Variable Resistance Sensors Work Better with Constant Current Excitation

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Constant voltage power supplies were all we had for most of the history of our art. That's no longer so, and there are practical advantages in a constant current drive.

RESISTANCE VARIATIONS caused by selected physical effects are the basis of many successful sensors. Sensitive, stable, and robust, variable resistance sensors are, however, passive devices that require a source of electrical energy to develop an output signal indicative of the sensed variable. Traditionally, this source has been a constant voltage power supply.

The more direct and fundamental approach to deriving an electrical signal proportional to a resistance is to use the linear relationship between voltage and resistance established by Ohm's Law, $E = IR$. If voltage is to have a direct relationship to resistance, the resistance must be excited by a constant current.

Figure 1 schematically illustrates one form of constant current power supply. The output current flows through a sensing resistor, R_s, and is controlled by a differential input regulator, which acts to maintain zero potential between its inputs. The output current for a properly designed supply can be expressed as

$$I = \frac{E_{Ref}}{R_s} \quad (1)$$

with negligible error.

Figure 2 illustrates the most basic application to a sensor. When I is a fixed and stable current, the output signal is a simple, direct function of the

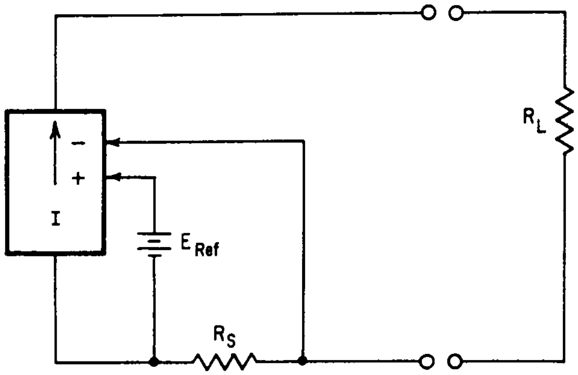


Figure 1. A practical constant current source usually incorporates some form of amplifier.

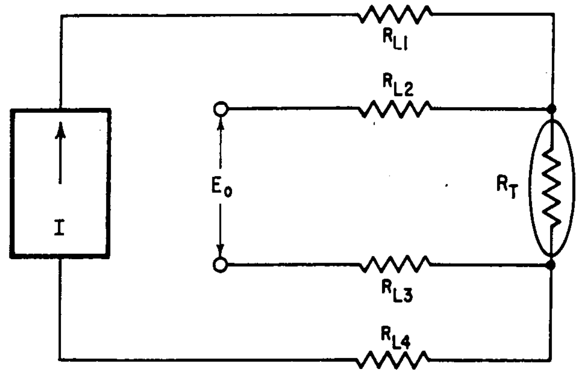


Figure 2. Basic constant current excitation — current sensing omitted for simplicity.

sensor resistance, independent of line resistances. For sensors whose total resistance is a function of the quantity to be measured, this is a very useful technique. An example is the measurement of temperature with a platinum resistance temperature sensor whose resistance is a function of absolute temperature, $R_T = f(T)$, and the output signal is

$$E_o = I\,f(T) \qquad (2)$$

There are many variable resistance devices whose resistance variations are small compared to the total sensor resistance. The prime example of this type is the strain gage, whose resistance can be expressed as $R_{T0} \pm \Delta R_T$. In addition, the resistance variation is generally a function of more than one quantity and can be expressed as $\Delta R_{T1} \pm \Delta R_{T2}$, where ΔR_{T1} is the resistance variation due to the quantity to be measured (primary input) and ΔR_{T2} is the resistance variation due to other quantities in the sensor's environment (secondary inputs).

The excitation current itself is never perfectly fixed and stable. In practical applications it is the combination of a theoretically perfect steady state current with error currents due to regulation, temperature instability, drift, and noise. When the excitation current is expressed as $I \pm \Delta I$, where ΔI represents the total error current, and the sensor resistance is expressed as $R_{T0} \pm \Delta R_{T1} \pm \Delta R_{T2}$ the Ohm's Law equation becomes

$$E_o = \pm I\,\Delta R_{T1} + [I\,(R_{T0} \pm \Delta R_{T2}) \pm \Delta I\,(R_{T0} + \Delta R_{T1} \pm \Delta R_{T2})] \qquad (3)$$

The term in brackets represents an undesired or error signal, and it shows that the ratio of desired signal to error signal is extremely poor when the primary resistance variation is small compared to the total resistance.

