Sensors and the Analog Interface

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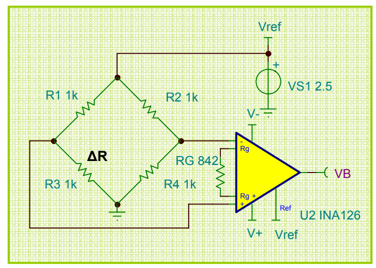
In this presentation we will discuss the way to monitor many different physical phenomena, such as temperature, air flow, humidity, and power. We will discuss numerous sensor characteristics and the various styles of sensor signal conditioning that you can implement in your systems. Throughout this presentation, the output of every sensor circuit will be suitable for a conversion to a digital signal. You will leave this session fully armed to tackle your on-board or remote sensor challenges.

Sensors and the Analog Interface

Presentation subjects

- *A measurement basis*
- *System attributes that may be monitored*
- *Sensor characteristics*
- *Analog interface*



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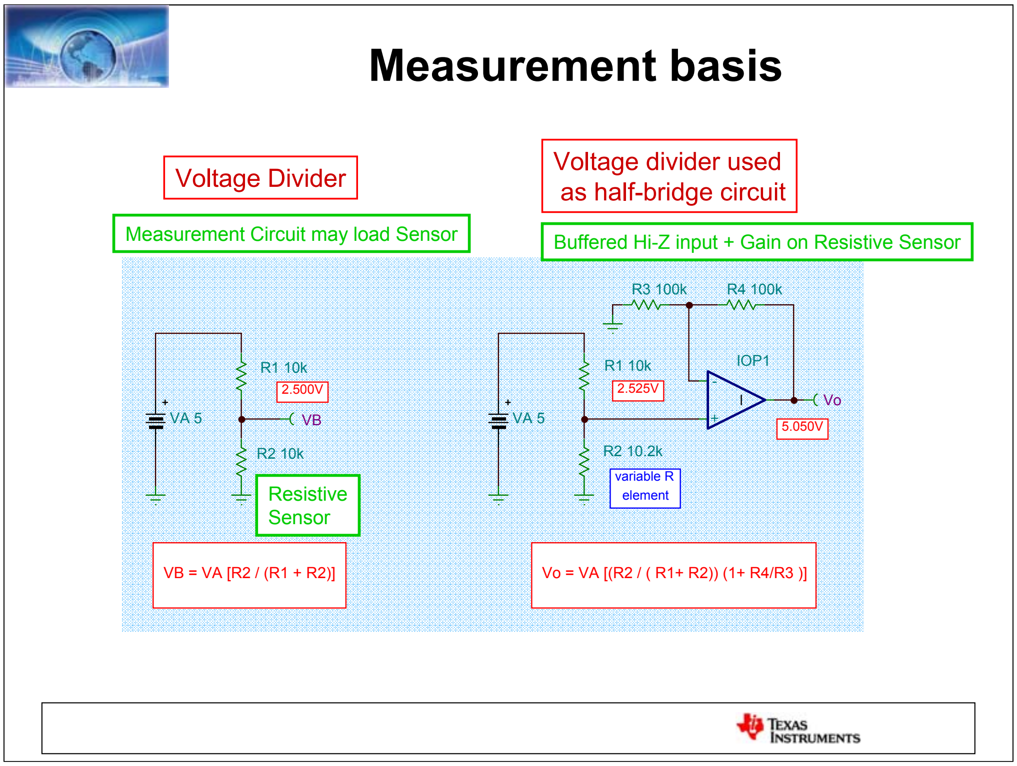
This seminar will focus on the task of measuring and monitoring a system's operating parameters.

We will start by reviewing a measurement bridge circuit that serves as the fundamental circuit for many sensors. There are several types of sensors that work as an integral part of the measurement bridge. We will then discuss the sensor response characteristics in some detail.

The bridge response to a stimulus is then conditioned by an analog interface circuit where it may be amplified, filtered, level shifted, etc, before being applied to a DAS input. Various circuits for accomplishing these tasks will be presented.

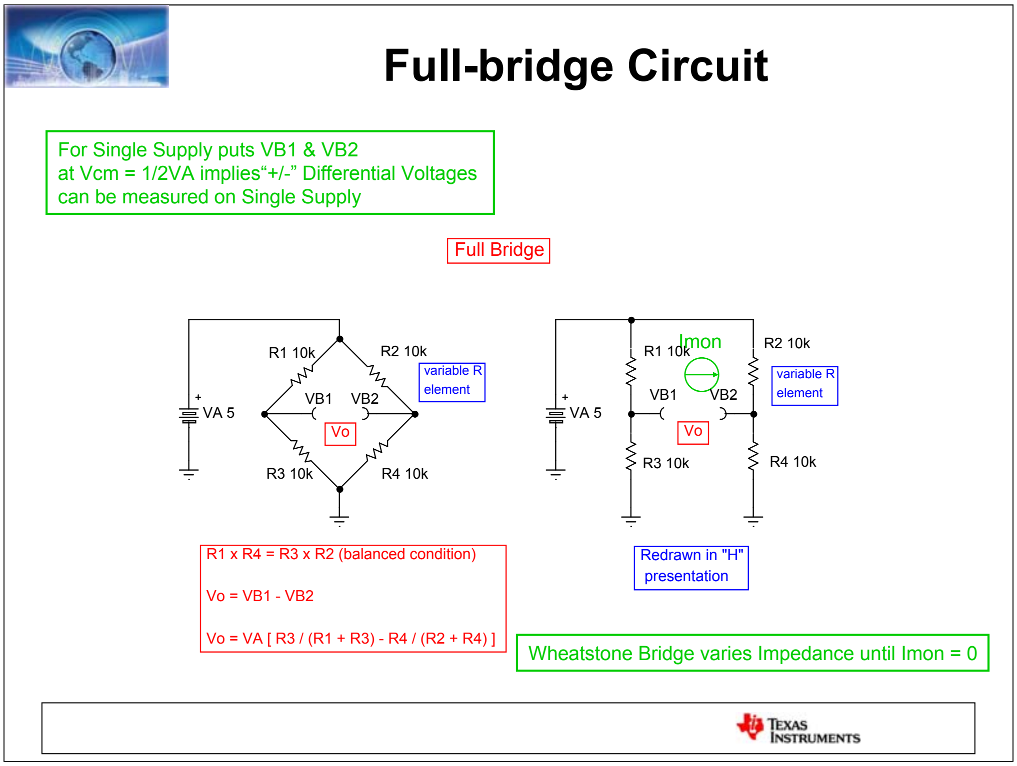
A Measurement Basis

It is helpful to establish a measurement basis before proceeding with the sensors and analog interface circuits.



The basis for many sensor circuits is the simple voltage divider; where one of the resistors in the divider is a resistive sensor. The voltage at the divider union, VB, changes in response to a change in the sensor resistance. This simple circuit is often referred to as a half bridge. Note that a load connected to VB will reduce the normal unloaded value measured and must be taken into consideration.

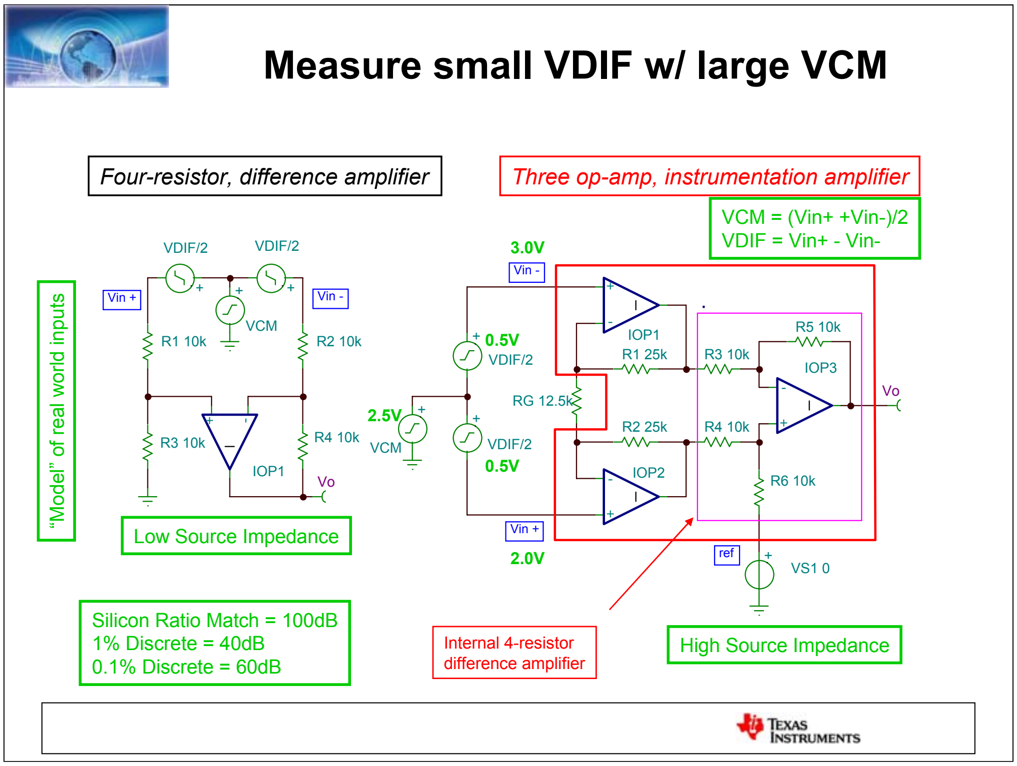
The half bridge output can be buffered with an operational amplifier which also can be configured for a voltage gain. The op-amp should be selected to minimize the loading on the divider *i.e*. have low input bias current.



If we take the simple voltage divider, or half-bridge, and place 2 of them back-to back a full-bridge is created. When all resistors are equal, the output voltage at each half is identical. Changing one or more resistors unbalances the bridge resulting in a differential voltage change (Vo).

The full-bridge is sometimes referred to as a measurement bridge. And although it has a similar appearance to a Wheatstone bridge, the two perform different functions.

The Wheatstone bridge incorporates a current meter at points VB1 and VB2, and is used to indicated when a balanced condition is achieved. At that point the voltage at VB1 and VB2 are equal resulting in no current flow through the meter path. Unknown resistance or reactance can be inferred by knowing the resistances or reactances in the other bridge legs.



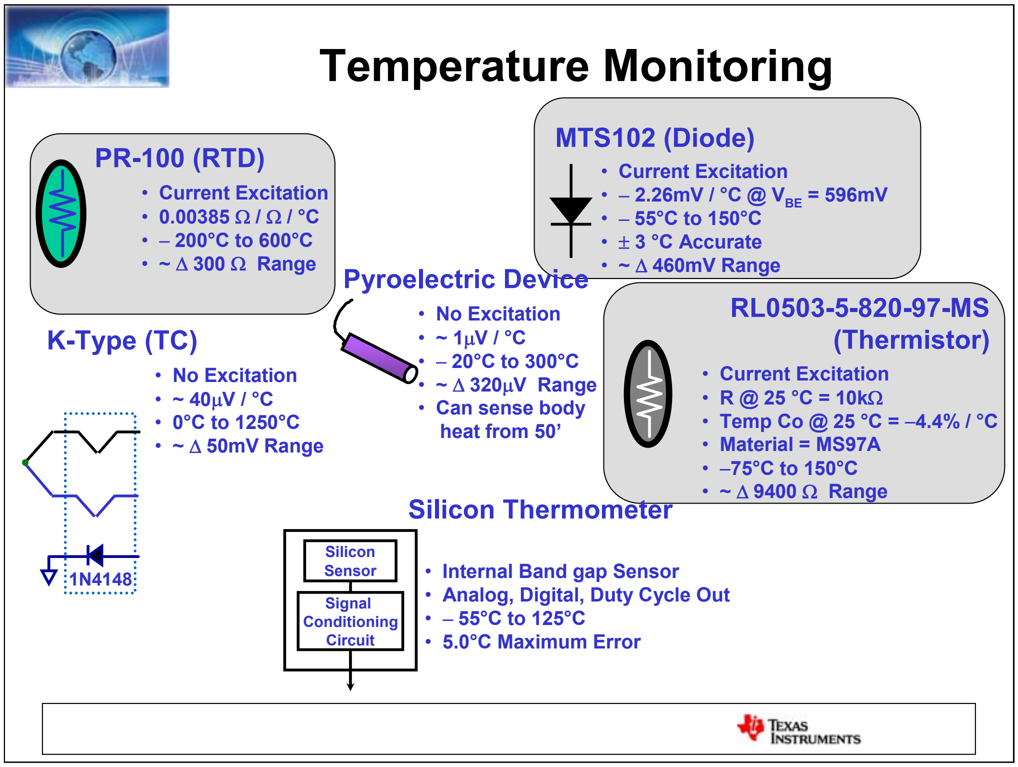
A difference amplifier is formed when the 4-resistor bridge is connected to an op-amp as shown. A common mode voltage (Vcm) applied to the two op-amp inputs, will be cancelled by the equal and opposite responses of the two inputs. If all resistors are exactly equal in value and the common mode rejection is very high, the output voltage will be nearly zero.

The difference amplifier has an output to input relationship:

$$Vo_{Dif} = (Vin+) - (Vin-)$$

The Vdif and Vcm source arrangement shown in the diagrams is an analysis model that conveniently allows both the differential and common-mode sources to be simultaneously applied. In reality, a split differential source is not a practical in this circuit.

If you buffer the difference amp with two input gain stages, a three op-amp, instrumentation amplifier is created. The instrumentation amplifier serves as the interface between the bridge and any subsequent signal conditioning circuits. It provides excellent common-mode rejection and high gain accuracy.

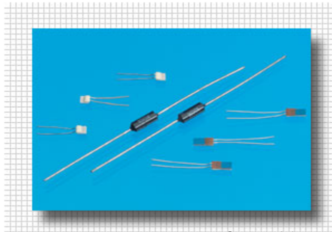


A good place to start our with monitoring circuits is temperature. Many types of temperature sensors are available. The sensor selected is usually selected on the basis of accuracy and cost.

