*Analog Engineer's Circuit*

# ***Precision, Three-Wire, Analog Current Output Transmitter Using the DAC80501 and XTR200***

## Design Objective

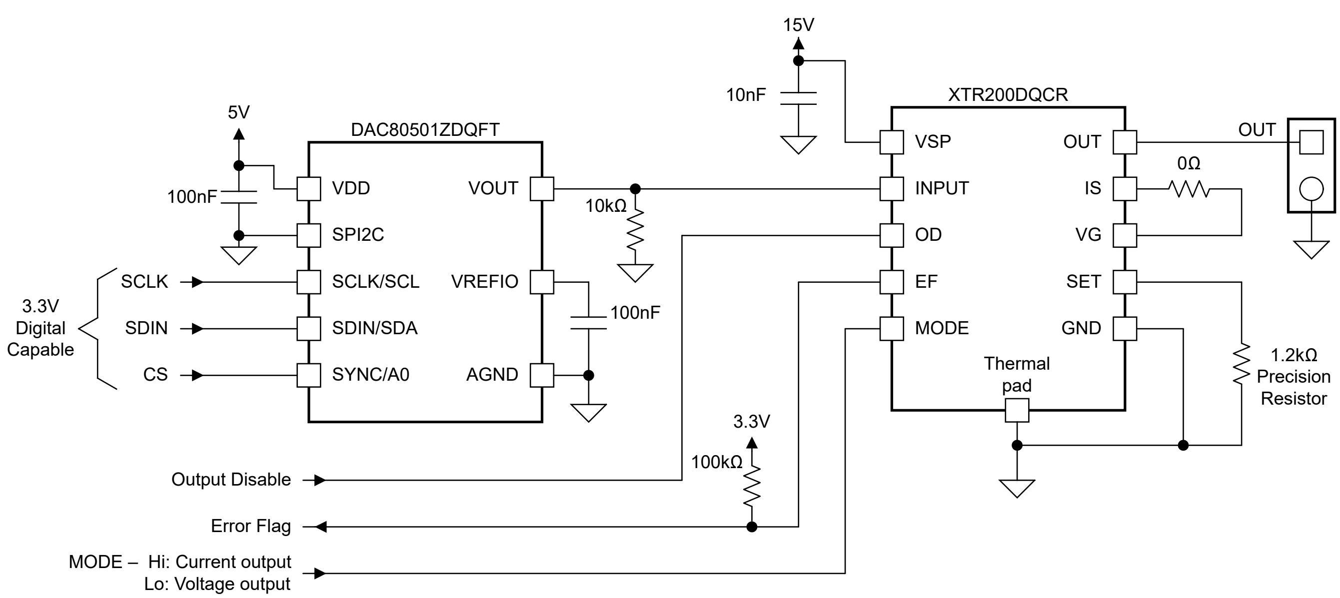
| Key Input Parameter | Key Output Signal | Recommended Devices |
|---|---|---|
| DAC output voltage<br>Operating range: 0V to 2.4V<br>Full-scale range: 0V to 2.5V | XTR output current<br>Operating range: 0mA to 20mA<br>Full-scale range: 0mA to 20.833mA | DAC80501, XTR200 |

## Objective

Generation of a 0mA to 20mA analog current 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 current output to an operating range of 0mA to 20mA, with a larger full-scale range to 20.833mA for calibration. The XTR200 uses a precision 1.2kΩ resistor to precisely set the current range. The circuit is constructed and tested using the DAC80502-01EVM and the XTR200EVM. The XTR200 has a pin-selectable mode to output either current or voltage. The following circuit is described as a current output but can also be configured as a voltage 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).







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## Specifications

| DAC80501 Output | XTR200 MODE Pin | XTR200 Output | Accuracy |
|---|---|---|---|
| 0V to 2.5V | Hi (Current output) | 0mA to 20.833mA | ±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 current output (MODE = Hi) or voltage output (MODE = Lo). 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 high range voltage output can be achieved using the same schematic by setting MODE = Lo.
3. The XTR200 SET pin connects to ground through a precision resistor. In current mode, this precision resistor scales the current level. If this circuit is also used in voltage mode, then this resistor is unused, but can be left in the circuit.
4. The DAC80501 operates on a 5V supply. If only current output is needed, then 3.3V can be used for the DAC80501 supply.
5. 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.
6. 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.
7. 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.
8. 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.
9. 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).
10. 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
11. 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.
12. As previously mentioned, the circuit can also be used for an analog voltage output without changes. This function is described in *Precision, Three-Wire, Analog Voltage Output Transmitter Using the DAC80501 and XTR200*.


