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IC BUILDING BLOCKS FORM COMPLETE ISOLATED 4-20mA CURRENT-LOOP SYSTEMS

By R. Mark Stitt and David Kunst (602) 746-7445

Current loops have become the standard for signal transmission in the process control industry. Current loops are insensitive to noise and are immune to errors from line impedance. Adding isolation to the 4-20mA current loop protects system electronics from electrical noise and transients. It also allows transducers to be electrically separated by hundreds of volts. Burr-Brown now offers all of the integrated circuit building blocks needed to assemble complete isolated 4-20mA current-loop systems. The product line includes two-wire transmitters, two-wire receivers, low cost isolation amplifiers, and low cost isolation power supplies. Three two-wire transmitters are available: one is general purpose, one designed for use with RTD temperature sensors, and one designed for use with bridge circuits.

THE BASIC ISOLATED 4-20mA TWO-WIRE SYSTEM

Figure 1 shows a typical isolated 4-20mA system. An XTR101 converts a position sensor output into a two-wire 4-20mA current-loop signal. An ISO122 low-cost isolation amplifier isolates the 0-5V signal. Power (±15V for the RCV420, 30V for the current loop) is supplied by the HPR117 low-cost DC/DC converter.

In this example, a Penny & Giles Model HLP 190 50mm linear potentiometer is used as the position transducer. One of the 1mA current sources in the XTR101 is used to bias the transducer. A 2kΩ fixed resistor in parallel with the 2kΩ potentiometer sets its output range to 0-1V. The 2.5kΩ resistor sets a 5V common-mode input level to bias the XTR101 instrumentation amplifier input into its linear region.

With the span-setting resistor connections open, the XTR101 current-loop output is:

$$I_O = 4mA + V_{IN}/62.5\Omega$$

Where:

I_O = current loop output (A)

V_{IN} = Differential IA input voltage between pins 3 and 4 (V)

The XTR101 directly converts the 0-1V position sensor output into a 4-20mA current loop output. The isolated voltage output from the ISO122 is 0-5V for 0-50mm displacement.

Other, more specialized two-wire transmitters are also available. See the brief summary at right of available building blocks.

HPR117 LOW-COST ISOLATED DC/DC CONVERTER

Provides ±15V, 30mA isolated output power with 15V input. Key specifications are:

$\pm V_{OUT} = V_{IN}$, ±5%
(V_{IN} = 13.5V to 16.5V, I_{OUT} = 25mA)
I_{OUT} = 30mA continuous at 70°C.
8mA quiescent current, no load; 80% efficiency, full load
750VDC isolation rating

ISO122 LOW-COST PRECISION ISOLATION AMPLIFIER

Precision analog isolation amplifier in a standard 16-pin plastic DIP. Key specifications are:

Unity gain (±10V in to ±10V out), ±0.05%
0.02% max nonlinearity
5mA quiescent current
140dB isolation mode rejection at 60Hz
1500Vrms continuous isolation rating (100% tested)

RCV420

Self-contained 4-20mA receiver. Conditions and offsets 4-20mA input signals to give a precision 0-5V output. Contains precision voltage reference, 75Ω precision sense resistor and ±40V common-mode input range difference amplifier. The RCV420 has a total combined span and zero error of less than 0.1%—adjustable to zero.

XTR101

General purpose two-wire 4-20mA current-loop transmitter. This transmitter has an instrumentation amplifier input and two 1mA current sources for transducer excitation and offsetting.

XTR103

Two-wire RTD 4-20mA current-loop transmitter with 9V compliance. Similar to XTR101, but with internal linearization circuitry for direct interface to RTDs (Resistance Temperature Detectors). The XTR103, along with an RTD, forms a precision temperature to 4-20mA current-loop transmitter. Along with an RTD, the XTR103 can achieve better than 0.1% span linearity over a –200°C to +850°C temperature span.

XTR104

Two-wire bridge 4-20mA current-loop transmitter with 9V compliance. Similar to XTR101, but with shunt regulator and linearization circuitry for direct interface to resistor transducer bridges. The XTR104 can provide better than 0.1% span linearity from bridges with uncorrected linearity in excess of 2%.

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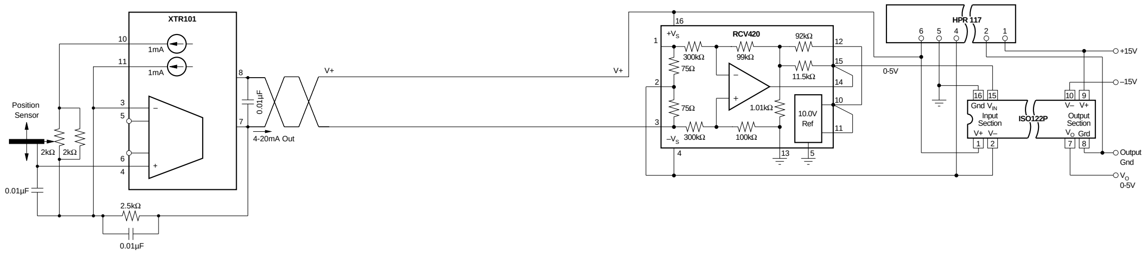


NOTE: Position sensor is Model HLP 190 50mm available from Penny & Giles Controls, Inc., 35 Reynolds St., Attleboro, MA 02703, (508)226-3008.

FIGURE 1. Four IC Packages and Transducer Form Complete Isolated 4-20mA Current-Loop System.

THERMISTOR-BASED TEMPERATURE MEASUREMENT

The most often measured physical parameter is temperature. Of the many commonly used temperature measurement transducers, the thermistor is the least expensive. Both positive and negative temperature coefficient types are available in all sorts of packages. Due to their high temperature coefficients, negative temperature coefficient types are the most common and widely used types. Thermistors are useful for temperature measurement from –55°C up to 300°C.

