

APPLICATION NOTE

DID YOU KNOW ?

Samuel Hunter Christie (1784-1865) was born in London the son of James Christie, who founded Christie's Fine Art Auctioneers. Samuel studied mathematics at Trinity College and, upon graduation, taught mathematics at the Royal Military Academy for almost 50 years. Christie made many contributions to magnetic science, such as the dependence of magnetic forces on temperature and solar ray effects on terrestrial magnetism. In 1833, he published a paper on the magneto-electric conductivity of various metals, illustrating how wire conductance varies inversely with length and directly as the square of wire diameter. Embedded in this paper was the description of a circuit used to measure and compare wire conductance. Charles Wheatstone (an English physicist and inventor) recognized the value of Christie's circuit; he was the first to put this circuit, which bears his name, to extensive use and to develop many significant applications for it. To this day (162 years later), the Wheatstone bridge remains the most sensitive and accurate method for precisely measuring resistance values. Samuel Christie never got recognition for his bridge circuit. At a royalty of five cents for every bridge circuit used, imagine what Christie's original circuit invention would be worth today.

Basic Bridge Circuits

Preamble

Bridge circuits have been in use for well over 150 years. To date, the bridge is still the most economical circuit technique for accurately measuring resistance. The original bridge circuit topology has had many unique modifications and has been applied to applications such as AC measurements, automatic balancing, oscillators, and amplifiers. Perhaps the best known application for Samuel Hunter Christie's circuit is the bridge strain gage for strain type measurements in mechanical assemblies and building structures.

This application note will focus primarily on some subtleties of bridge circuit excitation and associated performance. Analysis of all the many bridge topologies that compensate for small second order effects are beyond the scope of this application note. Readers interested in the in-depth details of complex bridge topologies and strain gage applications should explore the internet, which contains thousands of sites dedicated to such details. In addition, readers are encouraged to examine Dataforth's complete line of Signal Conditioning Modules (SCMs) dedicated to strain gage bridge applications, Reference 1.

Basic Bridge Circuits

The following examples focus only on Figure 1 type bridge circuit topologies with a single resistive variable element. Output responses, including the effects of excitation line resistance for both voltage and current bridge excitation as well as bridge linearity, are examined. Errors due to resistances of poorly made contacts and corrosive action of dissimilar metals are neglected. Moreover, the output line resistances are neglected since it is standard practice to measure bridge output voltages with high impedance (typically $> 1\text{M}\Omega$) devices.

Analytical investigations throughout this document focus on the R-ohm type bridge, which means all bridge resistors are "R" ohms when not exposed to the field process variables. Figure 1 represents the R-ohm bridge type field sensor with all bridge resistors (R_1 , R_2 , R_3 , R_x) located at the point of field measurement; however, as resistor R_x is the bridge resistive sensor element, it varies with process parameters such as temperature, flow, pressure, level, humidity, strain, etc. In R-ohm bridge topologies, R_1 , R_2 , R_3 are equal to R and $R_x = (R + \Delta R)$ where ΔR is a function of process variables.

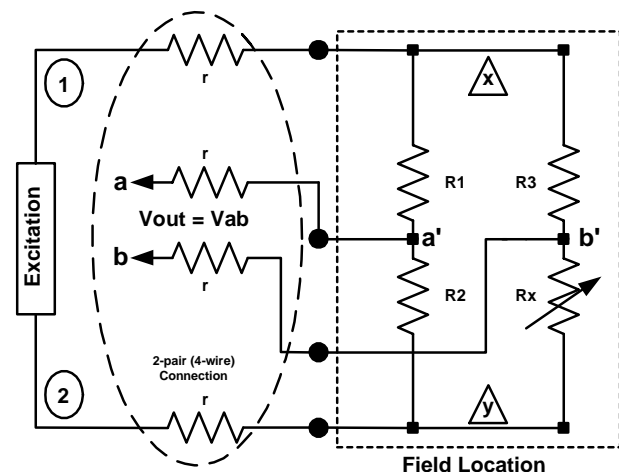


Figure 1
Basic Field Bridge Circuit with R_x Variable

Examples

Two categories of R-ohm bridge topologies will be examined. Category 1 bridges are defined as bridge topologies with all bridge resistors located in the field with one or more elements exposed to the process variable; Category 2 bridges are defined as having one or more bridge resistive sensor elements that are located in the field exposed to the process variables, with the remaining bridge resistors located at the point of electrical excitation. Bridges with one or two process variable elements are often referred to as quarter and half bridges, respectively.

