Low-Voltage Current Loop Transmitter

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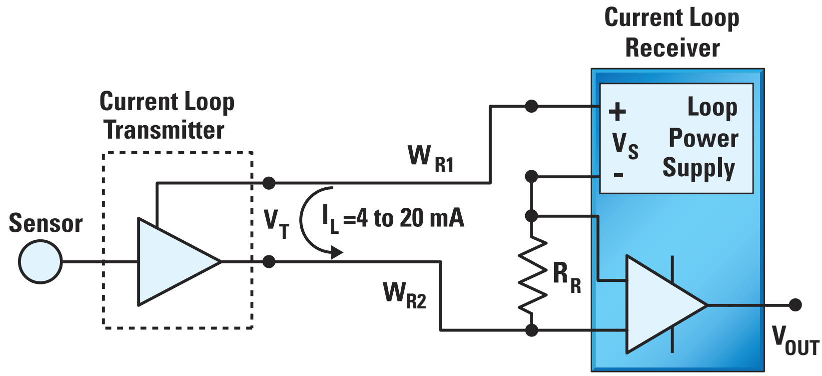

Figure 1. Current Loop Components and Connection

The 4 to 20 mA current loop, which is used extensively in industrial and process control systems, creates challenges for maximizing the operating loop length. In some cases, a very long loop is required and the combination of limited loop-power supply voltage and excessive loop wire resistance prevents it use. This article discusses the use of low-voltage amplifiers to minimize the transmitter's operating voltage requirements, which will maximize the operating loop length.

Typically, the current loop is powered from the receiver side while the transmitter controls the current flowing in the loop to indicate the value of the physical parameter being measured by the sensor. *Figure 1* shows the basic components and connection of a current loop.

The maximum distance between the transmitter and receiver is dependent on the power supply voltage (V_S), and the sum of the loop drops, which are the minimum transmitter voltage (V_T), the voltage drops across the wire resistance (W_{R1} and W_{R2}), and receiver resistor (R_R). In equation form:

EQ1 $$V_S = V_{WR1} + V_T + V_{WR2} + V_{RR}$$

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Substituting the loop current and loop resistances into EQ1:

EQ2 $$V_S = I_L W_{R1} + V_T + I_L W_{R2} + I_L R_R$$

Given the wire's resistance in X Ohms per foot, the maximum loop current of 20 mA, the value of R_R equal to 10Ω, and the equal lengths of wire, EQ2 can be rearranged to calculate the maximum loop distance in terms the loop parameters:

EQ3 $$ft = \frac{V_S - V_T - 0.2}{0.04\ (X\ \Omega/ft)}$$

EQ3 illustrates three ways to increase the maximum loop length: (1) increase the loop power supply voltage, (2) increase the wire gage, which will reduce the wire's ohms per foot, or (3) reduce the minimum voltage required for the current loop transmitter operation, which is the focus of the following section.

The use of low voltage amplifiers, such as the LMV951, and low drop out voltage regulators, such as the LP2951, can reduce the minimum voltage required for the current loop transmitter. ***Figure 2*** shows the schematic of a loop-powered 4 to 20 mA transmitter, which will function with a minimum of 1.9V, and a 4 to 20 mA receiver.

In this example, a temperature sensor, such as the LM94022, provides a signal for the transmitter.

The components A1, Q1, and R1 through R5 form a voltage-to-current converter. The noninverting input of A1, pin 3, is the summing node for three signals, the loop current, offset current, and sensor signal voltage. The resistor R2 is the current shunt that measures the current flowing in the loop and is fed back through R3. The total loop current is the sum of the currents flowing in resistor R2 and R3, $I_L = I_{R2} + I_{R3}$. The amplifier, A1, forces the voltages at its inputs, pins 3 and 4, to be equal by forcing more or less current through R2. The result is that R2 and R3 have the same voltage across them. The ratio of the currents in R2 and R3 is the inverse of the resistor ratio:

EQ4 $$\left(\frac{I_{R2}}{I_{R3}} = \frac{R_3}{R_2}\right)$$

This highlights that the current in R3 is also part of the voltage-to-current conversion and is not an error current. An error source that will affect the loop current is the offset voltage of amplifier A1, which will add an error current to the loop current. At the minimum loop current of 4 mA, the voltage V2 is very close to 0.040V.

