Isolated Industrial Current Loop Using the IL300 Linear

INTRODUCTION

Programmable logic controllers (PLC) were once only found in large manufacturing firms but now are used in small to medium manufacturing firms. PLCs are being retrofitted into manufacturing environments where temperature, pressure, and level sensor control signals are exposed to harsh electrical noise. The connection between these sensors and the controller requires the use of high noise immunity communication technology.

One solution to this communication problem is the analog current loop. A current loop is an interface technique that converts a process sensor's output to a DC current signal. When compared to voltage control techniques, a current loop receiver's low input resistance offers higher noise immunity. Current loops have the added advantage of better accuracy, because they eliminate sensor signal errors introduced by communication line resistance.

Electrical noise can be reduced further by providing isolation between the current loop receiver or transmitter and the process controller. An isolated receiver and transmitter can be constructed using the IL300 linear optocoupler. This application note will describe how to design a line powered isolated current loop receiver and transmitter. It will discuss the design process and show circuit variations compatible with common current loop pseudo-standards.

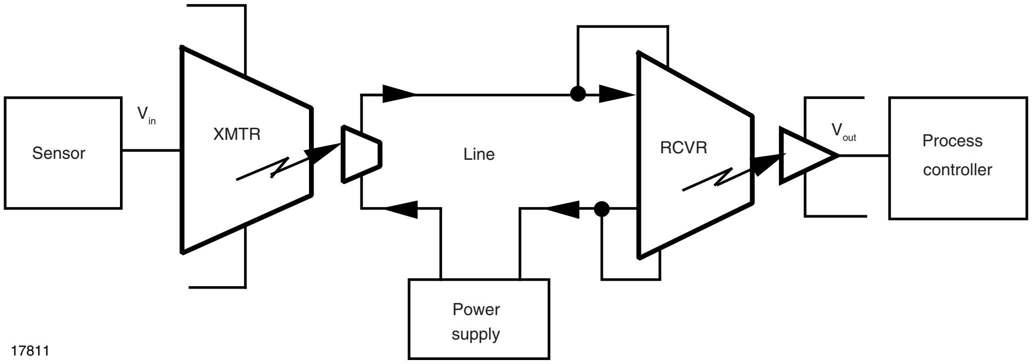

Fig. 1 - Isolated Transmitter and Receiver Current Loop

CURRENT LOOP ELEMENTS

A current loop typically consists of a transmitter, a receiver, and a DC power supply. The highest insulation and noise immunity is achieved when an isolated transmitter and an isolated receiver are used as shown in figure 1. However, there are many situations where only one end of the loop can be isolated. Figures 2 and 3 illustrate combinations of isolated and non-isolated current loop elements.

Isolated current loop transmitters and receivers commonly require separate isolated power supplies in addition to the standard loop voltage supply. The designs in this application note derive their power from the DC supply found in the loop. Commonly the loop power supply is an isolated voltage supply whose output voltage will range from 10 V to 24 V. Thus only a single isolated power supply is needed to power the loop.

CURRENT LOOP CONVENTIONS

The 4 mA to 20 mA current loop is the most common pseudo-standard. This convention defines a 4 mA loop current as the sensor's zero reference. The full scale of the sensor output corresponds to a 20 mA loop current, representing a minimum to maximum current ratio of 1:5. The sensor's signal output commonly has a zero reference of + 1 V and a full scale of + 5 V which also corresponds to a 1:5 signal ratio and a + 4 V span.

Figure 4 shows the transmitter's output loop current as a function of input sensor voltage. Other conventions include sensor signal spans of 5 V, where the sensor's zero reference is 0 V, and full scale is + 5 V (figure 5).

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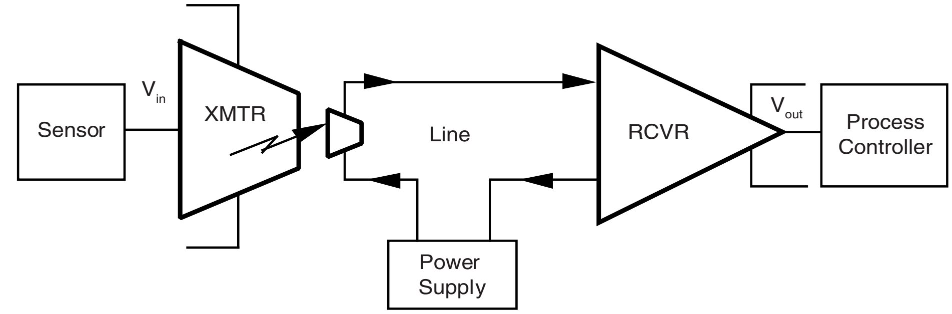

Fig. 2 - Isolated Transmitter and non-Isolated Receiver Current Loop

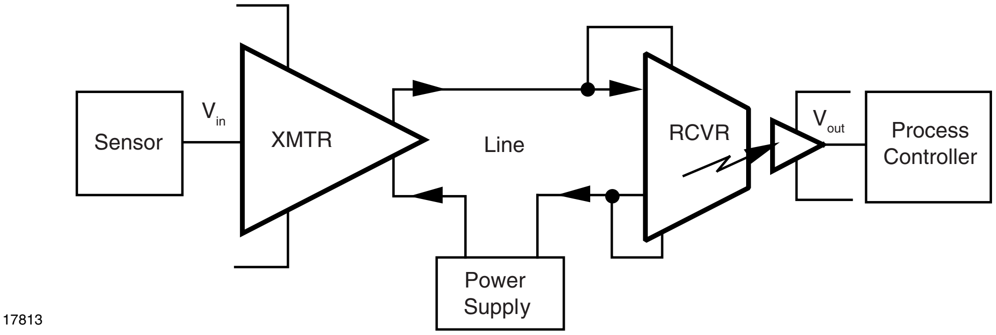

Fig. 3 - Non-Isolated Transmitter and Isolated Receiver

Figures 4 and 5 show the transmitter transfer function. The loop current (IL) is the product of the sensor voltage (V_{in}) times the transmitter trans conductance, milli-Siemens. The receiver in Figure 4 has a trans resistance of 250 Ω, while for Figure 5 it is 312.5 Ω.

