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REFERENCE SCHEMATIC 5610

High-Performance, High-Accuracy 4-20mA Current-Loop Transmitter Meets Toughest Industrial Requirements

By: Yuriy Kurtsevoy, Strategic Applications Enginee
Stuart Smith, Product Definer
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Abstract: This reference design shows how to develop a high-performance, high-voltage 2- or 3-wire 4–20mA current-loop transmitter suitable for industrial process control and smart sensors. Error analysis and overtemperature characterization data as well as hardware design and software are provided.

A similar version of this article appeared in the August 2013 issue of *EE Times China* and the November 2013 issues of *EDN Europe* and *ELEKTRONIK*.

Associated 4–20mA transmitter design calculator (XLSX) is available for download.

Introduction

The 4–20mA current loop has been widely used as an analog communication interface in industrial applications. It facilitates transmission of data from remote sensors over a twisted-pair cable to a programmable logic controller (PLC) in a control center. Simplicity, reliable data transfer over long distances, good noise immunity, and low implementation cost make this interface well suited for long-term industrial process control and automated monitoring of remote objects.

To no one's surprise, industry is evolving just like all electronic applications today. It has more stringent demands. There are new requirements for higher accuracy, lower power, reliable operation over an extended -40°C to +105°C industrial temperature range, added security and system protection, and implementation of the digital Highway Addressable Remote Transducer (HART®) protocol. Collectively, these requirements make the design of today's 4–20mA current loop quite challenging.

This reference design explains how to develop a 4–20mA current-loop transmitter, analyze its performance, and select the components that meet rigorous industrial requirements. Test data for error analysis, overtemperature characterization data, schematics, and analysis software are provided.

Principles of Operation and Key Design Parameters

We start by focusing on the new reference design. The block diagram in **Figure 1** shows the high-performance, low-power, 4–20mA current-loop transmitter that reduces component count and yields the best results for price versus performance.

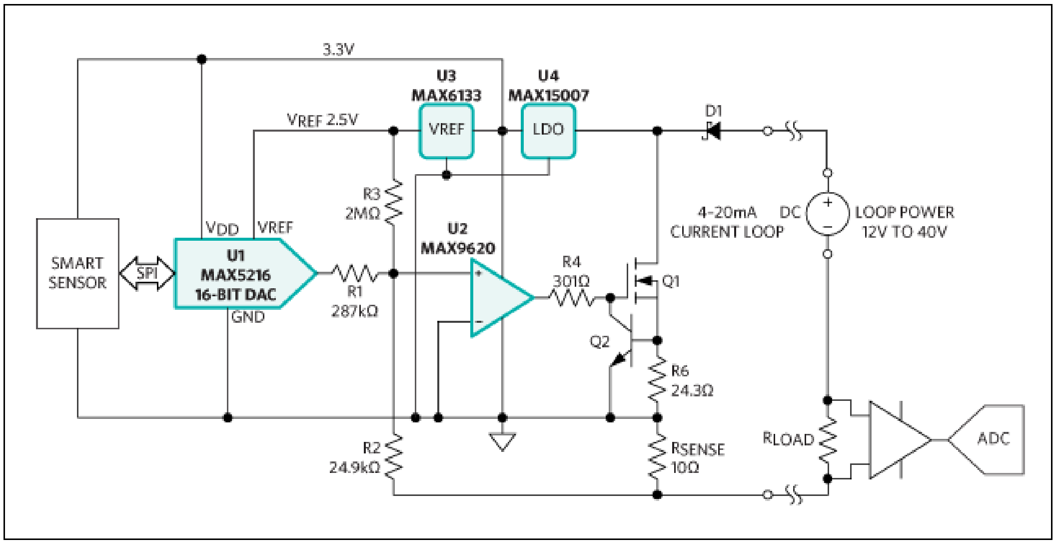

Figure 1. Reference design for a 4–20mA loop-powered transmitter features the MAX5216 16-bit DAC (U1), the MAX9620 op amp (U2), the MAX6133 voltage reference (U3), and the MAX15007 LDO (U4).

