TI Designs: TIDA-01535

Reference design for power-isolated, ultra-compact analog output module

TEXAS INSTRUMENTS

Description

This single-channel, power-isolated, analog output module reference design delivers current and voltage outputs using the highly-integrated DAC8771 digital-to-analog converter (DAC). The high integration of the DAC8771 coupled with the LM25180 primary-side regulated flyback converter lead to a compact, isolated design with 52-mm × 40-mm board dimensions and a maximum component height of 4 mm. Additionally, the design features external circuitry to provide transient protection for electromagnetic interference (EMI) and electromagnetic compatibility (EMC).

Resources

TIDA-01535	Design Folder
DAC8771	Product Folder
LM25180	Product Folder
ISO7741	Product Folder
ISO7721	Product Folder

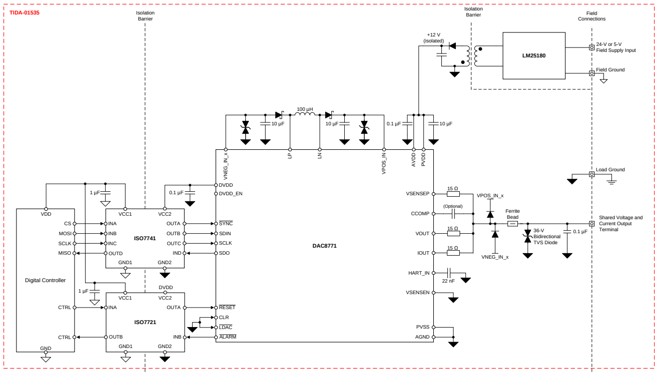
ASK Our E2E Experts

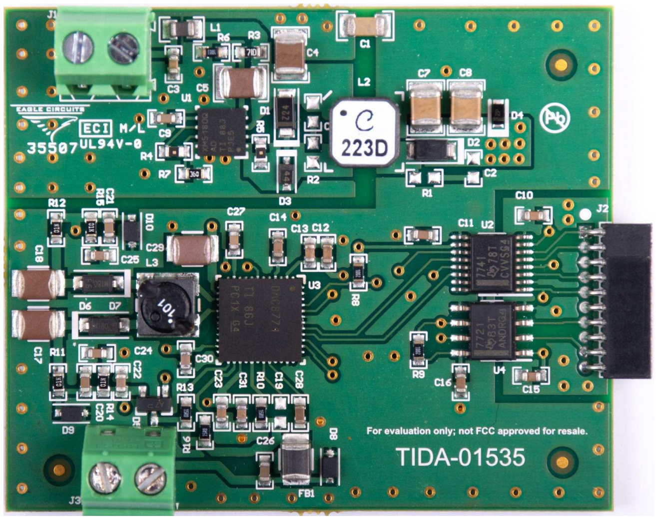
Features

- Isolated analog output for factory automation and control
- 16-Bit resolution
- Digital input isolation
- –24-mA to +24-mA current output
- ±12-V voltage output
- 12-V to 42-V supply input
- Adaptive power management for current outputs
- Compact design: 52 mm × 40 mm

Applications

- Factory automation and control
- Building automation
- Motor drives
- Grid infrastructure: protection relay, DCIO modules





An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Description

This analog output design accepts a standard industrial supply voltage of 12 V to 42 V. The system features a 16-bit voltage (±12 V) or current output (±24 mA), with a total unadjusted error (TUE) of less than 0.1% full-scale range (FSR). The use of an isolated power supply maintains the functional isolation from the power and data inputs to the output. The included external circuitry provides protection against transient electromagnetic interference (EMI). The system uses adaptive power management to minimize power and heat dissipation in the DAC8771, which improves accuracy by reducing self-heating and enabling smaller system enclosures.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Supply voltage	12 V to 42 V	Section 2.2.3
Input	Four-wire serial peripheral interface (SPI) – isolated	Section 2.2.1
Voltage output	±12 V	Section 2.2.1
Current output	–24 mA to +24 mA	Section 2.2.1
Total unadjusted error (TUE)	0.1% FSR	Section 2.2.1
Maximum component height	< 4 mm	Section 2.2.3