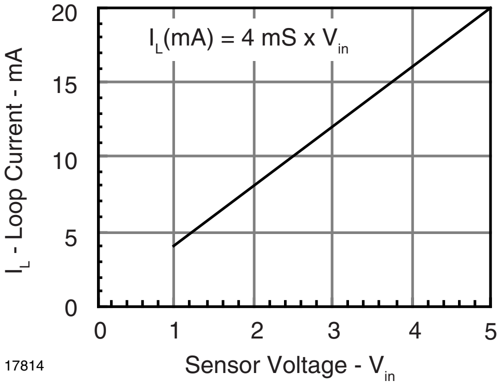

Fig. 4 - 1 V to 5 V, 4 mA to 20 mA Current Loop Transfer

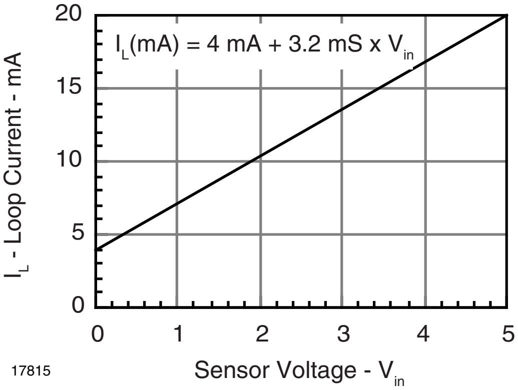

Fig. 5 - 0 V to 5 V, 4 mA to 20 mA Current Loop Transfer

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CURRENT LOOP TRANSMITTER

Figure 6 shows an isolated current loop transmitter with a 1 V to 5 V input and a 4 mA to 20 mA output. The sensor section consists of an optical feedback amplifier (U1, IL300) that converts the sensor voltage (V_{in}) to an output photocurrent (I_{P2}). The output amplifier, U2, operates as a current controlled current sink. The equation for the line current (I_L) as a function of the output photocurrent (I_{P2}) is given below:

$$I_O = \frac{I_{P2} \times R3}{R4} \qquad (1)$$

The equation for the output photocurrent, I_{P2}, as a function of the sensor voltage is given below:

$$I_{P2} = \frac{V_{in} \times K3}{R1} \qquad (2)$$

Combining equations 1 and 2 results in the complete transmitter DC transfer relationship with K3 the IL300's transfer gain.

$$\frac{I_O}{V_{in}} = \frac{K3 \times R3}{R1 \times R4} \qquad (3)$$

1 V to 5 V, 4 mA to 20 mA TRANSMITTER DESIGN

The design of the 1 V to 5 V input, 4 mA to 20 mA output isolated current loop transmitter starts with analyzing the isolated current to current converter. This amplifier (U2), a National Semiconductor LM10 operational amplifier, was chosen for its high output current and ability to operate from a single supply. The input sensor amplifier controls the output photocurrent (I_{P2}). I_{P2} develops a voltage across R3 at the inverting input of U2, forcing a loop current to flow through R4. Thus I_o times R4 is equal to the voltage developed across R3 times IP2 (Equation 4). Equation 5 shows that resistors R3 and R4 set U2's current gain.

$$I_{P2} \times R3 = I_O \times R4 \qquad (4)$$

$$\text{Current Gain} = \frac{I_{P2} \times R3}{R4} \qquad (5)$$

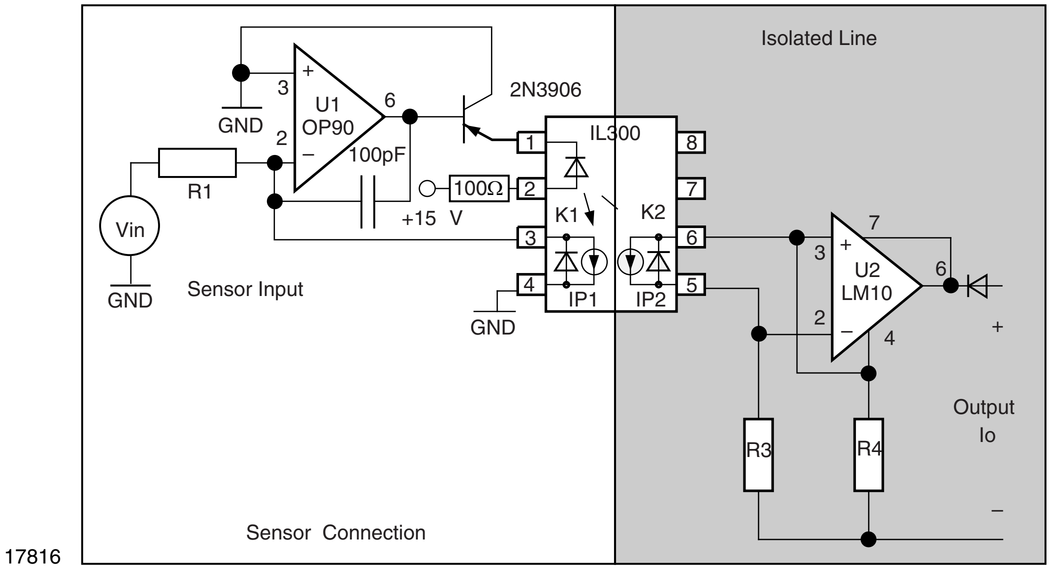

Fig. 6 - Isolated 1 V to 5 V, 4 mA to 20 mA Transmitter

A current gain of 400 is selected, with R4 equal to 50 Ω. From equation 5, R3 is 20 kΩ. Equation 1 shows that a loop current of 4 mA to 2 mA requires an output photocurrent (I_{P2}) of 10 µA to 50 µA.