Figure 2 shows the circuit for a thermistor-based two-wire 4-20mA current-loop temperature measurement system. A bridge is formed with a thermistor, R_{T1}, and a 5kΩ variable resistor. The bridge is excited by the two 1mA current sources in the XTR101. The 5kΩ variable resistor is used to set the temperature-range zero for 4mA current loop output. The XTR101 span setting resistor, R_S, sets the span to get 20mA current-loop output at full-scale. XTR101 current-loop output is:

$$I_O = 4\text{mA} + V_{IN}(1 + 2500\Omega/R_S)/62.5\Omega$$

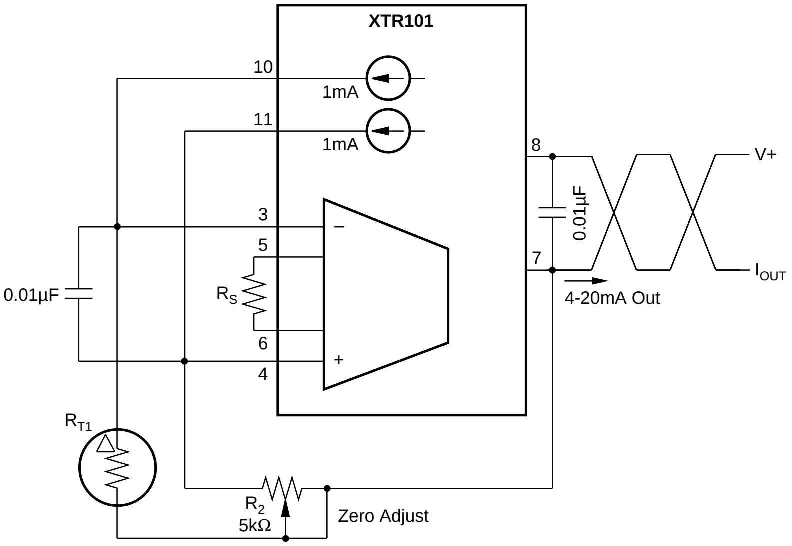


FIGURE 2. Basic Thermistor-Based Two-wire Temperature Measurement Using XTR101.

Where:

I_O = Current loop output (A)

V_{IN} = Differential IA input voltage between pins 3 and 4 (V)

R_S = Span-setting resistor (Ω)

Keep in mind that the maximum differential input range for the XTR101 is 1V.

Since the thermistor is a powered sensor, self heating can be a problem. For example, with a thermistor voltage of 5V, power dissipation is 5V • 1mA = 5mW. If a bead-in-glass type thermistor with a thermal resistance of 600°C/W is used, self-heating can increase the thermistor temperature by 3°C. To minimize this error, use a thermistor in a low thermal resistance package or lower the thermal resistance by heat sinking the thermistor to a thermal mass residing at the temperature to be measured. For example, if air temperature in an enclosure is to be measured, attach the thermistor to the package instead of mounting it in free air.

THERMISTOR-BASED LIQUID LEVEL INDICATOR

Due to high nonlinearities, thermistors can only be used for accurate temperature measurement over relatively small temperature spans. The high output of thermistors, however makes them attractive for other applications. In some applications thermistor self-heating can be used to advantage. Consider, for example, the liquid level indicator shown in Figures 3A and 3B. A bridge is formed by a pair of matched thermistors. The bridge is excited by the 1mA current sources in the XTR101. When both thermistors are submerged in liquid as shown in Figure 3A, the thermistors are at the same temperature—heat-sinked by the liquid. The potentiometer, R_3, is used to correct for component tolerances and zero the bridge for 4mA current-loop output.

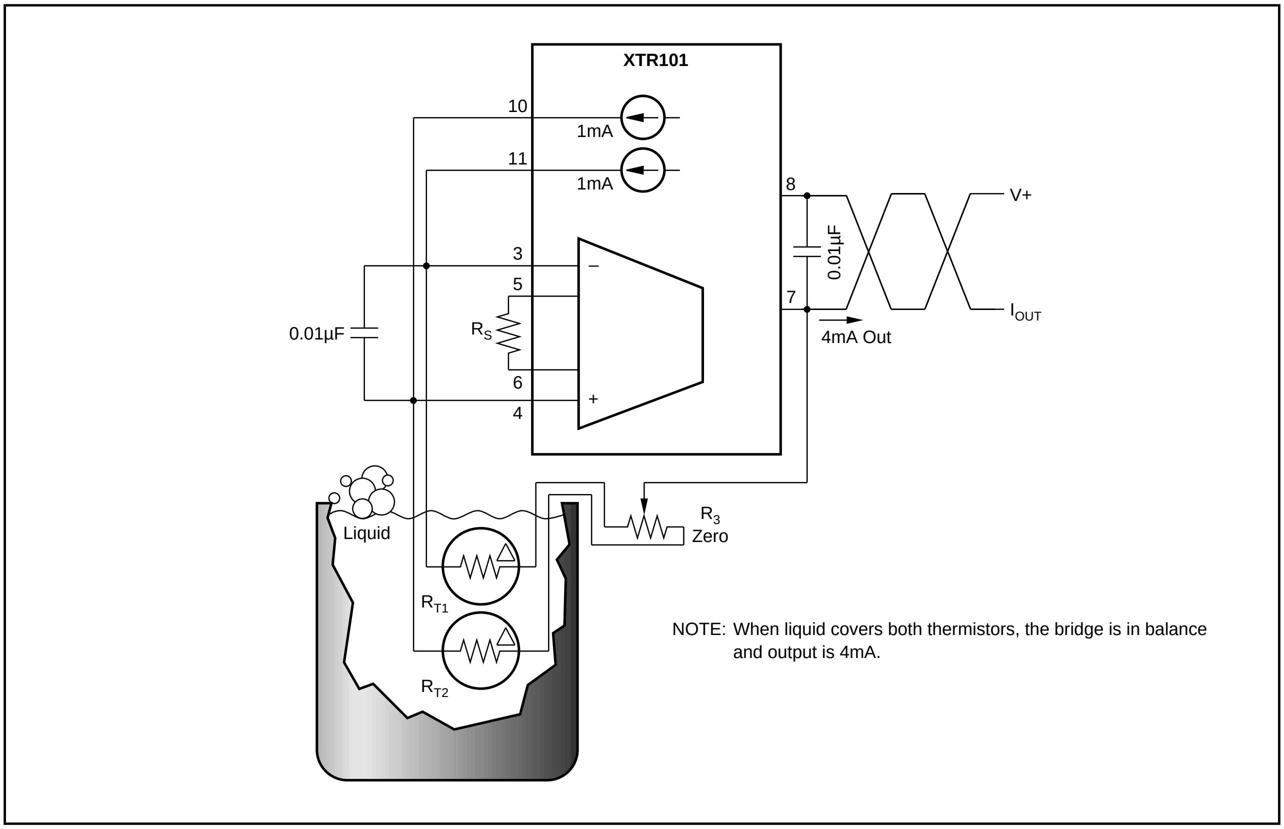
When the liquid level falls below thermistor R_{T1} as shown in Figure 3B, the temperature of R_{T1} increases due to self-heating. The resulting bridge imbalance is measured by the XTR. Span-setting resistor, R_S, is selected to give 10mA output under low liquid level conditions. There is no simple rule for selecting R_S. Its value depends on thermistor selection and liquid properties and conditions.