This reference design uses low-power, high-performance components that provide less than 0.01% at 25°C and less than 0.05% over the temperature range for the industry's most demanding 4–20mA current loop. The design features the MAX5216, a low-power 16-bit DAC (U1); the MAX9620, a zero-drift rail-to-rail input/output (RRIO), high-precision op amp (U2); the MAX6133, a voltage reference (U3); and the MAX15007, a 40V low-quiescent-current LDO (U4).

The U3 voltage reference provides low noise, low temperature drift of 5ppm/°C (max) and a precise 2.500V for U1. The smart sensor microcontroller commands U1 through a 3-wire SPI bus. The U1 output is divided and converted to the loop current by the Q1 power MOSFET, 10Ω (±0.1%) sense resistor (R_{SENSE}), and U2. The U1, U2, and U3 devices are powered by U4, which is powered directly from the loop. There is a current-limiting circuit made with Q2, a BJT transistor, and a sense resistor (R6). This circuitry limits the loop current to approximately 30mA, which prevents runaway conditions and any damage to an ADC on the PLC side. The Schottky diode (D1) protects the transmitter from reverse current flow.

Observations About Design Performance

The reference design operates at low power. The maximum current consumption of the selected components is less than 200µA at +25°C and less than 300µA over the -40°C to +105°C temperature range. The U2 op amp has a 25µV (max) zero-drift input offset voltage over time and temperature, so it is ideal for the accuracy and stability requirements of the application. The 10Ω current-sense resistor allows operation with a low loop supply voltage; its smaller resistance dissipates less power and allows the use of a smaller package, which further shrinks this transmitter. For example, if only a 10Ω R_{SENSE} and 10Ω load are present, then the maximum voltage drop on them at 30mA is 600mV. The U4 LDO requires only 4V for proper operation with a 3.3V output, and the total minimum loop supply can be as low as 5V. However, if the PLC load is 250Ω, then the minimum loop supply must be 4V + 30mA × (10 + 250)Ω = 11.8V.

Note that to determine a more accurate estimation of the minimum loop supply voltage, the loop cable resistance must also be considered.

During testing, the output exhibited approximately 1.7mV$_{RMS}$ noise over a 249Ω load resistor at the 4mA loop current, which corresponds to 9.5µA peak-to-peak noise at 10Ω. Increasing the value of the R_{SENSE} resistor will increase power dissipation and a minimum loop supply voltage, but it will also reduce noise on the loop. This is a trade-off that the user can control.

The U2 op amp tracks the voltage drop across R2 and R_{SENSE}, and maintains 0V at both of its input nodes. The following equations are used for this circuitry:

$I_{OUT} = I(R2) \times R2/R_{SENSE}$ (Eq. 1)

$I(R2) = I(R1) + I(R3)$ (Eq. 2)

Where I_{OUT} is the loop current, I(R2) is the current flowing through R2, I(R1) is the current flowing through R1, and I(R3) is the current flowing through R3. In Equation 2, we assume that the input current to IN+ and IN- of U2 is 0. Following Equations 1 and 2, the initial loop current of 4mA is set by the I(R3) current while I(R1) is 0. Therefore:

$I_{OUTINIT} = I(R3) \times R2/R_{SENSE}$ (Eq. 3)

Current through R3 is equal to the U3 voltage reference output divided by R3. Equation 3 can be overwritten as:

$I_{OUT\_INIT} = V_{REF}/R3 \times R2/R_{SENSE}$ (Eq. 4)

According to the Namur NE43 recommendations for failure information transmitted over a 4–20mA current loop, the signal range for measurement information is from 3.8mA to 20.5mA, allowing for a small amount of linear overrange process readings. In some cases when additional failure conditions are defined, an even larger dynamic range is required for the loop current, for example, from 3.2mA to 24mA. Thus, selecting R2 = 24.9kΩ, I_{OUT_INIT} = 3.2mA, and solving Equation 4 for R3 yields:

$R3 = V_{REF} \times R2/(R_{SENSE} \times I_{OUTINIT}) = 2.5 \times (24.9 \times 10^{3})/(10 \times 3.2 \times 10^{(-3)}) = 1.945 \times 10^{6}(\Omega)$ (Eq. 5)