When the primary input is dynamic, the addition of a simple, high pass filter results in considerable improvement in the desired signal to error signal ratio (Ref. 1), by eliminating the most significant error component in Equation 3, the dc component $I\,R_{T0}$. The secondary input quantity which results in significant resistance variation is usually temperature, which generally varies slowly with time. The excitation error currents due to line regulation and instability are also essentially static in nature. When the filter pass band is selected to pass the frequencies at which ΔR_{T1} is varying and to discriminate against low frequency signals due to secondary inputs and excitation current drift, Equation 3 can be reduced to

$$E_o = I\,\Delta R_{T1} \pm i_n(R_{T0} \pm \Delta R_{T1} \pm \Delta R_{T2}) \qquad (4)$$

with negligible error. The term i_n represents the noise component of excitation current, and it must be extremely small if acceptable signal to noise ratios are to be realized. For example: If the sensor is a wire strain gage, $\Delta R_{T1}/R_{T0}$ is approximately 0.1 percent at full scale strain, which means that i_n/I_{in} must be 0.0001 percent for a full scale signal to noise ratio of 1,000.

Multiple current sources

When the primary input quantity is static, or slowly varying with time, techniques other than high pass filtering must be used to eliminate the low frequency error components. The use of multiple current sources is one method for doing this. Figure 3 illustrates a dual source signal conditioning system employing an active and a dummy sensor. The system output is

$$E_o = I_1 R_T - I_2 R_D \qquad (5)$$

When $I_1 = I_2 = I$, $R_T = R_{T0} + \Delta R_{T1} + \Delta R_{T2}$, and R_D is truly a dummy gage so that $R_D = R_{T0} + \Delta R_{T2}$, Equation 5 becomes

$$E_o = I\,\Delta R_{T1} \qquad (6)$$

At first glance, the conditions necessary for the output of a dual source system to be a direct function of the primary transducer resistance variation seem simple and straightforward. But in practice they are difficult to achieve and place stringent requirements

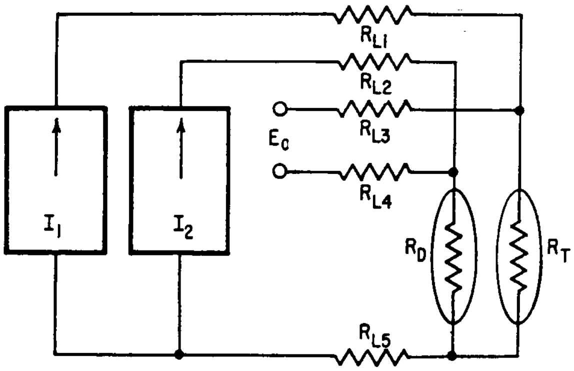


Figure 3. Two sources cancel some secondary input errors.

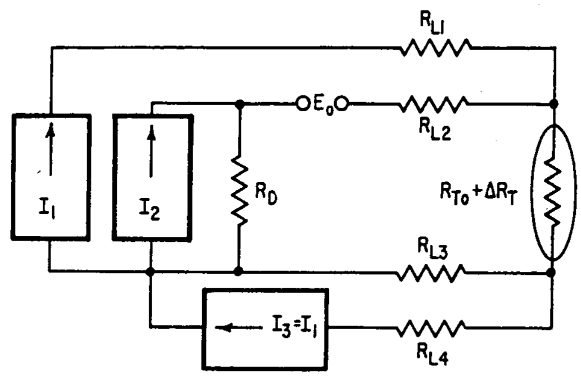


Figure 4. Three sources reduce effects of line resistance.

on the current sources and the dummy sensor. The effects of error currents and matching can be analyzed by substituting $I_1 = I_{10} + \Delta I_1$, $R_T = R_{T0} + \Delta R_{T1} + \Delta R_{T2}$, $I_2 = I_{20} + \Delta I_2$, and $R_D = R_{D0} + \Delta R_D$ into Equation 5. Then

$$E_o = I_{10}\,\Delta R_{T1} + I_{10}\,\Delta R_{T2} + \Delta I_1\,\Delta R_{T1} + \Delta I_1\,\Delta R_{T2} + I_{10}R_{T0} + \Delta I_1 R_{T0} - I_{20}R_{D0} - I_{20}\Delta R_D - \Delta I_2 R_{D0} - \Delta I_2 \Delta R_D. \quad (7)$$

