Application Brief

Ultra-Low-Power, Low-Voltage, 2-Wire, 4- to 20-mA Loop Transmitter Using AFE881H1

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Digital-to-Analog Converters

2-Wire, 4- to 20-mA Transmitters

Meeting the power and current limitations is especially challenging for loop-powered, two-wire, 4- to 20-mA sensor transmitters. As the transmitter modulates the current down to 4 mA at the low end of the output range, the loop current can even go down to 3.5 mA when a Highway-Addressable Remote Transducer (HART) signal is present. Because of this lower current output, the field transmitter current consumption is limited to 3 mA. The transmitter can perform all sensing functions, and accurately measure the field variable. The results must be transferred with high reliability, low noise, and high resolution over the loop current and still meet a stringent size requirement.

The ever-increasing demand on field transmitter features and functionality poses a special challenge when faced with the limited current. This requires more efficient low power circuits and devices. If standard architectures like designs for the DAC161S997 and the DAC8831[1], [2] cannot meet the power needs, PWM-based DACs can also be used to greatly reduce the power consumption[3], [4]. A microcontroller (MCU) with integrated analog resources can also be used to reduce power and area[5]. When currents exceeding the 3 mA are required for transmitter electronics, buck converters can be used instead of the typical regulator to provide the required current at lower voltage than the loop voltage.[6], [7]

AFE881H1 Loop Transmitter Front-End

AFE881H1 is designed to allow the implementation of an optimally-integrated, ultra-low power, 2-wire (loop-powered) 4- to 20-mA transmitter. The device does not integrate the voltage to current converter, or the loop power regulator. This allows more flexibility in power design, and accommodates intrinsic and functional-safety concerns.

The device works with a wide supply range for 1.8 V, and for 2.7 V to 5 V, and achieves 0.1% TUE over the full industrial temperature range.

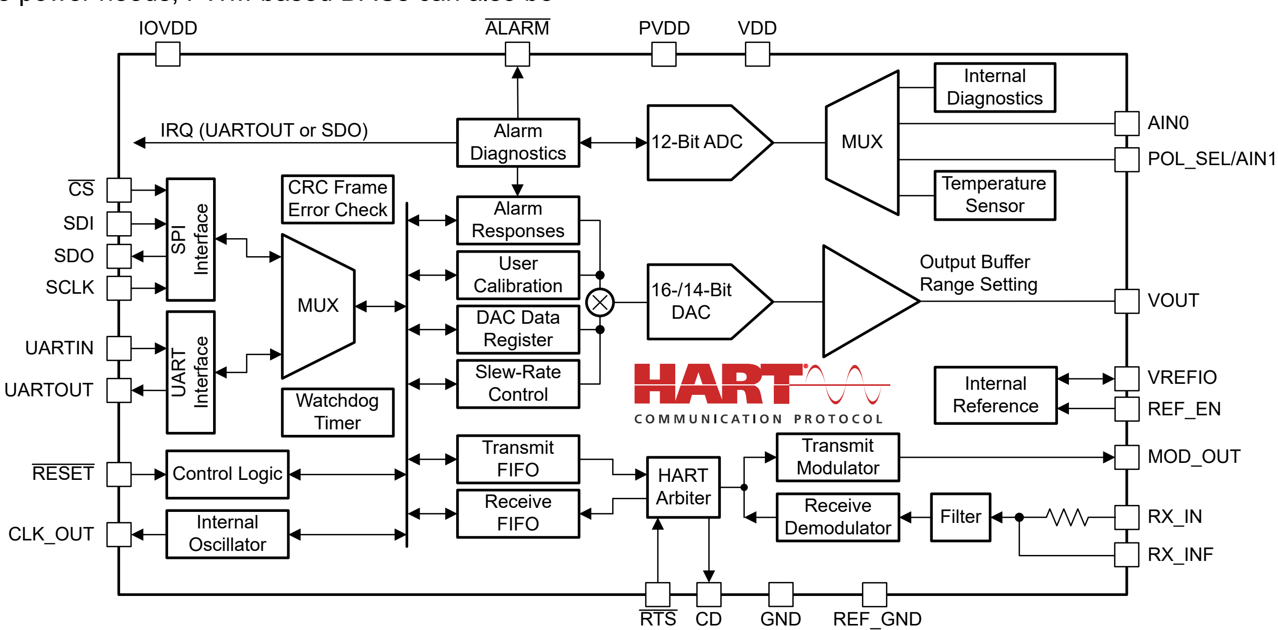

Figure 1. AFE881H1 Block Diagram

The device integrates a certified HART modem, as well as a diagnostic 12-bit analog-to-digital converter (ADC) which enables automatic self-check, detects errors of the internal circuits of the device, and optionally enters a fail-safe state. An integrated low-drift, 1.25-V reference and 1.288-MHz oscillator in a 4 mm × 4 mm package enables compact realization of the transmitter circuit.