Category 1 R-ohm Bridge with Voltage Excitation

This example is based on Figure 1 where the excitation source is voltage V12. The actual bridge excitation voltage, V_{xy}, is not constant because of voltage drops in the excitation line resistance. Bridge output voltage is V_{out} = (V_a-V_b) = V_{ab}. If V_{ab} is always measured with a high impedance (typically > 1MΩ) device, then sense line resistances can be neglected and V_{ab} = V_{a'b'}. As an example of the effects of sense line resistances, assume line resistance of 10Ω, voltmeter with 1MΩ input impedance, and a 120Ω bridge. The voltmeter loading on terminals a'-b' is approximately 0.99988, whereas the loading on terminals a-b is approximately 0.99987 or a difference of -0.001%.

Equation 1 illustrates the output voltage, V_{out} = V_{ab}, of Figure 1, neglecting all line resistances.

$$V_{ab} = V_{12} * \left[\frac{R_2}{R_2 + R_1} - \frac{R_x}{R_x + R_3} \right] = \frac{(R_2 * R_3) - (R_1 * R_x)}{(R_1 + R_2) * (R_3 + R_x)} \quad \text{Eqn. 1}$$

Equation 1 illustrates the classic bridge balance equation, which defines a set of resistor values that balances the bridge, resulting in zero bridge output voltage, V_{ab} = 0. This condition occurs when R₁*R_x = R₂*R₃. **Note:** The classic bridge balance condition is valid independent of line resistance and voltage excitation value. Clearly, this makes the bridge a useful circuit topology for balance measuring applications.

Christie's 1833 paper showed that if R_x is an unknown and R₂ = R₁, then the bridge output will be zero (it was easy to measure zero in 1833) when R₃ is adjusted to be equal to the unknown resistance, R_x. Many industrial transducers use bridge circuits with one or more bridge resistances that are functions of process variables such as temperature, flow, pressure, strain, humidity, etc. In these situations, bridge topology based transducers can not be conveniently (or economically) balanced at the field location; therefore, non-zero output bridge voltages are measured. Unlike balance measurements, bridge excitation and line resistances will contribute to measurement errors.

Industrial transducers with bridge circuit topologies have resistor sets that balance the bridge at a steady state value determined by a specific steady state field parametric input. As these steady state parameters change, the bridge becomes unbalanced and the output is non-zero. Measuring this unbalanced voltage with an appropriate scale factor applied is a direct indication of the change in field variable. The useful range of these voltages falls in the microvolt to millivolt category; consequently, low voltage measurement techniques must be utilized.

Equation 2 is the voltage output of R-ohm bridge circuit topologies shown in Figure 1, with voltage excitation including excitation line resistances.

$$V_{out} = \frac{V_{12}}{2} * \left(\frac{R - R_x}{(R + R_x) + \frac{r}{R} * (3R + R_x)} \right) \quad \text{Eqn. 2}$$

If excitation line resistances are negligible, this equation reduces to:

$$V_{out} = \frac{V_{12}}{2} * \left(\frac{R - R_x}{R + R_x} \right) \quad \text{line resistances } r = 0 \quad \text{Eqn. 2a}$$

Figure 2 depicts the output response of the 120Ω bridge topology shown in Figure 1 to changes in R_x. In this simulation, the excitation is 5VDC, R_x ranges from 20Ω to 220Ω, and three different excitation line resistances – zero, 5Ω, and 20Ω – are used. Output line resistance is neglected, which is a valid technique, as previously shown.