The sensors that we will discuss today are the Resistor to Temperature Device (RTD), Thermistor, and the silicon diode.

Temperature monitoring – RTD

Resistance Temperature Devices - RTDs



Source: Advanced Thermal Products, Inc.

- RTD: resistance temperature device
- Linear resistance change with temperature — Over Limited Temperature Range
- Positive temperature coefficient
- Wire-wound or thick film metal resistor
- Manufacturers: Advanced Thermal Products, U.S. Sensors, Sensing Devices Inc.

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The resistance temperature device, RTD, provides accurate, moderate cost temperature sensing. It features a very good, resistance to temperature linearity (ΔR/ΔT) within limited ranges of its full operating temperature range.

RTD Advantages

- Accuracy available to +/-0.1°C
- High linearity over limited temperature range; ex. -40°C to +85°C
- Wide temperature range: -250°C to 600°C (ASTM) 850°C (IEC)

The advantages of RTDs are accuracy and high-linearity.

The accuracy from an RTD can be specified up to +/- 0.1 °C. This specification surpasses the performance of thermocouples, thermistors, silicon sensors, and the silicon diodes. As a consequence, RTDs are the preferred sensor for high-precision laboratory equipment. The accuracy of the RTD is enhanced with its high-linearity. The highest RTD linearity extends from -40 °C to 85 °C, removing the need for processor look-up tables in most applications.

Although the RTD linearity is well-behaved from -40 °C to 85 °C, many devices can operate from -250 °C to 600 °C or 850 °C with reasonable linearity. You will find that the RTD linearity can be degraded across these temperatures and you may be tempted to use look-up tables in your application.

RTD Disadvantages

Up to 10kΩ, Down to 10Ω available

- Limited resistance range 100Ω to 1kΩ (typically)
- Low sensitivity, about +0.4Ω/°C for a 100Ω Pt100 RTD
- Requires linearization for wide range; ex. -200°C to +850°C
- Wire wound RTDs tend to be fragile
- Lead wire resistance may introduce significant errors
- Cost is high compared to a thermistor

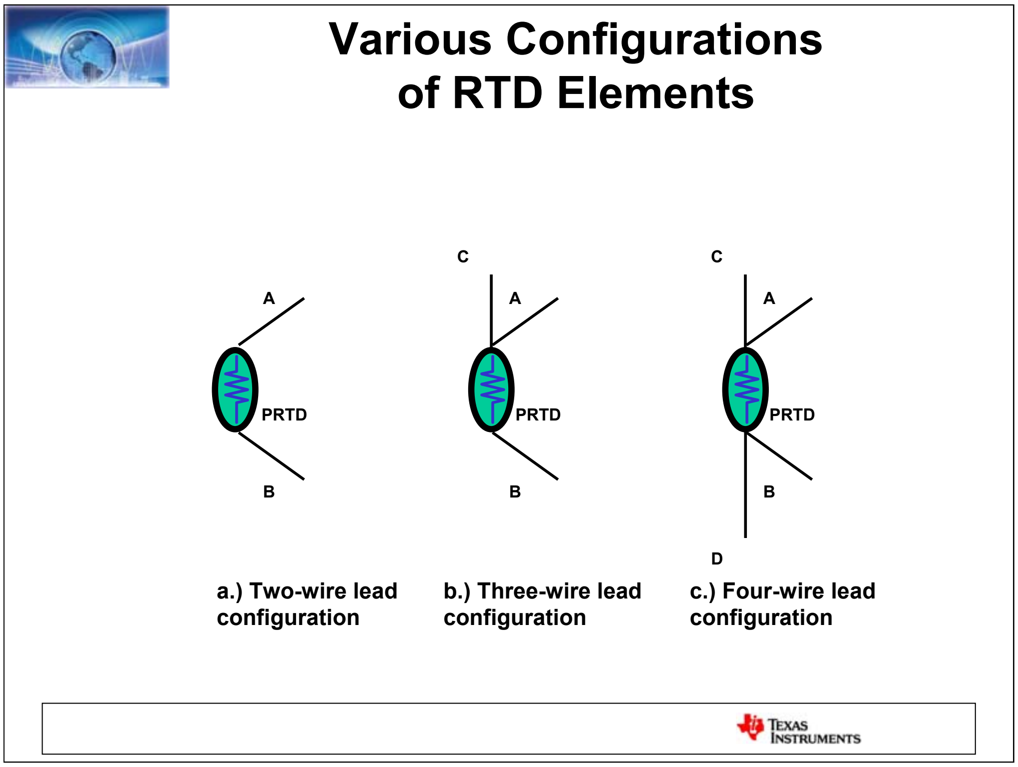
But Wider Temperature Range

TEXAS INSTRUMENTS

The RTD has a limited temperature range as well as an overall resistance. The lower-resistance range contrasts to the higher-resistance values of the yet to be discussed thermistor. The lower range also increases the difficultly when interfacing this device to the stages that following it. Although the resistance range of the RTD is limited, the sensitivity is in the range of +0.4 °C. Linearization of this element will be required for applications requiring high precision.

In terms of board assembly, the wire-wound RTDs are fragile and the lead resistance can introduce errors. Since the RTD is a low resistance device long lead wires can add resistance in the sensors path and cause errors. Three and four wire solutions exist and can be used to compensate this additional resistance component.

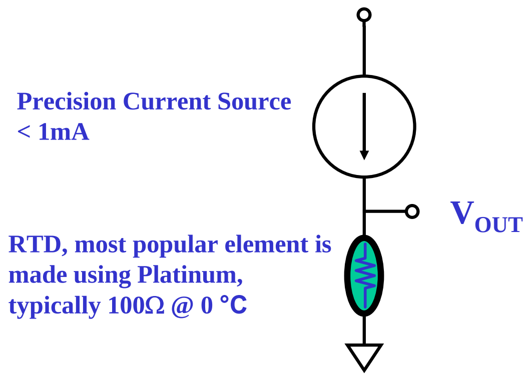
Finally, the cost of the RTD is high compared to the thermistor.



Two, three, and four-wire lead configurations are available with most RTDs. The two-wire configurations requires fewer connects to the element which relaxes the board and electronics requirements. On the negative side, the parasitic resistance at room and over temperature of the wires combine with the low resistance value of the RTD element.

The three-wire and four-wire configurations are most common in precision circuits. Both of these RTD devices can be configured with an amplifier or instrumentation amplifier so that the wire resistance at room and over temperature is significantly reduced or eliminated from the circuit’s output.

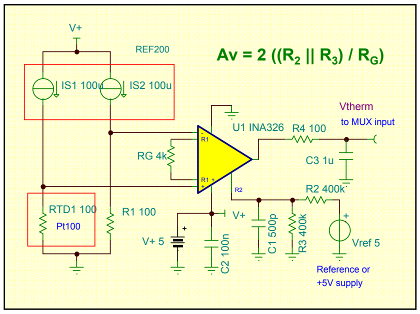
RTDs Require Current Excitation

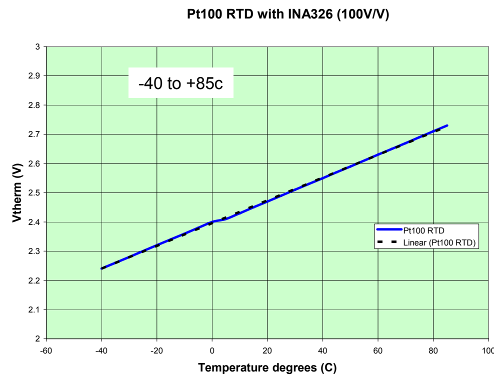


Current is the preferred excitation source for RTDs. In this slide a precision current source flows through the RTD element, creating a voltage across the resistive element. The current source must be less the one milliamp, and actually, the lower this current source is the better. If the current source is too high, self-heating errors will be generated by the RTD. If noise is a consideration in the RTD circuits, it is possible to make the current source magnitude too low.

If you use a voltage source to excite the RTD element, you will need to add a resistor in series. This added resistor creates a non-linear response because mathematically the RTD resistive element is in the denominator of the equation. For instance, if the voltage source and additional resistor are stacked on top of the RTD, the transfer equation is equal to $V_{OUT} = R_{TOP} /(R_{TOP} + R_{RTD})$.

Single-supply RTD solution





INA326 is special SS Inst Amp. Vcm can be close to either rail with High Differential Gain due to current mirror topology

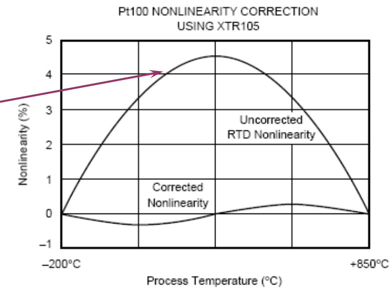
Vref scales Vtherm to +/- around 2.5V to match ADS7870 input. Instrumentation Amp → No Load on Bridge

- Single supply - mid scale centered at 2.5V
- C1 and C3 combine to form a 2nd-order, 1kHz LP filter
- Very low non-linearity, about 1% or less

This schematic a precise approach to biasing the RTD. This is easily accomplished with a REF200. The bridge bias current is low, 100uA, so the RTD dissipates little power.

An INA326 is employed as a single-supply, bridge amplifier. The INA326 circuit and can be configured to include a 2nd-order, low-pass filter, which can be helpful in reducing the noise response. The output of the this sensor circuit can be further amplified by the voltage-controlled amplifier (VCA) internal to A-to-D converters such as the ADS7870.

RTD linearization for wide temperature ranges



For $T < 0°C$ $R_T = R_o [1 + \alpha T + \beta T^2 + \chi T^3(T-100)]$
For $T \geq 0°C$ $R_T = R_o [1 + \alpha T + \beta T^2]$

where: **R_T = resistance at temperature T**
R_o = nominal resistance of RTD
α, β, χ are constants used to scale the RTD

Coeff	American	DIN 43760	ITS-90
α	3.9692E-03	3.9080E-03	3.9848E-03
β	-5.8495E-07	-5.8019E-07	-5.8700E-07
χ	-4.2325E-12	-4.2735E-12	-4.0000E-12

Linearity Improvement:
40:1 at mid point and end points
20:1 at worst case residual error points

4-20mA transmitters with RTD Linearization, Matched Current Sources, Inst Amp:
XTR105, simple hardware linearization
XTR108, digital calibration, RTDs from 10Ω to 10kΩ

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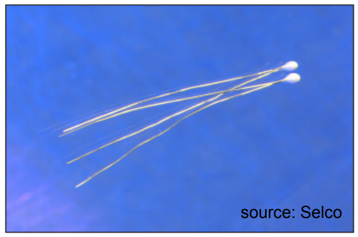
There may be applications where wide temperatures ranges must be monitored with high accuracy.

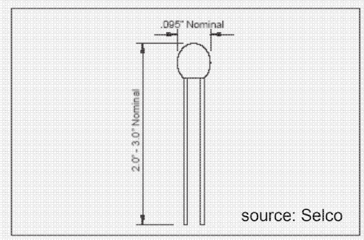
The RTD linearity has a predictable quadratic characteristic with a peak deviation approaching 5%. This quadratic curvature is shown in the accompanying diagram. Since it is predictable it is possible to reduce the error by applying linearization techniques.

The second curve in the diagram shows the reduction in the linearity error after linearization is applied. The XTR105, 4-20mA, 2-wire transmitter uses this particular RTD linearization technique. A technique of summing a secondary current into the RTD across temperature reduces the error to that shown in the second curve.

Temperature monitoring – thermistor



FEATURES:
- High accuracy tolerances to +/- 0.10°C
- Operating ranges from -50°C to 150°C
- Small size with ease of handling
- Proprietary processes produce top of the line quality and stability



Interchangeable refers to how accurately thermistors guarantee (R/T) curve over a range of temperatures. This allows every thermistor to be interchangeable with every other thermistor of the same series specifications without re-calibration of instrumentation.

- Thermistor – Thermally sensitive resistor
- Sintered metal oxide or passive semiconductor materials
- Suppliers – Selco, YSI, Alpha Sensors, Betatherm

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The thermistor serves well as an economical temperature sensor for less critical applications. It is available in a wide range of resistance values and with tolerance values to 0.1%. Note however that this is the tolerance specified at a specific temperature and not over a wide temperature range.

Thermistor advantages

- Low cost option for less critical applications
- Rugged construction
- Available in wide range of resistances: 100Ω to 40MΩ
- Available with negative (NTC) and positive (PTC) temperature coefficients. NTC is most common.
- Highly sensitive: -3.9% /°C to -6.4% /°C for an NTC thermistor

Three YSI Inc Thermistors

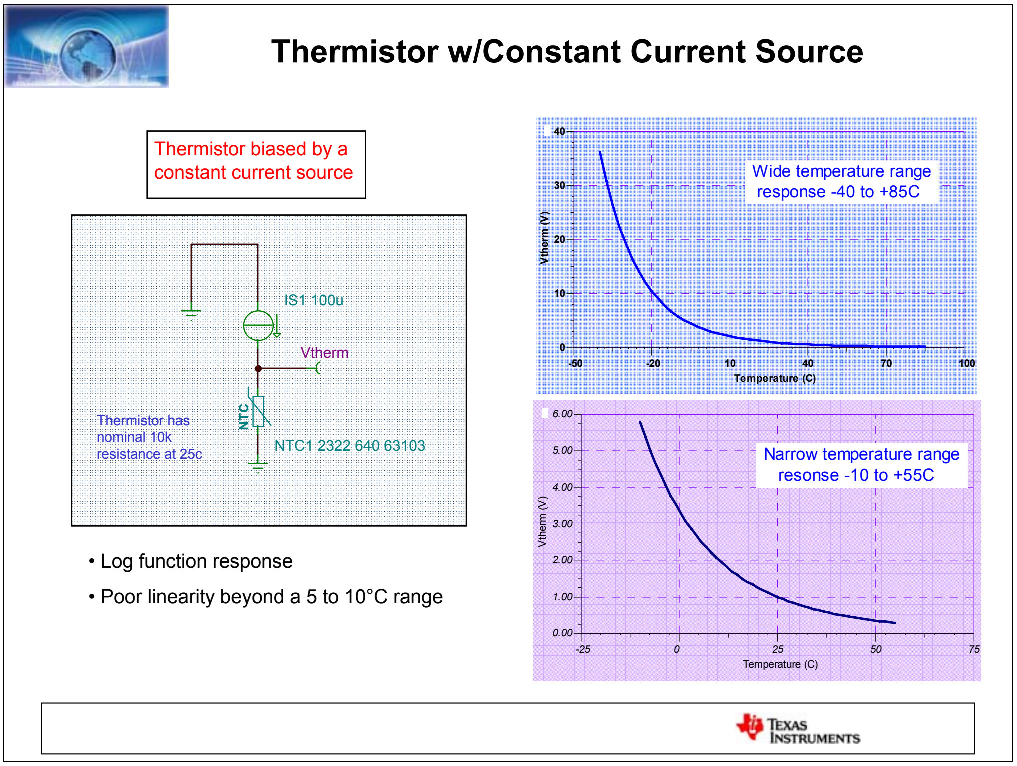
The Negative Temperature Coefficient (NTC) thermistor is by far the most common thermistor and is often used as a semi-precision temperature sensor to measure variable temperatures in a circuit or environment. The Positive Temperature Coefficient (PTC) thermistor is often employed as a temperature sensitive element that often acts to as a switch in the circuit, providing a digital high or low output.