The device is pin-to-pin compatible with the AFE88101 non-HART device. Both devices are also available in 14-bit resolution (AFE781H1, and AFE78101). This family of pin-to-pin devices can cover a wide range of application and cost requirements.

Transmitter Design

AFE881H1 is used to implement an ultra-low power 2-wire transmitter as shown in Figure 2. D1 is a TVS diode to protect from surge events. D2–D5 composes a bridge-rectifier to allow operation in reverse polarity. Zener diode D6 limits the input voltage to 5.1 V and U3 LDO (TPS7A1601) generates the main supply (1.8 V) for the transmitter. Sense resistor (R2) senses the current passing through the loop, and the current modulation circuit (U2 + Q2 + Q1) maintains that current at a certain level driven by the U1 DAC (AFE881H1). The current is modulated by modifying the effective impedance of Q1 and passes the required residual current through D6 to reach the desired loop current.

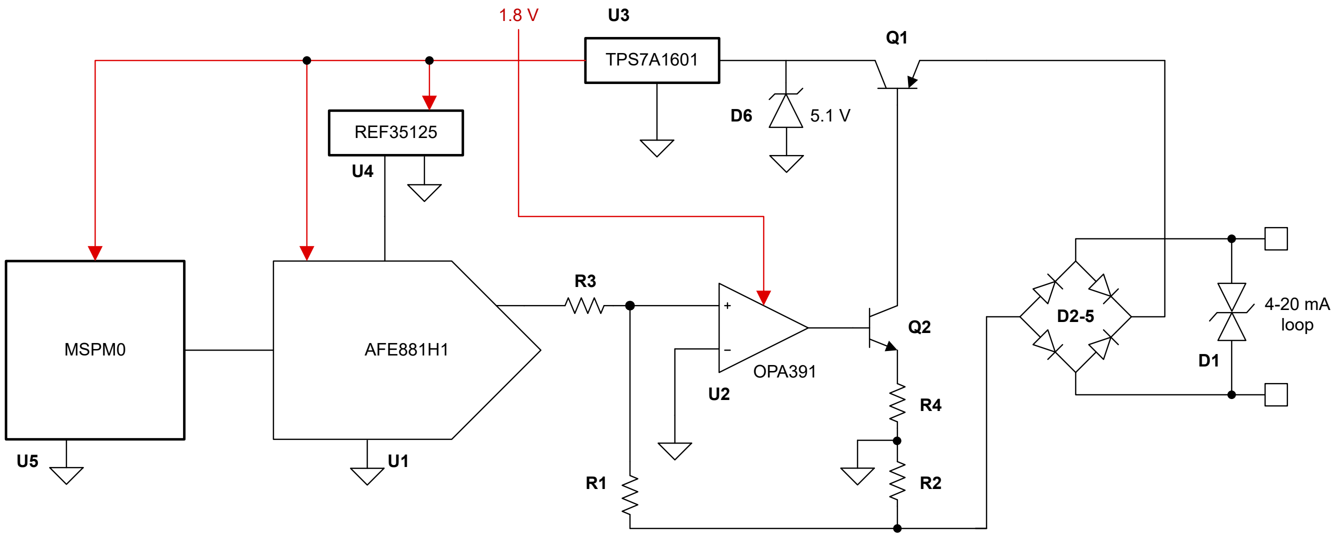

Figure 2. Ultra-Low Power, Low Voltage, 2-Wire 4- to 20-mA Transmitter

This design enables a wide input voltage range, while maintaining a low voltage operation of 1.8 V. Low-voltage operation provides many advantages by reducing overall power consumption for the same current, reducing the minimum loop voltage required for operation, and improving EMC emission performance.

At a higher loop current of 20 mA, the base current of Q1 (assuming a gain of 100) is close to 0.2 mA and Vbe(Q2) < 0.7 V, adding to this the voltage drop on R4, op amp U2 output is required to reach Vbe(Q2) + (R4 × 0.2 m). With proper selection of the R4 value, the maximum output voltage of U2 is less than 1.7 V. The OPA391 has a common-mode range from 0.1 V to 1.7 V with a 1.8-V supply. The device is also able to drive up to a few mV from the rail.

The circuit is designed for operating with a DC/DC converter instead of an LDO if a current higher than 3 mA is required for the sensor and processing side[6], [7]. Using external reference REF35125 reduces current consumption compared to the internal reference, However, the internal reference can still be used if absolute minimum area is required.

Power Measurement

To validate the design performance, a prototype board was tested, focusing mainly on power consumption and noise performance.

The quiescent current of each device is measured separately as shown in Figure 3 at 1.8-V supply and at room temperature.