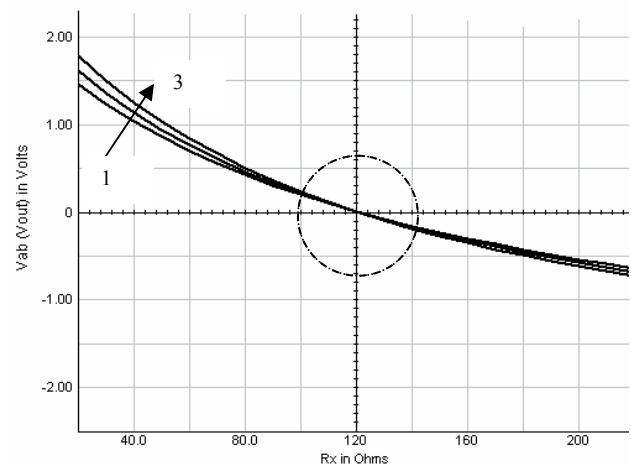


Figure 2
Output of the 120Ω Bridge in Figure 1
Excitation V12 = 5VDC with 20 Ω < R < 220 Ω
Output Voltage Line Resistance Neglected
 ▪ Bottom Curve 1: Line Resistance zero ohms
 ▪ Middle Curve 2: Line Resistance 5 ohms
 ▪ Top Curve 3: Line Resistance 10 ohms

Figure 2 and Equation 2 reveal some important facts about Category 1 bridges.

1. Bridge output is sensitive to excitation line resistance and will always be sensitive to excitation voltage, V12.
2. The bridge output voltage is nonlinear for nominal changes in Rx regardless of excitation line resistance and excitation voltage.
3. As range of Rx decreases, the bridge output voltage begins to approach zero and appears to become more linear. See circle in Figure 2.

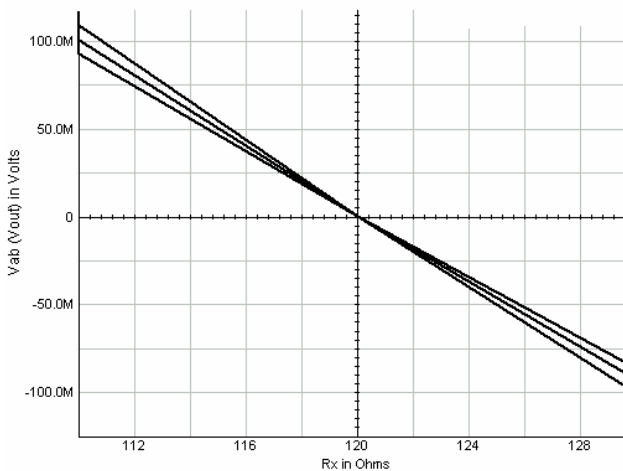


Figure 2a
Enlargement of Area Circled in Figure 2

Figure 2a shows that the bridge output voltage still appears to be linear for very small variations of Rx and remains sensitive to excitation line resistance.

A question arises here. Is the voltage output of the bridge topology in Figure 1 ever linear? To answer this, Equation 3 is the partial derivative of the R-ohm bridge Vout in Equation 2a with respect to Rx (change in Vout for a change in Rx) with all other variables assumed constant and no excitation line resistance.

$$\frac{\text{Change in Vout}}{\text{Change in Rx}} = V12 * \left[\frac{-R}{(R+Rx)^2} \right] \quad \text{Eqn. 3}$$

It is clear that Equation 3 is a nonlinear function and is not constant, which is the condition necessary for Vout to be a linear function of Rx. Thus, Figure 1 type bridge circuits cannot have outputs that are linear functions of Rx. See Figure 3.

For the range of Rx between 110 and 130 ohms, changes in Vout with changes in Rx (Equation 3 and Figure 3)

range between -11.3 and -9.6mV per ohm with an average value of -10.5mV per ohm at balance.

Although these numbers are interesting, it is not practical to use partial derivatives in calculating bridge outputs. Common practice is to recognize that bridge circuits have nonlinear outputs, which are influenced by excitation line resistance, and to accept manufacturers' specified transfer function data and installation instructions for their bridge sensors.

