Designing 4mA to 20mA loop-powered transmitters

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Introduction

In any process control system, sensor transmitters collate data from pressure and temperature to flow and level, and relay this information to the programmable logic controller (PLC) or distributed control system.

These transmitters depend on the 4mA to 20mA signal to transmit data to the controller. Despite the emergence of standards such as IO-Link and Profibus, 4mA to 20mA offers resiliency over long distances, reliability, immunity to noise, and universal compatibility with every PLC system.

In this article, I will provide an overview of the 4mA to 20mA transmitter structure, its operating principles, and design alternatives for implementing this transmitter type using catalog semiconductor products.

4mA to 20mA transmitter basics

4mA to 20mA transmitters are classified by power and number of wires: four, three and two wire. In this article, I will focus on the two-wire type.

The two-wire field transmitter in **Figure 1** forms a current loop by connecting to a field supply and analog input module. The first subsystem in the field transmitter is the sense subsystem, which connects to the physical sensor, conditions its output, and converts the signal to a digital code for processing, including linearization and calibration. The second subsystem is the transmit subsystem, which powers the transmitter by extracting power from the loop, sends process data by converting the digital signal back to an analog signal, and controls the loop current. The transmitter transmits the signal by regulating current within the loop, acting as a voltage-controlled current source.

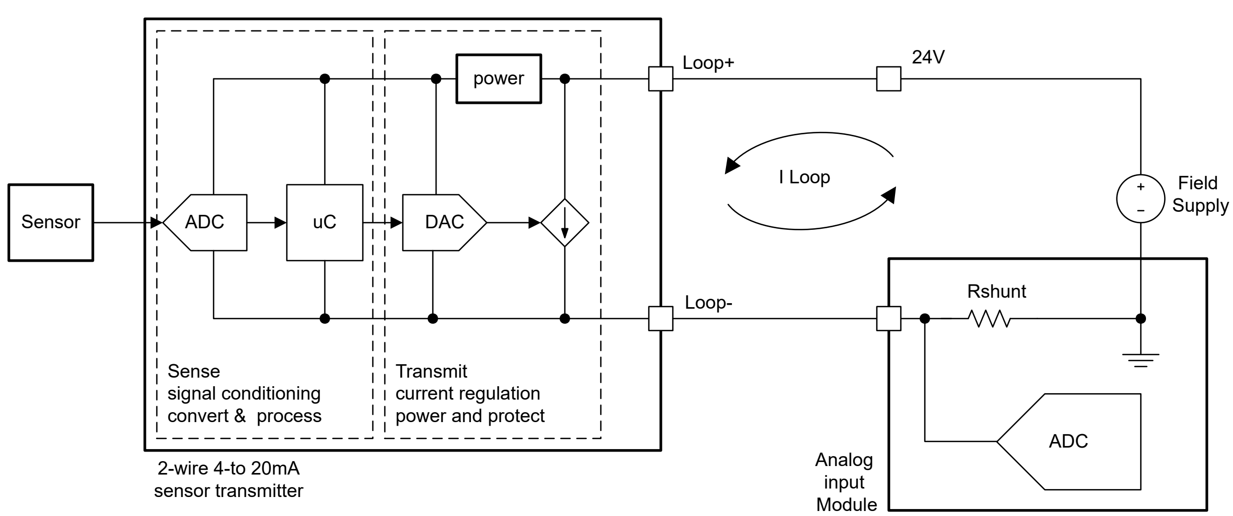


Figure 1. *Generic two-wire 4mA to 20mA sensor transmitter.*

In **Figure 2**, an N-channel P-channel N-channel (NPN) transistor sources and regulates the current, whose base is controlled through an amplifier driven by a digital-to-analog converter (DAC). A wide input voltage low-dropout (LDO) regulator powers the different components by stepping down the loop voltage to the transmitter supply level. You can use a voltage reference if the DAC does not have an integrated reference, while Highway Addressable Remote Transducer (HART)-enabled transmitters require a HART modem.