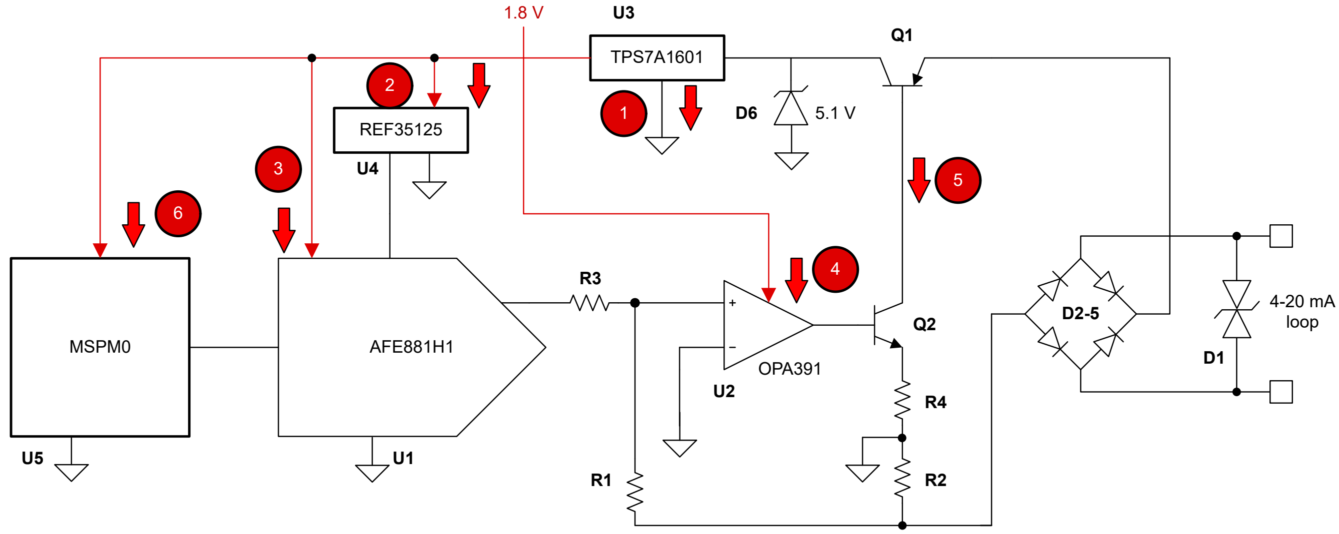

Figure 3. Different Current Components of the Transmitter Circuit

Table 1 lists each current and highlights the extremely low power nature of different components.

Table 1. Circuit Current Consumption

	Current Component	Value at 4 mA
1	HV LDO Quiescent	5 µA
2	Voltage Reference	3 µA
3	AFE881H1 (ext REF, no HART, no ADC)	133 µA
4	Op amp	24 µA
5	I(Q2)	15 µA
	Sum	**180**
6	MCU	43 µA
	Total	**223 µA**

Two currents are linearly changing with output current, the AFE881H1 current as higher voltage is generated, and hence higher current through R1, and the current through Q2. The total current change with output current changing from 3 mA to 25 mA is shown in Figure 4.

The MSPM0 MCU is used as the SPI host driving SPI commands to set the AFE881H1 data output register every 100 ms. The MCU current consumption associated with the SPI communication is measured to be 43 µA.

The current in D6 is residual current used to modulate current in the loop and can be brought to zero if the circuit requires more current to operate, so it is not counted as power consumption by the transmitter circuit. Make sure that D6 is rated well above the power generated at the maximum current level. Assuming a maximum current of 25 mA is going through D6, D6 dissipates 130 mW of power.

At 4-mA output, the transmitter circuit consumes only 180 µA, or 0.33 mW with a 1.8-V supply. Adding the MCU current, the total current of the circuit is 223 µA which is equivalent to 0.4 mW with 1.8-V supply.

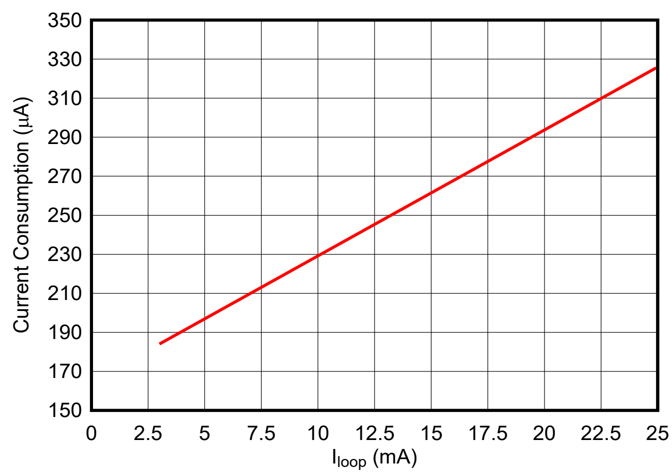

Figure 4. Total Current Consumption vs Loop Current

Noise Performance

As previously mentioned, the MCU is communicates with the AFE881H1 through SPI every 100 ms, switching between sleep and active mode. The MCU shares the same 1.8-V supply with the AFE881H1 and the change in the MCU power mode can affect the noise performance of the transmitter. To validate the circuit noise performance, the loop current noise is measured using a 24-bit, 31-kSPS ADC. Both the output histogram in Figure 5 and the output spectrum in Figure 6 are plotted to check precision and spectral noise.

