Analog Engineer's Circuit

Precision, Three-Wire, Analog Voltage Output Transmitter Using the DAC80501 and XTR200

Precision DAC: Factory Automation and Control

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Design Objective

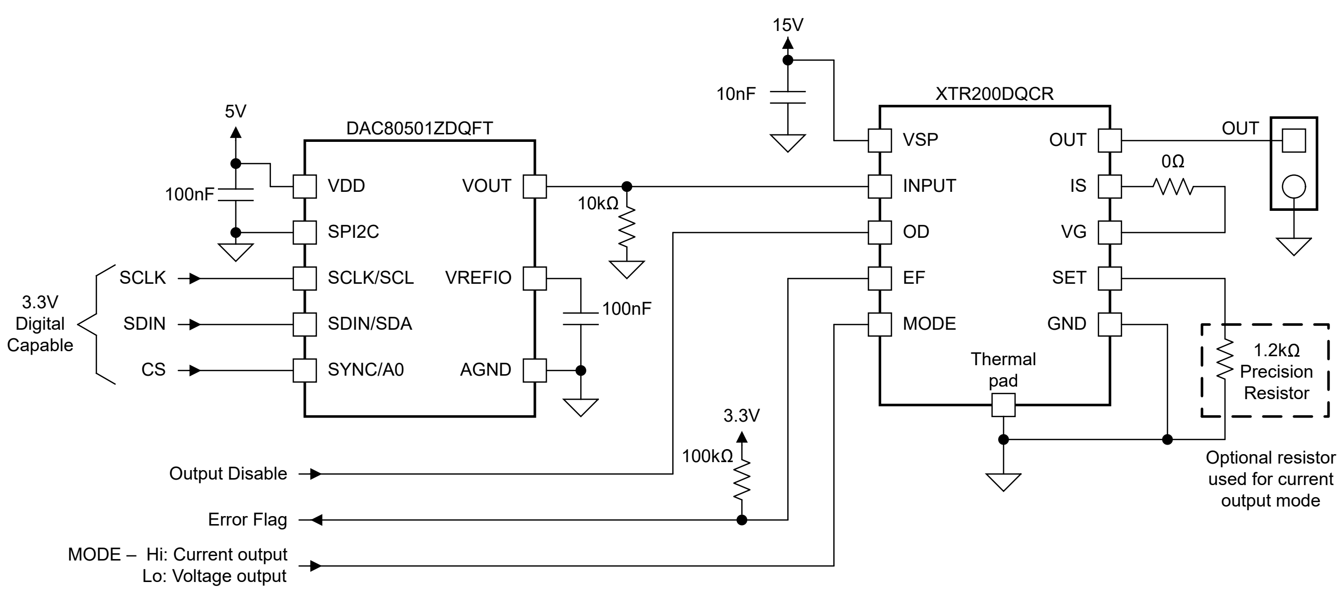
Key Input Parameter	Key Output Signal	Recommended Devices
DAC output voltage Operating range: 0V to 2.667 Full-scale range: 0V to 3.733V	XTR output voltage Operating range: 0V to 10V Full-scale range: 0V to 14V	DAC80501, XTR200

Objective

Generation of a 0V to 10V analog voltage output from a precision digital-to-analog converter (DAC) output using a transmitter (XTR) device. A higher full-scale range setting is designed into the output to allow for calibration if needed.

Design Description

In this circuit, the DAC80501 voltage output drives the XTR200 to set a precision analog voltage output to an operating range of 0V to 10V, with a larger full-scale range to 14V for calibration or wider range based on the 15V supply. The circuit is constructed and tested from the DAC80502-01EVM and the XTR200EVM. The XTR200 has a pin-selectable mode to output either current or voltage. This circuit is described with a voltage output but can also be configured with a current output without changing the schematic. This simple circuit is used in industrial automation and process control for analog outputs such as actuators and programmable logic controllers (PLCs).