When compared to level detectors using floats and moving parts, a thermistor-based liquid level indicator can have much better reliability.

GAS FLOW MEASUREMENT USING THERMISTORS

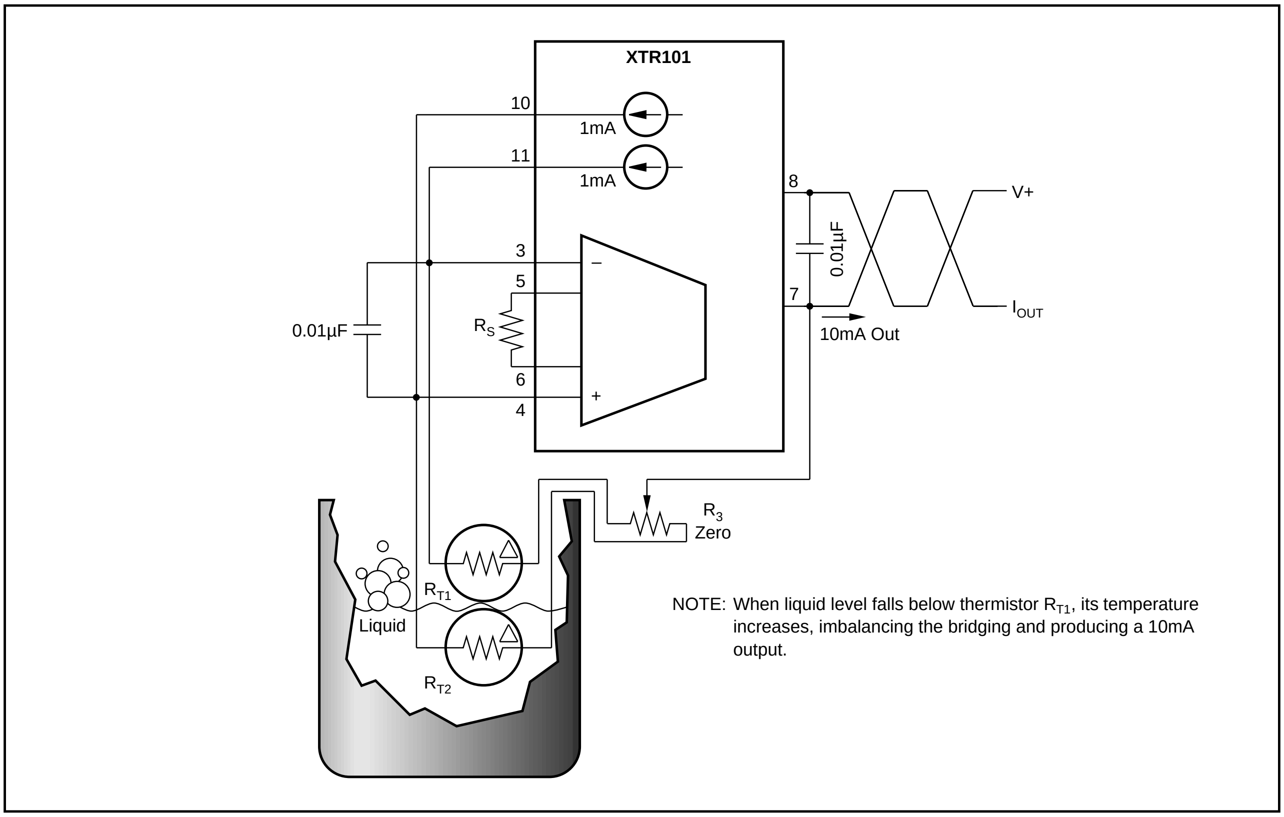
The liquid level indicator uses thermistor self-heating for a two-state high/low measurement. The gas flow measurement system shown in Figure 3C gives a quantitative flow rate measurement.

As in the previous example, a matched thermistor bridge is biased by the two 1mA current sources in the XTR101. One thermistor is positioned in the air flow stream. The other thermistor resides in still air—baffled from the air stream. The thermal resistance of the thermistor is proportional to the air flow rate. Potentiometer, R_3, is used to balance the bridge for 4mA out at zero flow rate. Span setting resistor, R_S, is selected to give a full-scale 20mA output at maximum flow rate. The value of R_S depends on thermistor characteristics and gas flow dynamics.