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### Design Steps

For operation in the current output mode, the XTR200 MODE pin is set Hi. The equation for the output current is given in the following:

$$\mathrm{IOUT} = \frac{10 \times V_{IN}}{R_{SET}}$$

The DAC80501 sets the input voltage to the XTR200. The DAC CONFIG register is set to REF-DIV = 1b and BUFF-GAIN = 1b. These settings internally divide the reference by two and increase the output buffer gain to two to set the DAC range from 0V to 2.5V. The XTR200 uses a precision 1.2kΩ resistor with high accuracy and low drift at the SET pin. This $R_{SET}$ resistor sets the current output. The DAC input voltage range and the resistor value set the final current output range.

$$\text{Full-Scale Current Range} = \frac{10 \times 2.5\text{V}}{1.2\text{k}\Omega} = 20.833\text{mA}$$

This output is the nominal value, and calibration can be used to precisely set the output. The output current from the XTR can be calculated from the DAC code from the following equation:

$$\text{Current output} = \left(\frac{\text{DAC code}}{2^{16}}\right) \times 20.833\text{mA}$$

With this configuration, the LSB size is 0.32µA for the 20.833mA range. If a different current range is required, the SET resistor at the XTR200 can be scaled to a different value from the previous equation. If a high resolution is not needed from the DAC, the 14-bit DAC70501 or 12-bit DAC60501 can be used in this application.

An optional setting for the DAC80501 is to set REF-DIV = 0b and BUFF-GAIN = 1b to have a reference gain of 1 and an output buffer gain of 2. This configuration sets the DAC full-scale voltage to 5V. The SET resistor is then set to 2.4kΩ to maintain the output current range. However, note that the 5V range is dependent on the DAC supply. If there is a 10% reduction in the supply, this additional variation must be considered in the selection of the SET resistor to avoid the DAC output headroom limitation. In the setting described first in this section, dividing the reference by two using REF-DIV = 1b, the DAC output does not have the potential reduction from the supply headroom of the output buffer.

### 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 current 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 DAC80501 and combines these errors to one maximum value in the *Electrical Characteristics* table. For this circuit, the DAC is set with REF-DIV = 1b and BUFF-GAIN = 1b. The device is in a WSON-8 package, which has a slightly smaller TUE error than the VSSOP package.

Note that the TUE error of the DAC80501 (REF-DIV = 1b) in the specification table of ±0.06% does not include the reference error or the reference drift. To calculate the total error in the DAC, use a root-sum-of-squares addition of these errors.

$$\mathrm{Err}_{\mathrm{DAC\ REF\text{-}DIV1}} = \sqrt{\mathrm{Err}_{\mathrm{REF}}^2 + \mathrm{Err}_{\mathrm{REF\ Drift}}^2 + \mathrm{Err}_{\mathrm{TUE}}^2}$$


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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:

$$\text{Err}_{\text{DAC REF-DIV1}} = \sqrt{0.1^2 + 0.05^2 + 0.06^2} = 0.127\%$$

After calculating the TUE from the DAC80501, the DAC error can be included in the TUE calculation for the XTR200. The XTR200 current mode contributing errors are the offset current error, offset current drift, span (gain) error, the span drift error, the nonlinearity, and the error from $R_{SET}$. The errors are combined with the DAC80501 TUE to determine the total TUE of the current mode output.

| Errors (%) | | | | | | |
|---|---|---|---|---|---|---|
| **XTR Current Offset** | **XTR Current Offset Drift** | **XTR Current Gain Error** | **XTR Current Gain Drift** | **Nonlinearity** | **$R_{SET}$ Resistor Tolerance** | **DAC80501 TUE Error** |
| ±0.067 | ±0.0288 | ±0.07 | ±0.02 | ±0.003 | ±0.1 | ±0.127 |

From the *XTR200 Precision, 3-Wire, Current-and-Voltage Transmitter* datasheet *Electrical Characteristics* table, the maximum current mode offset is 14µA. This value is converted to percent based on a 20.833mA full-scale current range. Drift errors are based on a 100°C change from room temperature for the maximum drift of 60nA/°C for the offset and 2ppm/°C for the gain error drift. The values of the components are squared and summed. The square root represents the TUE value of the current output.

$$\text{TUE}_{\text{IOUT}} = \sqrt{\text{Err}_{\text{IOS}}^2 + \text{Err}_{\text{IOS Drift}}^2 + \text{Err}_{\text{IGE}}^2 + \text{Err}_{\text{IGE Drift}}^2 + \text{Err}_{\text{INonLin}}^2 + \text{Err}_{\text{RSET}}^2 + \text{Err}_{\text{DAC}}^2}$$

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

$$\text{TUE}_{\text{IOUT}} = \sqrt{0.67^2 + 0.029^2 + 0.07^2 + 0.02^2 + 0.003^2 + 0.1^2 + 0.127^2}$$

$$\text{TUE}_{\text{IOUT}} = \sqrt{0.0367} = 0.192\%$$

## 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 12.5µA 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 current output of the XTR200 is nonlinear when the current is lower than 10µA. This value is listed as the lower end of the linear range for the output current.

Regardless, the circuit is tested with DAC80501 data codes from 256d to 65535d as the endpoint limits as described in the notes of the *Electrical Characteristics* table in the data sheet. The lower endpoint represents an output current of 81µA for the XTR200, while the upper endpoint represents 20.833mA.