Specifications

DAC80501 Output	XTR200 MODE Pin	XTR200 Output	Accuracy
0V to 3.733V	Lo (Voltage output)	0V to 14V	±0.2%

Design Notes

1. The example circuit is drawn for a microcontroller to configure the DAC80501 through SPI communication to set the DAC output voltage. If desired, the DAC80501 can be controlled through the I^2C protocol, by setting the SPI2C pin high instead.
2. The XTR200 MODE pin sets the device output to either voltage output (MODE = Lo) or current output (MODE = Hi). This pin is set from a GPIO from the microcontroller if both outputs are needed or can be tied high or low if only one type of output is needed. A current output can be achieved using the same schematic by setting MODE = Hi by including a precision resistor to ground at the SET pin. The placement of R_{SET} does not affect the operation of the XTR200 in voltage mode.
3. In this circuit, the DAC80501 operates on a 5V supply. When using a 5V supply, DAC80501 digital input pins are capable of 3.3V operation. The V_{IH} voltage is 1.62V and the V_{IL} is 0.45V. The DAC80501 does not have a SDO pin for reading back register configuration.
4. Additionally, the XTR200 MODE digital pin is also designed for 3.3V operation. Note that the V_{IH} voltage level is 1.65V and the V_{IL} voltage is 0.8V. The MODE pin has an internal pullup current of 4µA.
5. The XTR200 in this circuit is shown with a 15V supply. However, the device operates on a supply from 8V to 60V for greater range.
6. The DAC80501 and XTR200 devices both use decoupling capacitors close to the respective supply pins. The DAC80501 uses a 100nF capacitor at the VDD pin, while the XTR200 uses the same at the VSP pin. Use a decoupling capacitor for the DAC80501 rated at 10V or higher and use a decoupling capacitor for the XTR200 rated to 25V or higher.
7. In this circuit, the DAC80501 uses an internal reference for the DAC. This internal reference is enabled by default when power is first applied. The VREFIO pin uses another 100nF decoupling capacitor near the pin. If an external reference is needed for higher accuracy, place a 1kΩ resistor in series at the VREFIO pin to reduce the current contention and disable the internal reference after start-up by setting the REF_PWDWN bit [8] to 1 in the CONFIG register (0x03).
8. The XTR200 has internal circuitry that detects error states in the device. An alarm condition detected at the $\overline{EF}$ pin indicates if the device has one of the following circuit faults:
   - The output has reached the short-circuit current limit in voltage-output mode
   - There is insufficient headroom between the load voltage and the supply voltage to achieve the correct voltage or current output, detectable only if the input voltage is > 350mV and supply voltage is > 10V
   - The output is open-circuited when in current output mode, detectable only if the input voltage supply voltage is > 10V
   - The SET pin current is shorted or exceeds 1/10th of the output short-circuit current limit
   - The power supply voltage is under 8V
   - The die temperature exceeds 150°C
9. The DAC80501Z is shown in this schematic. The "Z" option has a default setting for the DAC code of 0x0000. The "M" option of this device has a default setting of midscale, with a DAC code of 0x8000.
10. As previously mentioned, the circuit can also be used for an analog current output without changes. This function is described in *Precision, Three-Wire, Current Transmitter Using the DAC80501 and XTR200*.

Design Steps

For operation in the voltage output mode, the XTR200 MODE pin is set Lo. The XTR200 in voltage mode output has a gain of 3.75. The equation for the output voltage is given in the following:

$$V_{OUT} = V_{IN} \times 3.75$$

The DAC80501 is set to REF-DIV = 0b and BUFF-GAIN = 1b. These settings internally set the reference to unity gain and increase the output buffer gain to two to set the DAC range from 0V to 5V. With this setting, the output voltage from the XTR200 is calculated as:

$$\text{Voltage output} = \left(\frac{\text{DAC code}}{2^{16}}\right) \times 3.75 \times 5\text{V}$$

In many industrial applications, a 0V to 10V range is required. In this circuit, the theoretical full-scale output range is 18.75V depending on supply voltage. However, in this circuit, the XTR200 has a supply voltage of 15V. Choosing an XTR200 output range of 0V to 14V, the DAC code range is set from 0x0000 to 0xBF25 (48933 dec). This code determines the resolution of the output voltage, which is approximately 286μV/LSB. If a high resolution is not needed from the DAC, the 14-bit DAC70501 or 12-bit DAC60501 can be used in this application.