A 1.945MΩ resistor is costly and, perhaps more important, not well suited either for automated production or for easy field calibration. Therefore, it is preferable to use a regular 1% tolerance resistor and regain accuracy by calibrating out the 4mA offset current and the 20mA full-scale current with the U1 DAC. In this case, some digital codes are needed for calibration to ensure the required accuracy. Thus, $I(R1) = V_{DAC}/R1$, where V_{DAC} is the U1 DAC output voltage. This can be rewritten as:

$I(R1)= (V_{REF} \times code)/(65535 \times R1)$ (Eq. 6)

And:

$I(R3) = V_{REF}/R3$ (Eq. 7)

Finally, Equation 1 can be rewritten as:

$I_{OUT} = V_{REF} \times [code/(65535 \times R1) + 1/R3] \times R2/R_{SENSE}$ (Eq. 8)

Error Analysis and Performance Optimization

Transmitter Error at +25°C

Table 1 presents the error analysis of the passive components and V_{REF} in the 4–20mA current-loop transmitter at +25°C. Data are based on Equation 8. This table is available for download as an Excel file. To find the appropriate codes for 4mA, 20mA, and 24mA I_{OUT}, use What-If Analysis/Goal Seek… in the Data Tools group on the Data tab of the Excel application ribbon (i.e., toolbar).

Table 1. 4–20mA Current-Loop Transmitter Error Analysis					
	Tolerance (±%)	**Min**	**Nominal**	**Max**	
V_{REF}	0.04	2.4990	2.5000	2.5010	V
R1	0.1	286.71	287	287.29	kΩ
R2	0.1	24.88	24.9	24.92	kΩ
R3	1	1980.00	2000	2020.00	kΩ
R_{SENSE}	0.1	0.00999	0.0100	0.01001	kΩ
Tolerance (±%)		**Min**	**Nominal**	**Max**	
Zero-scale DAC code		0	0	0	dec
Zero-scale I_{OUT}		3.07430	3.11250	3.15149	mA
4mA DAC code		2806	2682	2555	dec
4mA I_{OUT}		3.99984	4.00015	3.99999	mA
Full-scale DAC code		65535	65535	65535	dec
Full-scale I_{OUT}		24.69058	24.8024	24.91527	mA
20mA DAC code		51314	51025	50734	dec
20mA I_{OUT}		19.99988	20.00007	19.99995	mA
4mA error		-0.00410	0.00381	-0.00016	%FS
20mA error		-0.00061	0.00035	-0.00026	%FS
24mA I_{OUT} DAC code		63441	63111	62779	dec
24mA I_{OUT}		23.99989	24.00013	24.00002	mA

Thus, having the standard 1% tolerance 2MΩ R3 resistor and setting the U1 DAC to 2682 decimal code, the initial loop current of 4.00015mA is maintained. Note that the total calculated error is much less than the tolerance of the individual components because their errors are calibrated out by the high-resolution U1 DAC.

The effective number of bits (ENOB) of a 4–20mA current-loop transmitter can be calculated as:

ENOB = (LOG(20mA DAC code - 4mA DAC code))/(LOG(2)) (Eq. 9)

Based on the data from Table 1, the ENOB is equal to 15.56 bits. So, dropping less than 0.5 bit of the total resolution allows the calibration process to be automated and lowers the number of expensive precision components.

The selected resistors in Table 1 cover the current loop's dynamic range from 3.2mA up to 24.6mA. Different combinations of R1, R2, R3, and R_{SENSE} can shrink the dynamic range. Close attention should be paid to the temperature coefficients (TC) for each resistor.

Transmitter Error Overtemperature Analysis

The overtemperature error analysis of the passive components and V_{REF} is shown in **Table 2**.