Thermistor Disadvantages

- Limited temperature range: -100°C to 200°C
- Highly non-linear response
- Linearization nearly always required
- 50 deg C range for 10-bit accuracy

Considering the attractiveness of thermistor’s low cost, often less than $1.00, the downside isn’t too bad. The primary drawback of the device is the poor linearity performance if the application calls for monitoring a wide temperature range.

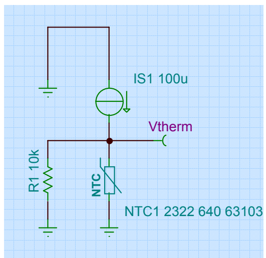
For many temperature monitoring applications the thermistor’s usable range and linearity are completely adequate – that is, once simple linearization techniques are applied.

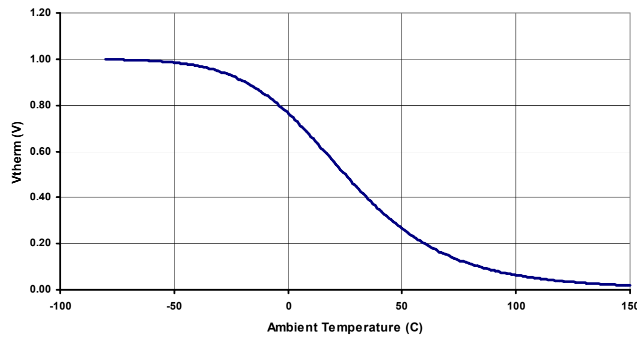


These plots depict the thermistor’s response to temperature over a narrow, and then a wider, temperature range. As shown, the non-linearity of the thermistor’s response is little improved as the range is narrowed. If the thermistor output is directly fed to an A/D converter the output codes will be spaced too far apart at high temperatures, and too closely spaced at low temperatures.

Adding a parallel or series resistor to the thermistor helps reduce these non-linear effects. Even when proper measures are taken to reduce the nonlinearity, linearity begins to suffer with temperature spans greater than about 50 °C.

Shunt R Linearization

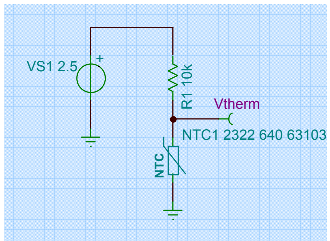


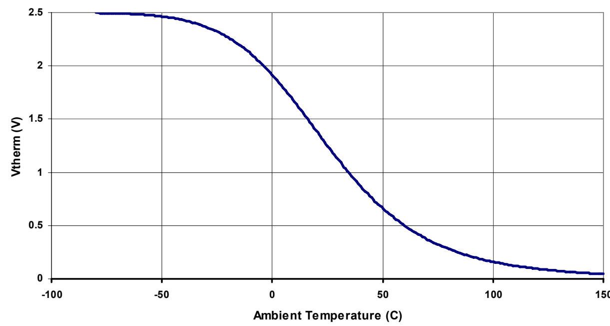


- Much improved linearity with shunt resistance added (limited temp range)
- Non-linearity is under 3% for example when R-shunt equal to the thermistor at the circuits median temperature
- Heavy shunting reduces output

Shunting the thermistor with a resistor drastically improves the linearity across temperature. However the output voltage range is reduced as the shunt resistor is reduced in value. The best compromise between linearity and output voltage is achieved when the shunt resistor is equal to the thermistor resistance at the median temperature of the system.

Series R Linearization





- The voltage source and resistor are equivalent to a non-ideal current source
- Non-linearity is under 4% for this example when R-series equal to the thermistor at the circuits median temperature
- Keep the bias current low to minimize self heating *i.e.* Pd less than 1/10 the power rating

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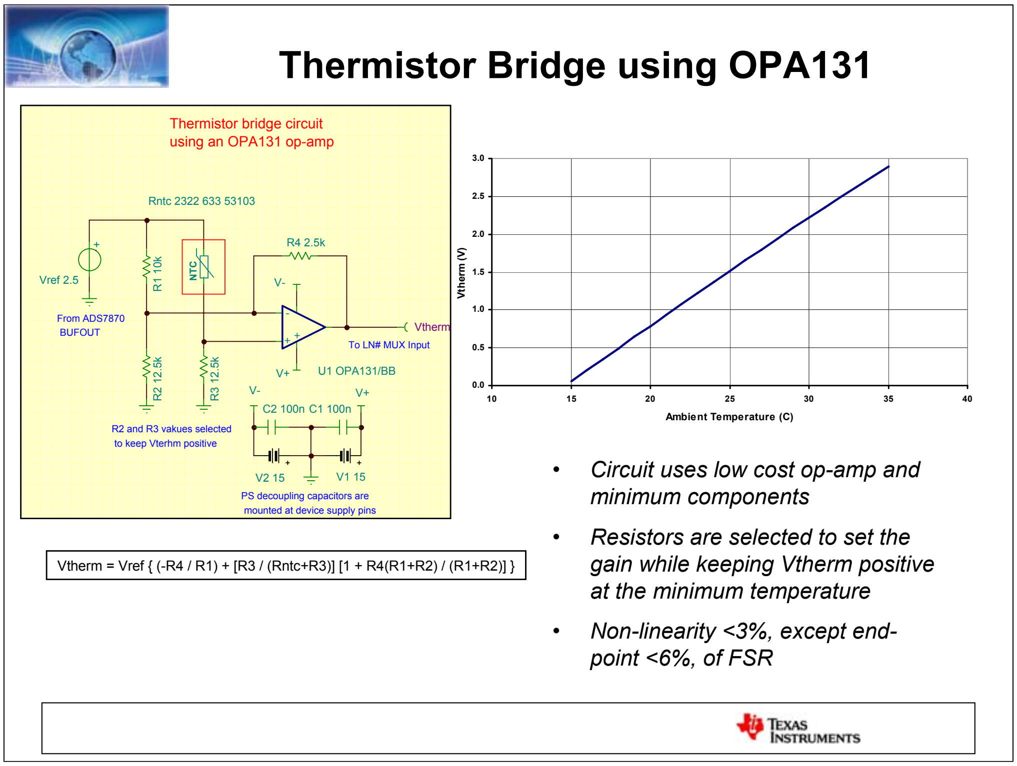
A thermistor also may be biased by a voltage source. A series resistor is added and helps establish the current through the thermistor. The voltage source and series resistor creates the equivalent of a simple current source.

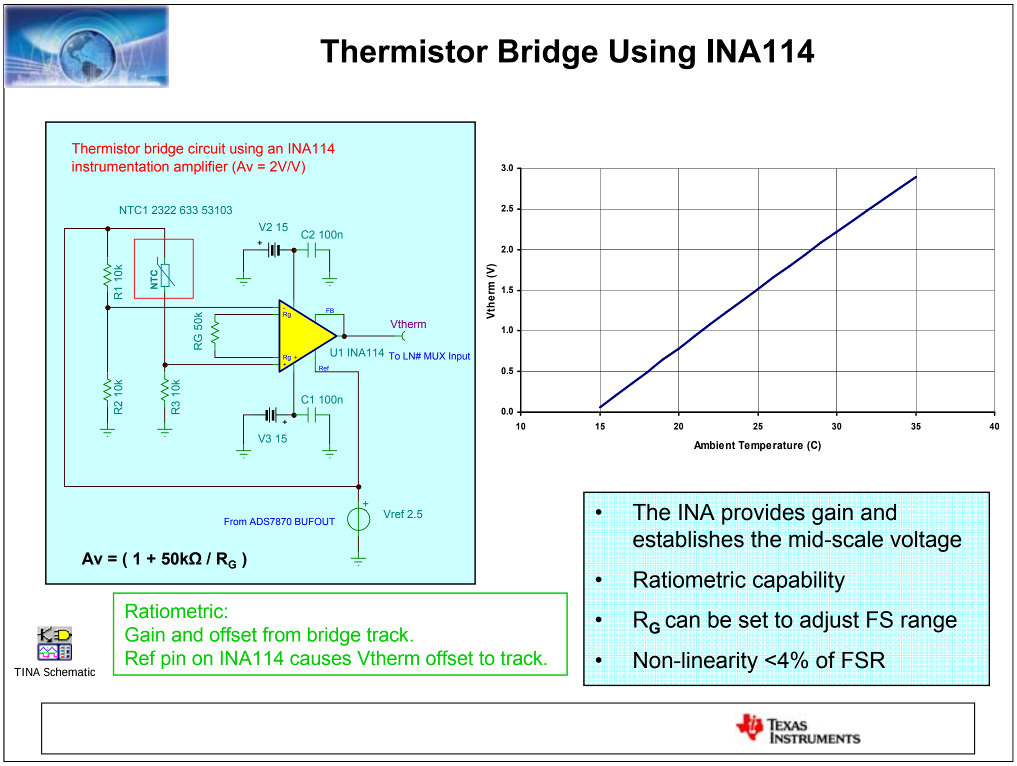
Like the shunt linearization circuit the series implementation provides improved thermistor linearity performance across temperature. Again best results are had when the series resistor is made equal to the thermistor resistance at the median temperature of the system.



This is a low cost, full-bridge circuit for a thermistor temperature sensor. The OPA131 that follows the bridge amplifies the voltage difference at the centers of the 2 legs in the bridge.

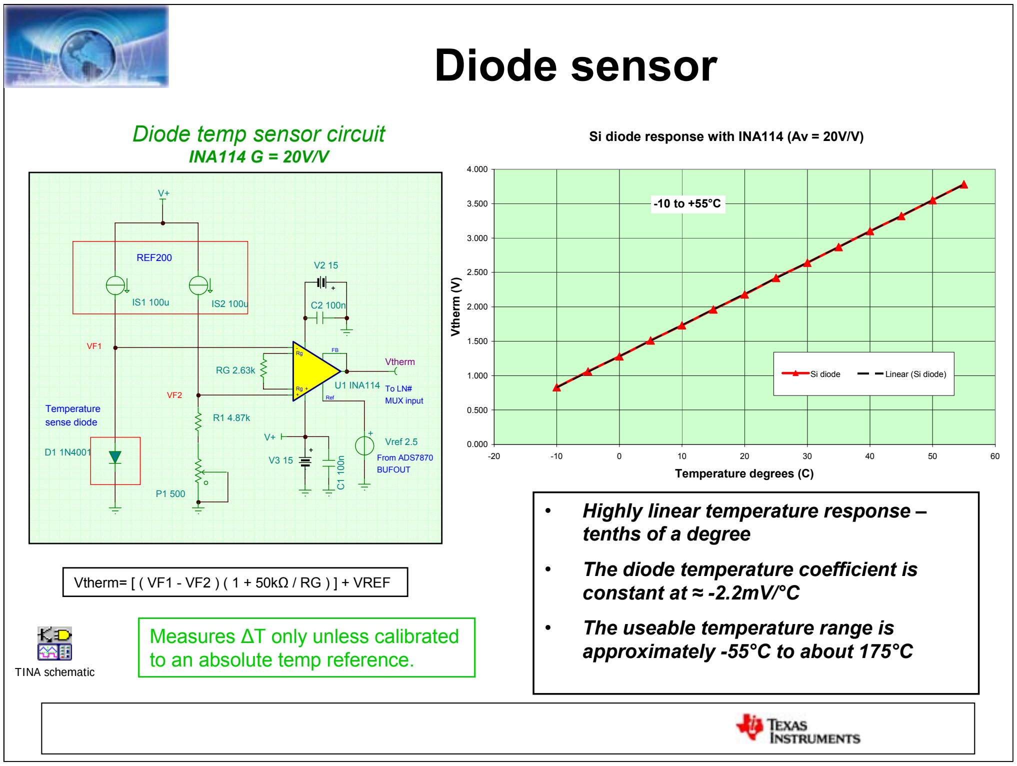
The circuit is a little tricky to set because the resistor values must be selected to set the gain and mid-scale voltage. The plot shows a linearity response that is adequate for many non-critical applications.

Tina-TI, TI's free circuit simulator, is a powerful tool that was used to analyze many of the circuits in this presentation. It is ideal for analyzing sensor circuit performance across temperature.



The INA114 instrumentation amplifier is an ideal interface between the bridge and a data acquisition system (DAS) system:

1. The INA voltage gain can be set as needed. Keep in mind that additional gain can be supplied by a D-to-A converter with an internal VCA.
2. A reference voltage may be applied to INA's Ref pin such that the mid-scale output DC level matches an A-to-D's mid-scale voltage.
3. The system reference voltage may be derived from the A-to-D internal reference. Buffering this reference voltage and applying to the INA114 reference pin and using it as the bridge bias voltage results in a common reference voltage. When this done the A-to-D input range, the INA114 reference pin voltage and bridge bias track each other, providing ratiometric performance.