2 System Overview

2.1 Block Diagram

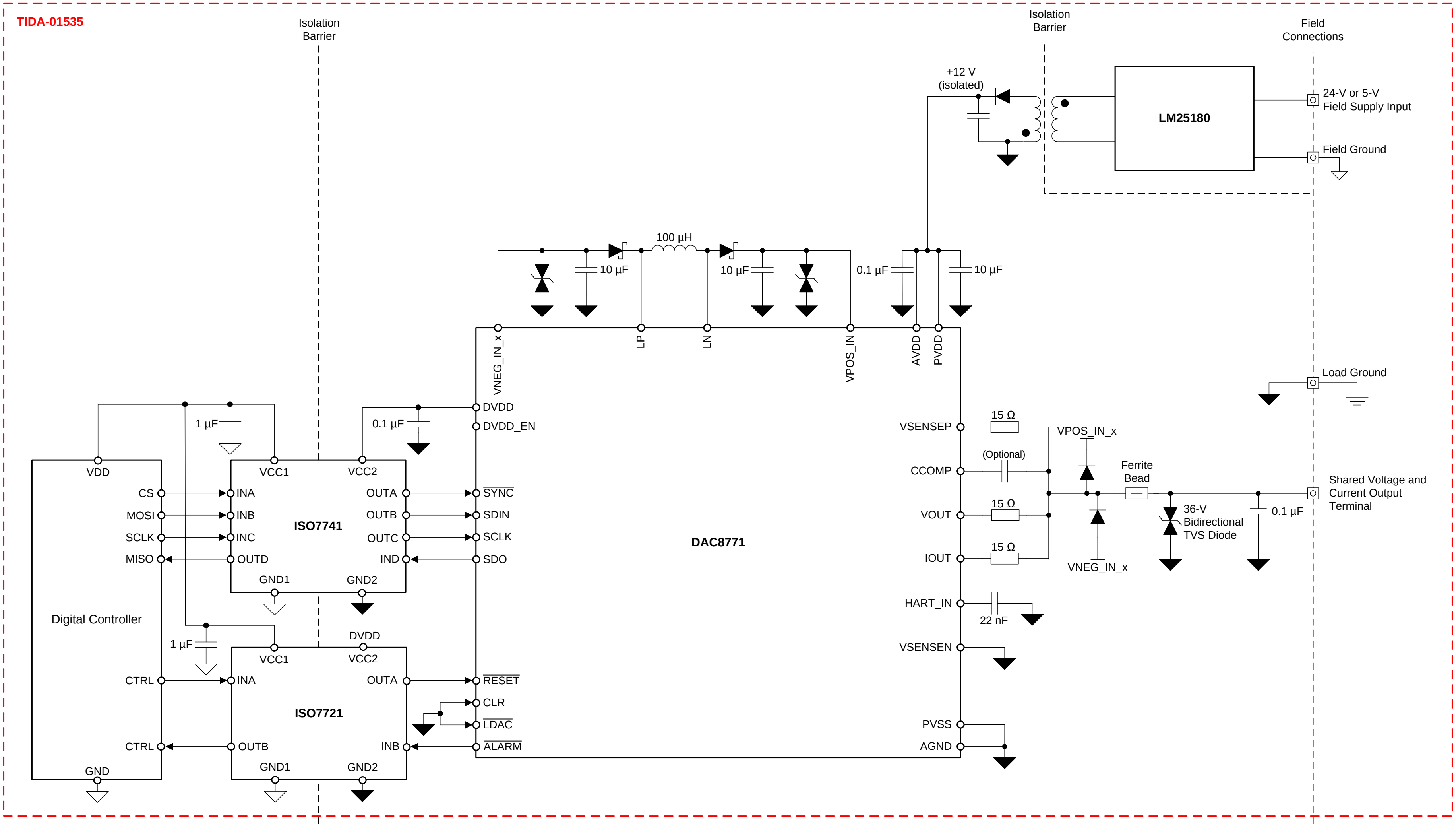


Figure 1. TIDA-01535 Block Diagram

2.2 Design Considerations

2.2.1 Specifications for Isolated Power Supply Design

A 12-V isolated supply voltage is selected to power the DAC8771. The device operates most efficiently at the low end of its input voltage range when it is boosting the voltage. Figure 2 shows the efficiency of the integrated buck-boost converter for the DAC8771.