NOTE: When liquid covers both thermistors, the bridge is in balance and output is 4mA.

FIGURE 3A. Thermistor-Based Two-wire Liquid Level Detector Using XTR101.



NOTE: When liquid level falls below thermistor R_{T1}, its temperature increases, imbalancing the bridging and producing a 10mA output.

FIGURE 3B. Thermistor-Based Two-wire Liquid Level Detector Using XTR101.

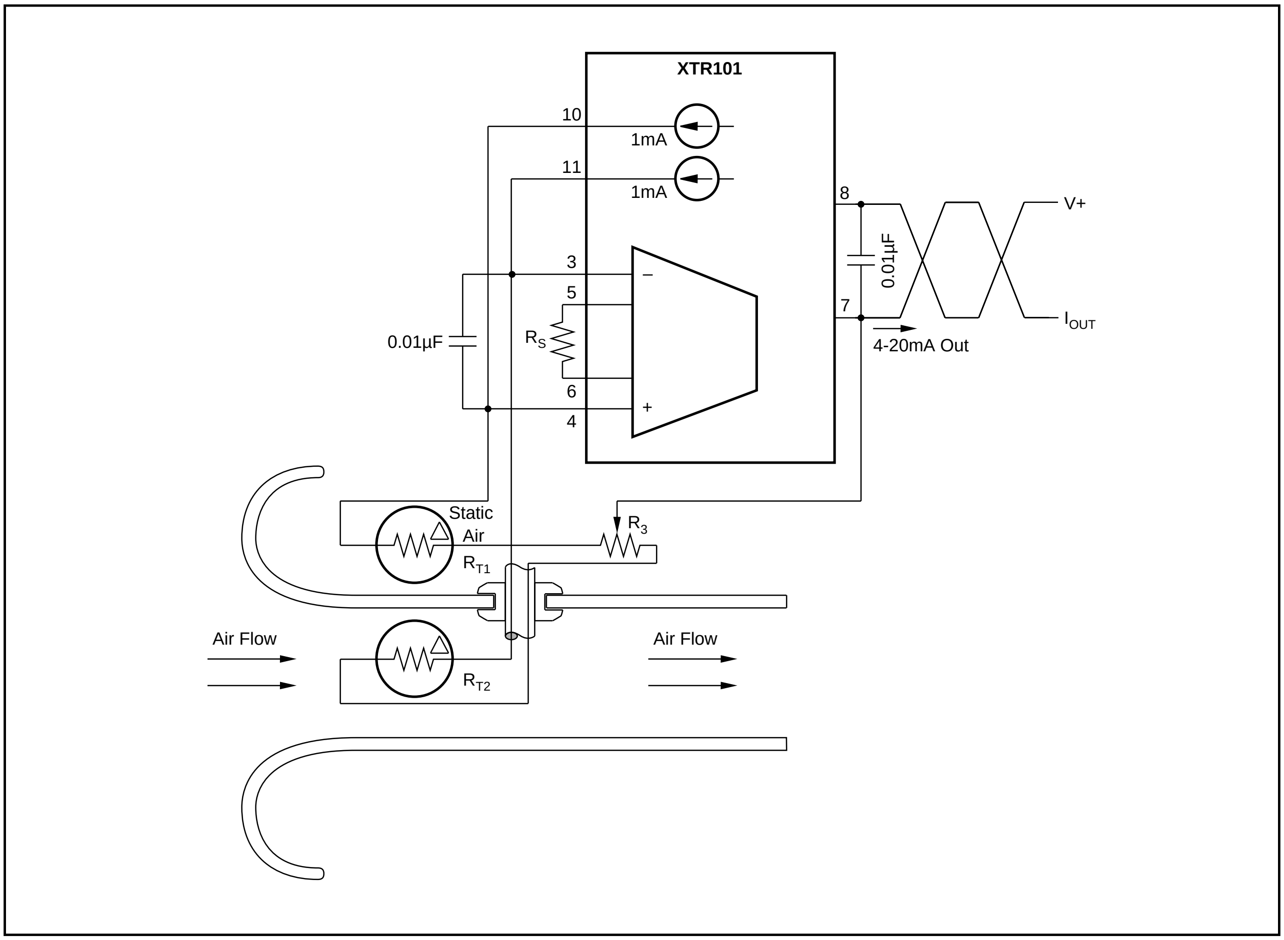


FIGURE 3C. Thermistor-Based Air Flow Rate Measurement Using XTR101.

Many systems today use resistance wire instead of thermistors for gas flow rate measurement. These are sometimes called hot-wire anemometers, and can have faster response due to lower (thermal mass)/(heat transfer) ratio.