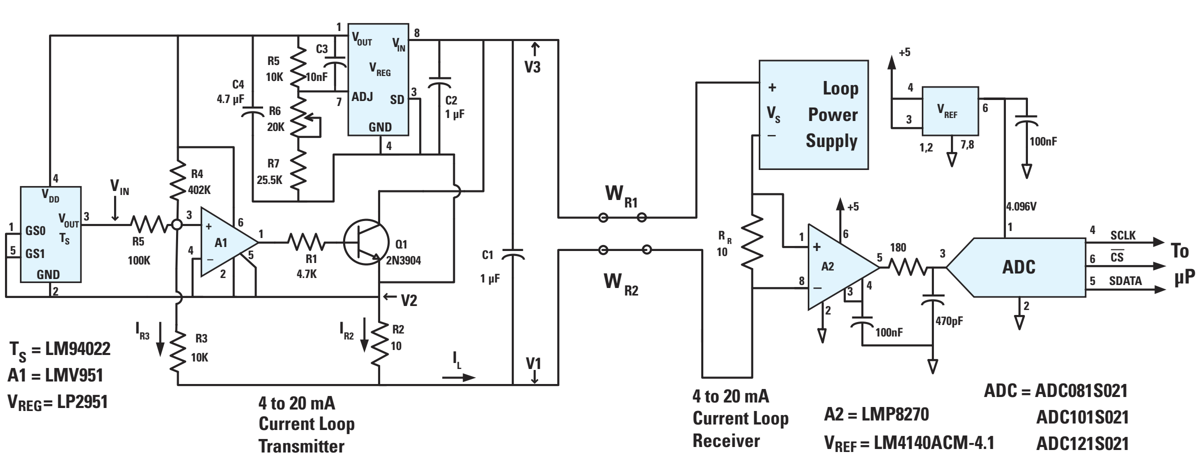

Figure 2. Loop-Powered Transmitter Schematic

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An offset voltage of 1 mV in A1 will cause an error of about 2.5% in I_{R3}:

EQ5 $$\frac{0.001V}{0.040V} \times 100 = 2.5\%$$

Because the ratio of I_{R2} to I_{R3} is 1000 to 1, an error of 2.5% in I_{R3} results in a 0.0025% error in the loop current.

The voltage supply requirements for the components in transmitter must be evaluated in order to determine the minimum operating voltage required by the transmitter. For this example, a full-scale sensor input signal of 1.6V is used and results in a 10 mA per volt scale factor:

EQ6

$$\frac{I_L MAX - I_L MIN}{V_{IN} MAX - V_{IN} MIN} = \frac{20\ mA - 4\ mA}{1.6V - 0V} = \frac{16\ mA}{1.6V} = 10\ mA/V$$

The minimum voltage required for the transmitter (V3 – V1) is the highest voltage requirement of the two paths from V3 to V1. Path one is from V3 to Q1 and R2 to V1. At the maximum loop current of 20 mA, the voltage drop across R2 is 0.2V (V2) and a collector emitter voltage of about 0.5V to stay out of saturation is a total of 0.7V. The second path is V2 plus the output voltage of the voltage regulator and its dropout voltage. The full-scale sensor input signal of 1.6V requires about a 1.65V output from the regulator and the dropout voltage of the voltage regulator is less then 50 mV. The path has a minimum voltage requirement of 1.9V (0.2 + 1.65 + 0.05). Note that the minimum operating voltage of the LMV951 is 0.9V so the minimum transmitter voltage could be reduced to about 1.3V by increasing the scale factor to 18 mA per volt. This is supported by the voltage regulator, V_R, which can be adjusted down to 1.25V, and with a drop out voltage of 50 mV, the loop transmitter can work down to 1.3V. The current loop transmitter functions by summing three signals: the loop current (R3), the offset current (R4), and the sensor (R5).

The loop current generates a voltage drop across resistor R2 such that V1 is negative with respect to V2 and then fed back through R3.

EQ7 $$V1 = V2 - R2(I_L)$$

The 4 to 20 mA current loop uses the offset current level of 4 mA to represent zero signal input. This is used as an open loop fault condition since zero current is a broken wire, transmitter failure, or another fault. The resistor R4 is connected to the output of the adjustable low drop-out voltage regulator to create the 4 mA offset current. Resistor R4, at 402 kΩ, sets approximately a 4 mA offset current when the output of the voltage regulator is 1.65V. The variable resistor R6 is used to set the loop current to 4 mA when the input signal is at zero volts. This adjustment compensates for error in the voltage regulator's output and resistor tolerance in R4, R5, and R7. The offset can be calibrated to 4 mA by measuring the voltage across R_R and adjusting R6 until the voltage across R_R is equal to 0.04V. The value of resistor R4 can be calculated for other supply voltages by equating the voltages at the amplifier's input pins and rearranging to solve for R4:

EQ8 $$R4 = \frac{R3 \times V_{OUT}}{R2 \times I_{R2}} - R_3$$

The resistor R5 is used to scale the signal input voltage to the 16 mA span of the loop current, and in this example, it is assumed the input signal span is 1.6V. The equation for calculating R5 can be developed by equating the voltages at the amplifier's input pins and rearranging to solve for R5. V_{IN} is the maximum signal input, 1.6V for this example, and I_{R2} is the change in output current, 16mA:

EQ9 $$R5 = \frac{R3 \times V_{IN}}{R2 \times I_{R2}}$$

This equation also indicates that changing the value of R5 can change the full-scale input voltage. A low resistance variable resistor could be used in series with R5 to add a full-scale calibration as shown in the following schematic (***Figure 3***).

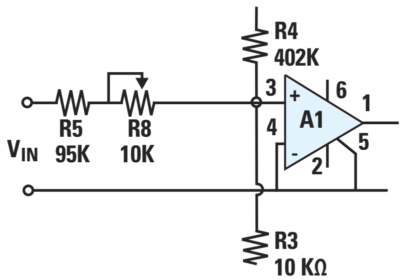

Figure 3. Input Calibration

In this example, a silicon temperature sensor is used as a signal source. The LM94022 is a low voltage, programmable gain temperature sensor that can be used to measure temperature from –50°C to 150°C. The schematic in ***Figure 2*** shows the LM94022's gain select pins connected to ground, or the lowest gain. With this gain, the sensor's output ranges from 1.299V for a temperature of –50° C to 0.183V for a temperature of 150°C.

As shown in ***Figure 1***, the current loop transmitter accounts for only part of the voltage drop in the loop. The current loop receiver frequently uses a resistor, R_R in ***Figure 1***, to generate a voltage drop that is used to measure the loop current. The measurement of the voltage across R_R can present some problems such as high common mode voltages, due to the loop power supply, as well as induced voltages from the environment. To overcome these measurement problems a differential amplifier, such as the LMP8270, can be used. The LMP8270 is a high common mode voltage differential amplifier with a fixed gain of 20. The gain of 20 also reduces the resistance of R_R, which reduces the loop voltage drop.

Referring to ***Figure 2***, the voltage across resistor R_R is recovered from whatever common mode voltage exists on the current loop, up to 28V, and is amplified and drives the input to an Analog-to-Digital Converter (ADC). Internal to the LMP8270 is a differential amplifier with a gain of 10 followed by an amplifier with a gain of two. The internal connection between the two amplifiers is brought out to pins 3 and 4. Also internal to the LMP8270 is a 100 kΩ resistor in series with the output of the first amplifier. A low pass filter is easily implemented by connecting a capacitor from pins 3 and 4 to ground.

Figure 2 shows a 4.096V reference being used by the ADC, representing the full-scale input. The differential input voltage to the LMP8270 for a 4.096V output is 4.096/20 = 0.2048V. The value of R_R for a voltage drop of 0.2048V at a current of 20 mA is 0.2048/20 = 10.24Ω. A 10Ω resistor is used because it is a standard precision value. The result is an output voltage from A2 of 0.8V to 4.0V for a loop current of 4 mA to 20 mA.

The current loop transmitter was calibrated using the end points, 0V and 1.6V, as the input voltages while measuring the voltage across the R_R resistor. With 0.0V applied to the input the resistor R6 is adjusted until 40 mV is across R_R. With 1.6V on the input, resistor R8, see ***Figure 3***, is adjusted until 200 mV is across R_R. ***Figure 4*** is the measured transfer function using a calibrated voltage source. The worst case deviation from a straight line was –8 µA, which is not observable on the graph in ***Figure 4***.

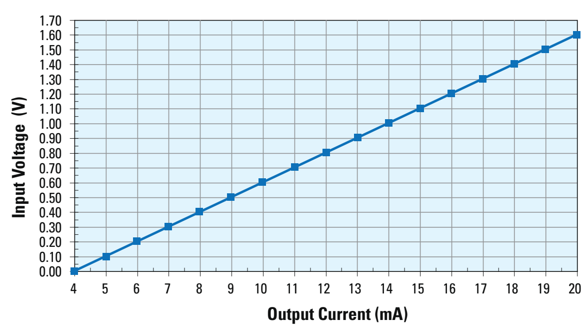

Figure 4. Output Current vs Input Voltage

In summary, by using a selection of components that function with very low supply voltages a current loop transmitter can be designed that operates with as little as 1.3V.