For a system output of zero when all inputs (and all Δ's) are zero,

$$I_{20} = I_{10}R_{T0}/R_{D0} \quad (8)$$

Substituting Equation 8 into Equation 7 results in

$$E_o = (\Delta R_{T1} + \Delta R_{T2})(I_{10} + \Delta I_1) - \Delta R_D(\Delta I_2 + I_{10}R_{T0}/R_{D0}) + \Delta I_1 R_{T0} - \Delta I_2 R_{D0} \quad (9)$$

If R_D is perfectly matched to R_T and is subjected to exactly the same secondary inputs as R_T, then $R_{D0} = R_{T0}$, $\Delta R_D = \Delta R_{T2}$, and Equation 9 simplifies to

$$E_o = I_{10}\,\Delta R_{T1} + [\Delta I_1\,\Delta R_{T1} + (R_{T0} + \Delta R_{T2})(\Delta I_1 - \Delta I_2)]. \quad (10)$$

The terms inside the brackets of Equation 10 are error terms. The first term is a primary sensitivity error due to the absolute error currents, and the second term is an apparent output due to differential error currents. Unfortunately the error currents do not cancel as the steady state currents because, in general, there is no definite relationship between them. Instead, they add and subtract in a random fashion. If it is assumed that the error currents are random, independent, and equal in magnitude, the most probable expression for E_o is

$$E_o = I_{10}\Delta R_{T1} \pm \Delta I_1 \Delta R_{T1} \pm \sqrt{2}\Delta I_1(R_{T0} + \Delta R_{T2}). \quad (11)$$

The errors caused by an imperfect dummy gage can be examined by assuming that the source currents are exactly equal in all respects allowing simplification of Equation 9 to

$$E_o = I_1\Delta R_{T1} + I_1(\Delta R_{T2} - \Delta R_D R_{T0}/R_{D0}). \quad (12)$$

It should be noted that with perfect tracking between the dummy and active gages there is still a secondary input error if the zero-input resistances are not equal:

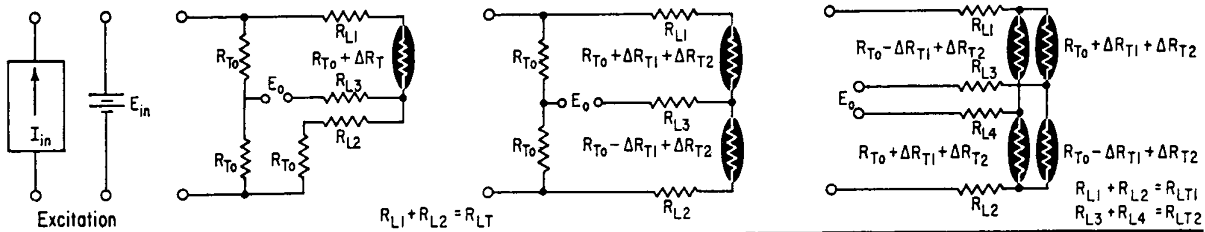
$$E_o = I_1\Delta R_{T1} + I_1\Delta R_{T2}(1 - R_{T0}/R_{D0}) \quad (13)$$

The dual source system of Figure 3 will produce twice the output, with a corresponding improvement in accuracy, if the dummy sensor is replaced with a second, active sensor. Figure 4 illustrates a triple source system which is useful when it is not necessary to discriminate against the effects of secondary inputs (Ref. 2). The third current source cancels the primary excitation current flowing through line resistance R_{L3}. The product I_2R_D is adjusted to equal I_1R_{T0} for zero system output of zero input.

Multiple source systems are particularly useful for exciting semiconductor strain gages. Their relatively large resistance variations (50 to 100 times that of wire or foil strain gages) make constant current excitation almost mandatory if the system output is to be a linear function of these variations; the corresponding large output signals allow for excellent performance characteristics with commercially available, reasonably priced instrument power supplies.

Bridges of sensors

Traditionally the most popular technique for recovering the information from resistance sensors has been to incorporate one or more in a bridge, which is excited by a constant voltage power supply. This technique approaches, and in some configurations achieves, the ideal of constant transducer current; provides for zero system output at zero primary input; and has the capability to discriminate partially against the effects of line resistances and secondary inputs. These characteristics are also provided by current excited bridges, but with a closer approach to constant transducer current and with more in-