DIODE-BASED TEMPERATURE MEASUREMENT

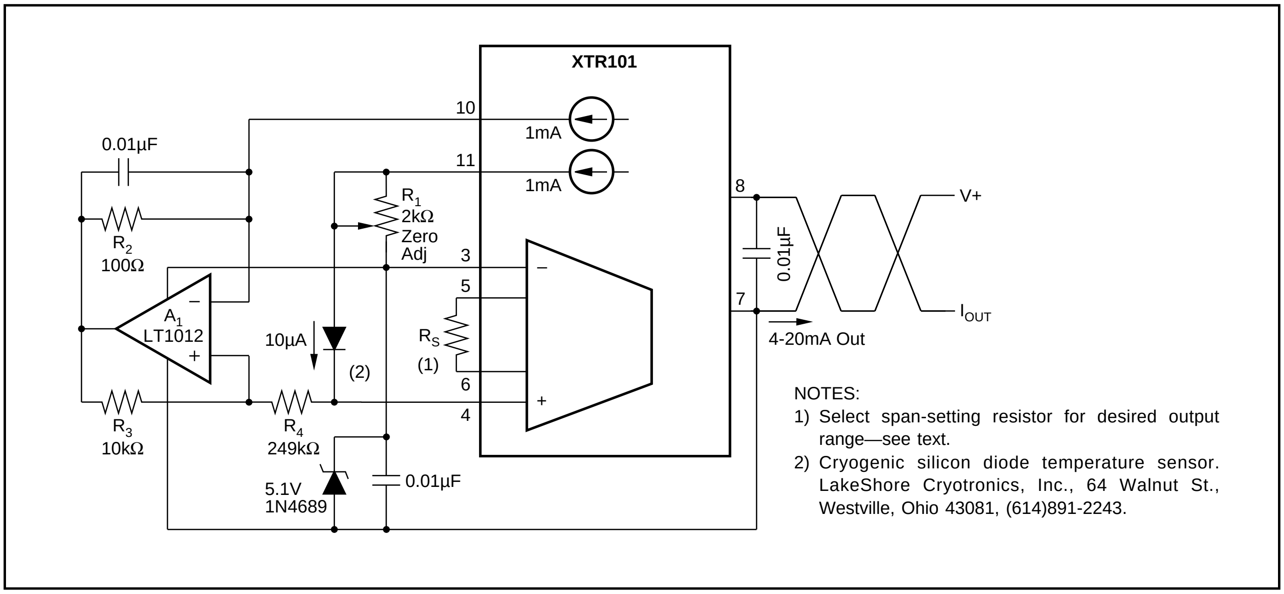
Cousin to the thermistor is the semiconductor diode temperature transducer. Regular silicon diodes, biased with constant current, have a forward voltage of about 0.6V with a temperature coefficient of about –2mV/°C. The usable upper temperature range for silicon semiconductors is about 125°C. Some high-temperature types are useful up to 200°C. In the future, novel semiconductor types such as silicon carbide and diamond promise to raise the upper usable temperature range of semiconductors into the 300°C to 600°C range. For now, thermocouples and RTDs can be used for higher temperature measurements.

Consider semiconductors for measurement of very low temperatures. Specialized silicon diodes can be used at very low temperatures. For example, the LakeShore Cryotronics, Inc., DT-470 series silicon diode cryogenic temperature sensor can be used to measure temperatures near absolute zero—from 1.4K to 475K.

Figure 4 shows a cryogenic temperature measurement circuit using a silicon diode temperature sensor. The sensor requires an accurate 10μA current source for excitation. One of the current sources from the XTR101 is scaled by a precision mirror to supply the 10μA excitation current.

To convert a 1mA current-source output into a precise 10μA for sensor excitation, a precision current mirror is formed with R_2, R_3, and A_1. The 1mA current source is connected to R_2 and the inverting input of the op amp. The op amp drives its inputs to the same voltage through R_3. The result is a precision 0.1V across both R_2 and R_3. The output current at the noninverting input is $1\text{mA} \bullet R_2/R_3 = 10\mu\text{A}$. With the amplifier specified, op amp bias currents add negligible error.

The other 1mA current source in the XTR101 supplies both a precision zero-set voltage and power for the op amp. The current source is connected to a 5.1V zener through R_1. The current through R_1 is precisely 1mA – 10μA. Zero-set voltage is $R_1 \bullet 990\mu\text{A}$. The 5.1V zener sets the supply voltage of the op amp. The 249kΩ resistor in series with the temperature sensor diode forces the op amp to operate in its linear common-mode and output ranges.



NOTES:

1) Select span-setting resistor for desired output range—see text.
2) Cryogenic silicon diode temperature sensor. LakeShore Cryotronics, Inc., 64 Walnut St., Westville, Ohio 43081, (614)891-2243.

FIGURE 4. Silicon-Diode-Based Cryogenic Temperature Measurement System Using XTR101.

OTHER SILICON TEMPERATURE SENSORS

Although diodes are common in temperature measurement applications, their accuracy is limited. The temperature coefficient of a silicon diode has a nonlinearity of about 1% over a 0-100°C temperature span. Also, the stability of the forward voltage with time is limited.

Better accuracy can be obtained from silicon diodes by measuring the difference in forward voltage drops between diodes operating at different current densities. This voltage has a positive temperature coefficient proportional to absolute temperature. If the diodes have low bulk resistance and are well-matched, temperature coefficient linearity of better than 0.01% is possible.

THERMOCOUPLE-BASED TEMPERATURE MEASUREMENT

In the United States, the most commonly used precision temperature sensor is the thermocouple. Depending on the type, wire size, and construction, thermocouples can be used to measure temperatures from about –250°C up to 1700°C.

When designing thermocouple-based measurement systems, it is helpful to understand how thermocouples work. A common misconception is that temperature somehow creates an EMF in the thermocouple junction.

Thermocouples are based on the Thomson effect, which states that, in a single conductor, a voltage difference will exist between two points that are at different temperatures. The voltage difference is proportional to the temperature differential, and its magnitude and direction depends on the conductor material.

A thermocouple is formed when a pair of dissimilar conductors are connected at one end. If a temperature difference exists along the length, between the two ends of the thermocouple, a voltage output proportional to the temperature difference is generated. This phenomenon is known as the Seebeck effect. The measure of the Seebeck effect is known as the Seebeck coefficient. Seebeck coefficients for common thermocouple types range from about 6µV/°C to 60µV/°C.

A thermocouple responds to the temperature difference between its output and the temperature measuring point where the thermocouple wires are joined. To determine the temperature at the measuring point you must know the temperature at the thermocouple output. One way to do this is to keep the output in an ice bath at 0°C. Thermocouple calibration tables were derived this way, and, following tradition, the thermocouple output junctions have come to be known as *the cold junction*. In reality, the measurement junction may be colder.