TUE Analysis

Total Unadjusted Error (TUE) is calculated from a root-sum-of-squares addition of the contributing errors to the total output error. This calculation is usually made up of gain error, gain error drift, offset error, offset error drift, and nonlinearity error. For the TUE analysis of the XTR200 voltage output, start with the TUE calculation of the DAC80501 output.

The *DACx0501 16-Bit, 14-Bit, and 12-Bit, 1-LSB INL, Voltage-Output DACs With Precision Internal Reference* datasheet conveniently specifies the TUE error of the DAC and combines these errors to one maximum value in the *Electrical Characteristics* table. For this circuit, the DAC is set with REF-DIV = 0b and BUFF-GAIN = 1b.

Note that the TUE error of the DAC80501 (REF-DIV = 0b) in the specification table of ±0.08% does not include the reference error or the reference drift.

$$\text{Err}_{\text{DAC REF-DIV0}} = \sqrt{\text{Err}_{\text{REF}}^2 + \text{Err}_{\text{REF Drift}}^2 + \text{Err}_{\text{TUE}}^2}$$

With a reference error of ±0.1% (2.5mV on a 2.5V reference) and a drift of ±0.05% (5ppm/°C over 100°C from 25°C to 125°C, the maximum drift from room temperature), the following result is derived:

$$\text{Err}_{\text{DAC REF-DIV0}} = \sqrt{0.1^2 + 0.05^2 + 0.08^2} = 0.137\%$$

After calculating the TUE from the DAC80501, the DAC error can be included in the TUE calculation for the XTR200. The XTR200 voltage mode contributing errors are the offset voltage error, offset voltage drift, gain error, the gain drift error, and the nonlinearity. The errors are combined with the DAC80501 TUE to determine the total TUE of the voltage mode output.

Errors (%)					
XTR Voltage Offset	**XTR Voltage Offset Drift**	**XTR Voltage Gain Error**	**XTR Voltage Gain Drift**	**Nonlinearity**	**DAC80501 TUE Error**
±0.0268	±0.008	±0.05	±0.005	±0.0006	±0.137

From the *XTR200 Precision, 3-Wire, Current-and-Voltage Transmitter* datasheet *Electrical Characteristics* table, the maximum voltage mode offset (referred to the output) is 3750μV. This value is the maximum input offset voltage, multiplied by the XTR200 gain of 3.75. The maximum voltage mode offset is converted to percent based on a 14V full-scale voltage range.

The drift errors are based on a 100°C change from room temperature for the maximum input offset voltage drift of 3μV/°C (again multiplied by 3.75 for the output offset voltage drift) and 0.5ppm/°C for the voltage gain error drift. The values of the components are squared and summed. The square root represents the TUE value of the voltage output.

$$\mathrm{TUE_{VOUT}} = \sqrt{\mathrm{Err}_{\mathrm{VOS}}^2 + \mathrm{Err}_{\mathrm{VOS\ Drift}}^2 + \mathrm{Err}_{\mathrm{VGE}}^2 + \mathrm{Err}_{\mathrm{VGE\ Drift}}^2 + \mathrm{Err}_{\mathrm{VNonLin}}^2 + \mathrm{Err}_{\mathrm{DAC}}^2}$$

After inserting in the error values, the following result is calculated for the voltage output TUE:

$$\mathrm{TUE_{VOUT}} = \sqrt{0.027^2 + 0.008^2 + 0.05^2 + 0.005^2 + 0.00065^2 + 0.137^2}$$

