Application Report
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PGA900 as a 4- to 20-mA Current Loop Transmitter

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ABSTRACT

This application note shows the PGA900 used as a 2-wire, 4- to 20-mA current loop transmitter, a common method of transmitting sensor information in industrial process-monitoring applications. Transmitting sensor information (physical parameter measurements) through a current loop is particularly useful when the information must be sent to a remote location over long distances (1000 feet or more).

This note describes the configuration of the PGA900 as a loop-powered, 2-wire, 4- to 20-mA transmitter and analyzes the performance. The designer must first determine the minimum available transmitter voltage. With this information, the designer can select the operating Q-point, then an emitter resistor. The added emitter resistor minimizes the impact of the loop components' variation and provides adequate gain of the control loop. This leads to a lower closed-loop frequency and better phase margin.

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1 Introduction

In a 2-wire, 4- to 20-mA transmitter, a sensor measures physical parameters such as temperature, pressure, speed, liquid flow rates, and so forth. Transmitting the sensor information over a current loop is particularly useful when the information must be sent to a remote location over long distances (1000 feet or more).

The current loop's operation is straightforward: a sensor's output voltage is first converted by PGA900 to a proportional current, with 4 mA normally representing the sensor's zero-level output, and 20 mA representing the sensor's full-scale output. Then, a receiver at the remote end converts the 4- to 20-mA current back into a voltage which in turn can be further processed by a PLC, controller, computer, or display module.

Sending a current over long distances produces voltage losses proportional to the wiring's length. However, these voltage losses—also known as loop drops—do not impact the 4- to 20-mA current as long as the transmitter and loop supply can compensate for these drops. The magnitude of the current in the loop is not affected by voltage drops in the system wiring because all of the current originating at the negative (–) terminal of the loop power supply has to return back to its positive (+) terminal.

Adequate phase margin in the control loop is required to achieve stable current loop operation. Low-gain feedback circuitry or improper placement of capacitors can degrade the circuit performance.

2 PGA900 DAC Current Loop DC Characteristics

PGA900 can be configured to work as a loop-powered, 2-wire, 4- to 20-mA transmitter. The on-board 14-bit digital-to-analog converter (DAC) uses an internal reference voltage of 1.25 V. The DAC converts input DAC_REG register code from 0x0000 to 0x3FFF into the equivalent loop current.

Figure 1 shows the principles of PGA900 operation in loop-powered transmitter mode. The circuit details were omitted for clarity. In Figure 1, I_{DD} represents supply (quiescent) currents of the internal digital and analog blocks and the sense element such as resistive bridge and thermocouple.

The DAC, DAC GAIN (the on-board operational amplifier), and external NPN transistor create a control loop. Equation 1 expresses the loop current as a function of the input DAC_REG code.

$$I_{LOOP} = 1001 \frac{1.25\ \text{V}}{40\ \text{k}\Omega} \frac{\text{DAC\_REG}_{\text{CODE}}}{0\text{x}3\text{FFF}} \quad (1)$$

From Figure 1, observe that I_{LOOP} is a sum of two currents:

$$I_{LOOP} = I_{DD} + I_E$$

where only I_E is a value regulated by the control loop to maintain the relationship shown. (2)

The base current of the transistor can be neglected in the analysis due to high DC current gain (for BCP56-16 h_{FE} = 100 – 250).

Because only the magnitude of I_E is controlled, I_{LOOP} has a lower limit. This limit depends on the quiescent current of the sensor transmitter, I_{DD}.