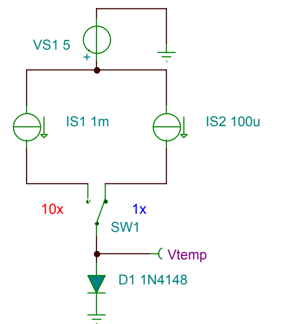


A silicon diode may be employed as a temperature sensor. The forward biased PN junction has voltage temperature coefficient of approximately - 2.2mV/°C which remains constant over its useable temperature range, about -55°C to +175°C. The diode provides very good linearity performance in this application.

This is basically the same full-bridge circuit that was applied to a thermistor. Note that this circuit doesn't directly measure temperature, but rather temperature change. It must be calibrated using a temperature reference.

Determining temperature using 2-current method

Single Diode Temperature Sensing



Current Ratios typically 10:1 or 100:1

Advantages
- Single diode improves accuracy
- no matching

Disadvantages
- Small voltage change in presence of large diode voltage
- Switching circuit

$T(°K) = \Delta V \cdot q / N \cdot k \cdot \ln(I_1 / I_2)$

$T(°C) = [\Delta V\ (1.160e4) / 1.7 \cdot \ln(I1 / I2)]\ -273°C$

Where: $\Delta V = (V_1 - V_2)$ at I1and I2 the 2 current levels
k = 1.3085e-23j /°K q = 1.6e-19C,
N = 1.7 for 1N4148

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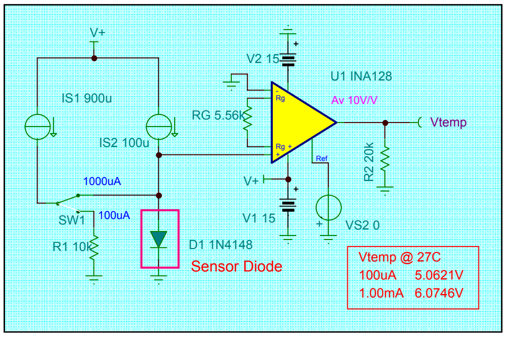
A single diode can be used to indicate the actual temperature. The simple circuit presented here shows how this is accomplished.

The diode is subjected to a temperature environment and then the diode forward voltage is measured at 2 significantly different current levels. The current ratio is usually on the order of 10:1 to 100:1. The main consideration with high ratios is the current may be quite high in the high current measurement. This high current can cause the junction to self heat which introduces an error.

The resulting forward voltages are entered into the equation from which temperature is derived.

Single diode Temp Sensor

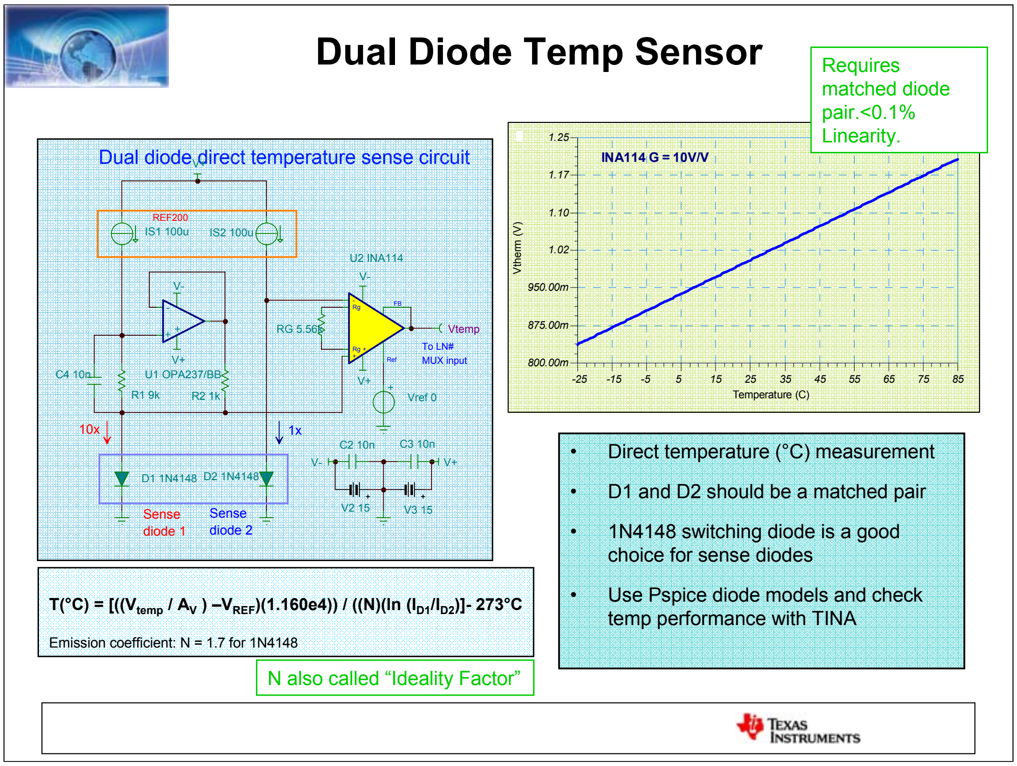
Conceptual implementation of the single-diode temp sensor (using 2-current method)



- Current source switching is required
- Diode forward voltage will be amplified by INA
- INA ref voltage can be adjusted to match ADS mid-scale voltage
- There is an easier way…

This circuit shows the concept of switching the 2 current levels. An INA114 instrumentation amplifier follows the diode providing a gain of 10V/V.

The diode's forward voltage is large, compared to the voltage change that occurs at the 2 current levels. The instrument amp will gain this relatively large voltage up. This also results in a large DC value at the output. A reference voltage can be applied to the ref pin to provide a offset so that the instrumentation amplifier's output can be set to the ADS mid-scale voltage.



The requirement to switch currents can be eliminated by using 2 temperature sensing diodes, one operating at 1x current and the other at a higher current such as 10x. The diodes should be matched for the application.

One-half of a REF200 establishes the 1x (100uA) current for one diode. The other half of the REF200 supplies a reference current for a voltage-to-current converter which in turn supplies the 10x (1000uA) current to the other diode.

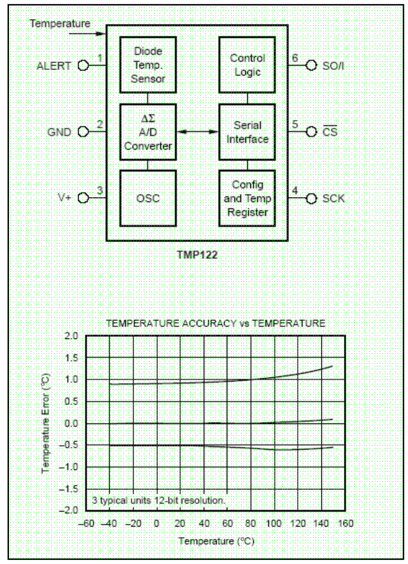
The INA114 inputs connect to the anode of the two diodes in differential fashion. The INA responds to the difference voltage at these 2 nodes and amplifies it. A reference voltage can be applied to the ref pin to match the INA output with the ADS mid-scale voltage. Also, the INA gain can be adjusted for the appropriate input range.

The temperature can be calculated using the equation.

Texas Instruments Temp Sensors

TMP Sensors

- Diode temp sensors with built-in A/D
- Resolution – programmable, 9 to 12-bit + sign bit
- Accuracy
  - +/-1.5°C *-25°C to +85°C*
  - +/-2.0°C *-40°C to +125°C*
- Digital output – SPI compatible
- 2.7V to 5.5V supply



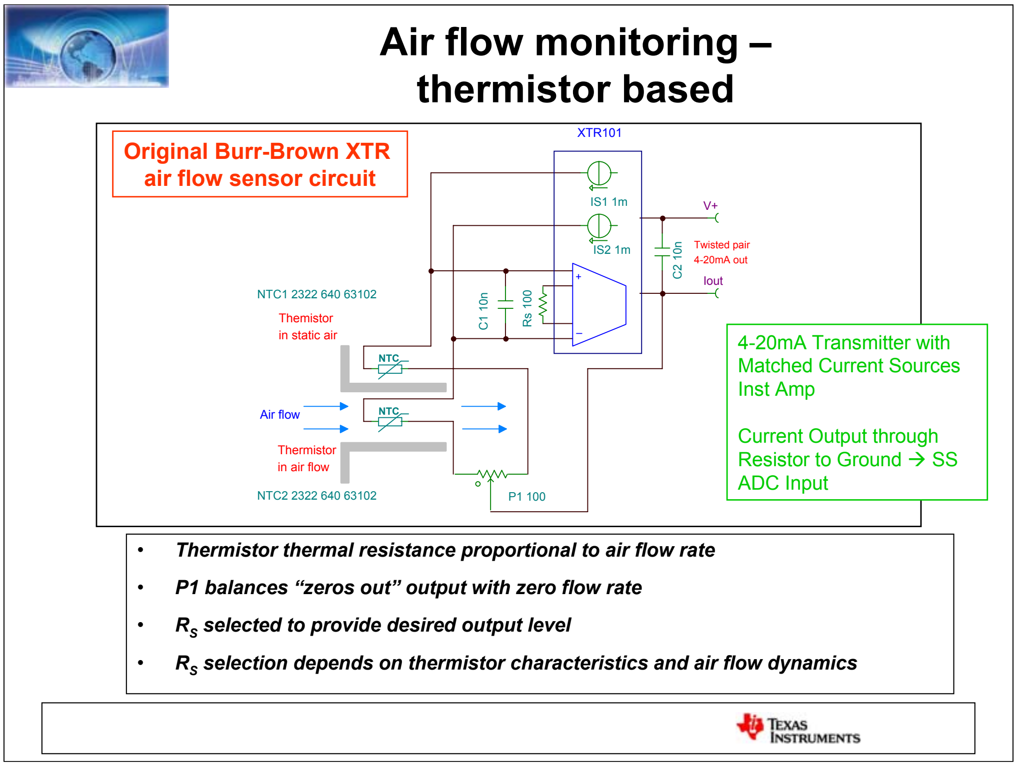
TMP122
Direct Digital Interface
Silicon Temp Sensor

The TMP family of integrated temperature-sensors offers an easily applied, temperature measurement solution. A/D conversion is accomplished by the integrated ΔΣ converter which is programmable from 9 to 12-bits. The digital output is SPI compatible.

With these devices a diode-temperature-sensor configuration is built into the converter. The accuracy can be as high as +/-1.5 °C over a limited temperature range. The integrated temperature-sensors are well suited for board level temperature sensing. The list of appropriate applications include power-supply monitoring, computer peripheral protection, notebook computers, cell phones, office machines, to name a few.

Air flow monitoring

Air flow monitoring is especially important when a piece of equipment requires a high air flow rate for cooling.



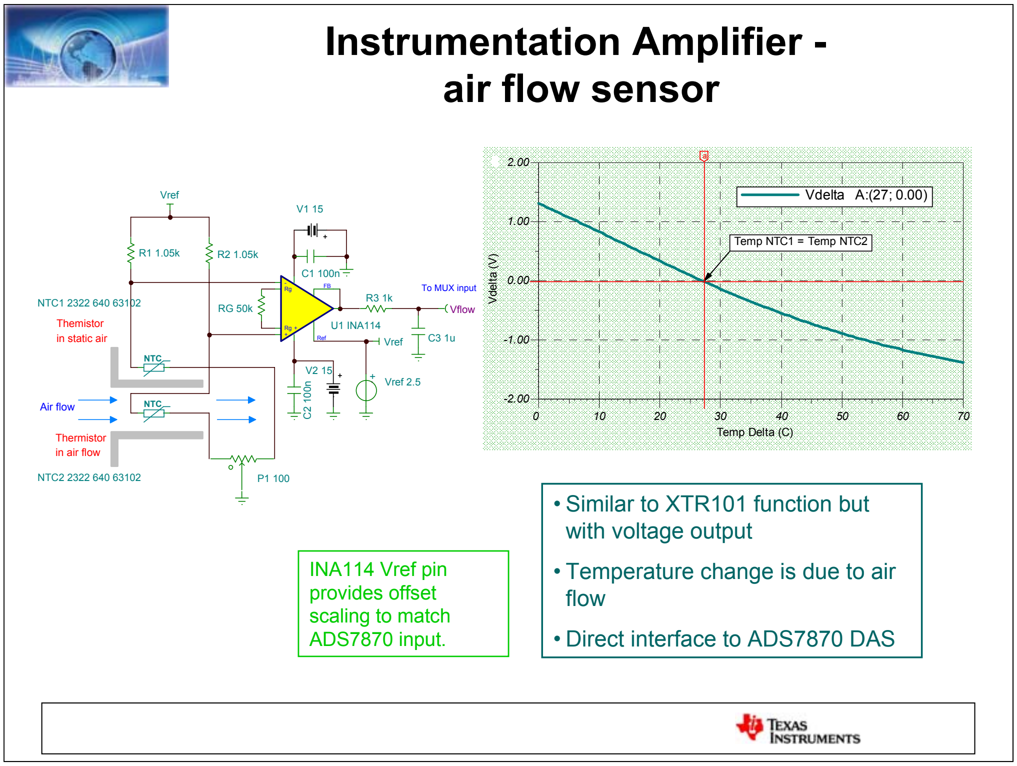
The air flow monitor shown here is an outgrowth of the temperature monitors presented in the previous section. A thermistor serves as the air flow sense element. This circuit uses an XTR101, 4-20mA current loop transmitter implementation originally presented in Burr-Brown applications bulletin AB-032A.

Two thermistors are used in the bridge. One thermistor is located in the still environment while the other is placed in the air stream. The thermistor environments should be at the same temperature so as not to introduce a temperature gradient error. Both thermistors have a small bias current flowing through them and self-heat to a small degree. This is an important point to keep in mind.