Table 2. Temperature Error Analysis of the 4–20mA Current-Loop Transmitter					
	TC (±ppm/°C)	Min	Nominal	Max	
V_{REF}	5	2.4991	2.5000	2.5009	V
R1	10	286.7919	287	287.2081	kΩ
R2	25	24.8549	24.9	24.9451	kΩ
R3	100	1985.5000	2000	2014.5000	kΩ
R_{SENSE}	10	0.00999	0.0100	0.01001	kΩ
		Min	Nominal	Max	
Zero-scale DAC code		0	0	0	dec
Zero-scale I_{OUT}		3.08114	3.11250	3.14433	mA
4mA DAC code		2806	2682	2555	dec
4mA I_{OUT}		4.00647	4.00015	3.99302	mA
Full-scale DAC code		65535	65535	65535	dec
Full-scale I_{OUT}		24.69253	24.8024	24.91297	mA
20mA DAC code		51314	51025	50734	dec
20mA I_{OUT}		20.00289	20.00007	19.99655	mA
4mA error		0.04047	0.00095	-0.04362	%FS
20mA error		0.01807	0.00044	-0.02157	%FS
24mA I_{OUT} DAC code		63441	63111	62779	dec
24mA I_{OUT}		24.00199	24.00013	23.99751	mA

The following formulas are used to calculate the minimum and maximum resistance thermal drift:

$$R(T) = R_{NOM} \times (1 \pm (TC \times \Delta T)/(2 \times 10^6)) \quad \text{(Eq. 10)}$$

$$V_{REF}(T) = V_{REFNOM} \times (1 \pm (TC \times \Delta T)/(2 \times 10^6)) \quad \text{(Eq. 11)}$$

Where TC is the temperature coefficient in ppm/°C and ΔT is the total temperature range of 145°C.

As can be seen from Table 2, the 0.05%FS error is achievable with the following TC for R1, R2, R3, and R_{SENSE}:

R1 = 287kΩ ±0.1%, 10ppm/°C
R2 = 24.9kΩ ±0.1%, 25ppm/°C
R3 = 2MΩ ±1%, 100ppm/°C
R_{SENSE} = 10Ω ±0.1%, 10ppm/°C

Note that total error is the square root of the sum of the squares of each source of error: the component's tolerance, temperature coefficient, measurements, etc.

If a smart sensor consumes more than 3.4mA, it cannot be used as part of a loop-powered 2-wire transmitter. This happens, for example, when a microcontroller or ADC consumes more than 3mA or when a sensing element requires a higher supply current to increase its dynamic range and/or resolution. In such cases, the extra current has to flow through an additional third wire. This configuration, called a 3-wire transmitter, can be modified, as shown in **Figure 2**. This design makes it universal as a 2- or 3-wired smart sensor transmitter.