The last design step is to determine the input resistor (R1) by rearranging Equation 3. The trans conductance, I_o/V_{in} of Figure 6, is 4 milli-Siemens (mS). The remaining variable is the IL300's transfer gain, K3. The part to part variation of the transfer gain offers a range of 0.56 to 1.53. With K3 = 1, R1 is calculated to be 100 kΩ from equation 6. See figure 7 for the spread of R1 versus the guaranteed range of K3. Thus a 200 kΩ, 10 turn potentiometer will compensate for the full distribution of K3.

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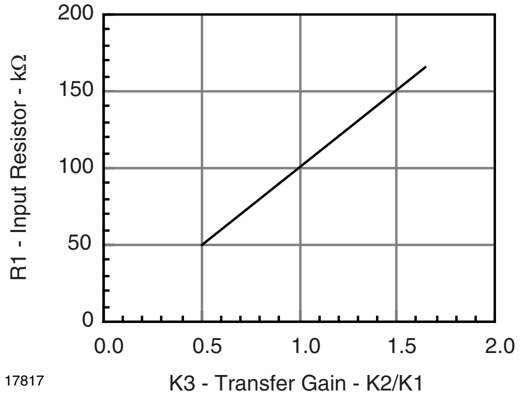

Fig. 7 - R1 vs. K3 for Isolated 1 V to 5 V, 4 mA to 20 mA Transmitter

$$R1 = \frac{K3 \times 20\ k\Omega}{6\ ms \times 50\ k\Omega} \qquad (6)$$

$$R1 = 100\ k\Omega \text{ for } K3 = 1.0$$

0 V to 5 V, 4 mA to 20 mA TRANSMITTER DESIGN

A current loop transmitter conforming to the pseudo-standard of 0 V to 5 V input to 4 mA to 20 mA output can be designed using the general circuit topology in figure 6. With the addition of a bias source (V_{ref}) 4 mA of line current will flow when V_{in} = 0 V. The LM10 offers an integrated 200 mV band gap reference source with voltage follower buffer amplifier. The LM10's voltage reference and differential amplifier make it uniquely qualified as the output current amplifier. Figure 8 shows the schematic of a current transmitter including a bias source, U3.

By inspection and using Equation 4, the transmitter current transfer function can be determined. The transfer function for figure 8 is given in equation 7.

$$I_O = \frac{V_{in} \times K3 \times R3}{R1 \times R4} + \frac{V_{ref} \times R3}{R2 \times R4} \qquad (7)$$

This equation shows that the loop current is the sum of the sensor controlled signal (V_{in}) and current provided by the bias source (V_{ref}). The bias source consists of a voltage follower (U3) that buffers a 200 mV band gap reference. This voltage reference is converted to a current source by the R2 resistor. The value of R2 can be calculated from equation 8, when V_{in} = 0 V, and I_o = 4 mA.

$$I_{ref} = \frac{V_{ref}}{R2}$$

$$I_O = \frac{V_{ref}}{R2} \times \frac{R3}{R4} \qquad \text{when } V_{in} = 0\ V$$

$$R2 = \frac{V_{ref} \times R3}{I_O \times R4} \qquad (8)$$

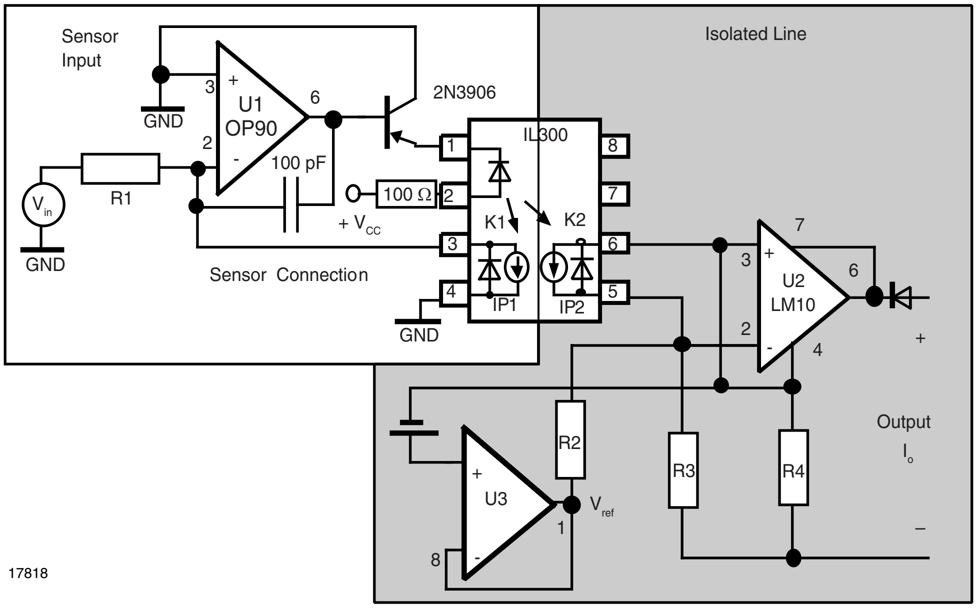

Fig. 8 - Isolated 0 V to 5 V, 4 mA to 20 mA Transmitter

Isolated Industrial Current Loop Using the IL300 Linear

Given the current gain, R3/R4 = 400, V_{in} = 0 V, and I_o = 4 mA, R2 is calculated to be 20 kΩ.