$$\mathrm{TUE_{VOUT}} = \sqrt{0.0222} = 0.149\%$$

Zero-Code Error

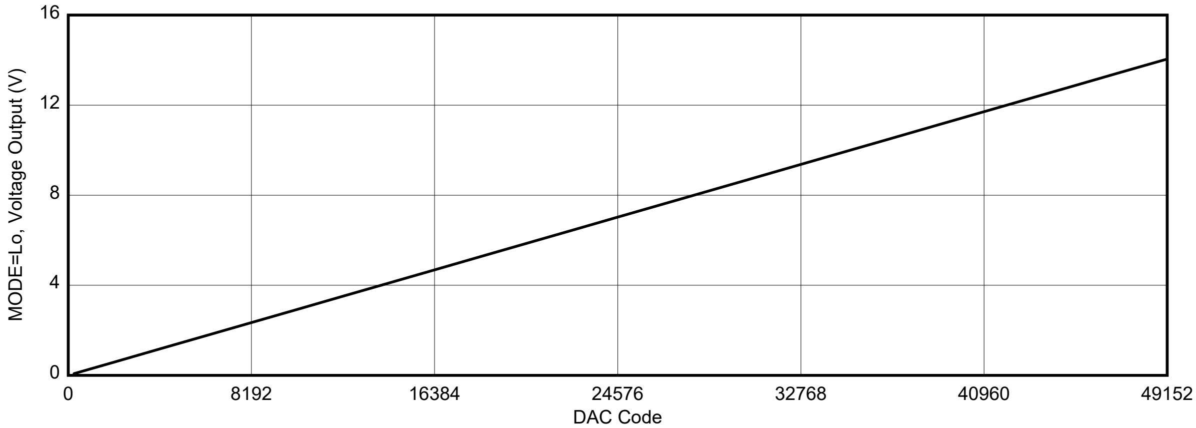
Entering a DAC code of 0x0000 for the DAC80501 does not set an output of exactly 0V. For unipolar supply DACs, a zero-code error is associated with the output buffer. This endpoint error is created when the output buffer cannot drive the output to 0V. For the DAC80501, the zero-code error is 1.5mV maximum. This voltage represents an output of 5.6mV for the XTR200.

If a different DAC with a lower zero-code error is used, the XTR200 has an additional limitation near 0V input. The output voltage of the XTR200 is nonlinear when the voltage is lower than 4mV. This value is listed as the lower end of the linear range for the output voltage.

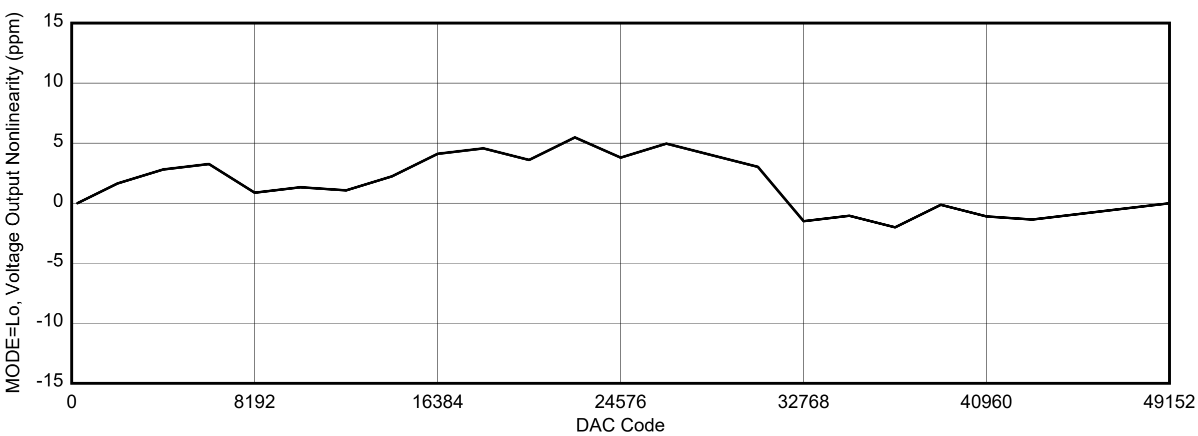
Regardless, the circuit is tested with DAC80501 data codes from 256d to 48934d as the endpoint limits for the limited range based on the supply voltage of the circuit. The lower endpoint represents an output voltage of 19.5mV for the XTR200, while the upper endpoint represents 14V.