Passing air flow removes heat from the exposed thermistor, changing its temperature relative to the thermistor in the static air environment. The amount of temperature change will be related to the air flow dynamics.

The change in thermistor temperature leads to a resistance change that imbalances the bridge, which in turn appears as a voltage difference to the two-wire-transmitter inputs.

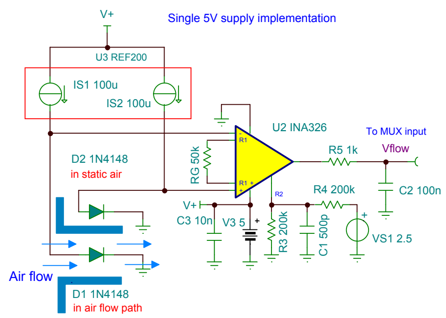
An XTR can be used in remote system monitoring applications, however for use with the ADS7870 DAS, the current output (4-20mA) would have to be converted to a voltage.

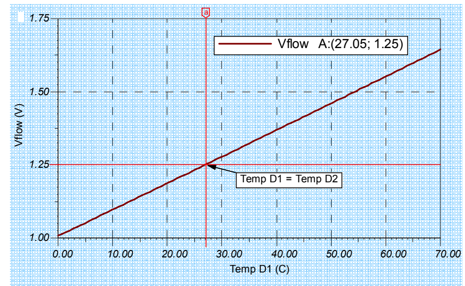


This is an implementation of the previous thermistor bridge in conjunction with an instrumentation amplifier. The instrumentation amplifier provides a voltage output that can be directly interfaced with a data acquisition system (DAS) such as the ADS7870.

The plot shows the delta voltage relative to the Vref voltage. The voltage change is directly related to the heating or cooling of the sense response to the air flow. The “delta” is zero when the temperature of the two thermistors is exactly the same. Air flow will cause a temperature delta in accordance with the plot.

Diode air flow sensor





- D1 and D2 are in the same temperature environment
- D1’s junction temperature and voltage are set by the air flow
- The air flow must be correlated to the change in D1 voltage
- Temperature linearity within tenths of a degree

As previously mentioned, the silicon diode exhibits a linear junction voltage change with temperature of approximately -2.2mV/°C. This was shown to be a direct indicator of junction temperature change. In similar fashion to the thermistor, and by virtue of the junction’s voltage change in response to heating or cooling, the diode can be used as an air flow sensor.

The air flow dynamics dictate how much the voltage will increase or decrease for a given flow rate. Therefore, the relationship between temperature and flow rate would have to be established for a method such as this to be useable.

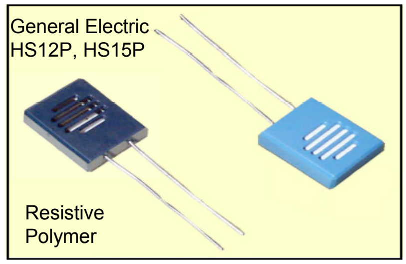
Humidity Monitoring

Humidity sensors are typically resistive or capacitive sensors. Their electrical characteristics are much different than the previously discussed sensors and require different interfacing approaches.

Humidity monitoring

Humidity sensor types

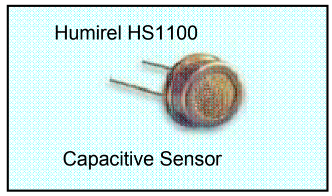
- Resistive – ceramic
- Resistive – polymer
- Capacitive - ΔC
- Capacitive with built-in electronics – V output



Source: General Electric

Suppliers

- Resistive — AC Excitation to prevent polarization
  - GE, ESI, Ohmic
- Capacitive — AC Excitation to prevent polarization
  - Humirel, ESI, Ohmic
- Capacitive with built-in electronics
  - Honeywell, Ohmic



Source: Humirel

Texas Instruments

Resistive humidity sensors usually consist of a hygroscopic (absorbs moisture) medium such as conductive salt or polymer deposited over noble metal electrodes on a nonconductive substrate.

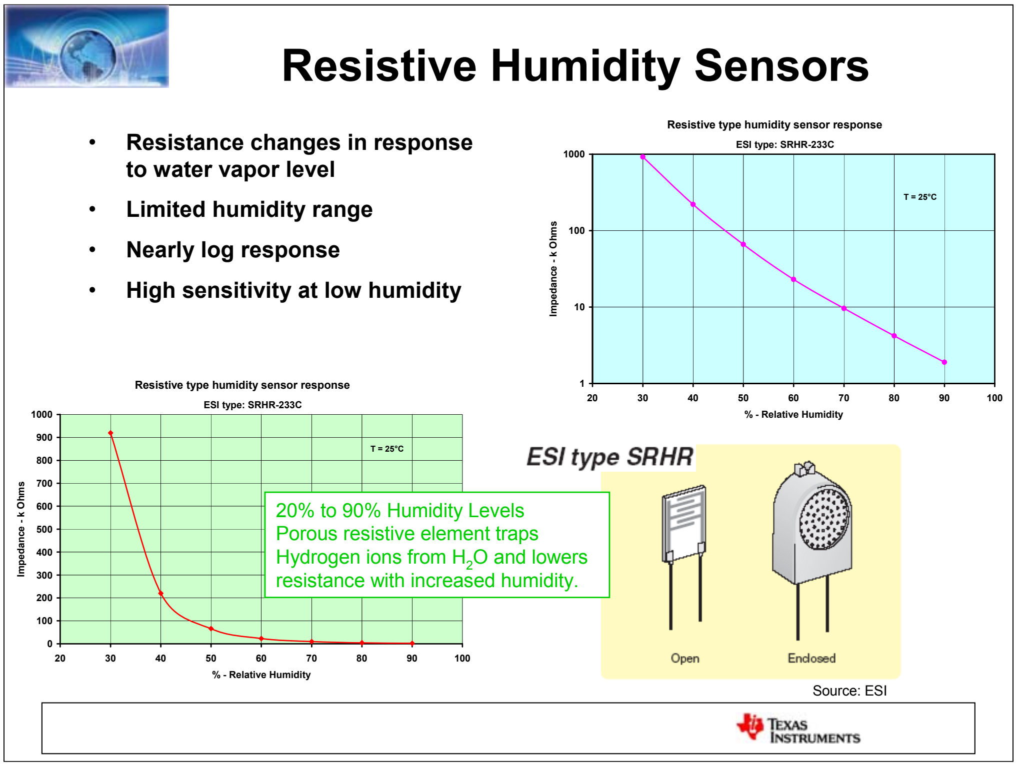
When the sensor is in the presence of water vapor it is absorbed, causing the functional ionic groups to disassociate, and resulting in increased conductivity. Response times are slow ranging from 10 to 30s for a 63% step change.

Most resistive sensors use a AC excitation to prevent sensor polarization. The resulting current is rectified and converted to DC where it can then undergo linearization and be amplified as necessary. The AC signal applied to the sensor ranges from 30Hz to 10kHz.

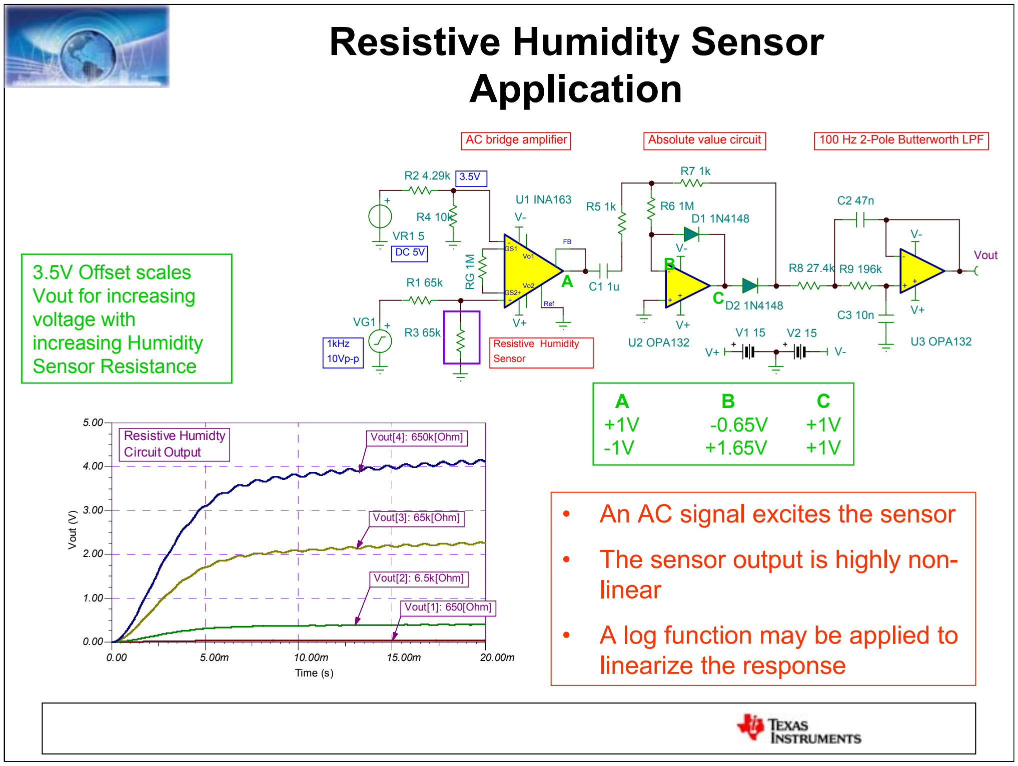
The capacitive sensor is constructed of a thin polymer or metal-oxide deposited between two conductive plates on a ceramic, glass or silicon substrate. The sensing surface is then coated with a porous metal coating to protect it from contamination and exposure to condensation. An incremental change in the dielectric constant of the sensor takes places in the presence of moisture.

A 3rd humidity sensor type is based on a 2-thermistor design. One thermistor is sealed in dry nitrogen and serves as the reference, while the other is exposed to the ambient air. The “dry” thermistor has a greater capacity to sink or release heat than the exposed “wet” thermistor. The thermistors are biased to self-heating levels. Since their ability to dissipate heat is different, the resistance of each takes on a unique value that unbalances a bridge.

(source sensormag.com/articles)



The resistive type humidity sensor has a nonlinear response for a uniform change in relative humidity. When the points are re-plotted on a logarithmic scale the response has a more linear appearance.



A 1kHz AC sine wave is used to excite the a half-bridge which includes the resistive humidity sensor. As can be seen from the graphs the output voltage is proportional to the voltage divider voltage established by the upper resistor and resistive sensor. The resistive humidity sensor is excited with an AC signal, instead of a DC voltage, to prevent sensor polarization.

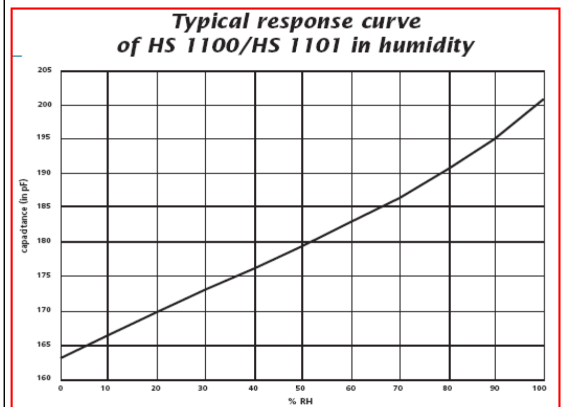
A DC pedestal voltage is applied to the inverting input by way of a voltage divider. This DC voltage is subtracted from the AC voltage by the instrumentation amplifier and a difference voltage appears at the output. The DC level assures that the difference voltage at the two inputs results in a increasing output voltage as the voltage difference increases.

The output of the AC bridge amplifier is then AC coupled, to remove the DC content, to the absolute value circuit which performs a full-wave rectifier function. The rectified voltage is then applied to the input of a 2-pole, low-pass filter. This removes most of the 1kHz ripple.

Since the humidity sensor produces a highly, non-linear resistance change with a linear change in humidity level, the output voltage is non-linear as well. Inclusion of an log amplifier could be employed to help improve the output voltage versus humidity response.

Capacitive Humidity Sensors

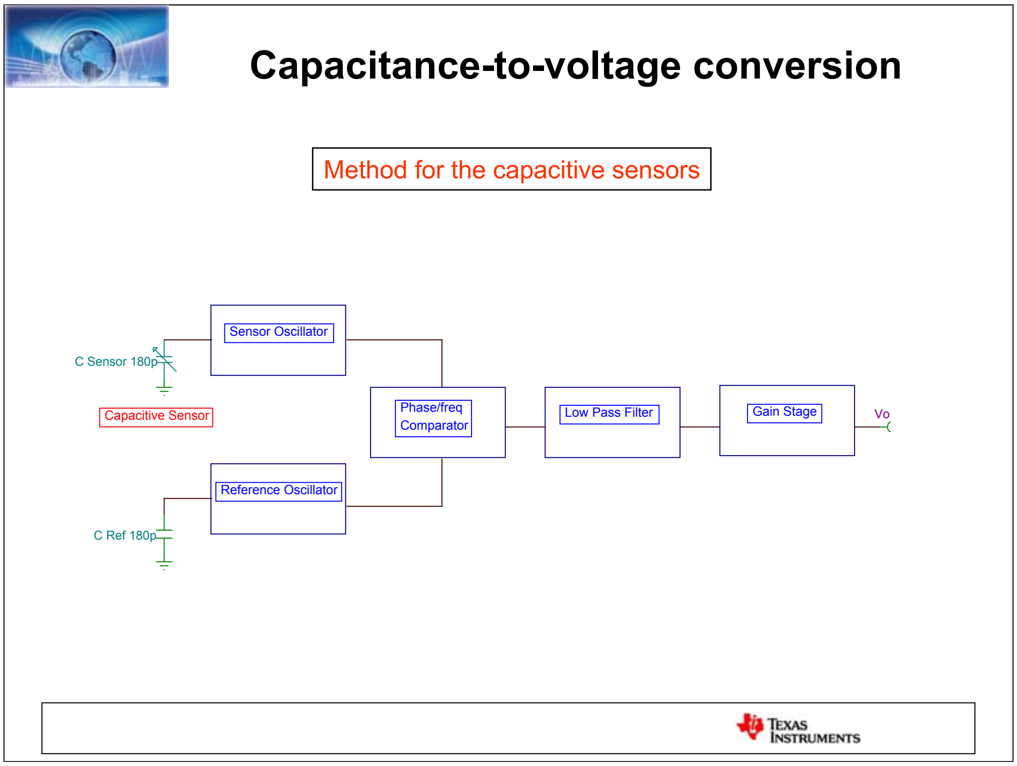
- **Useful range from 0 to 100% RH**
- 100 - 500pF bulk capacity at 50% RH, 25°C
- For example, Humirel HS1100, 180pF at 50% RH, 25°C
- Delta capacitance function
- 0.2 - 0.5pF for 1% RH change
- Low TC
- Moderate linearity
- Requires capacitance to voltage or current conversion



Source: Humirel

Texas Instruments

The capacitive humidity sensor has a more linear response than the resistive sensor. It is also usable over the entire range of 0 to 100% relative humidity, where the resistive element is limited to about 20 to 90% relative humidity.