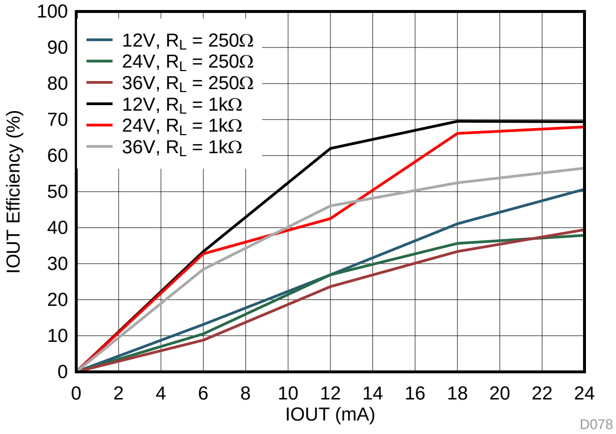


Figure 2. DAC8771 Internal Buck-Boost Converter Efficiency vs Load

The internal buck-boost converter of the DAC8771 uses the 12-V to 36-V supply to generate its own positive and negative voltages, as well as the required digital supply voltage. The inductor current of the internal buck-boost can have a peak of 0.5 A and operates in pulse frequency modulation (PFM) mode without a fixed frequency. In this design, 12-V is chosen to supply the DAC8771 because this voltage is the most efficient for the internal buck-boost converter to generate the required rails.

The average current requirement of the device depends on operating conditions; however, the average is less than 100 mA at 12 V. The target current for the isolated supply design is 150 mA to provide headroom. Both the output capacitance of the flyback converter and the onboard local bypass capacitors supply these peaks. Table 2 lists the power supply design specifications.

Table 2. Isolated Power-Supply Design Parameters

PARAMETER	SPECIFICATIONS
Input voltage	12 V to 42 V
Output voltage (secondary)	12.5 V
Output current (secondary)	150 mA
Switching frequency	10-kHz to 350-kHz

2.2.2 Flyback Operation

A flyback converter is used to provide galvanic isolation between the input power supply and the onboard circuitry of this reference design. The flyback converter functions as a buck-boost converter with a coupled inductor or transformer to transfer power to the isolated side. During the on time, t_{ON}, the internal switch between SW and GND is closed. This closed switch allows current to flow through the primary side of the transformer, and thus stores energy in the magnetic field. The flyback diode D1 is reverse biased during t_{ON} blocking current flow in the secondary side. During the off time, t_{OFF}, energy stored in the magnetic field during T_{ON} charges the output capacitance on the secondary side. This process is illustrated in Figure 3

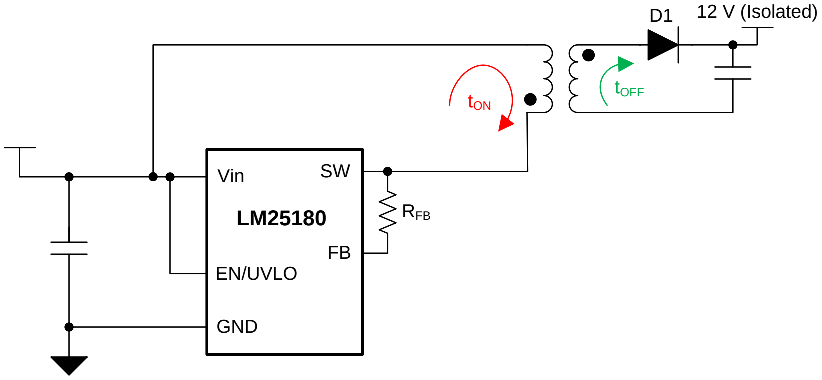


Figure 3. Flyback Operation

The LM25180 flyback converter uses feedback from the primary side to regulate the secondary-side output voltage, eliminating the need for an optocoupler to provide feedback through the isolation barrier. For efficiency across the load-current range, the LM25180 operates with varying frequency, changing operating modes in order to maximize efficiency at different load conditions.