The input resistor (R1) sets the trans conductance ($\Delta I_{P2}/\Delta V_{in}$) of the input amplifier. The current transmitter's trans conductance equals the trans conductance of the input amplifier times the current gain of the output amplifier. The transmitter incremental trans conductance is calculated given a ΔV_{in} of 5 V, (0 V to 5 V), and ΔIo of 16 mA (4 mA to 20 mA). A transmitter trans conductance 3.2 milli-Siemens results.

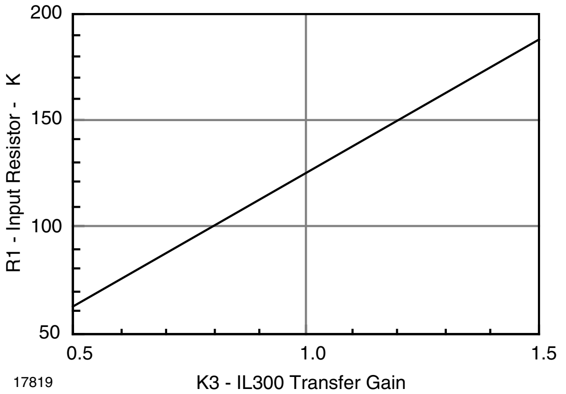

Fig. 9 - R1 vs. K3 for Isolated 0 V to 5 V, 4 mA to 20 mA Transmitter

$$\frac{\Delta I_{P2}}{\Delta V_{in}} = \frac{K2}{R1}$$

$$\frac{\Delta I_O}{\Delta V_{in}} = \frac{K3}{R1} \times \frac{R3}{R4} \qquad (9)$$

$$\frac{R1}{\Delta I_O} = \frac{V_{in} \times K3 \times R3}{R4} \qquad (10)$$

Assume an output amplifier current gain of 400 (R3 = 20 kΩ, R4 = 50 Ω), a typical K3 = 1, and a transmitter trans conductance of 3.2 ms. Substituting R3, R4, and K3 into Equation 10, R1 can be determined.

$$R1 = \frac{1.0 \times 20\ \text{k}\Omega}{3.2\ \text{ms} \times 50\Omega} \qquad (11)$$

$$R1 = 125\ \text{k}\Omega$$

Figure 11 shows the relationship of R1 as a function K3.

See Table 1 for the component values for each design.

Isolated transmitter resistor values, K3 = 1.

	0 V to 5 V to 4 mA to 20 mA	1 V to 5 V to 4 mA to 20 mA
R1	125 kΩ	100 kΩ
R2	20 kΩ	INF
R3	20 kΩ	20 kΩ
R4	50 kΩ	50 Ω

1 V to 5 V, 4 mA to 20 mA TRANSMITTER PERFORMANCE

The transmitter described in figure 6 was constructed and evaluated for accuracy and linearity as a function of input sensor voltage and ambient temperature. The transmitter was calibrated by adjusting R1 for 12 000 mA loop current with an input voltage of 3000 V at T_A = 23 °C. Figure 10 shows the percent error deviation from the expected loop current. This circuit offers a typical accuracy of ± 0.2 % over a temperature range of 0 °C to 75 °C. Note that the temperature performance appears to follow a parabolic contour.

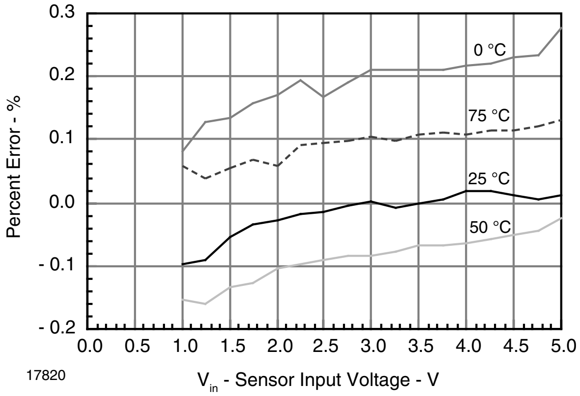

Fig. 10 - Percent Error vs. Input Sensor Voltage
1 V to 5 V, 4 mA to 20 mA Transmitter

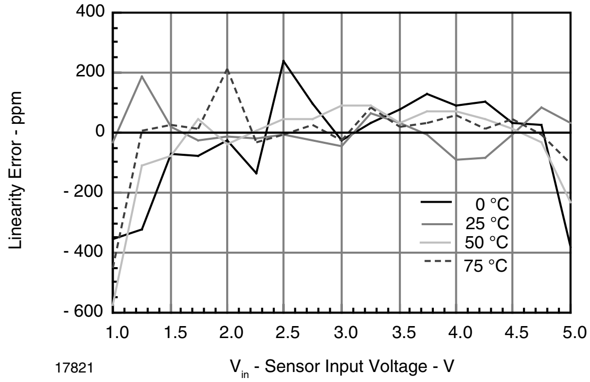

Fig. 11 - Linearity Error vs. Input Sensor Voltage
1 V to 5 V, 4 mA to 20 mA Transmitter

Many industrial controllers have calibration techniques that can compensate for temperature imposed accuracy errors. These techniques are only valid if the transmitter exhibits a high degree of linearity. Figure 11 shows the linearity error for the transmitter. The linearity error is expressed as a deviation in parts per million (ppm) from a best fit linear regression at each temperature. Figure 11 shows a typical linearity of + 200 ppm to - 600 ppm over a 0 °C to 75 °C temperature range.