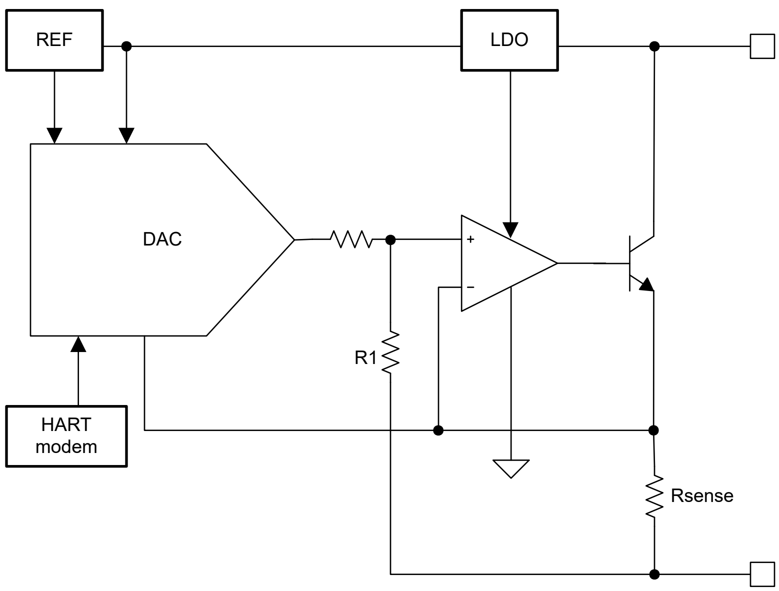


Figure 2. *Two-wire 4mA to 20mA transmitter circuit.*

The principle of operation is pretty simple: hold both inputs of the operational amplifier at virtual local ground. Whatever voltage R1 holds, Rsense also holds. With proper scaling, Rsense carries a scaled version of the R1 current. Given that Rsense current is nearly the whole current of the field transmitter (even for the sense part, not depicted in **Figure 2**), the DAC output controls the whole transmitter current. The NPN transistor and amplifier loop bypass the necessary current to complement any current used by the transmitter itself in order to achieve the required output current.

4mA to 20mA transmitter design aspects

4mA to 20mA transmitter design considerations include:

- Low-power operation.
- A small footprint.
- Accuracy and low noise over the entire industrial temperature range.
- HART protocol support.
- Low cost.

Design performance metrics

There are several transmitter performance metrics to evaluate:

Loop Compliance Voltage is the range of the loop voltage at which the transmitter is functioning. It is mainly determined by LDO limits and affected by series elements within the loop, including protection devices. The typical loop compliance voltage range is 12V to 36V.

Resolution is the number of distinct current output values that the transmitter can generate and is directly linked to the DAC native resolution. Commercial 4mA to 20mA transmitters have resolutions between 12 bits and 16 bits.

Linearity error is mostly determined by the DAC's integral nonlinearity, which is the maximum error (in least significant bits [LSBs]) over the whole output range.

Noise is measured by the root-mean-square (RMS) of output noise current. This noise can render some of the output level indistinguishable, reducing the effective resolution. Effective resolution in this context is a measure of noise performance. For 16-bit-resolution systems, effective resolution between 13 bits and 15 bits is expected, depending on signal bandwidth.

Accuracy measures the deviation of the current output from the ideal current value. This includes the RMS sum of offset errors, gain errors and nonlinearity error, plus the temperature drifts of these values. Total unadjusted error indicates the level of inaccuracy.

Dynamic performance includes signal bandwidth and transmitter stability. Bandwidth refers to the maximum current signal bandwidth that can be transmitted over the loop. This bandwidth is determined by the DAC settling time and amplifier circuit bandwidth, as well as the transconductance of the bypass transistor. Using a degeneration resistor eliminates the dependence on variation of the transistor transconductance (g_m). Often, the amplifier circuit is externally compensated as well. Stability is related to the bandwidth of the loop and compensation capacitor values. Reducing capacitance on critical nodes of the loop will ensure stability. See the DAC161S997 data sheet for a detailed analysis of loop stability and its requirements. For HART-enabled transmitters, reducing the bandwidth with external components helps prevent interference with the HART signal.