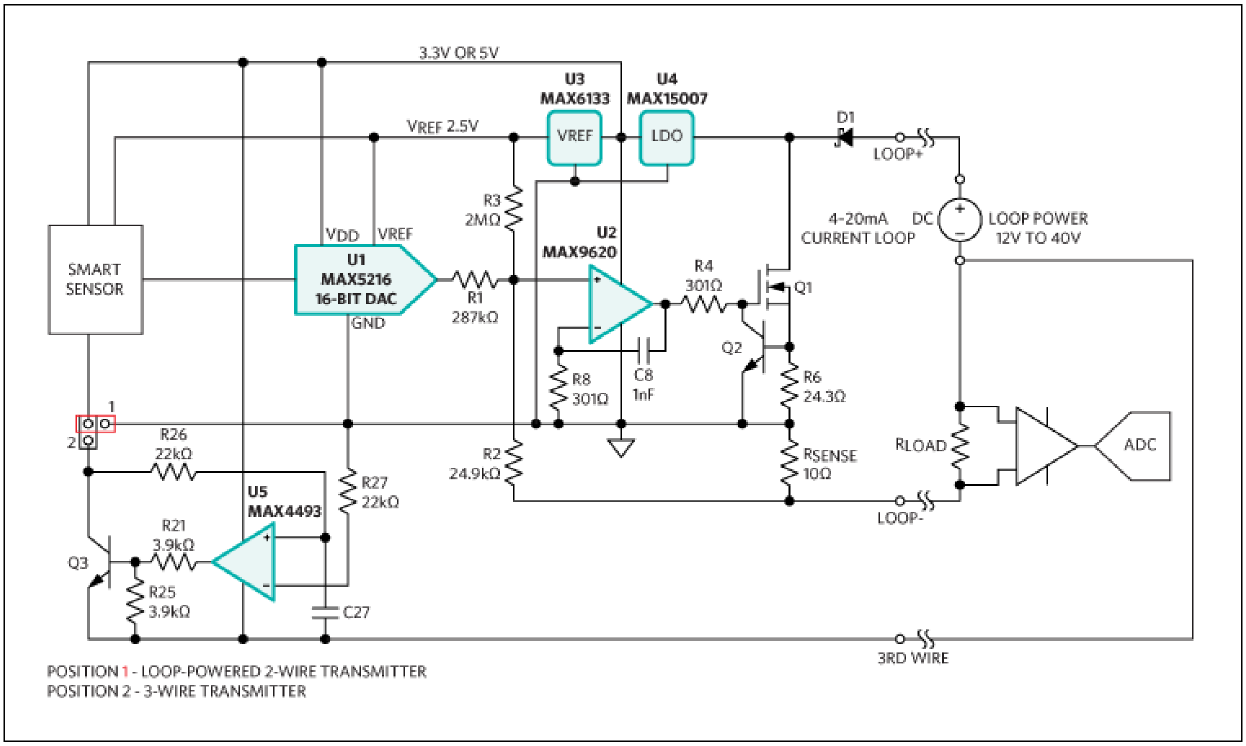

Figure 2. Block diagram for a universal 2- or 3-wire smart sensor transmitter.

The U5 op amp and Q3 buffer in Figure 2 are sensing the virtual ground, continuously maintaining the common point for the smart sensor and keeping it at the constant voltage of the U4 output. The U5 op amp must be capable of accepting a maximum supply voltage of 12V with a PLC R_{LOAD}/sense resistor value up to 250Ω. The C8 and R8 negative feedback network stabilizes the loop current and assures stability for all normally expected loading conditions.

Selecting the Power Transistor and Protection Components

There are no special requirements for the Q1 power transistor. It could be either a MOSFET or a bipolar power transistor that satisfies maximum safe operating area criteria. For example, if the loop power supply is 36V and the highest limiting current is 35mA, then the maximum dissipation requirement is 1.26W. Close attention should be paid to proper layout, trace width, and the heatsink capabilities of the PCB.

The Schottky diode (D1) (see Figure 1) is a safety device to prevent any damage to the transmitter from reverse current flow. In addition, a transient voltage suppressor (D2, not shown in the block diagram) can be added between the LOOP+ and LOOP- inputs to protect from overvoltage surge conditions. The requirements for D1 and D2 depend on the safety standards of the application.

Testing the Design

A 4–20mA loop-powered transmitter evaluation (EV) kit, the MAX5216LPT, was built and characterized with a 1000ft 22-gauge shielded communication cable and load resistor of 249Ω ±0.1%. The loop current was measured with an Agilent® HP3458A DVM as the voltage drop across that load resistor. The characterization data from the MAX5216 DAC are presented in **Figures 3** to **9**. Refer to the MAX5216LPT EV kit data sheet for more information about components and board layout.

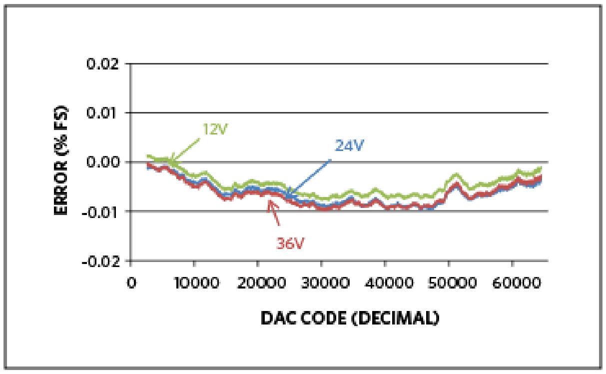

Figure 3. Transmitter error at 25°C. Data for the MAX5216 DAC.