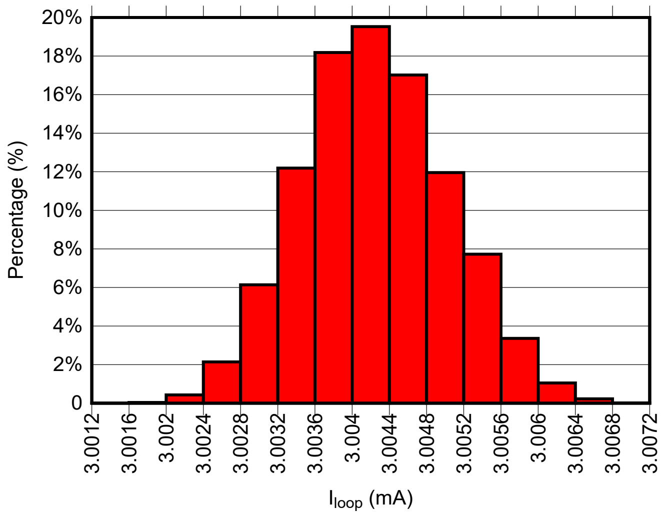

Figure 5. Histogram of Loop Output Current at 3-mA Setting

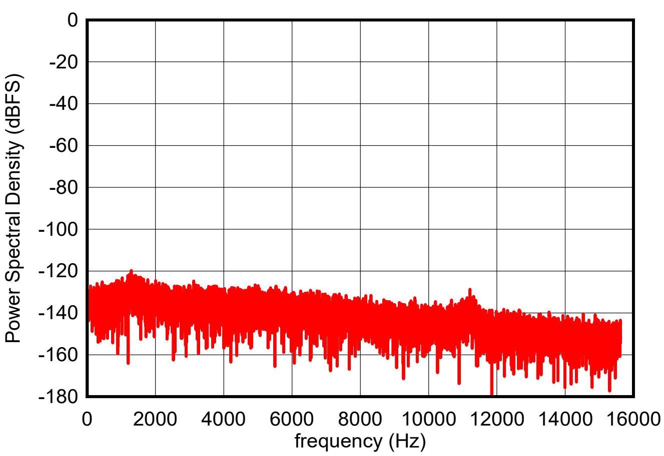

Figure 6. Loop Current Spectrum at Static 3-mA Setting

Table 2 summarizes noise performance of the transmitter at 3 mA, the minimum current for AFE881H1 output to have the maximum effect on SNR. The RMS noise is less than 0.8 μA and is equivalent to 17-bit performance which demonstrates the low-noise nature of the design. The loop current spectrum shows that MCU switching modes does not affect spectral content of the output signal.

Table 2. Noise Performance at 3-mA Loop Current

Parameter	Transmitter at 3 mA
Number Samples	16383
Average	3.00425 mA
minimum	3.00152 mA
maximum	3.00698 mA
P-P noise	5.45382 μA
RMS noise	782 nA
Noise free bits	14.2 bits
RMS resolution	17 bits

Conclusion

The AFE881x1 product family is an excellent choice to build an ultra-low power (0.4 mW), low-voltage (1.8 V), high-accuracy (0.1% FS TUE over temperature range) 2-wire transmitter. With 14-bit and 16-bit devices, with and without HART modem, all in pin-to-pin compatible 4-mm × 4-mm packages, the whole range of high-performance and cost-effective sensor-transmitter loop interfaces can be built. An ultra-low power transmitter was demonstrated, and validated through individual part current consumption, and overall noise performance.

References

1. TIDA-00648: 4-20mA Current Loop Transmitter Reference Design
2. TIDA-01504: Highly-Accurate, Loop-Powered, 4mA to 20mA Field Transmitter With HART® Modem Reference Design
3. Designing high-performance PWM DACs for field transmitters
4. High-Performance 16-bit PWM to 4- to 20-mA DAC for Field Transmitters
5. TIDA-00247: Single Chip 2-Wire Loop Powered, 4 to 20mA Current Loop RTD Temperature Transmitter Reference Design
6. Low-I_Q synchronous buck converter enables intelligent field-sensor applications
7. TIDA-00167: Isolated Ultra-Low Power Design for 4 to 20 mA Loop Powered Transmitters