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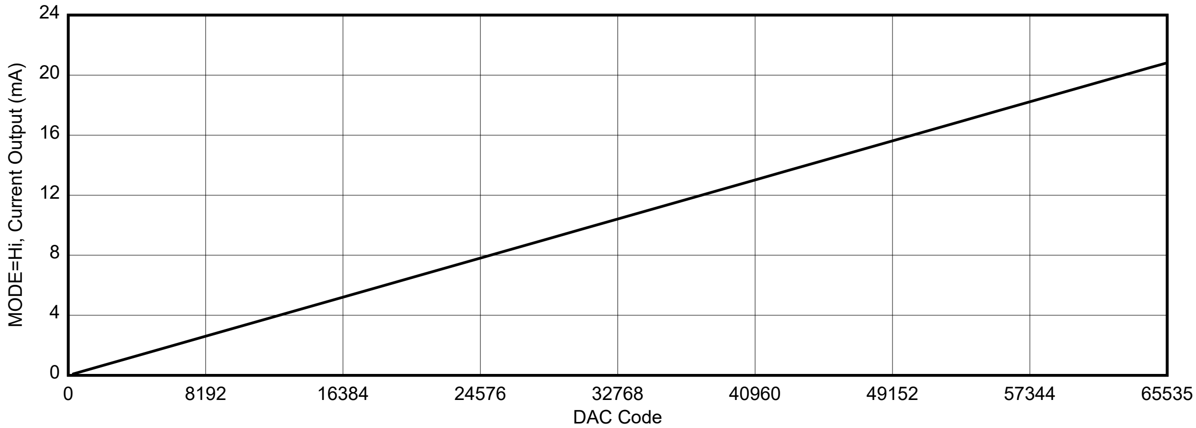
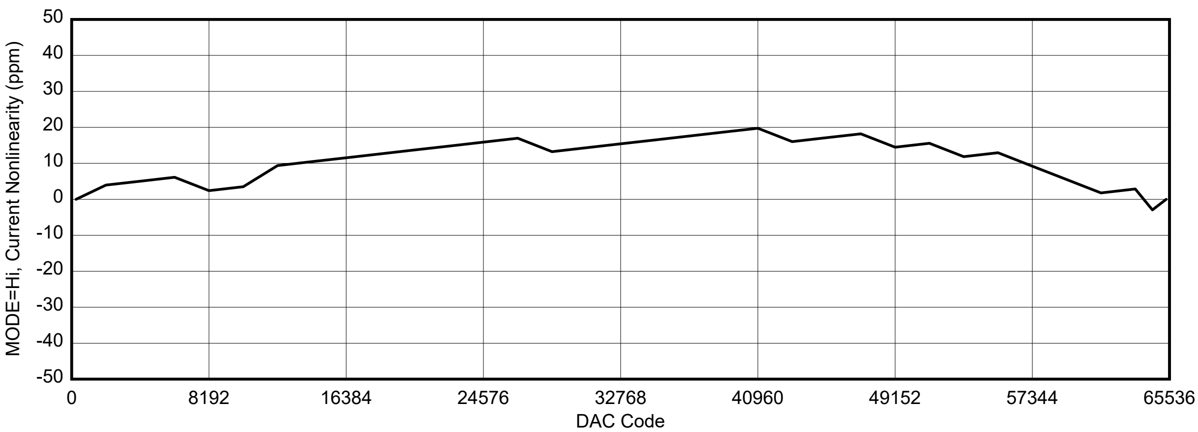
### Measured Results

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 current output mode with MODE = Hi, the measured transfer function from DAC code to output current 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 65535d.




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

| Parameter | Measured Value |
|---|---|
| Gain Error | –0.027% |
| Offset | 0.66μA |
| Nonlinearity | 19.8ppm |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### 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 | 0x0101 | [15:9] 0000000b: Reserved |
| | | | [8] 1b: REF-DIV, divide the reference voltage by two |
| | | | [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 current output. These examples show configuration of the DAC using SPI communication. Note that the DAC80501 has an option to use $I^2C$ for communication.

```
Configure the SPI communication of the microcontroller to SPI mode 1 (CPOL = 0, CPHA =1 );
// Current mode
{Set microcontroller GPIO output to set MODE pin Hi 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 0x040101;
    // DAC80501 output range 0V to 2.5V
    // Set DAC REF-DIV = 1b [8], BUFF-GAIN = 1b [0] in GAIN register
    // DAC output full-scale range set to reference voltage
Set CS to device Hi;
}
// Set DAC80501 Data Code
{Set CS to device Lo;
    Send 24 SCLKs, Write 0x083127;
    // Write DAC output code to 0x3127 (12583d), sets output current to 4mA
Set CS to device Hi;
}
```


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| 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 Product Overview*
- Texas Instruments, *Precision, Three-Wire, Analog Voltage Output Transmitter Using the DAC80501 and XTR200*

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