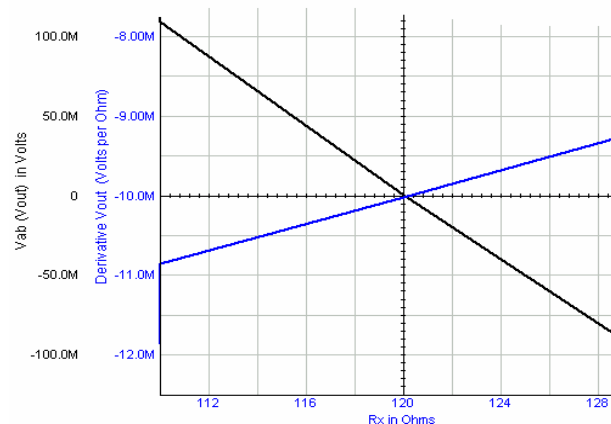


Figure 3
Output of the 120Ω Bridge in Figure 1
Black Curve: 120Ω Bridge Output Voltage
Blue Curve: Derivative of Bridge Output vs. Rx

- Excitation 5VDC with No Line Resistance
- Output Voltage Line Resistance Neglected
- 110Ω < Rx < 130Ω
- Reference Figures 1, 2, 2a, and Eqn. 3

Category 1 R-ohm Bridge with Current Excitation

For well over a century, bridge topologies with voltage excitation have been used. Today, with modern semiconductor circuit technology, current source excitation is also an option. Equation 4 represents the output of a current, Iexc, excited R-ohm bridge (Figure 1) with output voltage line resistance neglected and no excitation line resistance.

$$Vout = (Iexc * R) * \left(\frac{R-Rx}{3*R+Rx} \right) \quad \text{all line r's} = 0 \quad \text{Eqn. 4}$$

Equation 4 becomes Equation 4a when the current excitation is adjusted to be Iexc = (V12 / R).

$$Vout = (V12) * \left(\frac{R-Rx}{3*R+Rx} \right) \quad V12 = R * Iexc \quad \text{Eqn. 4a}$$

Note the similarity between Equations 2a and 4a.

Equation 5 is the partial derivative of the R-ohm bridge Vout in Equation 4a with respect to Rx (change in Vout

for a change in R_x) with all other variables assumed constant.

$$\frac{\text{Change in } V_{out}}{\text{Change in } R_x} = -(V_{12}) * \left[\frac{4 * R}{(3 * R + R_x)^2} \right] \quad \text{Eqn. 5}$$

Where $V_{12} = R * I_{exc}$

Figures 4 and 5 provide a visual comparison of the output voltages for the Category 1 R-ohm bridge with both voltage and current excitation.

Figure 4 illustrates the performance of a 120Ω bridge circuit as shown in Figure 1 with current source excitation at terminals 1 and 2 where line resistances are zero. The value of this current source was selected to be 41.667mA, which is 5VDC / 120Ω. This value of current provides 5VDC excitation at the bridge terminals when R_x is 120Ω, the condition of no field parametric inputs.

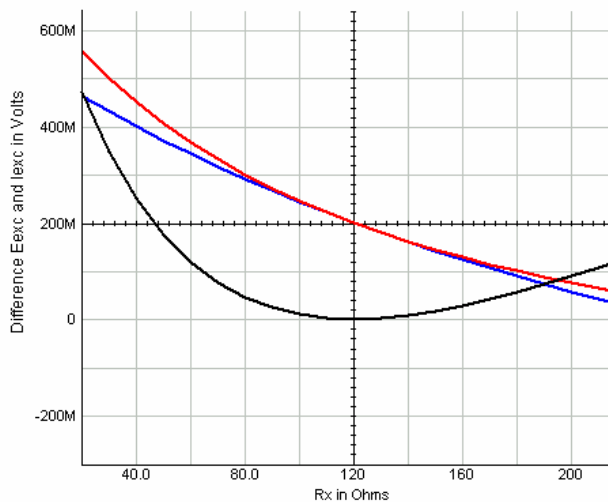


Figure 4

Output of the 120Ω Bridge in Figure 1

Red Curve: 5VDC Excitation, Eqn. 2a

Blue Curve: 41.67mA (5V / 120Ω) Excitation, Eqn. 4a

Black Curve: Difference [Vout (Eexc) - Vout (Iexc)]

- All line resistances neglected
- Y-axis not shown for Red and Blue curves

Figure 5 shows that the output behavior for the 120Ω bridge topology shown in Figure 1, with current excitation including different line resistances of zero, 5, and 10 ohms, is independent of excitation line resistances. In this case, the change in V_{out} for a change in R_x varies from -10 to -10.8mV per ohm with an average of -10.4mV per ohm, which is approximately the same as for voltage excitation but clearly still not constant.