Isolated Industrial Current Loop Using the IL300 Linear

0 V to 5 V, 4 mA to 20 mA TRANSMITTER PERFORMANCE

The transmitter in figure 8 was constructed and evaluated for accuracy and linearity as a function of input sensor voltage and ambient temperature. The transmitter was calibrated by adjusting R2 for 4000 mA loop current with an input voltage of zero volts (0.000 V).

The R1 resistor is then adjusted for 12000 mA loop current with an input voltage of 2.5 V at T_A = 23 °C. Figure 12 shows the percent error deviation from the expected loop current. This circuit offers a typical accuracy of + 0.4 % over a temperature range of 0 °C to 75 °C. Note that the temperature performance appears to follow a parabolic contour.

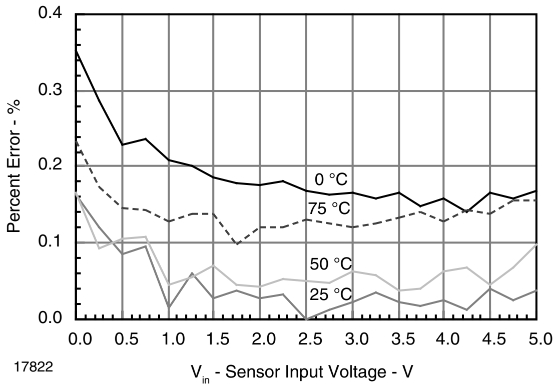

Fig. 12 - Percent Error vs. Input Sensor Voltage
0 V to 5 V, 4 mA to 20 mA Transmitter

Figure 13 shows the linearity error for the transmitter. The linearity error is expressed as a deviation in parts per million (ppm) from a best fit linear regression at each temperature. Figure 13 shows a typical linearity of + 600 ppm to - 1000 ppm over a 0 °C to 75 °C temperature range.

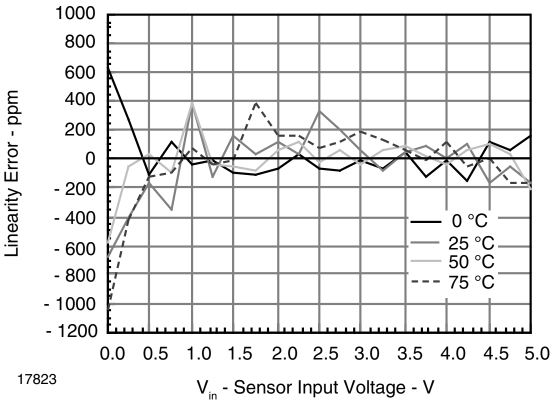

Fig. 13 - Percent Error vs. Input Sensor Voltage
0 V to 5 V, 4 mA to 20 mA Transmitter

CURRENT LOOP RECEIVER

The sensor controlled, current loop signal is converted to a voltage by the current loop receiver. The receiver's conversion gain and output voltage span is determined by the adopted current loop standard. A 4 mA to 20 mA loop current is commonly converted to a 1 V to 5 V output signal. The receiver design in this section conforms to this standard. Signal conversion and isolation are provided by an IL300, linear optocoupler. The circuit is loop current powered. The isolation feature and the receiver's low operating voltage drop permits multiple receivers within the loop.

RECEIVER OPERATION

The isolated current loop receiver consists of two sections. They include a loop current to photocurrent current amplifier, U1, and an output trans resistance amplifier, U2. Figure 14 shows a simplified schematic. The receiver's linearity and stability are insured by using optical feedback within the loop current to photocurrent amplifier.

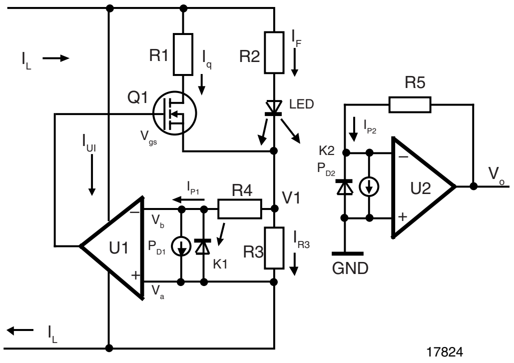

Fig. 14 - Isolated Current Loop Receiver

The optical feedback amplifier provides precise control of the LED's output flux. A bifurcated optical signal path within the IL300 provides an equally well controlled photocurrent for the output trans resistance amplifier.

The loop current to photocurrent current amplifier consists of a single-supply micro-powered differential control amplifier, U1, and an LED current shunt regulator, Q1. Shunt control of the LED current was chosen to accommodate the receiver's need for a low supply voltage operation.

The current loop receiver circuit functions as follows. The loop current (I_L) flows into the junction of U1's V_{cc} (R1 and R2). U1's supply current (IU1) is substantially smaller than the loop current and will be omitted in the analysis. The loop current is divided at the juncture of R1 and R2. The sum of the currents flowing in each leg is equal to the loop current. The individual currents (I_q and I_F) are determined by the required LED current to generate the needed photocurrent (I_{P1}) connected to the control network at U1. Figure 15 shows the I_q and I_F relationships for the receiver.