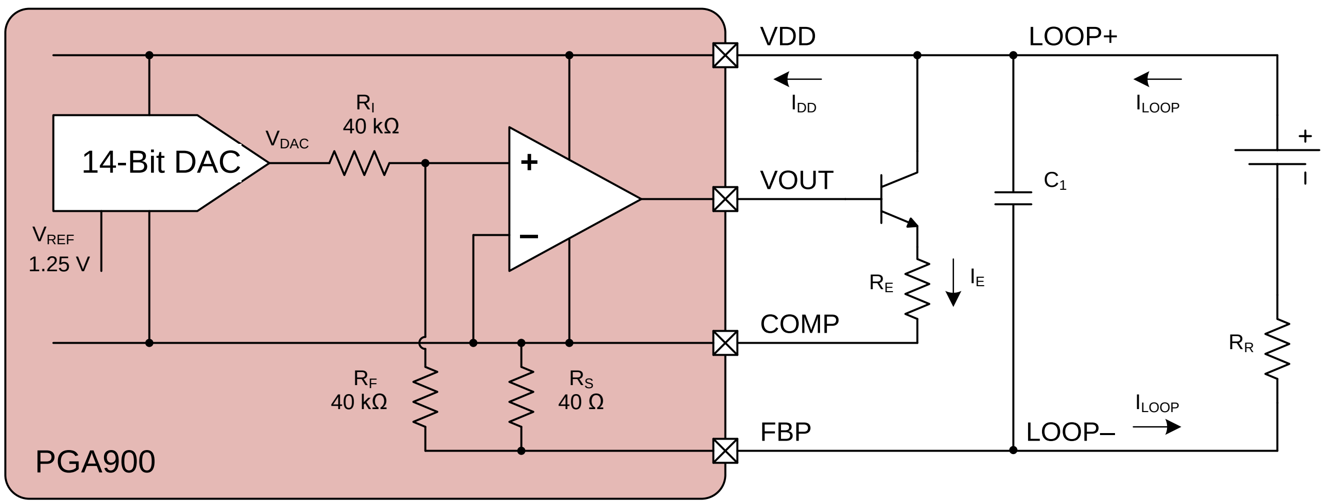

Figure 1. Loop-Powered PGA900 Transmitter

3 DC Input/Output Transfer Function

The output current sourced by the FBP pin of the device is expressed by Equation 1. The valid DAC_REG range is the full 14-bit code space (0x0000 to 0x3FFF), which results in the VDAC range of 0 to approximately 1.25 V. The theoretical maximum output current sourced out of the FBP pin, I_{LOOP}, is 31.28 mA. However, this does not result in the I_{LOOP} range of 0 to 31.28 mA. The minimum output current depends on the system implementation. The last component current, I_E, can be theoretically controlled down to 0 mA, but, due to the stability considerations of the control loop, do not allow I_E to drop below 500 µA.

Figure 2 shows the DAC transfer characteristic of the 4- to 20-mA transmitter, including minimum current limit. In this example, the minimum current limit for the loop-powered transmitter is about 2.6 mA (I_{DD}).

The PGA900 data sheet specifications section lists typical values for I_{DD}. The minimum I_E depends on the BJT device used and control loop stability.