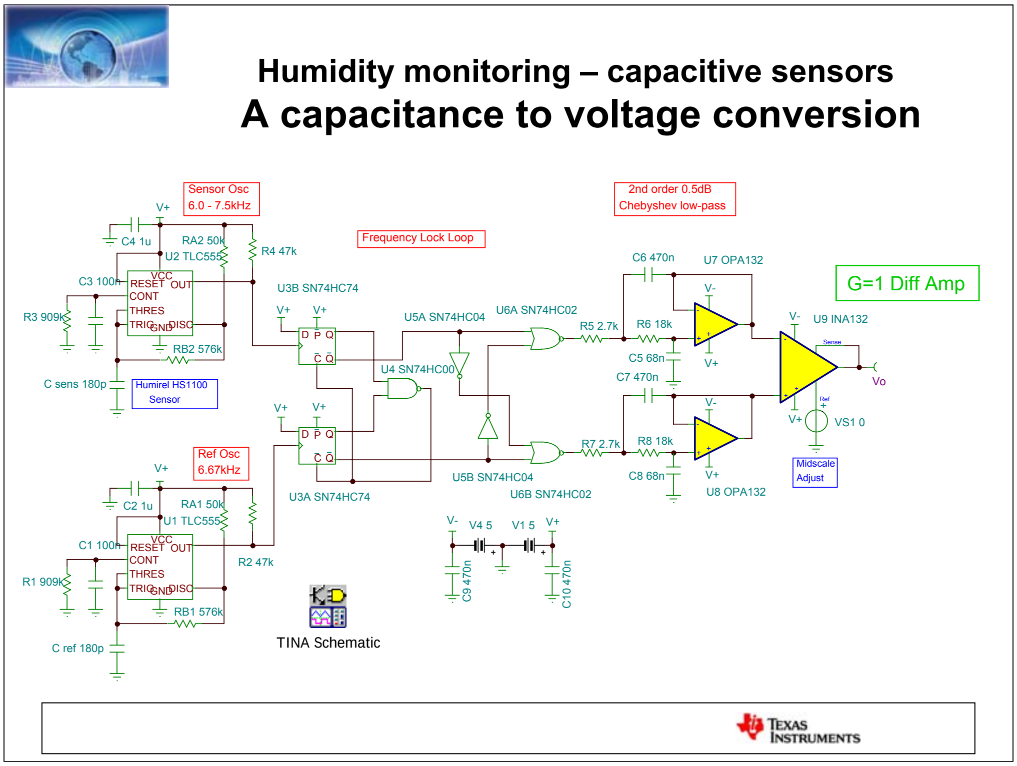


Capacitive sensors produce a capacitance change (ΔC) in response to a change in the monitored attribute. This capacitance change is often converted to a voltage which necessitates a capacitance-to-voltage (C-V) conversion.

One technique employed for the C-V conversion involves applying an oscillator frequency to the capacitive sensor. Then, any capacitance change will alter the oscillator frequency.

In the accompanying diagram, a reference oscillator with a fixed frequency, and a sensor oscillator, with a variable frequency, are shown. The output signals from the two oscillators are then compared by a phase or frequency comparator, sometimes referred to as a phase discriminator.

Depending on the design, the phase/frequency discriminator will produces a DC level or pulse-width modulated (PWM) pulse train that is a function of the phase or frequency difference of the two oscillator signals. The output is then applied to a low-pass filter or integrate the discriminator output. It may then be amplified by a gain stage as needed.

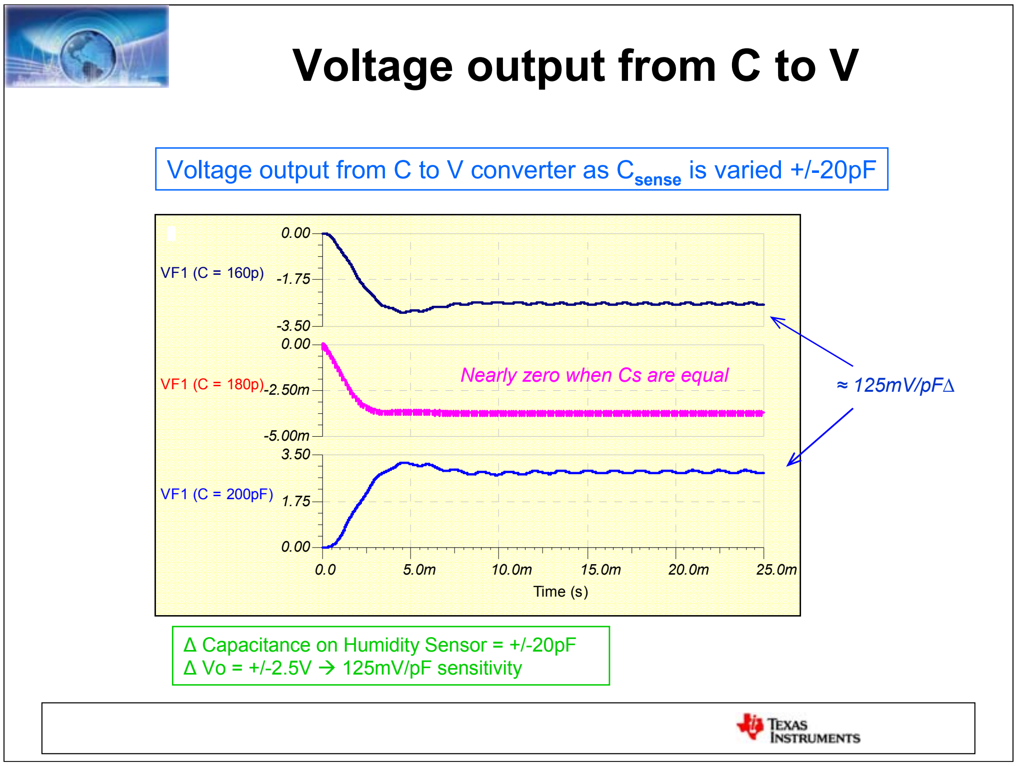


Here is an implementation of the C-V conversion just described. It uses two TLC555, bi-stable multi-vibrators as the oscillators and a frequency-lock-loop (FLL), as a frequency difference detector.

The reference oscillator has a fixed frequency of 6.7 kHz, while the sensor oscillator has a frequency that changes from 6.0 to 7.5 kHz, with a +/-20pF sensor capacitance change.

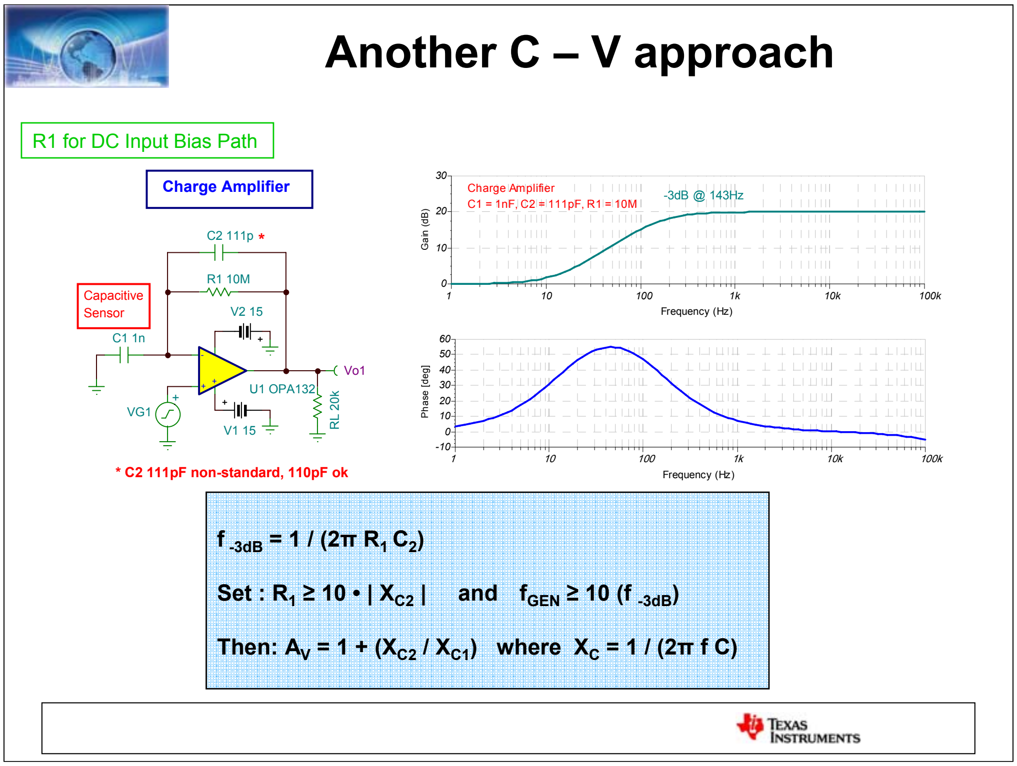
If the sensor oscillator frequency moves relative to the reference frequency, one or the other NOR gate in the FLL begins to output a series of pulses who's width increases with larger frequency differences. This is essentially a pulse-width-modulated (PWM) pulse-train. When the oscillators are operating at the same frequency, the FLL does not produce an output.

The pulse-train then passes through the second-order low-pass filter, which serves as an integrator. The integrator function produces a DC level in proportion to the pulse width. Then, the differential amplifier amplifies the differential DC level while rejecting any common responses.



This is the output response for the C-V circuit with a +/-20pF capacitance change. The center plot shows that the output voltage is nearly zero when the 2 oscillators are on the same frequency.

However, if the sensor oscillator is at either one of the frequency extremes, then the output voltage moves off zero to approximately +/- 2.5V. The circuit exhibits excellent sensitivity, about 125mV/pF.



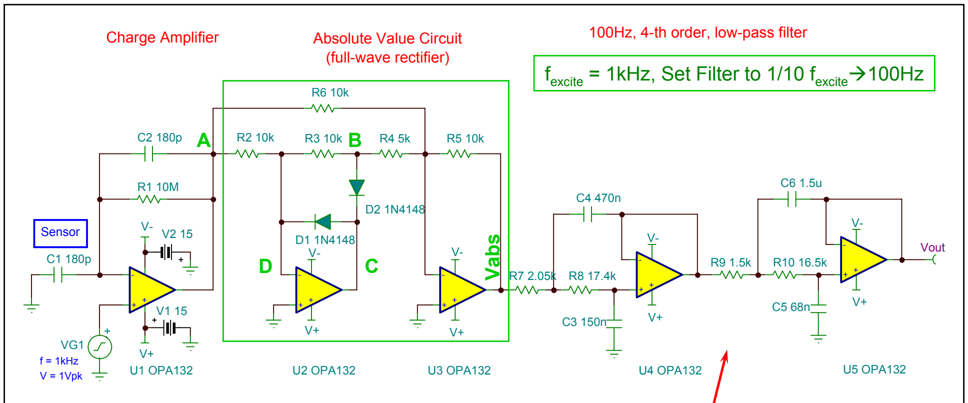
Another approach to C-V conversion is the Charge Amplifier. Here, the op-amp, closed-loop voltage gain (Av) is a ratio function of the capacitive reactances ($-jX_C$) in the feedback and inverting input circuits.

If either reactance changes, the Av of the amplifier will change as well. A carrier signal applied to the non-inverting input will be amplified, but by different gain levels depending on the reactance ratio.

This varying AC signal can then be rectified to extract a DC voltage level.

Charge amplifier implementation

with capacitive humidity sensor



A	B	C	Vabs equation	Vabs
+1V	-1V	-1.65	Vabs = -A-2B	+1V
-1V	0V	+0.65	Vabs = -A*	+1V

Op amp always in closed loop (**D**=0V)

*No current flow in D2

Filter Pro used to design filter

Texas Instruments

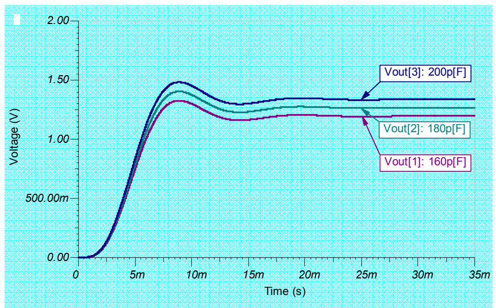
This is a complete charge-amplifier circuit useful for detection of a capacitive sensor’s capacitance change.

The charge-amplifier is followed by an absolute-value-circuit which serves as a full-wave rectifier. This converts the varying AC signal from the charge-amplifier to a DC level. However, the DC level is unfiltered at this point and contains the carrier-frequency-ripple.