Isolated Industrial Current Loop Using the IL300 Linear

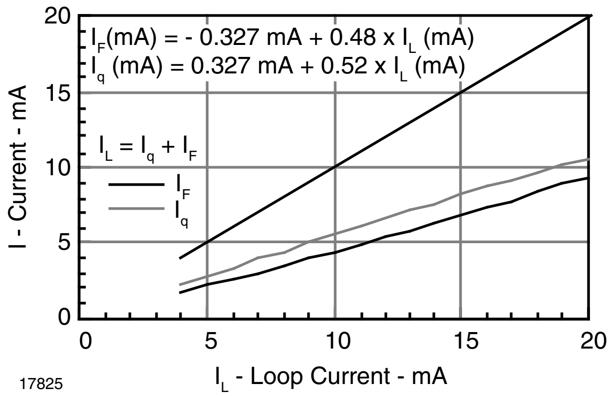

Fig. 15 - LED Current Shunt Control

The total loop current flows into the junction, V1. This current, IR3, develops a voltage across R3. Under initial conditions, this positive voltage appearing at the inverting input of U1 will force U1's output towards the negative rail. This V_{gs} forces Q1 into cut-off. Under this condition the LED current (I_F) equals the loop current (I_L). This rise in LED current generates an optical flux which falls on the feedback photodiode (PD1) and generates a photocurrent (I_{P1}). This photocurrent will rise to a value where voltage developed across R4 equals the voltage across R3. This satisfies the differential amplifier requirement of $V_a = V_b$. U1's output provides the control signal for Q1's gate, forcing it into conduction and shunting excess loop current away from the LED current path. The feedback control relationship is shown in equation 12.

$$I_{P1} \times R4 = I_{R3} \times R3; \qquad I_{R3} \sim I_L$$

$$I_{P1} \times R4 = I_L \times R3 \tag{12}$$

$$I_{P1} = K1 \times I_F \tag{13}$$

$$I_{P2} = K2 \times I_F \tag{14}$$

$$I_{P2} = I_{P1} \times K3 \tag{15}$$

Where: I_{P1} = feedback photocurrent
K1 = feedback gain
P2 = output photocurrent
K2 = output gain
K3 = transfer gain (K2/K1)

With equations 12 and 15, solve for I_{P2}.

$$I_{P2} = \frac{R3}{R4} \times I_L \times K3 \tag{16}$$

The transfer gain can be written from equation 16.

$$\frac{I_{P2}}{I_L} = \frac{R3}{R4} \times K3 \tag{17}$$

The output current, I_{P2}, is converted to a voltage by the trans resistance amplifier U2. The output voltage gain equation is shown below.

$$V_O = I_{P2} \times R5 \tag{18}$$

Combining equations 18 and 17 results in the current loop transfer gain solution, V_O/I_L (equation 19).

$$\frac{V_O}{I_L} = \frac{R3}{R4} \times R5 \times K3 \tag{19}$$

LED CURRENT SHUNT OPERATION

The differential amplifier, U1, provides the control signal to the LED current shunt regulator. U1's output is connected to the gate of an n-channel FET, Q1. This transistor is the control element of the LED current shunt regulator. The regulator consists of a network made up of the series connection of the FET and R1, in parallel with the series connection of the IL300's LED and R2.

The amplifier's output signal controls the FET's drain to source resistance, R_q. As the gate voltage is increased, the FET resistance will decrease causing a larger percentage of the loop current to be diverted away from the LED signal path. Thus a rising control voltage, V_{gs}, causes the LED current to decrease. A Siliconix TN0201L enhancement low-voltage FET was selected as the control device for two reasons. First, with $I_q \leq 20$ mA, the FET's gate voltage should be less than 3 V. The TN0201L control characteristics as a function of loop current are shown in figure 16. Second, the FET's dynamic resistance should be in the same order of magnitude as the IL300's LED dynamic resistance. The dynamic resistance of both the LED and FET are shown in figure 17.

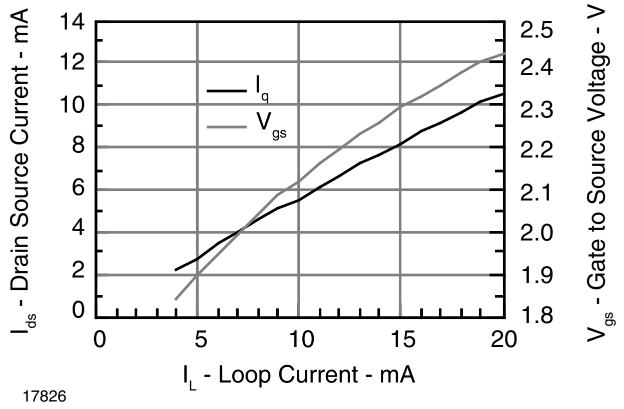

Fig. 16 - TN0201L Gate Voltage vs. Drain Current

Isolated Industrial Current Loop Using the IL300 Linear

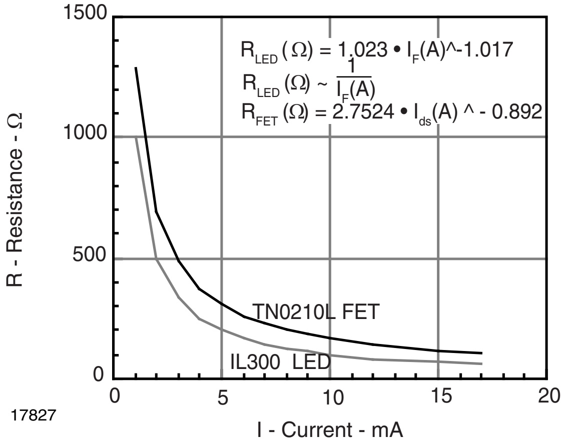

Fig. 17 - Dynamic Resistance vs. Current

The shunt regulator includes a series resistor in each leg of the network. These resistors are included in the design for two reasons: first, to provide a measure of current overload protection for the LED and FET, and second to set the initial control conditions for the network.