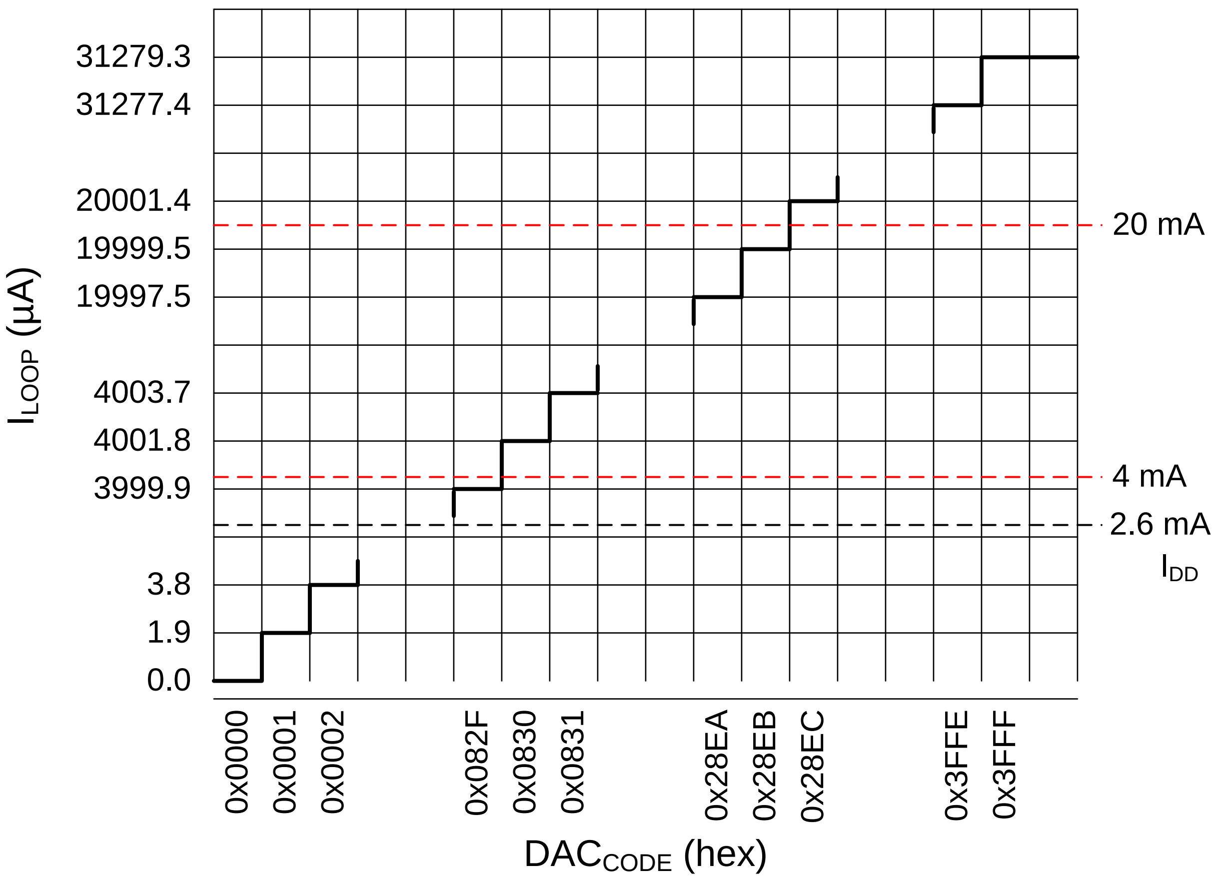

Figure 2. PGA900 DAC Transfer Function

4 AC Characteristics

Use the circuit from Figure 1 to analyze the AC characteristics of the loop drive circuit. From the circuit in Figure 1, assume that the internal PGA900 amplifier dominates the frequency response of the system (UGBW = 1.7 MHz). It has one dominant pole and pole-zero pair at 0.5 mHz, 142 kHz, and 274 kHz, respectively. BJT's response (for BCP56 f_T = 180 MHz) in the bandwidth of the control loop (f_{CL} = 100 – 200 kHz) is assumed to be frequency independent and is characterized by the transconductance (g_m) and the output resistance (r_o). Figure 3 shows small-signal hybrid-π model of BJT and open-loop output impedance (Z_O) and open-loop gain (A_{OL}) of the PGA900 internal operational amplifier.

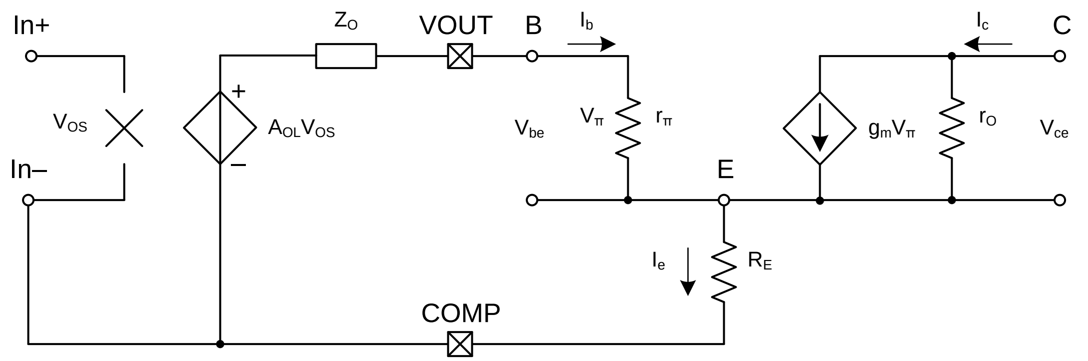

Figure 3. Small-Signal Hybrid-π Model of BJT and PGA900

Components of the small-signal hybrid-π model are directly dependent on the particular Q-point at which the transistor operates. Equation 3 through Equation 5 describe hybrid-π model components.