Configuration	Constant current	Constant voltage
Single active arm	$R_0' = 2R_{T0}\left[\frac{2R_{T0}+\Delta R_T+R_{LT}+R_{L2}(\Delta R_T+R_{L1})/2R_{T0}}{4R_{T0}+\Delta R_T+R_{LT}}\right]+R_{L3}$	$R_{T0}\left[\frac{4R_{T0}+3(\Delta R_T+R_{LT})+2R_{L2}(\Delta R_T+R_{L1})/R_{T0}}{4R_{T0}+2(\Delta R_T+R_{LT})}\right]+R_{L3}$
Two active arms	$R_0'=2R_{T0}\left[\frac{2R_{T0}+2\Delta R_{T2}+R_{LT}+(\Delta R_{T1}R_{L2}-\Delta R_{T1}R_{L1}+\Delta R_{T2}R_{LT}+R_{L1}R_{L2}+\Delta R_{T2}^2-\Delta R_{T1}^2)/2R_{T0}}{4R_{T0}+2\Delta R_{T2}+R_{LT}}\right]+R_{L3}$	$R_{T0}\left[\frac{4R_{T0}+3(2\Delta R_{T2}+R_{LT})+2(\Delta R_{T1}R_{L2}-\Delta R_{T1}R_{L1}+\Delta R_{T2}R_{LT}+R_{L1}R_{L2}+\Delta R_{T2}^2-\Delta R_{T1}^2)/R_{T0}}{4R_{T0}+4\Delta R_{T2}+2R_{LT}}\right]+R_{L3}$
Four active arms	$R_0' = R_{T0}+\Delta R_{T2}+R_{LT2}$	$\frac{(R_{T0}+\Delta R_{T2})(R_{T0}+\Delta R_{T2}+R_{LT1})-\Delta R_{T1}^2}{R_{T0}+\Delta R_{T2}+R_{LT1}}+R_{LT2}$

Configuration	Constant current	Constant voltage
Single active arm	$E_0' = \frac{I_{in}R_{T0}(\Delta R_T+R_{L1}-R_{L2})}{4R_{T0}+\Delta R_T+R_{LT}}$	$\frac{E_{in}(\Delta R_T+R_{L1}-R_{L2})}{4R_{T0}+2(\Delta R_T+R_{LT})}$
Two active arms	$E_0' = \frac{I_{in}R_{T0}(2\Delta R_{T1}+R_{L1}-R_{L2})}{4R_{T0}+2\Delta R_{T2}+R_{LT}}$	$\frac{E_{in}(2\Delta R_{T1}+R_{L1}-R_{L2})}{4R_{T0}+4\Delta R_{T2}+2R_{LT}}$
Four active arms	$E_0' = I_{in}\Delta R_{T1}$	$\frac{E_{in}\Delta R_{T1}}{R_{T0}+\Delta R_{T2}+R_{LT1}}$

Figure 5. Characteristics of one-, two-, and four-active-arm bridges

dependence from the effects of line resistances, secondary inputs, and output loading.

The characteristics of resistance bridges can be expressed in terms of an equivalent circuit output voltage (E_o') and output impedance (R_o'). Three commonly used bridge configurations are illustrated by Figure 5, with the corresponding expressions for R_o' and E_o' in the Table.

The Table shows why bridges in general require readout devices with very high input impedances. The equivalent circuit output impedance is a complicated function of the nominal bridge resistance, all variations of this resistance, and line resistances. If the bridge is appreciably loaded, the output voltage becomes an unpredictable, non-linear function of primary resistance variation. Note that the output impedance of current excited, four active arm bridges is not a function of primary resistance variation. If line resistances are known and stable, and secondary inputs are controlled, this bridge can be heavily loaded with the only effect being a fixed attenuation of the open circuit output voltage.

The Table also shows that single active arm bridges are nonlinear, regardless of the excitation, but this nonlinearity is less with current excitation. Both single and double active arm bridges have open circuit output voltages which are dependent on the effects of line resistances and secondary inputs. If line resistances are equal, their effect on zero offset is eliminated, but not their effect on sensitivity. Again, current excitation offers superior performance in that it results in an open circuit output voltage whose sensitivity is less dependent on line resistances and secondary inputs.

The most striking example of the advantages of current excitation is the four active arm bridge. With this configuration, current excitation results in an almost error-free circuit. The only error source is the dependence of equivalent circuit output impedance on secondary inputs and line resistances, and this is negligible if the bridge is lightly loaded. Of particular importance are the facts that heavy loading of the bridge does not produce nonlinearity, and that both zero output and sensitivity are independent of line resistances and secondary inputs.

The practical significance of the advantages of current excited, four active arm bridges that many precision sensors for physical phenomena such as pressure, torque, load, and acceleration mechanically convert the primary input to strain. The strain is sensed and converted to a proportional electrical signal by a four active arm strain gage bridge.