Circuit protection protects the transmitter from abnormal conditions such as reverse loop polarity and surge events. Reverse polarity is blocked by a diode. If operating the transmitter with reverse polarity, use a rectifier bridge, as shown in Figure 3. Surge protection requires a transient voltage suppressor diode (such as the TVS3301) and passive elements to limit current during high-voltage events. These protection elements require some headroom during operation, and increase the minimum compliance voltage.

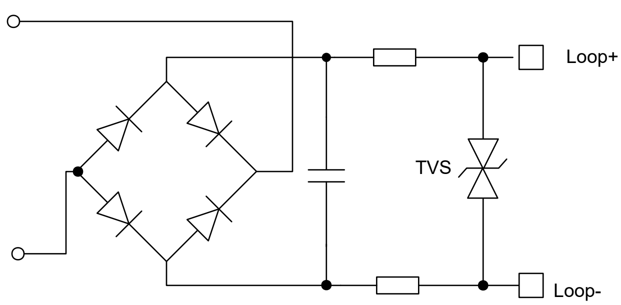


Figure 3. *Typical protection section for two-wire transmitter.*

Transmitter circuit implementations

The difference between the implementations for the block diagram in Figure 2 lies in the integration approach. The bypass transistor is always a discrete component to enable better thermal management. All of the following implementations can support the HART protocol by adding a HART modem such as the DAC8740H.

Dedicated loop converter

One approach is to use a DAC such as the DAC161S997 data sheet with an integrated voltage reference and output amplifier. This solution consists of the DAC, a wide-input-voltage LDO and an NPN transistor, as shown in Figure 4. This implementation has 130µA of current consumption and excellent accuracy without calibration. The DAC161S997 has diagnostic functions to detect current-loop errors in case of low supply or high current loads, and signals an error-low current below 4mA.

The design is simple, with a few external components to ensure loop stability and limit inrush current. This approach has a maximum operating temperature of 105°C.

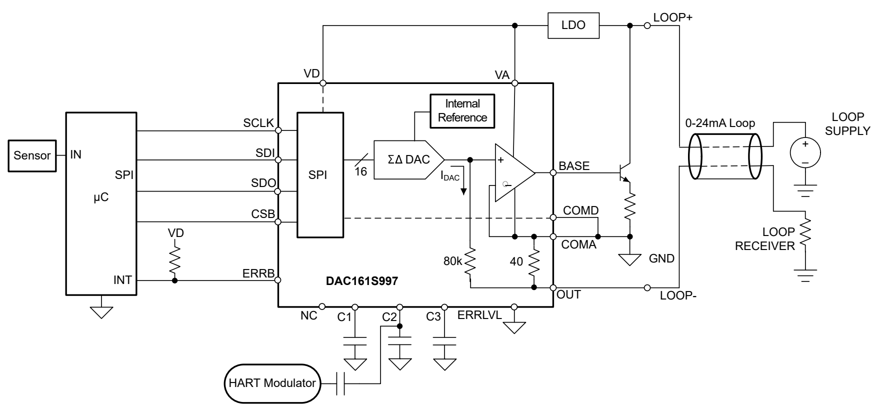


Figure 4. *Two-wire 4mA to 20mA transmitter using the DAC161S997.*

Loop transmitter device

Another implementation uses a low-power DAC such as the DAC8551, followed by a dedicated loop transmitter such as the XTR115 with an integrated LDO, voltage reference and output amplifier. This approach minimizes noise and has less than 1% gain error.

There are a couple of limitations: the XTR115 operating temperature is limited to 85°C, and the integrated LDO has a maximum input of 36V. As an alternative, the XTR117 comes in a smaller package, consumes lower quiescent current, and operates at temperatures as high as 125°C. The XTR117's integrated LDO works up to 40V. The XTR117 does not integrate a voltage reference, so counting an external reference, the solution becomes a three-device solution: an LDO, a DAC and a voltage reference, as shown in **Figure 5**.