In most modern thermocouple-based temperature measurement systems, the thermocouple output end simply resides at the ambient temperature. To compensate for variations in ambient temperature, a temperature-dependent voltage is summed with the thermocouple output. This method is known as cold-junction compensation.

A thermocouple-based 4-20mA temperature measurement system with cold-junction compensation is shown in Figure 5. In this application, a *type J* thermocouple is combined with an XTR101 to give a 4-20mA output for a 0-1000°C temperature change. One of the 1mA current sources in the XTR101 biases a silicon diode used as a temperature transducer for cold-junction compensation. For good accuracy, the thermocouple output junctions and the diode must be maintained at the same temperature. The diode has a forward-voltage temperature dependance of about –2mV/°C. The R_1, R_2 resistor divider attenuates the temperature dependence to match the thermocouple Seebeck coefficient. The other 1mA current source is connected to R_3 for zero adjustment. The 2.5kΩ resistor establishes a 5V bias to keep the XTR101 IA in its linear range. Adjust R_3 for 4mA out with the thermocouple measurement end at 0°C. The span-setting resistor is chosen to give a 4-20mA output for the 58mV/1000°C thermocouple output. Nominal component values and Seebeck coefficients for recommended thermocouples are shown in the table in Figure 5 below.

RTD-BASED TEMPERATURE MEASUREMENT

The highest performance temperature measurement transducer in common use is the platinum resistance temperature detector (RTD). RTDs can be used to accurately measure temperatures from –200°C to 850°C. As with other temperature transducers, best performance requires correction for nonlinearities. The XTR103 is a special purpose 4-20mA current-loop transmitter with built-in circuitry for RTD linearization.

To understand how the linearization circuitry works, consider how an RTD works. In the range from 0°C to 850°C, the temperature/resistance relationship of a Pt-type RTD is:

$$\text{RTD} = R_0 \bullet (1 + A \bullet T + B \bullet T^2)$$

Where:

RTD = DC resistance value of RTD (Ω) at temperature T (°C)

R_0 = Value of RTD at 0°C (Ω)

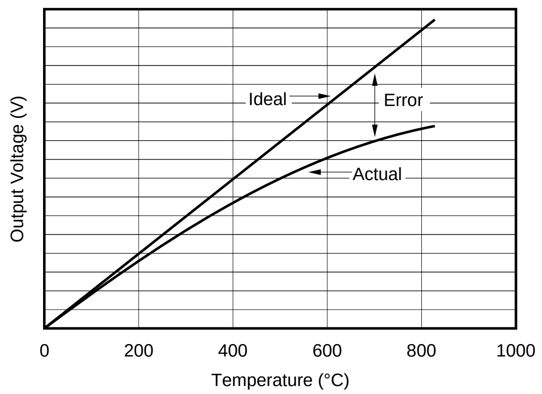


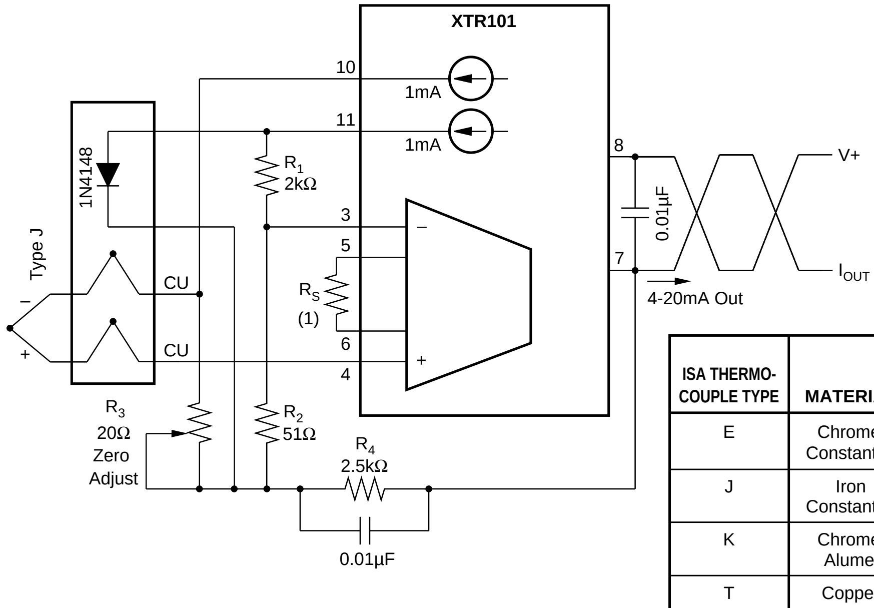
FIGURE 6. RTD Output Voltage vs Temperature.

R_0 = 100Ω for Pt100 = 200Ω for Pt200

A = Detector constant = 3.908×10^{-3} (°C^{-1}) (for Pt100)

B = Detector constant = -5.802×10^{-7} (°C^{-2}) (for Pt100)

The second-order term, $B \bullet T^2$, in the temperature/resistance relationship causes a nonlinearity in the response of ≈3.6% for a 0°C to 850°C temperature change. Figure 6 shows a plot of the voltage across an RTD with constant current excitation. The nonlinearity is exaggerated to show its characteristic shape. Increasing the current through the RTD by an appropriate amount as temperature increases will “straighten out” the curve and reduce the nonlinearity.



NOTE: (1) For 4-20mA with 0-1000°C, R_S = 153.9Ω, nominal R_3 = 16.3Ω.