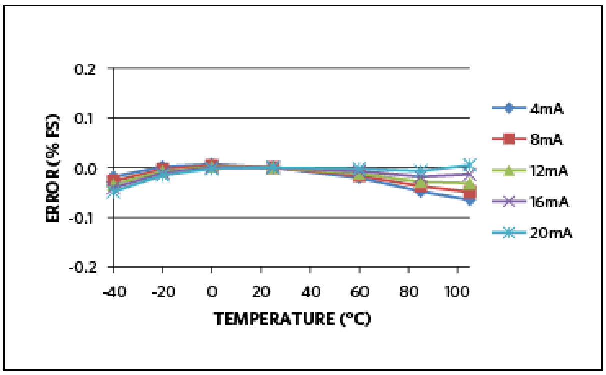

Figure 4. Transmitter error change versus temperature with a 12V loop supply.

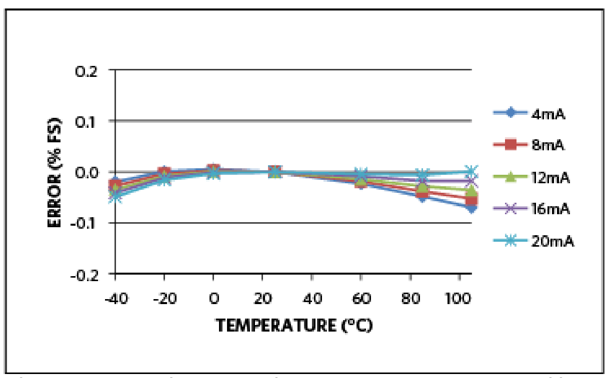

Figure 5. Transmitter error change versus temperature with a 24V loop supply.

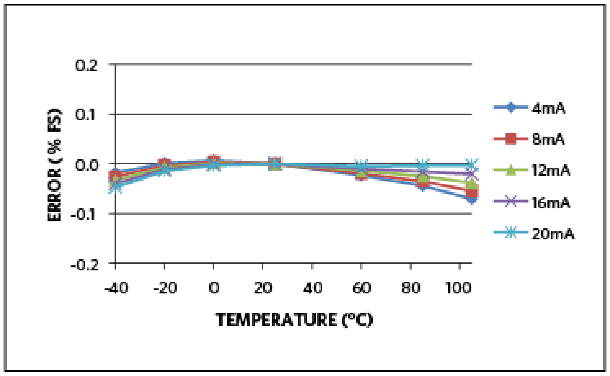

Figure 6. Transmitter error change versus temperature with a 36V loop supply.

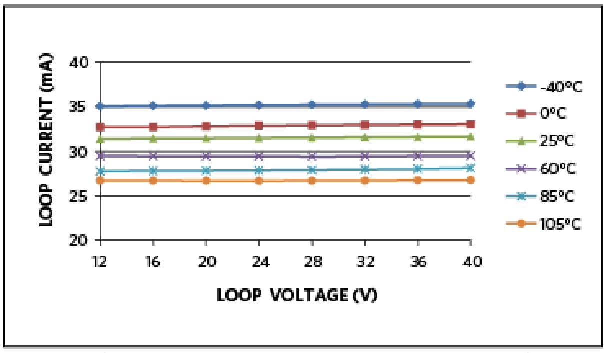

Figure 7. Current limit versus loop voltage with a 24.3Ω sense resistor.

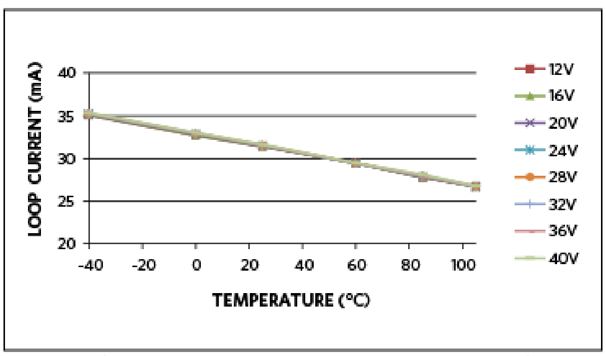

Figure 8. Current limit versus temperature with a 24.3Ω sense resistor.