2.2.3 LM25180 Simplified Design Procedure

The first design step is to select the flyback transformer turns ratio, and set the output voltage by selecting R_{FB}. The turns ratio (N_{PS}) at maximum duty cycle and minimum input voltage is given by Equation 1. A turns ratio of 1 is selected based on commonly available coupled inductors. This ratio corresponds to a maximum duty cycle of 51%.

$$N_{PS} = \frac{D_{MAX}}{1 - D_{MAX}} \times \frac{V_{IN(min)}}{V_{OUT} + V_D} = \frac{0.6}{1 - 0.6} \times \frac{12\ V}{12.5\ V + 0.5\ V} = 1.38$$

where

- D_{MAX} is the maximum duty cycle
- $V_{IN(min)}$ is the minimum input voltage
- V_D is the forward voltage drop across the flyback diode
- V_{OUT} is the output voltage (1)

Equation 2 calculates R_{FB} in order to set the output voltage.

$$R_{FB} = (V_{OUT} + V_D) \times N_{PS} \times \frac{R_{SET}}{V_{REF}} = (12.5\ V + 0.5\ V) \times 1 \times \frac{12.1\ k\Omega}{1.21\ V} = 130\ k\Omega$$

where

- V_{OUT} is the isolated output voltage
- V_D is the forward voltage drop of the flyback diode
- N_{PS} is the turns ratio
- V_{REF} is the internal reference voltage (2)

The required minimum inductance is calculated by Equation 3. A 22-µH, 1:1 coupled inductor is chosen with a saturation current of 1.73 A, well above the peak inductor current.

$$L_{MAG} \geq \frac{(V_{OUT} + V_D) \times N_{PS} \times t_{off,min}}{I_{PRI-PK(FFM)}} = \frac{(12\ V + 0.3\ V) \times 1 \times 500\ ns}{0.3\ A} = 21.6\ \mu H$$

where

- L_{MAG} is the magnetizing inductance
- $t_{off,min}$ is the minimum off time
- $I_{PRI\text{-}PK(FFM)}$ is the primary-side peak current (3)

Choose a flyback diode that can withstand the reverse voltage. Equation 4 shows the calculation for the reverse-diode voltage. A 100-V, 1-A diode is chosen for this design.

$$V_{D-REV} \geq \frac{V_{IN(max)}}{N_{PS}} + V_{OUT} = 42\ V + 12.5\ V = 54.5\ V \tag{4}$$

Use sufficient input and output capacitance to minimize voltage ripple. Specific calculations are available in the LM25180 data sheet. For this reference design, 20-µF is used for the input capacitance and 44-µF is used for the output capacitance in order to reduce the isolated supply ripple for the DAC8771.

For more information and design examples, see the *LM25180 data sheet* and *LM25180 PSR flyback quickstart design tool* .

2.2.4 DAC8771 External Circuitry

This reference design uses the DAC8771, with the recommended external discrete circuitry for the internal buck-boost converter operation, and protection from IEC61000-4 transients. The DAC8771 internal reference is used to minimize external components and solution size. Two digital isolators are used to isolate the SPI bus, ALARM pin, and hardware reset pin. On the isolated side, the digital isolators are powered from the DAC8771 internal DVDD LDO.

The design includes series resistors, clamp-to-rail diodes, a TVS diode, ferrite bead, and capacitor at the output of DAC8771 in order to provide protection from industrial transients. For more information on this protection circuit for the DAC8771, see *TIPD216, Quad-Channel Industrial Voltage and Current Output Driver Reference Design (EMC/EMI Tested)*.