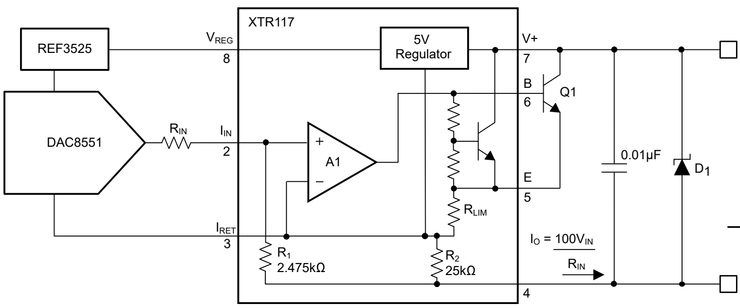


Figure 5. *Two-wire 4mA to 20mA transmitter using the XTR117.*

MCU integrated DAC

Cost-sensitive applications can employ an MCU with analog resources. The MSPM0G MCU enables a transmitter stage implementation including an integrated 12-bit DAC, internal reference and output amplifier. An LDO is the only external device needed, as shown in **Figure 6**. Given the implementation of analog functions on the MCU's digital process, they have relatively higher power consumption compared to their dedicated analog device counterparts. This approach is attractive for applications that require 11 bits of effective resolution at a very low cost. Using the VREF– pin as an internal reference negative pin instead of ground can improve performance. Separating the VREF– pin isolates digital noise from the analog reference.

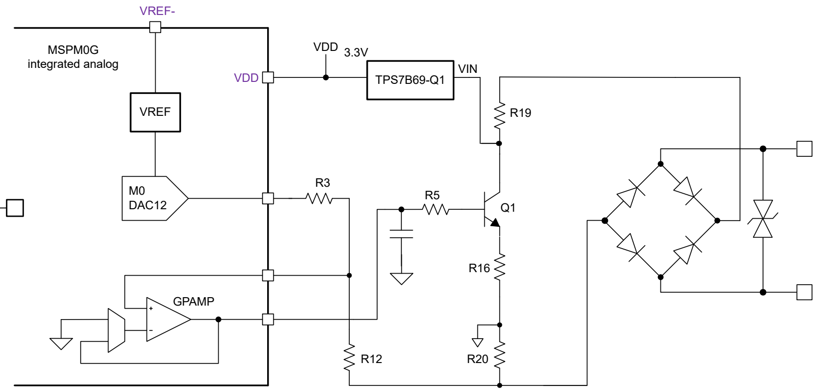


Figure 6. *Two-wire 4mA to 20mA transmitter implemented using the MSPM0G.*

PWM-based DAC

A more generic approach using an MCU (without an integrated DAC) is to rely on pulse-width modulation (PWM) to generate DAC outputs. A simple PWM DAC has a resolution of 10 bits to 12 bits. However, it is possible to realize a 16-bit resolution DAC with more advanced techniques such as two-path PWM and active ripple suppression.

To achieve a high effective resolution, the PWM signals are buffered using voltage reference-powered logic gates; the MCU needs proper bypassing to avoid digital noise injection into the loop current. The implementation depicted in **Figure 7** is low power, stable over temperature, and achieves greater than 13 bits of effective resolution at a very low cost.