$$r_\pi = \left.\frac{\partial v_{BE}}{\partial i_B}\right|_{Q-pt} = \frac{V_T}{I_{BO}} = \frac{\beta V_T}{I_{CO}} \tag{3}$$

$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{Q-pt} = \frac{I_{CQ}}{V_T} \tag{4}$$

$$r_o = \left.\frac{\partial v_{CE}}{\partial i_C}\right|_{Q-pt} = \frac{V_T}{I_{CO}} \tag{5}$$

The external emitter resistor, R_E, determines the gain of 1/β and the frequency that the 1/β and A_{OL} curves intersect. Selecting a proper value for R_E reduces the impact of Z_O, r_π, g_m, and the Q-point on the stability of the control loop. R_E values close to zero degrade the system phase margin resulting in high overshoot and ringing.

The first step when selecting the external emitter resistor is to determine the operating Q-point of the selected transistor. To ensure proper operation of OWI communication and to be able to calibrate PGA900, the minimum voltage between V_{DD} and GND must be 4 V. The maximum saturation voltage between V_{DD} and V_{OUT} is 0.2 V. A maximum base emitter saturation voltage of 0.8 V was used for this calculation in Equation 7.

$$R_E = \frac{V_{DD} - V_{CE\_sat} - V_{BE\_max}}{I_{OUT\_max}} \tag{6}$$

Using these values, calculate R_E.

$$R_E = \frac{4\text{ V} - 0.2\text{ V} - 0.8\text{ V}}{20\text{ mA}} = 150\ \Omega \tag{7}$$

Based on the calculated R_E value, a load line can be plotted over the I_C vs V_{CE} graph for the selected transistor, in this case the BCP56-15, as shown in Figure 4. The transistor provides the difference between the 4- to 20-mA loop current and the 2.6-mA quiescent current of the transmitter. Therefore, the transistor emitter current will vary from 1.4 to 17.4 mA and the V_{CE} voltage will vary from 3.8 to 1.4 V.

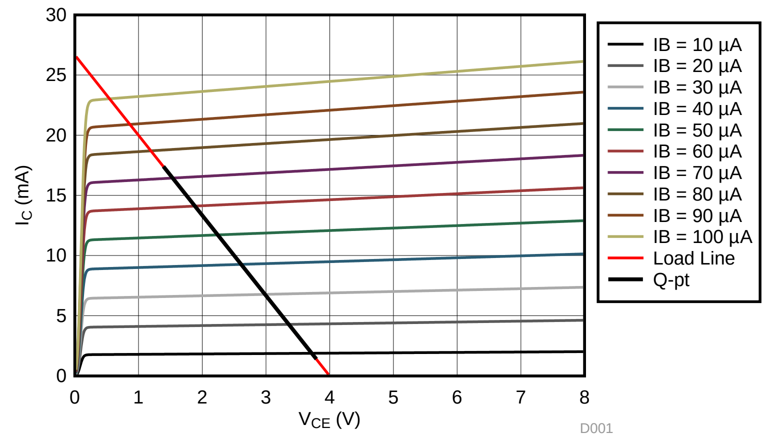

Figure 4. BCP56-16 DC Load Line for the Common Collector Circuit Used for 4- to 20-mA Transmitter

From Figure 1, observe that the emitter resistor is part of the feedback network. This resistor impacts the closed-loop gain of the amplifier. Selecting a value of 150 Ω creates 1/β of 18 dB, the amount of the output voltage fed back to the feedback point. Figure 5 shows the gain and phase of the PGA900 DAC gain operational amplifier.