ISA THERMO-COUPLE TYPE	MATERIAL	SEEBECK COEFFICIENT AT 0°C (μV/°C)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
E	Chromel Constantan	58.5	2k	60.3	19.0
J	Iron Constantan	50.2	2k	51.5	16.3
K	Chromel Alumel	39.4	2k	40.2	12.8
T	Copper Constantan	38.0	2k	38.7	12.3

FIGURE 5. Thermocouple-Based Two-wire Temperature Measurement Using XTR101.

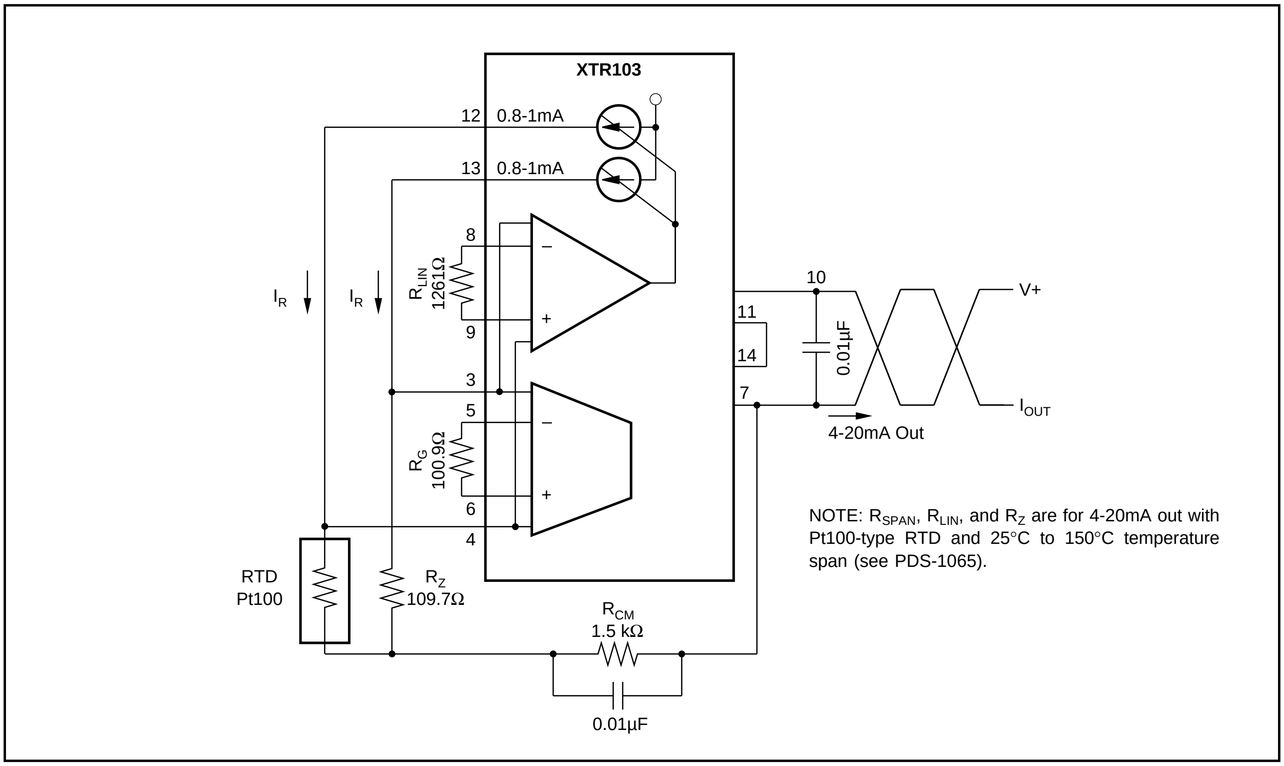


FIGURE 7. RTD-Based Two-wire Temperature Measurement Using XTR103.

An RTD measurement circuit using the XTR103 is shown in Figure 7. The XTR103 is similar to the XTR101, but contains two instrumentation amplifiers—one in the main current control loop, one for linearization.

As with the thermistor-based system, a bridge is formed with an RTD and a fixed resistor, R_Z. The bridge is excited by the two current sources in the XTR103. R_Z is selected to set the temperature-range zero for 4mA current loop output. The span-setting resistor, R_G, sets the IA gain for a 20mA current-loop output at full-scale. The 1.27kΩ resistor biases the IA into its linear range.

The two instrumentation amplifiers are internally connected in parallel. The second IA controls the current sources used to excite the RTD bridge. Gain of the second IA is set by R_{LIN}. With R_{LIN} open the current sources are fixed at 0.8mA. Under control of the second IA, current source output can be increased to 1.0mA—adequate for –200°C to 850°C linearization of both Pt100 and Pt200 type RTDs. Current source output is controlled by the IA input signal according to the following equation.

$$I_R = 0.0008 + V_{IN}/(2 \cdot R_{LIN})$$

Where:
I_R = Current source output (A)
V_{IN} = Voltage difference at the input of the IAs (V)

With the proper R_{LIN}, current source output is increased at the correct rate to correct RTD nonlinearity. Simple selection procedures for R_{LIN} are outlined in the XTR103 product data sheet.

Figure 8 shows the residual nonlinearity for a 0 to 850°C span of both a linearized and an uncorrected RTD. The nonlinearity is improved from 3.6% to better than 0.1%, an improvement of better than 30 to 1. Correction of nonlinearity for smaller spans is even better. The nonlinearity of a 0°C to 100°C span can theoretically be improved from 0.38% to 0.001%. In practice, nonlinearity of better than 0.01% can be expected.