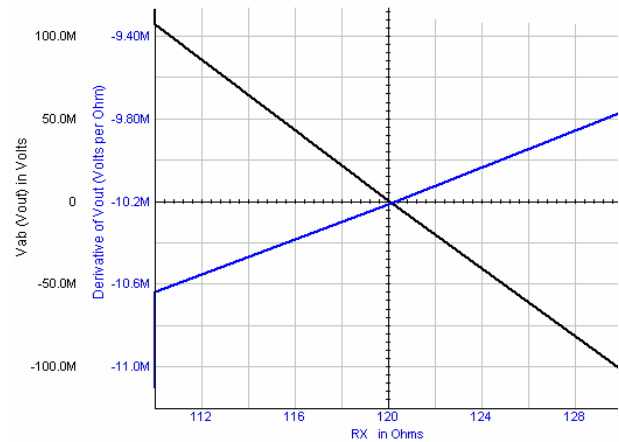


Figure 5

Output of the 120Ω Bridge in Figure 1

Black Curve: 120Ω Bridge Output Voltage

Blue Curve: Derivative of Bridge Output vs. R_x

- Current Excitation, 41.67mA (5V / 120Ω)
- Excitation Line Resistances of 0, 5, and 10Ω
- Output Voltage Line Resistance Neglected
- 110Ω < R_x < 130Ω
- Reference Figures 1, 2, 2a, and Eqn. 5

Comparison of Category 1 R-ohm Bridge Excitations

The list of observations below are based on the 120Ω bridge topology of Figure 1 with either 5VDC voltage excitation or 41.67mA current excitation, with excitation line resistances of zero, 5, and 10 ohms included and output voltage line resistance neglected.

1. Equations 4, 4a, and Figure 5 (Black Curve) show that *for current excitation the output of the R-ohm bridge topology shown in Figure 1 is independent of excitation line resistance.*
2. Figure 4 shows that when line resistance is neglected the R-ohm 4-wire bridge output **is** more linear over a large range of R_x for current excitation (**blue curve**) than for voltage excitation (**red curve**).
3. Equation 6 and Figure 4 (**black curve**) show that the bridge outputs as illustrated by voltage excitation (Equation 2a) and current excitation (Equation 4a) are essentially identical near balance. Near balance, one can assume that $R \gg \Delta R$. Note that $R_x = (R + \Delta R)$ and I_{exc} is defined as V_{12} / R .

$$V_{out} \sim -\frac{V_{12}}{4} * \left(\frac{\Delta R}{R} \right) \quad \text{Eqn. 6}$$

Interesting note: In Figure 1 type strain gage applications where changes in R_1 , R_x are positive equal and changes in R_2 , R_3 are negative equal, Equation 6 becomes

$$V_{out} \sim -V_{12} * \left(\frac{\Delta R}{R} \right) \quad \text{Eqn. 6a}$$

Choosing Excitation

Excitation line resistances have different effects on bridge output voltages depending upon which bridge category (Category 1 or 2) and which excitation (current or voltage) are used. Figures 6 and 7 illustrate the output behavior of Category 2 R-ohm bridges with a single bridge resistor located in the field connected to the remainder of the bridge with two and three wires, respectively.