The design equations are given below:

$$L = I_q \times I_F \tag{20}$$

$$V_n = I_q \times (R_{FET} + R1) \tag{21}$$

$$V_n = I_F \times (R_{LED} + R2) \tag{22}$$

Where: I_L = loop current
I_q = Q1 drain current
I_F = LED forward current
R_{FET} = Q1 dynamic resistance
R_{LED} = LED dynamic resistance
V_n = Voltage across the control network

Combining equations 20, 21, and 22:

$$I_q \times (R_{FET} + R1) = I_F \times (R_{LED} + R2) \tag{23}$$

Replacing I_q in terms of I_F and setting to zero gives equation 24.

$$0 = R_{FET} - R_{LED} + R1 - R2 \tag{24}$$

The LED and FET dynamic resistance equations are substituted into EQ 24.

$$0 = (2.7524 \times (I_L - I_F)^{-0.892}) - \frac{1}{I_F} + R1 - R2 \tag{25}$$

This transcendental equation is best solved by iterative techniques.

CURRENT LOOP RECEIVER DESIGN

The current loop receiver design is divided into two sections. The first is the shunt regulator; the second is the feedback control amplifier. The shunt regulator design relies on equation 25 and intuitive selection of an LED operating point. The LED forward current is bounded by the loop current range which is 4 mA to 20 mA. The selection of R1 and R2 is determined by solving equation 25 when the LED current, I_F = 10 mA, for a loop current equal to 20 mA. This point is selected to provide sufficient FET current control range given the initial value range of K1 and its temperature dependence. Under the I_F and IL conditions selected, Equation 25 will provide the resistance range for R1 and R2.

$$R2 - R1 = 67\ \Omega \tag{26}$$

Equation 26 shows that R2 is greater than R1, and the recommended difference is 67 Ω. Given this guidance, a 100 Ω resistor is selected for R2. A larger value than the recommended 33 Ω is selected for R1. A 47 Ω resistor is used providing for greater LED current limiting. Given R1 = 47 Ω and R2 = 100 Ω, the LED current is calculated equation 25 at loop current extremes. At I_L = 4 mA, the LED current (I_F) is equal to 1.735 mA, while for a loop current of 20 mA, I_F = 9.42 mA.

The next part of the design is selecting the resistors, R3 and R4, surrounding the feedback control amplifier. Recall that R3 is the loop current sense resistor and should be valued less than 100 Ω. For this design example, R3 = 20 Ω. equation 27 shows the relationship of R4 in terms of circuit variables.

$$R4 = \frac{R3 \times I_L}{I_F \times K1} \tag{27}$$

Figure 18 shows the nonlinear nature of the feedback gain, K1, for the IL300. The worst case condition occurs when the loop current is at its minimum, I_L = 4 mA. Under this condition I_F = 1.75 mA. Figure 14 can be used to determine K1 under these conditions. The figure shows that at I_F = 1.75 mA, K1 equals 0.00475.

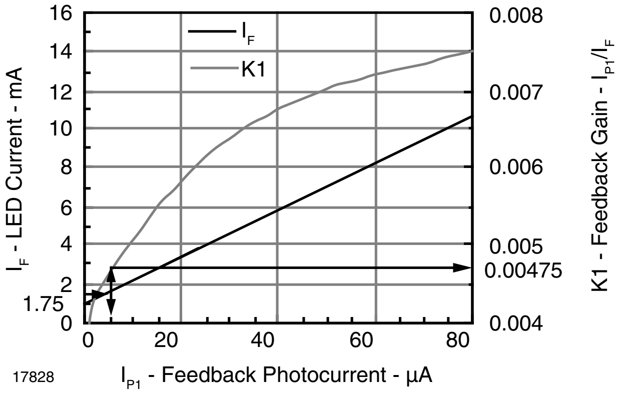

Fig. 18 - LED Current and Feedback Gain vs. Feedback Photocurrent

Substituting these values into equation 27, R4 can be determined.

$$R4 = \frac{20\ \Omega \times 4\ \text{mA}}{1.75\ \text{mA} \times 0.00475} \tag{28}$$

R4 = 9.62 kΩ, a 10 kΩ resistor is selected.

Isolated Industrial Current Loop Using the IL300 Linear

The final section of the design centers on the selection of the trans resistance of the output amplifier shown in figure 19. The feedback resistor (R5) combined with the operation of the output amplifier (U2) converts the IL300's output photocurrent (I_{P2}) into the output voltage (V_o). The output voltage span (ΔV_o) will be 1 V to 5 V, given a loop current span (ΔI_L) of 16 mA.

This relationship substituted into equation 19 can be used to solve for R5.

$$R5 = \frac{\Delta V_O \times R4}{\Delta I_L \times K3 \times R3} \tag{29}$$

$$\Delta V_O = V_{O\,max.} - V_{O\,min.}$$

$$\Delta I_L = I_{L\,max.} - I_{L\,min.} \tag{30}$$

$$R5 = \frac{(V_{O\,max.} - V_{O\,min.}) \times R4}{(I_{L\,max.} - I_{L\,min.}) \times K3 \times R3} \tag{31}$$

$$R5 = \frac{(5\text{ V} - 1\text{ V}) \times 10\text{ k}\Omega}{(20\text{ mA} - 4\text{ mA}) \times 1.0 \times 20\ \Omega} \tag{32}$$

$$R5 = 125\text{ k}\Omega$$

The final circuit of the isolated current loop receiver is shown in figure 19.