Measured Results

The circuit is constructed using a DAC80502-01EVM and an XTR200EVM. The DAC80502-01EVM is set up with a VDD supply of 5V drawn from USB power. The XTR200EVM is powered at VSP from an external 15V supply. Measurements are performed with an Agilent® 34410A. In voltage output mode with MODE = Lo, the measured transfer function from DAC code to output voltage is shown in the following figure:



The nonlinearity is calculated and plotted from measurements of the output range. The endpoint fit is calculated from DAC codes 256d to 48934d.



The total gain error, offset, and nonlinearity measurements from the constructed circuit are displayed in the following table.

Parameter	Measured Value
Gain Error	–0.077%
Offset	–53µV
Nonlinearity	5.5ppm

Register Settings

A register map of DAC80501 settings for this application are shown in the following table.

Register Settings for DAC80501

Register Address	Register Name	Setting	Description
0x03	CONFIG	0x0000	[15:9] 0000000b: Reserved
			[8] 0b: REF_PWDWN, set this bit to 1 if using an external reference
			[7:1] 0000000b: Reserved
			[1] 0b: DAC_PWDWN, set this bit to 1 to power down the DAC
0x04	GAIN	0x0001	[15:9] 0000000b: Reserved
			[8] 0b: REF-DIV, set the reference voltage to unity gain
			[7:1] 0000000b: Reserved
			[0] 1b: BUFF-GAIN, set the gain of the buffer amplifier to two
0x08	DAC	0x0000	[15:0] 00000000b DAC-DATA, set the DAC output code

Pseudocode Example

The following pseudocode sequence shows the steps required to set up the DAC80501 and the XTR200 for voltage output. These examples show configuration of the DAC using SPI communication. Note that the DAC80501 has an option to use I^{2}C for communication.

```
Configure the SPI communication of the microcontroller to SPI mode 1 (CPOL = 0, CPHA = 1);
// Voltage mode
{Set microcontroller GPIO output to set MODE pin Lo for the XTR200;
}
// Internal reference and DAC output are enabled at start by default
// If using external reference, add series 1kΩ resistance at VREFIO to reduce contention current
// and disable internal reference, else skip this step
{Set CS to device Lo;
    Send 24 SCLKs, write 0x030100;
    // Set DAC REF_PWDWN = 1b [8] in CONFIG register, disables internal reference
    // DAC output can also be disabled in this register with DAC_PWDWN = 1b [0]
Set CS to device Hi;
// Configure DAC80501 output gain
}
{Set CS to device Lo;
    Send 24 SCLKs, write 0x040001;
    // DAC80501 output range 0V to 5V
    // Set DAC REF-DIV = 0b [8], BUFF-GAIN = 1b [0] in GAIN register
    // DAC output full-scale range set to reference voltage × 2
Set CS to device Hi;
}
// Set DAC80501 Data Code
{Set CS to device Lo;
    Send 24 SCLKs, write 0x088888;
    // Write DAC output code to 0x8888 (34952d), sets output voltage to 10V
Set CS to device Hi;
}
```

Design Featured Devices

Find other possible devices using the parametric search tool.

Device	Key Features	Link
DAC80501	DACx0501 16-Bit, 14-Bit, and 12-Bit, 1-LSB INL, Voltage-Output DACs With Precision Internal Reference	DAC80501
XTR200	XTR200 Precision, 3-Wire, Current-and-Voltage Transmitter	XTR200
DAC80502-01EVM	DAC80502 and DAC80501 evaluation module	DAC80502-01EVM
XTR200EVM	XTR200 evaluation module	XTR200EVM

Design References

See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.

Additional Resources

- Texas Instruments, *DAC80502-01 Evaluation Module User's Guide*
- Texas Instruments, *XTR200 Evaluation Module User's Guide*
- Texas Instruments, *Simplify 4-20mA Current and Voltage Output 3-Wire Transmitters With XTR200*
- Texas Instruments, *Precision, Three-Wire, Current Transmitter Using the DAC80501 and XTR200*

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