The rectified DC is then passed through a 2-stage, 4-pole low pass filter to remove the ripple. This results in a DC voltage that is a function of the charge-amplifier, closed-loop gain. Texas Instrument’s Filter Pro tool was used to design this 4th order filter.

Single input charge amp circuit

Output voltage for +/-20pF capacitance change

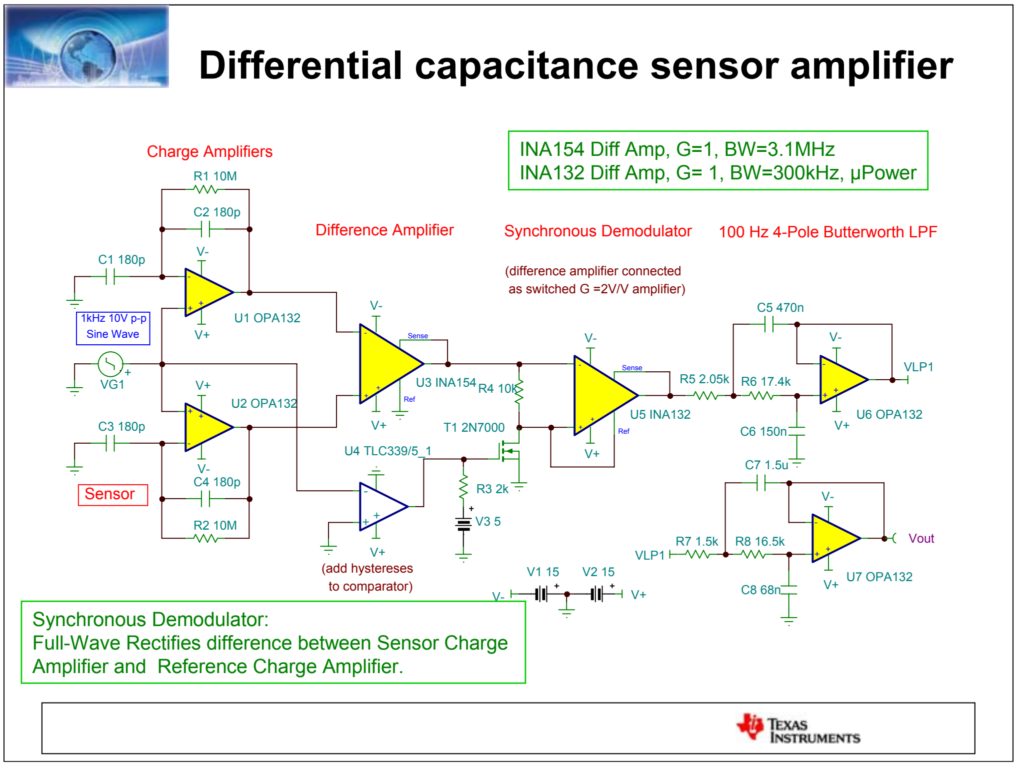


- About 140mV Vout delta for a +/-20pF change
- The DC voltage is 2x the Vin RMS value
- The nominal DC level may be an issue

Texas Instruments

The previous charge-amplifier circuit produces a stable DC level for a fixed charge amp gain. Here the input sensor capacitance is changed to 3 different values; 160, 180 and 200pF, resulting in three different charge-amplifier gains and corresponding DC levels.

The circuit is not overly sensitive and a large DC level is present. Adding gain would help exaggerate the DC change that results from the capacitance change, but the large DC level would be gained up as well. This would have to be dealt with in a subsequent stage.



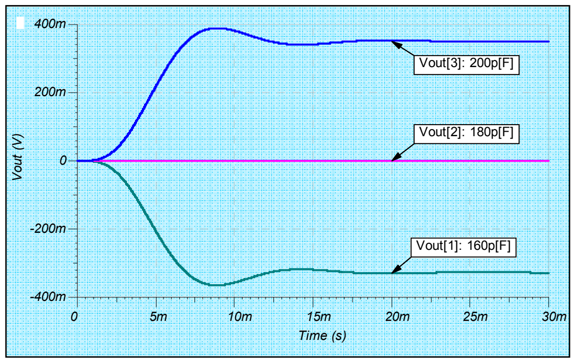
A unique differential implementation of the charge-amplifier is shown here. The output from the sensor charge-amplifier is compared to that of a reference charge-amplifier. Differential signals applied to the differential amplifier (U3) inputs are amplified, while common-mode signals are rejected. This removes the large common-mode DC voltage had with the previous, single-ended charge-amplifier circuit.

The resulting AC output is converted to a rectified DC level by a synchronous demodulator consisting of U4, T1 and U5. As with the earlier circuit, carrier ripple is present and must be filtered. The 100Hz, 4-pole, Butterworth filter accomplishes this task.

Differential Capacitance Sense Amplifier

Output

Humidity Sensor Capacitance Min = 160pF (180pF-20pF) → Vout = -350mV
Humidity Sensor Capacitance Nominal = 180pF (180pF-20pF) → Vout = 0V
Humidity Sensor Capacitance Max = 200pF (180pF+20pF) → Vout = +350mV



Texas Instruments

The output from the differential capacitance sensor amplifier is shown in the accompanying graph. The plots show that after approximately 20ms the DC level stabilizes to a final value. When the charge-amplifier capacitances are equal the circuit is balanced and the output is zero.

When the sensor capacitance is at its minimum (nominal -20pF) the output voltage is approximately -350mV. The output voltage is opposite and equal at +350mV when the sensor capacitance is at its maximum (nominal +20pF).

Power Monitoring

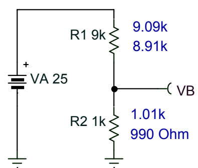
Foremost in importance is monitoring the power at the remote site. Voltage and current levels can be easily and precisely monitored with traditional analog techniques.

Power monitoring - voltage

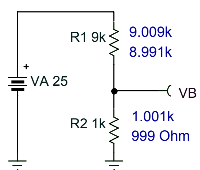
Voltage Monitoring

10:1 Resistive Dividers

1% Resistors



0.1% Resistors



10:1 with +/-1% resistors

RA (%)	RB (%)	VB (V)	error (mV)	error (%)
0	0	2.500	0	0
-1	-1	2.500	0	0
-1	1	2.455	-45	-1.8
1	-1	2.545	45	1.8
1	1	2.500	0	0

10:1 with +/-0.1% resistors

RA (%)	RB (%)	VB (V)	error (mV)	error (%)
0	0	2.5000	0	0
-0.1	-0.1	2.5000	0	0
-0.1	0.1	2.4955	-4.5	-0.18
0.1	-0.1	2.5045	4.5	0.18
0.1	0.1	2.5000	0	0

Texas Instruments

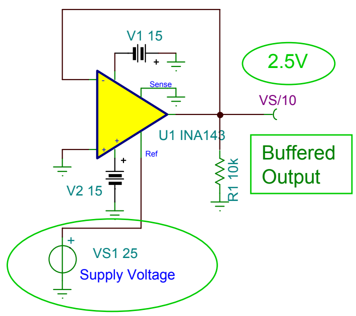
Many data acquisition systems (DAS) are capable of handling input voltages of 0 to 5V when powered with a 5V supply and a 2.5 reference voltage is employed. Often, the voltage exceeds this level and simple voltage divider can be inserted before the DAS to reduce the voltage to a level it can safely handle.

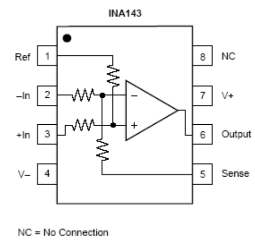
This slide provides an example where the supply voltage of 25V is divided by a factor of 10. Two dividers are shown in the example and the resistor tolerances ate +/-1% and +/-0.1%, respectively.

Depending on the direction of each resistor’s tolerance it is seen that resistors with a 1% tolerance can result in a divider error as high as +/-1.8%. Similarly, the 0.1% tolerance resistors may result in an error as high as +/-0.18%. Either may be acceptable. It just depends on the system requirements.

Voltage Monitoring

INA143 Difference Amplifier
Voltage Monitor Circuit (G = 0.1V/V)





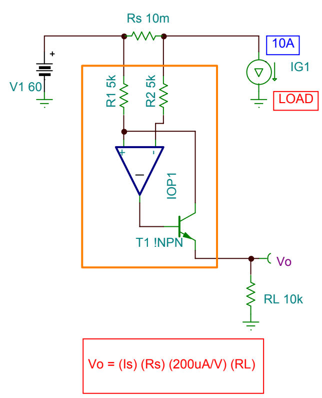
- The INA143 provides an active 10:1 voltage divider solution
- Note connections of inputs, sense and ref pins
- The internal resistors are matched better than 0.01%
- Worst-case errors total about 1.6mV for the INA143 U-grade in this application

The INA143 may be configured to provide a precise, 10:1, voltage-divider function which is useful for monitoring voltage. This is accomplished by reversing the feedback and input resistor on the inverting input and the divider resistors on the non-inverting input which results in a gain of 0.1V/V.

One might wonder why one would resort to this approach. Mostly, it comes down to the accuracy required and the cost. One-percent resistors cost about 10 cents or less, in quantity, at this time. One-tenth percent resistors cost about a half dollar to over a dollar, and 0.01% resistors cost $5 to $10 a piece. Two resistors are required for the voltage divider.

Considering the INA143 internal resistors are matched to better than 0.01%, at a cost around $1.50, it offers an accurate, buffered, cost effective solution.

High-side Measurement
Current Shunt Monitor



Current shunt monitor concept

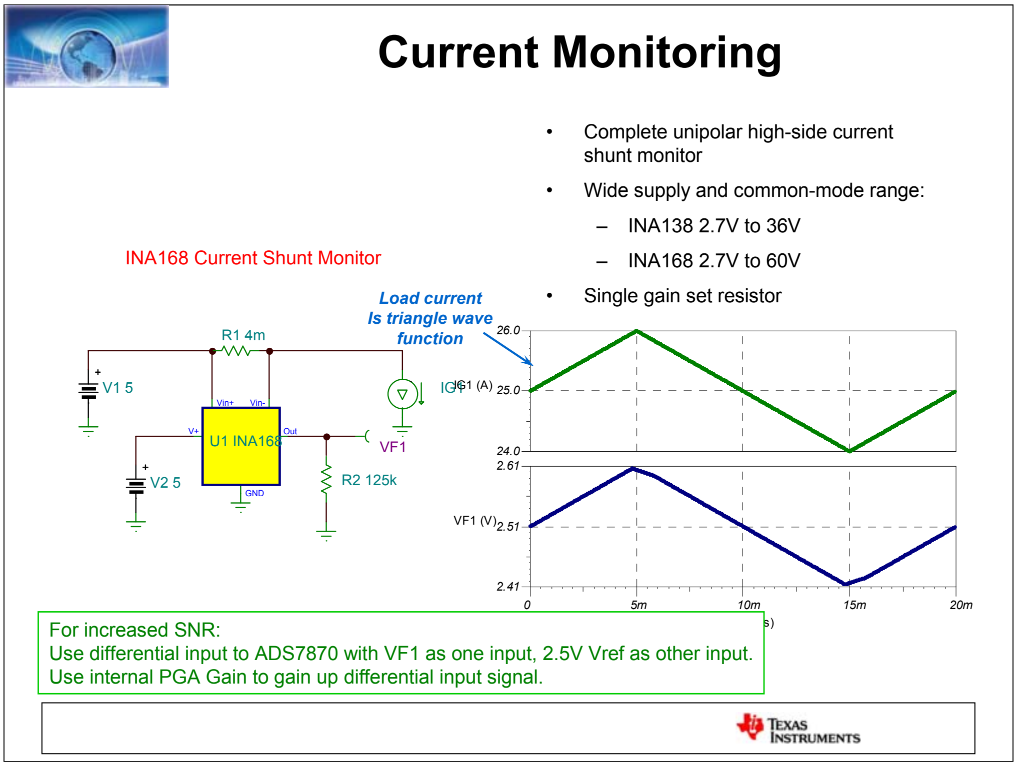
- High-side CMV capability to supply rail
- Very high common-mode rejection amplifier
- A small differential voltage is developed in response to load current
- Monitor voltage (Vo) is proportional to current

High Side Level Shift from 60V to 2.5V
Vo scaled by RL relative to Gnd

Texas Instruments

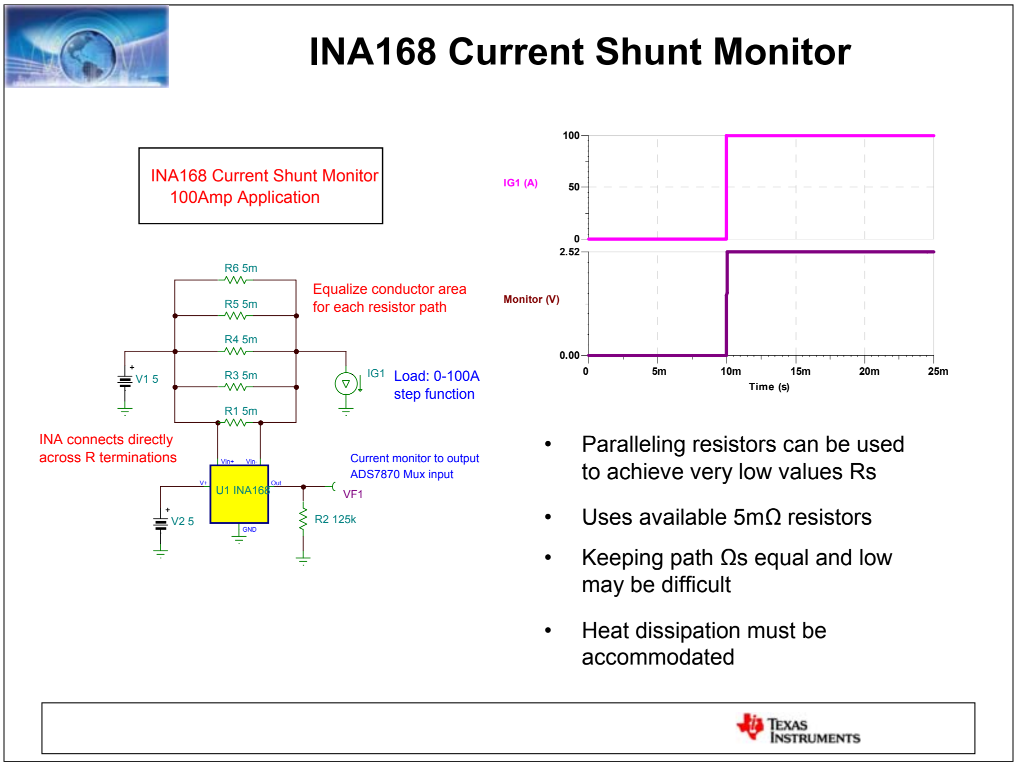
The high-side measurement, current-shunt monitor provides a convenient means to monitor a load current. In a sense, the circuit performs a function similar to a classical-ammeter. In a classical-ammeter circuit, a sensitive voltmeter, with a full-scale range of 50 to 100mV, is shunted by a very low value current-shunt resistor. The meter voltage is proportional to the current flowing through the shunt resistor.