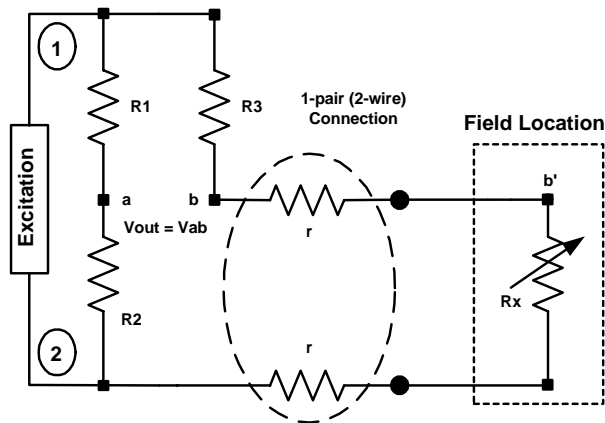


Figure 6
Two-Wire Quarter Bridge

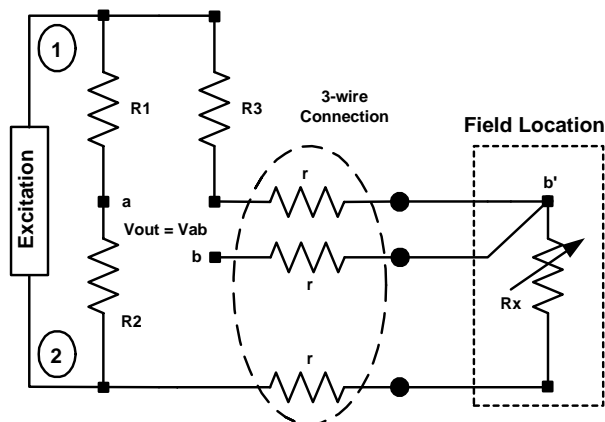


Figure 7
Three-Wire Quarter Bridge

Review

In the following Figure 1 bridge output voltage expressions, $R_1 = R_2 = R_3 = R$ and $R_x = (R + \Delta R)$. Voltage excitation is V_{12} and current excitation is I_{exc} flowing into terminal 1. For convenience, behavioral

equations for the bridge shown in Figure 1 are revisited here. Recall that voltage output line resistances are neglected in Figure 1 and that $R_x = (R + \Delta R)$.

Figure 1 Equations (4-Wire Category 1)

Voltage excitation V_{12} :

$$V_{out} = \frac{V_{12}}{2} * \left(\frac{-\Delta R}{(2R + \Delta R) + r * \left(4 + \frac{\Delta R}{R} \right)} \right)$$

Current Excitation, with $I_{exc} = V_{12} / R$:

$$V_{out} = \left(\frac{V_{12}}{2} \right) * \left(\frac{-\Delta R}{2R + \frac{\Delta R}{2}} \right) \quad \text{Let } V_{12} = R * I_{exc}$$

Figure 6 Equations (2-wire Category 2)

Voltage excitation V_{12} :

$$V_{out} = \frac{V_{12}}{2} * \left(\frac{-\Delta R - 2r}{2R + \Delta R + 2r} \right)$$

Current Excitation, with $I_{exc} = V_{12} / R$:

$$V_{out} = (V_{12}) * \left(\frac{-\Delta R - 2r}{4R + \Delta R + 2r} \right) \quad \text{Let } V_{12} = I_{exc} * R$$

Figure 7 Equations (3-wire Category 2)

Voltage excitation V_{12} :

$$V_{out} = \frac{V_{12}}{2} * \left(\frac{-\Delta R - r}{2R + \Delta R + 2r} \right)$$

Current Excitation, with $I_{exc} = V_{12} / R$:

$$V_{out} = (V_{12}) * \left(\frac{-\Delta R - r}{4R + \Delta R + 2r} \right) \quad \text{Let } V_{12} = I_{exc} * R$$

Conclusions

The following observations are made based on Figure 6 and Figure 7 topologies:

1. Bridge voltage outputs are nonlinear regardless of whether current or voltage excitation is used.

2. Category 1 bridge topologies have output voltages that are independent of line resistances when current excitation is used.
3. Category 2 bridge topologies have output voltages that are always dependent on line resistances regardless of whether current or voltage excitation is used.
4. If $(r \ll \Delta R \ll R)$, i.e., if line resistances can always be neglected and if changes in the sense resistor R_x are very small compared to R , then bridge output is the same for voltage or current excitation.

$$V_{out} = V_{12} * \left(\frac{-\Delta R}{4R} \right) \text{ Voltage Excitation, or}$$

$$V_{out} = I_{exc} * \left(\frac{-\Delta R}{4R} \right) \text{ Current Excitation} = (V_{12} / R)$$

Output responses for R-bridge circuits containing more than one variable resistive element, with equal but opposite changes to process variables, are common in strain gage bridge circuits. These circuits are discussed in Dataforth's application note on strain gages.