From Figure 5, observe that 1/β crosses the A_{OL} curve at 210 kHz. The loop-gain phase margin at the crossing frequency is 75°. This direct relationship between phase margin and overshoot is shown in Figure 6. For a high phase margin, the operational amplifier output overshoot will be negligible.

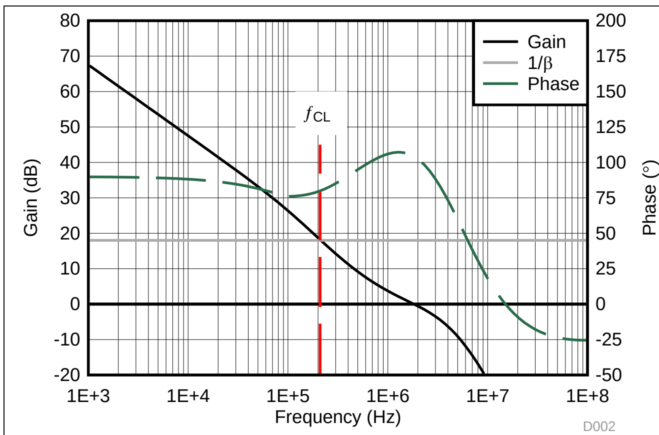

Figure 5. Gain and Phase of the PGA900 Current Loop Transmitter With R_E = 150 Ω

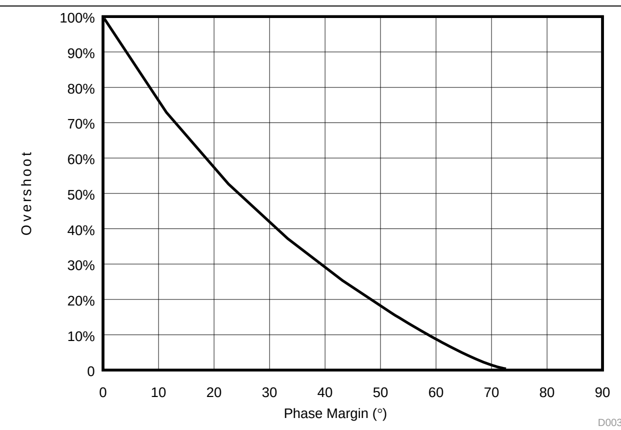

Figure 6. System Overshoot vs Phase Margin

4.1 Simulated Results

Figure 7 displays the simulated results when a small-signal step response is applied to the inputs of the DAC gain operational amplifier. The operational amplifier output quickly settles to the final value with minimal overshoot and ringing which correlates to the high phase margin measured previously. Figure 8 shows the simulated large-signal response of the circuit. The current loop response depends on the value of the decoupling capacitor and loop load resistance.

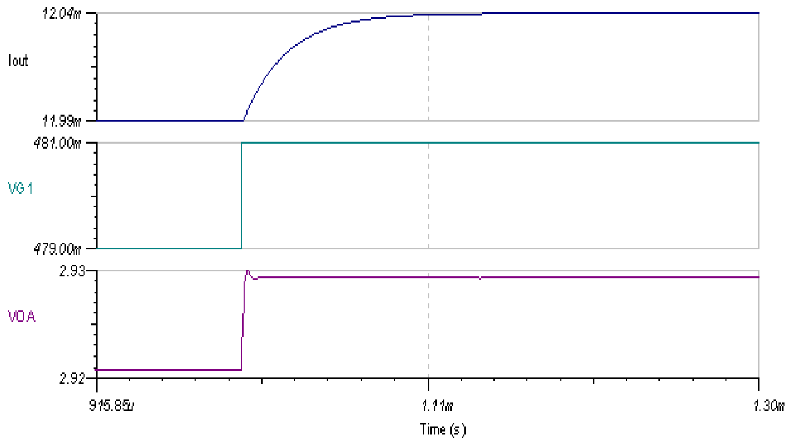

Figure 7. Small-Signal Response of the PGA900 Current Loop Transmitter With R_E = 150 Ω