Tri-terminal current generator

When it is desired to measure small static resistance variations in a single active transducer which is insensitive to secondary inputs or in situations where secondary inputs are controlled, consideration of the current source design as an intimate part of the total system design can result in a technique which is far more accurate than a single active arm bridge and far less complex and expensive than a triple current source system.

A very simple modification to a conventional single active arm bridge is illustrated by Figure 6. The bridge completion resistor adjacent to the active arm is used as the current sensing resistor, resulting in a controlled gage current rather than controlled

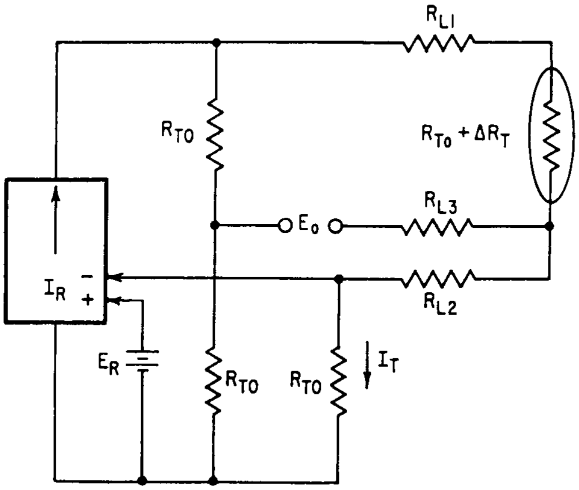


Figure 6. Tri-terminal method has most of the advantages of a bridge.

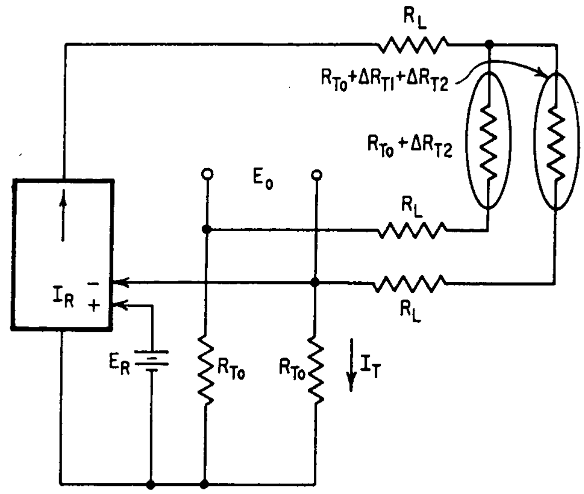


Figure 7. Adding dummy gage to tri-terminal connection compensates for secondary inputs.

total bridge current. The equivalent circuit characteristics are

$$E_o' = \frac{E_R(\Delta R_T + R_{L1} = R_{L2})}{2R_{T0}}, \text{ and} \qquad (14)$$

$$R_o' = R_{T0} + \frac{R_{L1} + \Delta R_T}{2} + R_{L3}. \qquad (15)$$

When the bridge is lightly loaded and line resistances are equal, the output is

$$E_o = \frac{E_R \, \Delta R_T}{2R_{T0}} \qquad (16)$$

Unlike a conventional single active arm bridge, the output voltage is linear and independent of line resistances (providing they are equal).

The conditions of open circuit operation and equal line resistances are easily met in many practical measurement situations. Precision voltage measuring devices feature input impedances in excess of one megohm, a value several orders of magnitude greater than normally encountered sensor resistances. By making the lines to the sensor the same length and of the same type and gage of wire, and by containing them in a single shielded cable, their resistances will be very close to equal, if not exactly equal, even under varying environmental conditions.

The Tri-Terminal signal conditioning technique can be modified to minimize the effects of secondary inputs, as shown in Figure 7. The output of the modified system is

$$E_o = \frac{E_R \, \Delta R_{T1}}{2R_{T0} + R_L + \Delta R_{T2}} \qquad (17)$$

The output is still a linear function of the primary resistance variation, but sensitivity becomes a function of both line resistance and transducer resistance variations caused by secondary inputs.

For measurements involving single sensors, the tri-terminal technique combines the excellent zero offset, noise, and stability characteristics of bridges with the linearity resulting from constant sensor current. In addition, its output characteristics are independent of line resistances, when they are equal. In many commonly encountered measurements, the technique is capable of providing performance equal to or better than that of multiple source techniques with no more complexity than is encountered in a conventional single active arm bridge.

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