A high CMV tolerant operational amplifier replaces the meter with the current shunt monitor IC. Current flowing though the shunt resistor produces a differential voltage that is amplified by the op-amp and scaled as needed to indicate the current magnitude.



The INA138 and INA168 are examples of high-side measurement, current-shunt monitor ICs. This TINA example shows that they can be employed not only in DC but AC applications as well.

The common-mode voltage (CMV) input range is independent of the supply voltage. This high voltage capability of the shunt monitor allows input voltages well above the supply voltage to be monitored.



When monitoring very large current levels, hundreds-of-amperes or more, it may be difficult to find suitable, high power shunt resistors. Shunt resistors with values below 5mΩ are less available than higher value resistors. One option is to split the shunt resistor up among several resistors connected in parallel. In this example the 1mΩ resistance is satisfied by 5 equal value, paralleled resistors, each with 1/5 the power rating requirements of a single resistor.

There is some risk that unequal resistor contact resistance could affect the current through each resistor path.

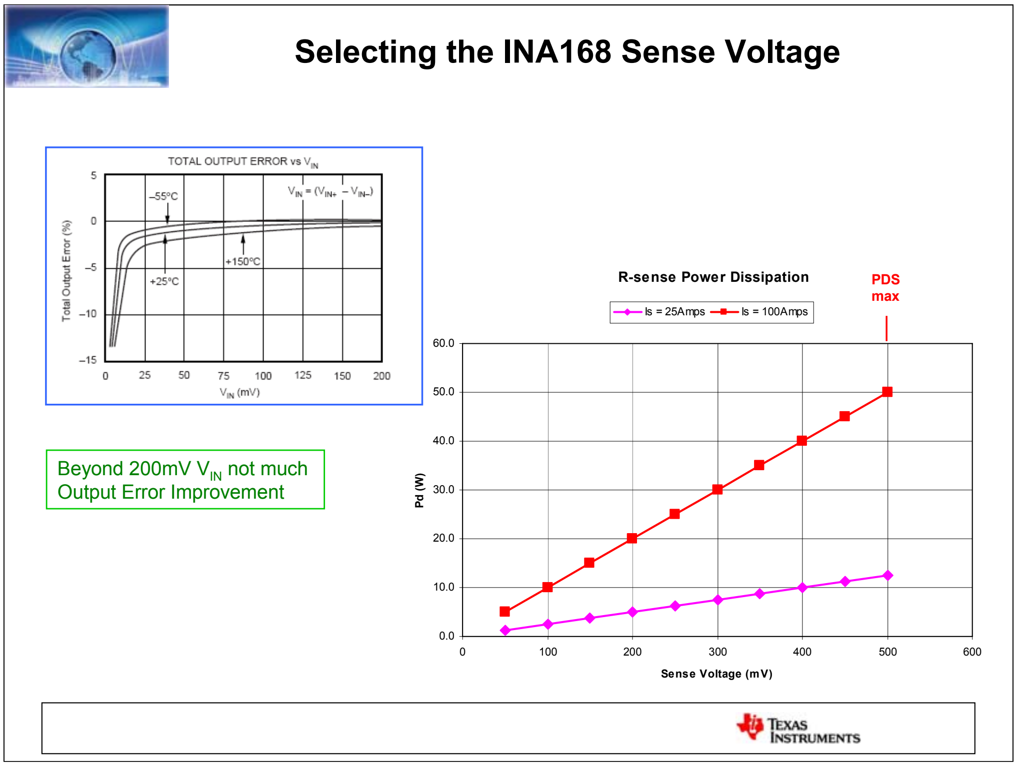
INA168 Sense Resistor Requirements

INA168 Sense Resistor Requirements							
	Sense I (A)		Vo		Sense I (A)		Vo
	25		2.5		100		2.5
Sense V mV	**Sense R Ω**	**Pd W**	**Rl k @2.5Vo**	**Sense V mV**	**Sense R Ω**	**Pd W**	**Rl k @2.5Vo**
50	0.002	1.25	250.0	50	0.0005	5.00	1000.0
100	0.004	2.50	125.0	100	0.0010	10.00	500.0
150	0.006	3.75	83.3	150	0.0015	15.00	333.3
200	0.008	5.00	62.5	200	0.0020	20.00	250.0
250	0.010	6.25	50.0	250	0.0025	25.00	200.0
300	0.012	7.50	41.7	300	0.0030	30.00	166.7
350	0.014	8.75	35.7	350	0.0035	35.00	142.9
400	0.016	10.00	31.3	400	0.0040	40.00	125.0
450	0.018	11.25	27.8	450	0.0045	45.00	111.1
500	0.020	12.50	25.0	500	0.0050	50.00	100.0

Keeping Sense Voltage between 50mV and 100mV helps minimize Pd with good accuracy.
However, High Current Levels (100A) require very small values of Sense R.

Texas Instruments

This table provides the details for the sense resistors required for specific sense voltages, at the 2 different current levels; 25A and 100A. Keeping the INA168 sense voltage to 50 or 100mV results in lower power dissipation, but also at very high current levels, results in minute resistor values may be difficult to realize.

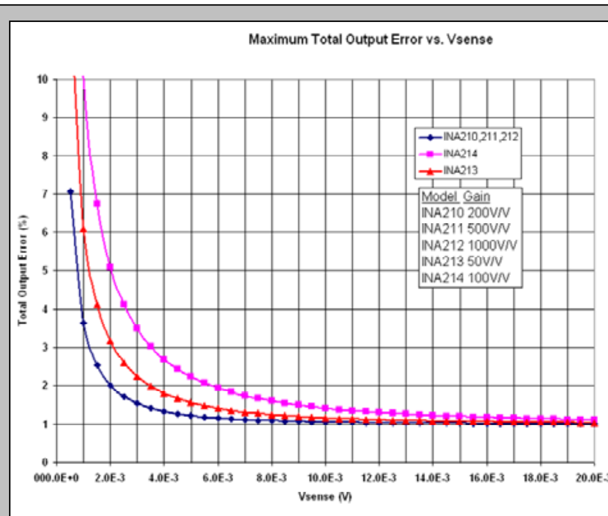


There is a tradeoff between minimizing the INA168 total output error and the sense resistor power dissipation. Increasing the sense voltage minimizes the errors (to a point), but power dissipation in the sense resistor increases. Even though the lowest output errors are attained by using a larger sense voltage, there is little reason for using a sense voltage above 200mV - even though the product has a 500mV maximum specification.

INA21x – improving current-shunt monitor performance

INA210 – INA214

- *bidirectional, zero-drift*
- *-0.3V to +26V common-mode voltage range*
- *±35uV max. voltage offset (INA210)*
- *±1% max. gain error over temperature*
- *Gains from 50V/V to 1000V/V*
- *High or low side measurement*

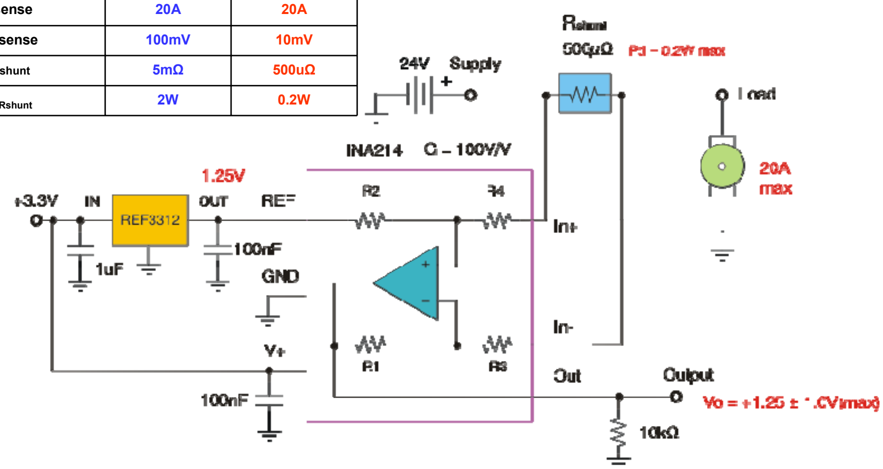


The INA21x family represents a newer generation of current-shunt monitors that feature very low input voltage-offset and noise. This allows much lowers for lower sense voltage to be used when compared to earlier current-shunt monitors.

The Maximum Total Error graphs indicate that a maximum error of about ±1.5% occurs with a sense voltage as small as ±10mV. Keep in mind that this is the maximum, and in reality most devices don’t exceed about ±0.3%. A sense voltage less than 10mV is often quite useable.

INA21x – improving current-shunt monitor performance

	INA198	INA214
Gain	100V/V	100V/V
Offset (max)	±2mV	±60uV
Isense	20A	20A
Vsense	100mV	10mV
Rshunt	5mΩ	500uΩ
P_{Rshunt}	2W	0.2W



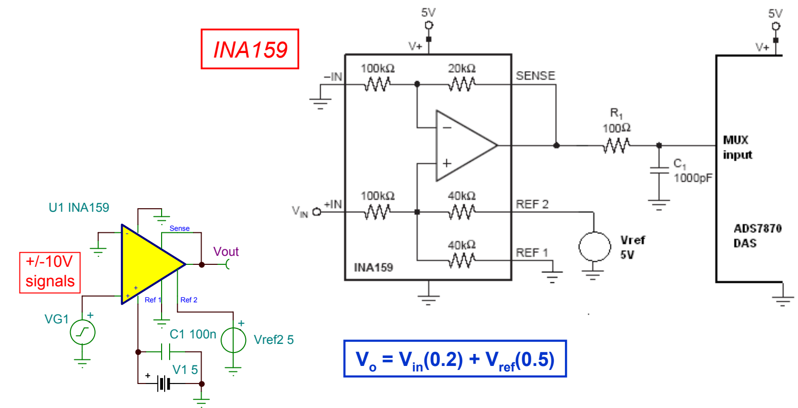
This circuit is a typical high-side current-shunt monitor application where the motor current is to be monitored. The motor in the example will have a maximum current requirement of 20 amps, but depending on speed and load conditions the current may be less than that value.

An INA214 current-shunt monitor is employed and the components have been selected for an output voltage range that extends from 0.5V to 1.5V. A table provides a comparison in the shunt resistor requirements for the more conventional INA198 current-shunt monitor and the newer INA214.

The INA214 having much lower voltage-offset is able to accurately sense much smaller differential voltages than the higher offset INA198. Because of this the shunt resistor may be much smaller in value for a given current level. The INA198 shunt resistor will dissipate 10x the power then when the INA214 is employed. Another benefit of the smaller value shunt resistor is the lesser voltage drop that is incurred. By comparison the drop is 1/10th of that had by the INA198 shunt resistor.

Note that the INA198 is not a bidirectional current-shunt monitor like the INA214. The INA214 will allow the current to be monitored should it flow in the reverse direction which can occur under some motor run conditions. The INA214 output voltage is centered about the +1.25V reference voltage. Should reverse current occur the output will move below +1.25V, towards 0V.

Interface +/-10V sensor circuit to 0 to +5V input



The output from the capacitive proximity sensor circuit can be large enough to overdrive the DAS input - especially when the dielectric permittivity is very high compared to air. When using sensor circuits that have a high unipolar or bipolar output voltage the INA159 may be the perfect interface between it and the DAS.

The INA159 has the transfer function: $V_o = V_{in}\ (0.2) + V_{ref}\ (0.5)$

Thus, the output signal will be 1/5 the input value plus a DC level equal to ½ the voltage applied to the Ref 2 input. This DC level can be conveniently set to the DAS mid-scale input voltage. If the Ref 2 voltage is set to 5V, then this DC level will be 2.5V, which works nicely with the ADS7870. It is perfect for interfacing high output, such as +/-10V ($20V_{p\text{-}p}$) sensor outputs to a 0 to 5V input range device.

The INA159 has precision gain scaling and a low voltage offset (+/-100uV).

In Summary

- *Measurement basis*
  - *measurement bridge and instrumentation amplifier*
- *Many system attributes can be monitored without excessive cost*
  - *power, temperature, humidity, air flow, etc.*
- *Understanding sensor characteristics*
  - *response over range, output voltage or current, linearity, etc.*
- *Analog interface*
  - *instrumentation amplifiers, op-amps and current shunt monitor ICs make the tasks easier*

Monitoring a system's measurement attributes can be accomplished without adding excessive circuit complexity and cost. An integrated data acquisition system (DAS) makes the collection of sensor outputs, subsequent signal conditioning and data conversion easy.

A measurement bridge, in conjunction with an op-amp or instrumentation amplifier, can provide the basis for a measurement system. The amplifier can be configured to provide the required signal conditioning such as amplification, level shifting and filtering. Since the DAS has a built in voltage controlled amplifier even further voltage gain can be applied to any channel.

The sensors may be fairly simple in design and application as demonstrated in the circuit examples. And as long as their characteristics and limitations are well understood, then they can be properly applied to the measurement task.