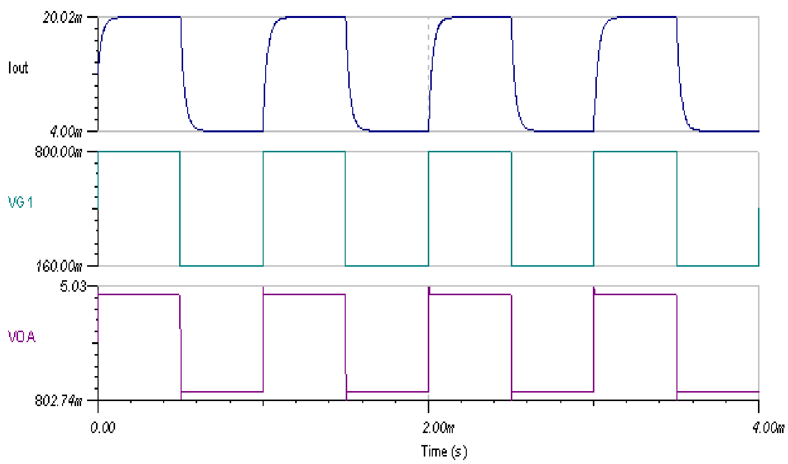

Figure 8. Large-Signal Response of the PGA900 Current Loop Transmitter With R_E = 150 Ω

4.2 Measured Results

Figure 9 shows the measured large-signal step response.

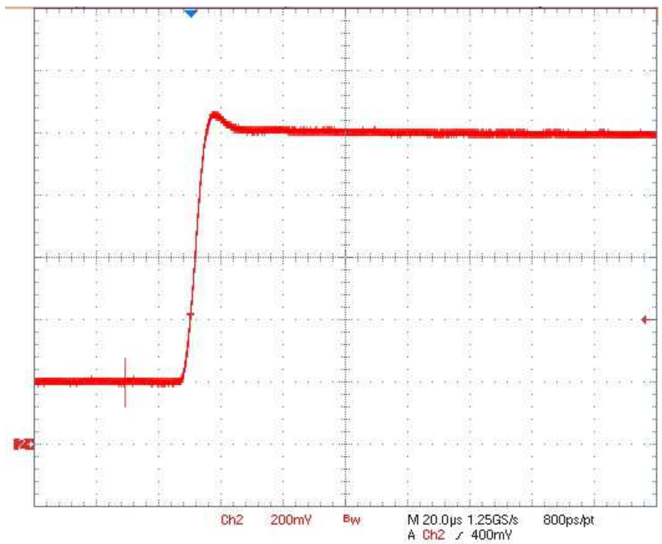

Figure 9. Large-Signal Step Response, 4- to 20-mA Measured at R_S

5 Recommendations from the Analysis

This analysis needs to be performed using the minimum loop voltage. The closed loop response does not change when the supply voltage increases from the minimum value to the maximum value of 30 V. TI recommends using the largest possible emitter resistance for the specified minimum supply voltage. Take special care not to add capacitors between VDD and GND or DACCAP and GND. The addition of one or both of these capacitors adds an unwanted zero in the feedback loop and causes stability problems. TI recommends to add a capacitor between Loop+ and Loop– or between VDD and FBP to minimize the effects of loop noise on the PGA900. As this capacitor is out of the PGA900 current control loop, it does not impact system stability. This analysis used a general-purpose BCP56-16 NPN transistor. Using similar transistors like 2N2222 does not change the design procedure and response results.

6 Conclusion

PGA900 is designed to operate as a 2-wire current loop transmitter. The designer must first determine the minimum available transmitter voltage. Based on that, proper selection of the operating Q-point leads to selecting an emitter resistor. The added emitter resistor minimizes the impact of the loop components' variation and provides adequate gain of the control loop. This leads to lower closed-loop frequency and better phase margin. Small-signal and large-signal step response exhibit quick settlement to the final value with minimum overshoot.

7 References

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