = \frac{1}{f_0 \cdot t_x} \times 100\%, \qquad (3)$$

where f_0 = 20 MHz is the reference frequency; t_x is the unknown time interval, we get the following relative error for the mentioned time intervals: 0.025 %, 0.0042 % and 0.005 %. Taking into account that the sensor error is 1.1 %, and based on the rule of neglect of small components of error [36], all these components of the resulting error can be neglected.

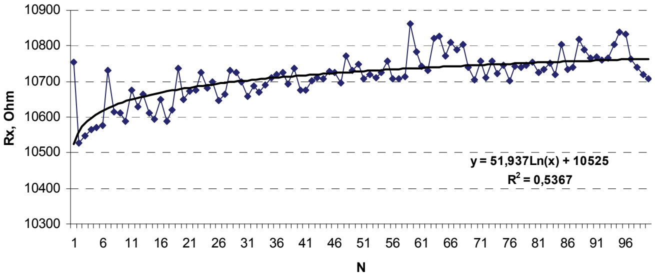

Figure 9. Therimistor's resistance increasing due to self-heating effect..

Let compare the USTI IC with other existing integrated converters for thermistors available. The ispPAC30-based thermistor interface circuit from Lattice Semiconductor offers higher level of integration in comparison with a traditional implementation, which has significantly higher component count [37]. But this converter has only an analog output and needs high-resolution ADC.

The MAX6682 IC converts an external thermistor's temperature-dependent resistance directly into digital form compatible with 3-wire SPI interface. This IC does not linearize the highly nonlinear transfer function of NTC thermistors, but it does provide linear output data over limited temperature ranges, for example, +10 ^{0}C to +40 ^{0}C and 0 ^{0}C to +70 ^{0}C [38].

The MAX6691 four-channel thermistor temperature-to-pulse-width converter measures the temperature of up to four thermistors and converts them to a series of output pulses whose widths are related to the thermistors' temperatures [39]. An external microcontroller must be used to measure accurately appropriate pulse width and pulse space.

The Universal Transducer Interface (UTI) provides interfacing for 1 kΩ - 25 kΩ thermistors and has a microcontroller-compatible period-modulated output [40]. The typical value of linearity is 13 bit.

The number of channels and available interfaces for all mentioned integrated converters for thermistors are shown in Table 4. Only USTI IC has three different, popular serial interfaces and can convert frequency, PWM and period input signals into digital, and support three various measuring modes for thermistors: resistive, resistive bridge and frequency measuring modes.

TABLE IV. COMPARATIVE CHARACTERISTIS OF INTEGRATED CONVERTERS FOR THERMISTORS

IC	Number of Channels	Output
ispPAC30	1	Analog (V)
MAX6682	1	SPI
MAX6691	4	Pulse-width modulated
UTI	1	Period-modulated
USTI	3	SPI, I2C, RS232

V. CONCLUSIONS

The novel USTI IC designed by authors for multichannel smart temperature sensing system based on thermistors, supports various modes for thermistor interfacing: resistive measuring mode; resistive bridge measuring modes and can work with all existing thermistor based temperature-to-frequency (period, PWM) converters. It has three channels and three popular serial interfaces: RS232, SPI and I2C. The USTI's does not introduce any significant error into a measuring channel, and resulting error of the temperature sensor system is determined only by thermistor's error. Such design approach lets considerably reduce a time-to-market for various thermistor based sensor systems.

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