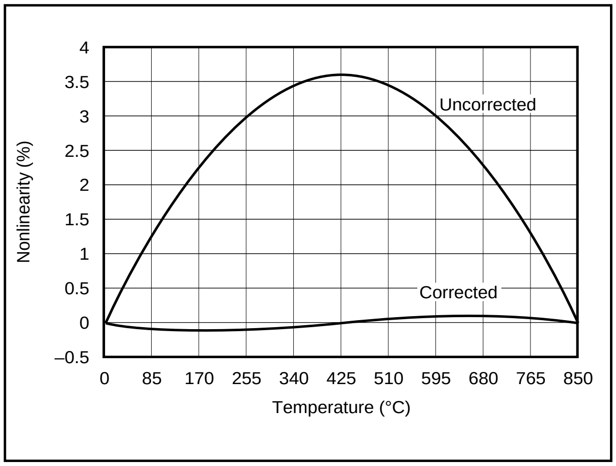
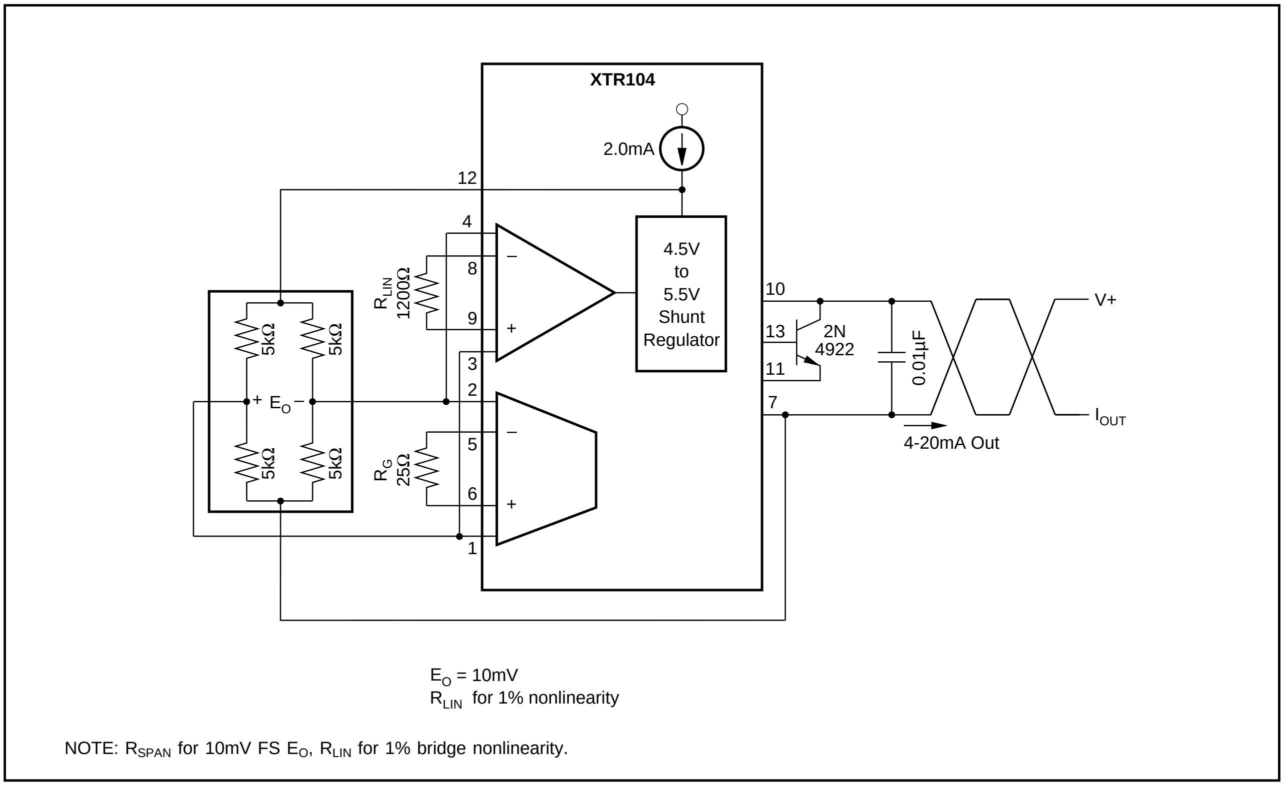


FIGURE 8. Nonlinearity vs Temperature Plot Comparing Residual Nonlinearity of Corrected and Uncorrected RTDs.



E_O = 10mV
R_{LIN} for 1% nonlinearity

NOTE: R_{SPAN} for 10mV FS E_O, R_{LIN} for 1% bridge nonlinearity.

FIGURE 9. Bridge-Based Two-wire Measurement System Using XTR104.

BRIDGE MEASUREMENT 4-20mA CURRENT-LOOP SYSTEMS

Another common transducer is based on the four-resistor (Wheatstone) bridge. Wheatstone bridges are commonly used for pressure measurement. Bridges are usually intended to be biased with a voltage rather than a current source. By changing the voltage bias in response to the bridge output, bridge nonlinearities can be eliminated.

The XTR104 is a two-wire 4-20mA current loop transmitter designed specifically for use with bridges. It is similar to the XTR103 in that it contains two instrumentation amplifiers—one for signal, one for linearization. The difference is the addition of a 5V shunt regulator. The shunt regulator can be adjusted from 4.5V to 5.5V range under control of the second IA. The inputs to the second IA are brought out separately because, unlike RTD linearization, the correction signal may need to be either polarity for bridge linearizaton. Simple selection procedures for R_{LIN} are outlined in the XTR104 product data sheet.

The complete bridge-based 4-20mA current loop transmitter circuit is shown in Figure 9. The XTR104 requires an external pass transistor as shown. Using an external pass device keeps power dissipation out of the XTR104 and improves accuracy. As an option, the XTR103 can use an external pass transistor. In either case, a garden variety bipolar transistor such as the 2N4922 shown is adequate.

Notice that, as with the other two-wire transmitters, only 2mA is available for bridge excitation. This means that, for accurate 5V regulation, bridge elements can be no less than 2.75kΩ unless additional resistance is added in series with the bridge.