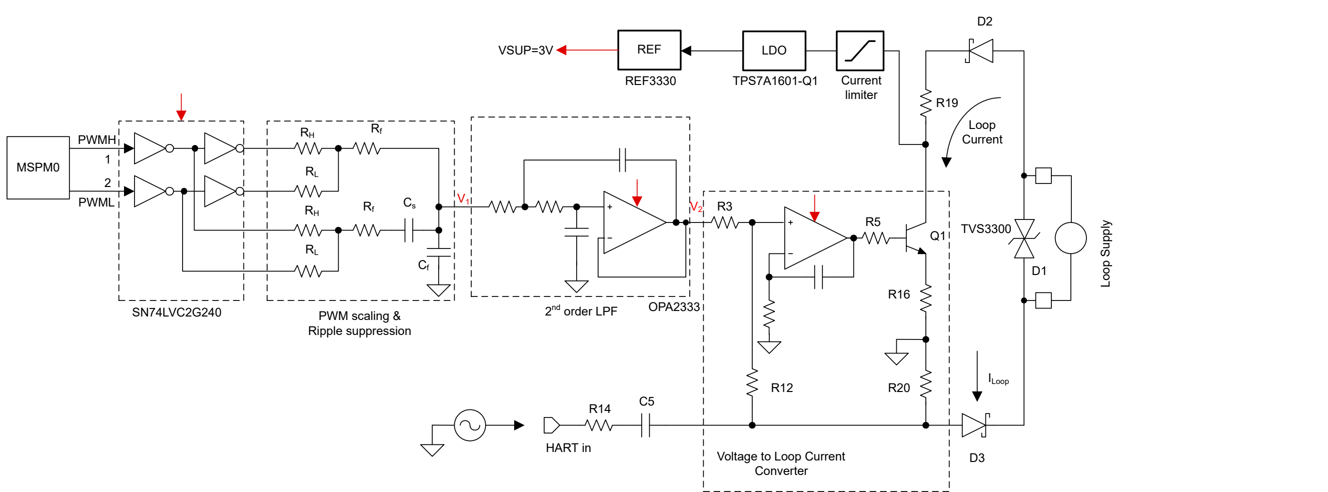


Figure 7. *Two-wire 4mA to 20mA transmitter implemented using a PWM DAC.*

Stand-alone low power DAC

Using a low-power, stand-alone DAC to realize a 4mA to 20 mA transmitter such as the **AFE88101** in **Figure 8** achieves the best resolution and linearity performance. To reduce power further, a low-power voltage reference such as the REF35125 can reduce current down to 180µA. Additionally, the **AFE88101** has extensive diagnostic features, including a 12-bit ADC and a defined fail-safe mode.

The **AFE881H1** is pin-to-pin compatible with the **AFE88101**, with an integrated HART modem for a compact HART-enabled transmitter. The **AFE881H1** has low current consumption when HART is enabled. A HART modem typically consumes 10µA during operation, making it the device of choice for low-power, HART-enabled transmitters. Another feature of the **AFE88101** is compatibility with 1.8V logic to allow low-voltage digital operation and reduce power further on the MCU input/output side, as well as reducing electromagnetic emissions.

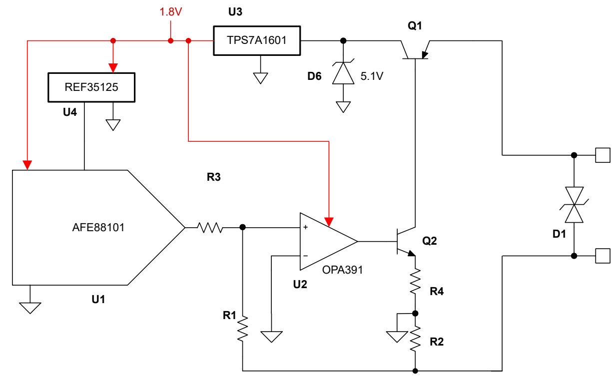


Figure 8. *Two-wire 4mA to 20mA transmitter implemented using the AFE88101.*

A lower-cost variant with the **DAC8311** DAC, LDO and external low-power reference runs with 130µA of current and still achieves reasonable performance.

Implementations Comparison

Table 1 and **Table 2** show each of the implementations, their suggested bill of materials (BOM) and their expected performance. The performance numbers are based on limited measurements.