Figure 8 is a block diagram of Dataforth's Bridge Signal Conditioning Module Series SCM5B38. These modules are designed to interface with Category 1 full bridge circuits with options for Category 2 half and quarter bridge topologies. This module's predominant application is in industrial strain gage instrumentation applications; however, it is well-suited for any bridge type instrumentation application.

Dataforth's bridge SCMs SCM5B38 and DSCA38 have multiple (typically 5-7) pole filters with anti-alias filtering on the field side. Moreover, these modules have 4-way isolation, which includes precision isolated voltage for field excitation, isolated field-side power, isolated computer-side power, and signal isolation. Dataforth's DIN rail DSCA38 series of modules has both narrow and wideband filter options to accommodate a wide range of applications. In addition, the DSCA38 series has +/-5% front-panel adjustments for zero and span. Zero adjustments are particularly useful for balancing bridge circuits. The reader is encouraged to visit Dataforth's website, Reference 1, and examine all the options for the SCM5B38 and DSCA38 bridge modules, as well as Dataforth's complete line of SCMs.

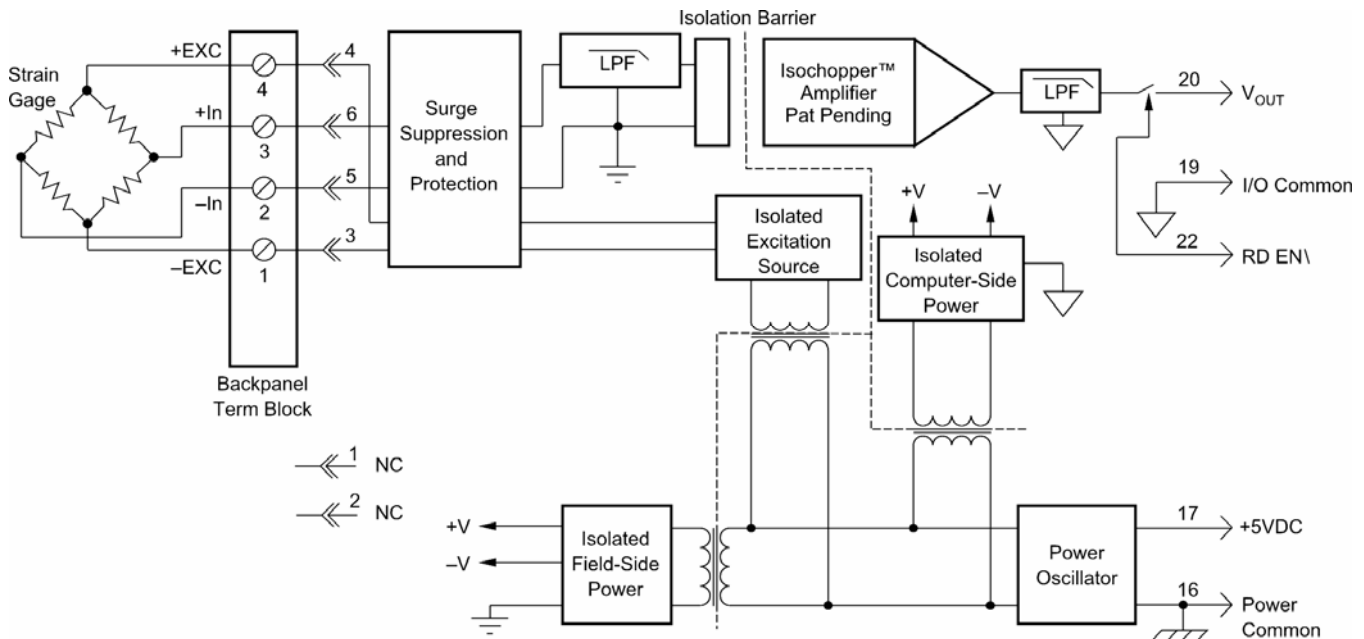


Figure 8
Dataforth SCM5B38 Strain Gage Signal Conditioning Bridge Module

Dataforth References

1. Dataforth Corp., <http://www.dataforth.com>