The circuit is completed by adding two diodes placed in series with the loop. The diode, D2, is a protection device which will block current flow if the receiver's loop voltage source is improperly connected. The diode, D1, performs two functions:

(1) a visual indicator of loop current flow,
(2) functions as a 2 V drop in the loop.

This voltage drop is needed to provide supply head room for the control of the shunt regulator FET.

RECEIVER PERFORMANCE 4 mA to 20 mA LOOP CURRENT, 1 V to 5 V OUTPUT

The receiver in Figure 19 was constructed and evaluated for accuracy and linearity as a function of input loop current and ambient temperature. The receiver was calibrated by adjusting R6 for 3.00 V output with a loop current of 12.00 mA at $T_A = 23$ °C. Figure 20 shows the percent error deviation from the expected output voltage. This circuit offers a typical accuracy of + 0.8 % to - 0.5 % over a temperature range of 0 °C to 75 °C. Note that the temperature performance appears to follow a linear temperature characteristic. Figure 18 shows a typical temperature coefficient of 175 ppm/°C.

Many industrial controllers have calibration techniques that can compensate for temperature imposed accuracy errors. These techniques are only valid if the receiver exhibits a high degree of linearity. Figure 21 shows the receiver's linearity error as a deviation in parts per million (ppm) from a best fit linear regression at each temperature. Figure 21 shows a typical linearity of + 300 ppm to -1000 ppm over a 0 °C to 75 °C temperature range.

CONCLUSION

Isolated current loops offer the industrial control designer the peace of mind that electrical noise and grounding problems will not influence the sensor signal. This application note has shown the design technique and results to construct a line powered 4 mA to 20 mA current loop receiver.

It also presented two isolated current loop transmitters, one conforming to the 1 V to 5 V input and a second to the 0 V to 5 V input standard.

The performance data in this application note shows that the receiver and transmitter easily conform to a 8 bit operation over a 0 °C to 75 °C operating range.

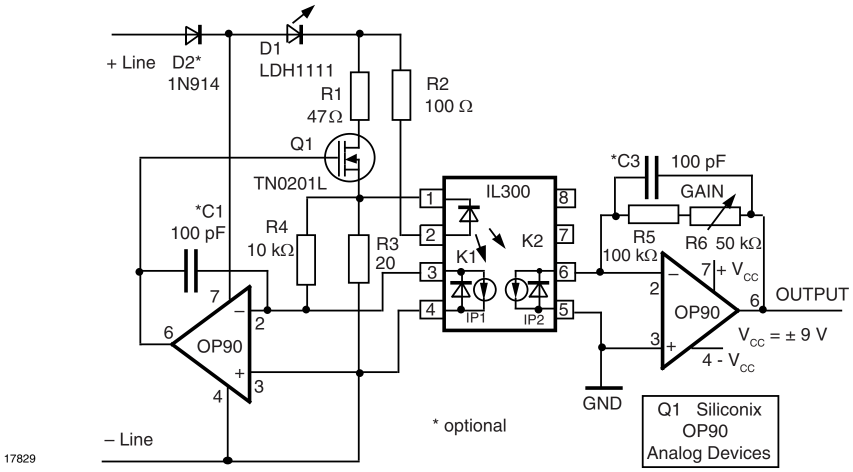

Fig. 19 - Isolated Current Loop Receiver

Isolated Industrial Current Loop Using the IL300 Linear

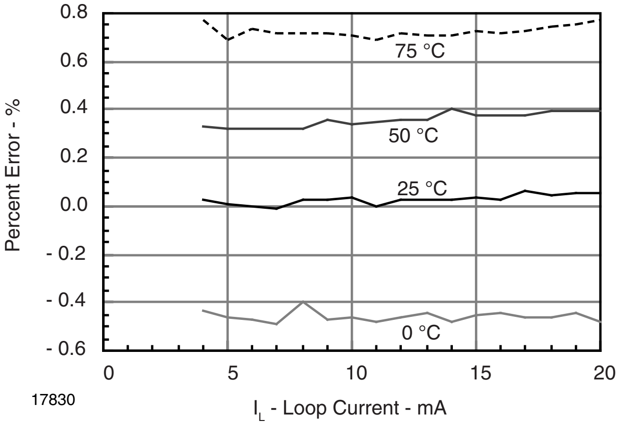

Fig. 20 - Percent Error vs. Loop Current 4 mA to 20 mA Receiver

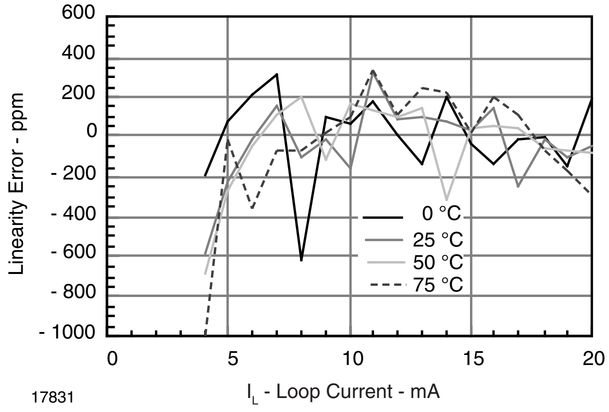

Fig. 21 - Linearity Error vs. Loop Current 4 mA to 20 mA Receiver