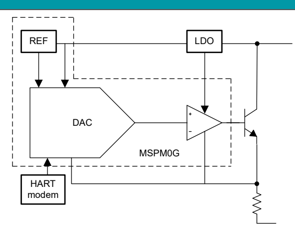
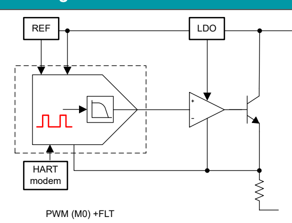
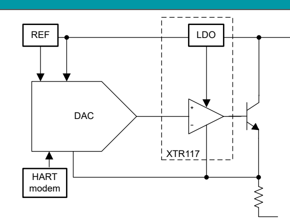
	MSPM0 DAC12	PWM using M0	XTR117
			
BOM	MSPM0G, TPS7B69, DAC8740H	TPS7A1601, REF3330, TLV2333, DAC8740H	XTR117, DAC8551A, REF3525
Compliance (volts)	40	60	40
Resolution (bits)	12	16	16
Linearity (LSBs)	2	<6	8
Effective resolution (bits)	11	13.4	14
Accuracy	1% full scale, 6uA	1% full scale, 6uA	0.7% full scale, 20uA
Current (µA)	425	240	440
Temperature (°C)	125	125	105
Advantages	Low cost	Low cost, high resolution, low power	high resolution

Table 1. *Design options for a 4mA to 20mA transmitter, suggested BOM and performance (MSPM0 DAC12, PWM using M0, XTR117).*

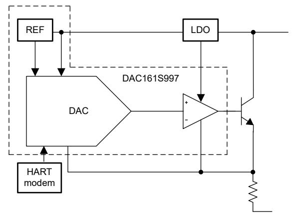
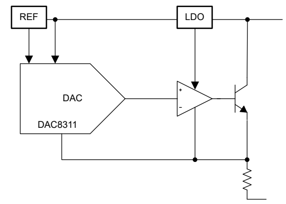
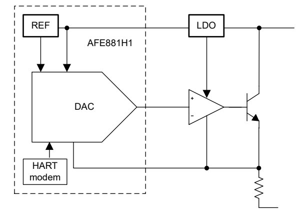
	DAC161S997	DAC8311	AFE881H1
			
BOM	DAC161S997, TPS7A1601, DAC8740H (1)	DAC8311, REF3525, OPA391, TPS7B69, DAC8740H	AFE88101 (1), REF35125, OPA391, TPS7A1601
Compliance (volts)	60V	40	60
Resolution (bits)	16	14	16
Linearity (LSBs)	5	4	4
Effective resolution (bits)	13.4	13.4	16
Accuracy	0.01%, 1uA	0.15%	0.07%
Current (µA)	130	130	180 (240 w/intREF)
Temperature (°C)	105	125	125
Compliance (volts)	Ultra-low power, high resolution, high accuracy	Ultra-low power, low cost	high resolution and accuracy, low power, low voltage

Table 2. *Design options for a 4mA to 20mA transmitter, suggested BOM and performance (DAC161S997, DAC8311, AFE881H1).*

(1) The DAC8740 has maximum power-down current of 180µA, and about 300µA when active with a crystal oscillator. The AFE881H1 HART modem, however, consumes 10µA on average. Add the corresponding current if enabling HART.

Conclusion

This selection process can help you decide the correct implementation when designing a 4mA to 20mA transmitter:

- If you are building a safety system, and need the highest accuracy and lowest noise performance, or looking for a HART-enabled transmitter with power below 200µA, the **AFE88101** and **AFE881H1** should be your first choices.
- The **DAC161S997** implementation offers the lowest possible power and footprint, followed by the **DAC8311** implementation, followed by the **XTR117** implementation if prioritizing performance over power consumption.
- For the lowest cost, choose the MSPM0G implementation. If its performance is not satisfactory, the next cost-optimized solution would be the PWM solution.

Related websites

- **4-20mA Current Loop Transmitter Reference Design**
- **Dual Sensor Measurement Using Single Current-Loop with FSK Modulation Reference Design**
- **2-wire, 4-20mA Transmitter, EMC/EMI Tested Reference Design**
- **High-Performance 16-bit PWM to 4- to 20-mA DAC for Field Transmitters**
- **Designing High-Performance PWM DACs for Field Transmitters**
- **Ultra-Low-Power, Low-Voltage, 2-Wire, 4- to 20-mA Loop Transmitter Using AFE881H1**
- **Highly Accurate, Loop-Powered, 4mA to 20mA Field Transmitter With HART Modem Reference Design**