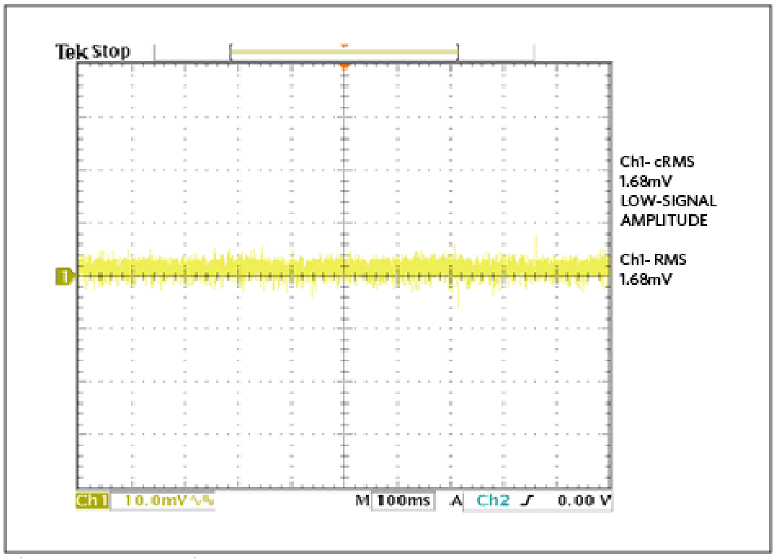

Figure 9. Output noise.

This transmitter reference design also supports the HART protocol. It allows simple connection with a HART modem such as the DS8500 (see **Figure 12**). **Figures 10** and **11** show HART signals over a 1000ft 4–20mA current loop with a 249Ω load resistor.

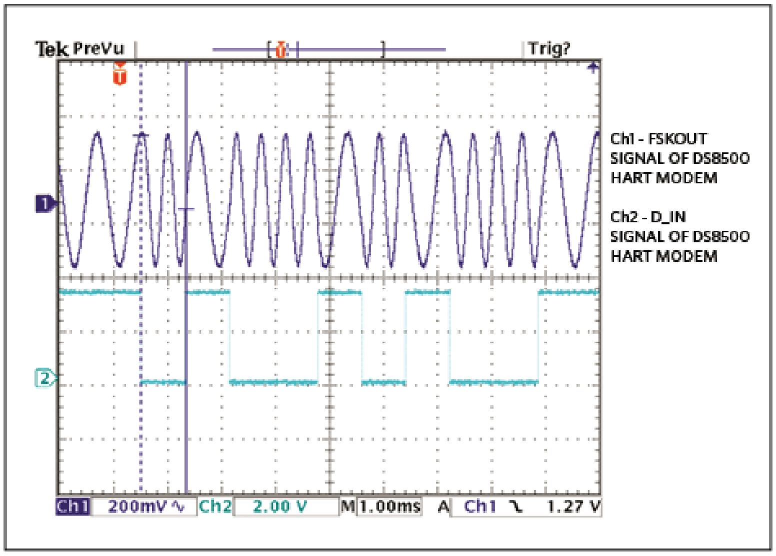

Figure 10. HART communication over a 4–20mA current loop.

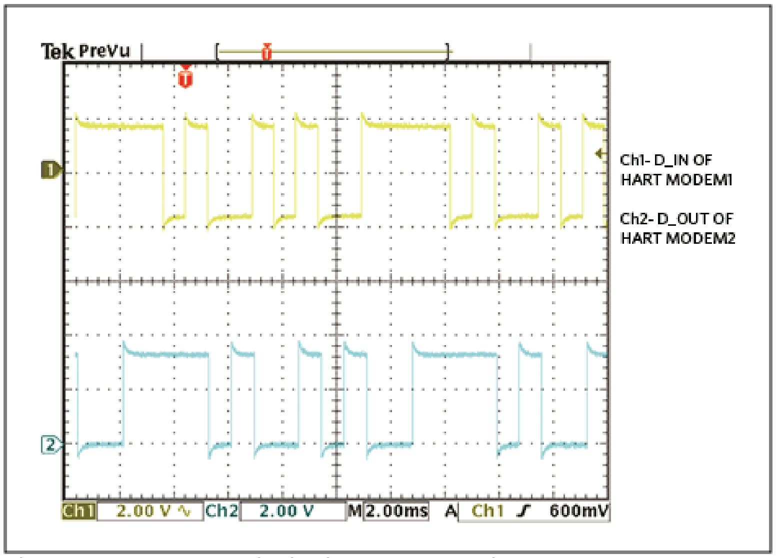

Figure 11. HART communication between two modems.

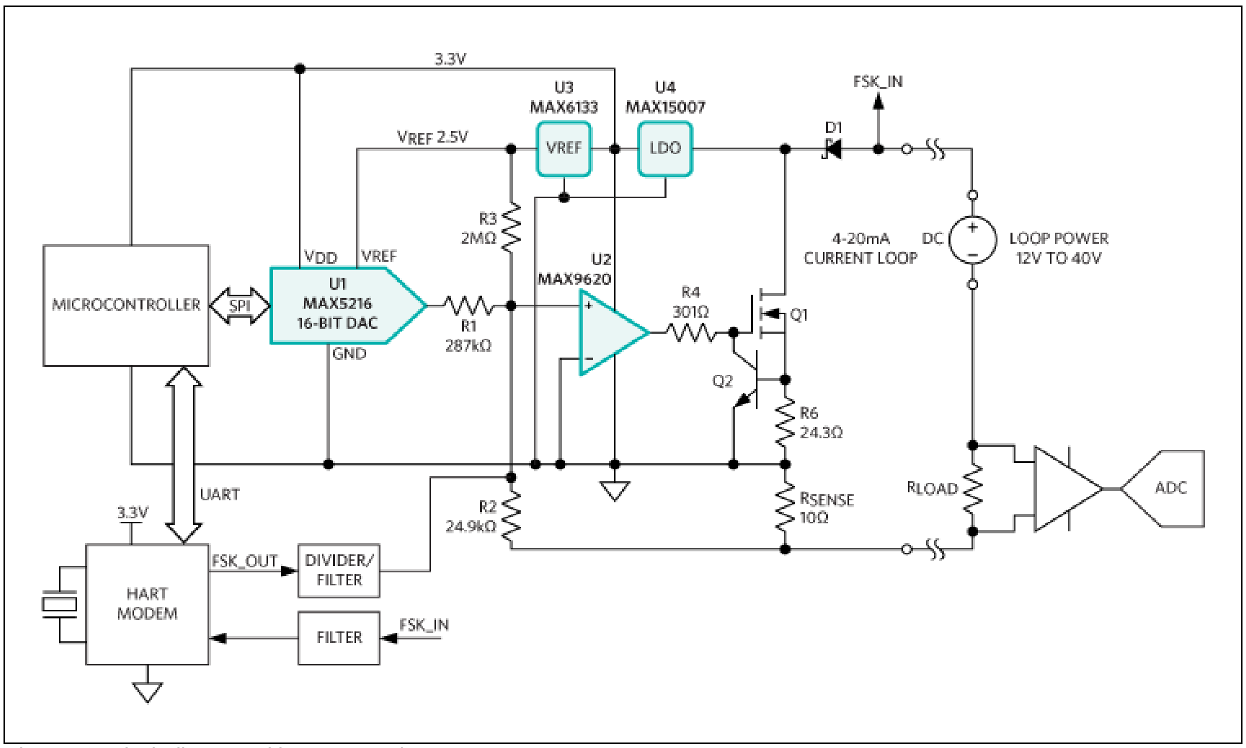

Figure 12. Block diagram with HART modem.

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Related Parts		
DS8500	HART Modem	Free Samples

MAX15007	40V, Ultra-Low Quiescent-Current Linear Regulators in 6-Pin TDFN/8-Pin SO	Free Samples
MAX5216	14-/16-Bit, Low-Power, Buffered Output, Rail-to-Rail DACs with SPI Interface	Free Samples
MAX6133	3ppm/°C, Low-Power, Low-Dropout Voltage Reference	Free Samples
MAX9620	High-Efficiency, 1.5MHz Op Amps with RRIO	Free Samples

More Information
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REFERENCE SCHEMATIC 5610, AN5610, AN 5610, APP5610, Appnote5610, Appnote 5610