2.3 Highlighted Products

2.3.1 DAC8771

The DAC8771 device is chosen for this design because of the high level of integration and the internal buck-boost converter, which simplifies the design process. The DAC8771 includes the digital-to-analog converter (DAC), current and voltage amplifiers, regulated voltages, voltage reference, and all of the switches, transistors, and resistors required to create a configurable integrated solution for industrial voltage and current output drivers. The DAC8771 features a maximum 0.1% FSR TUE specification, which includes the offset error, gain error, and integral non-linearity (INL) baseline for the final system accuracy. This accuracy is maintained across the full –24-mA to +24-mA and ±12-V ranges across an ambient operating temperature of –40°C to +125°C. The maximum differential non-linearity (DNL) specification of ±1 least significant bit (LSB) provides fully-monotonic operation for both V_{OUT} and I_{OUT}.

The DAC8771 has an internal buck-boost converter which can accept a voltage input range of 12 V to 36 V. The device uses a single inductor multiple output (SIMO) configuration to generate the positive and negative voltages required for operation. In current outputs, the load can be used to vary the voltage across the output transistor to reduce the power dissipation. The recommended inductor value is 100 µH ±20% with a peak current rating of 500 mA or greater.

Figure 4 shows the DAC8771 functional block diagram.

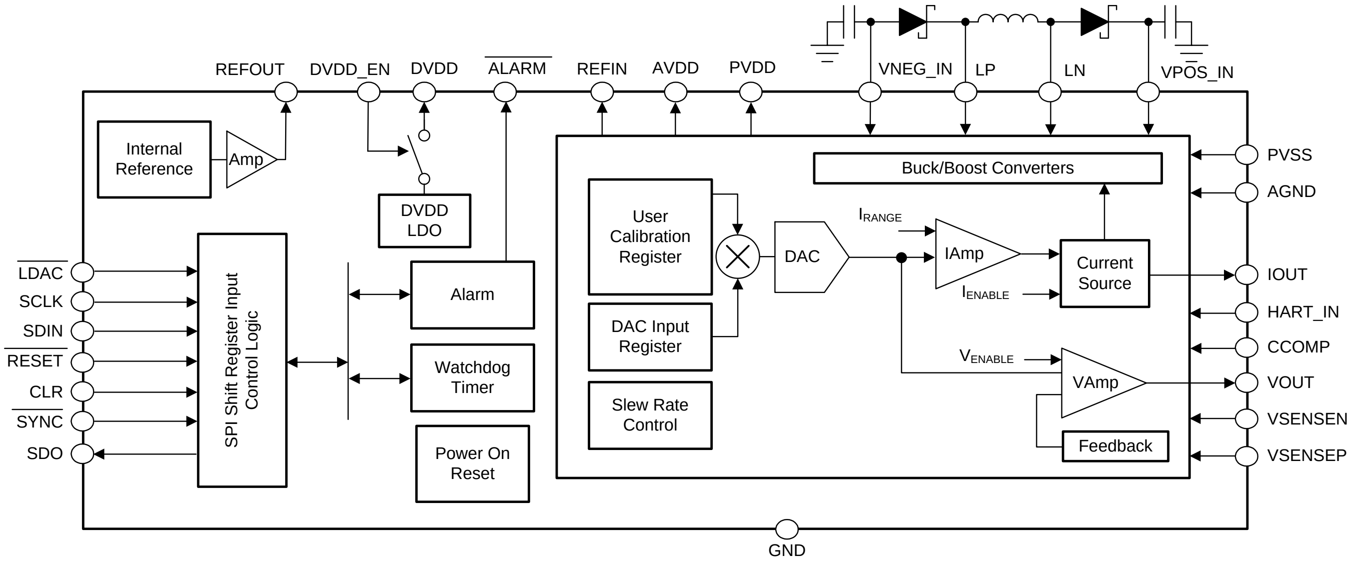


Figure 4. DAC8771 Functional Block Diagram

2.3.2 LM25180

The LM25180 is a primary-side regulated (PSR) flyback converter with high efficiency over a wide input voltage range of 4.5 V to 42 V. The isolated output voltage is sampled from the primary-side flyback voltage, eliminating the need for an optocoupler, voltage reference, or third winding from the transformer output for output voltage regulation. A 1:1 coupled inductor is chosen to minimize the board area and component height. Because of the high efficiency at low output current and design simplicity, the LM25180 is used for this reference design in order to provide an isolated supply for the DAC8771.

Figure 5 shows the LM25180 functional block diagram.

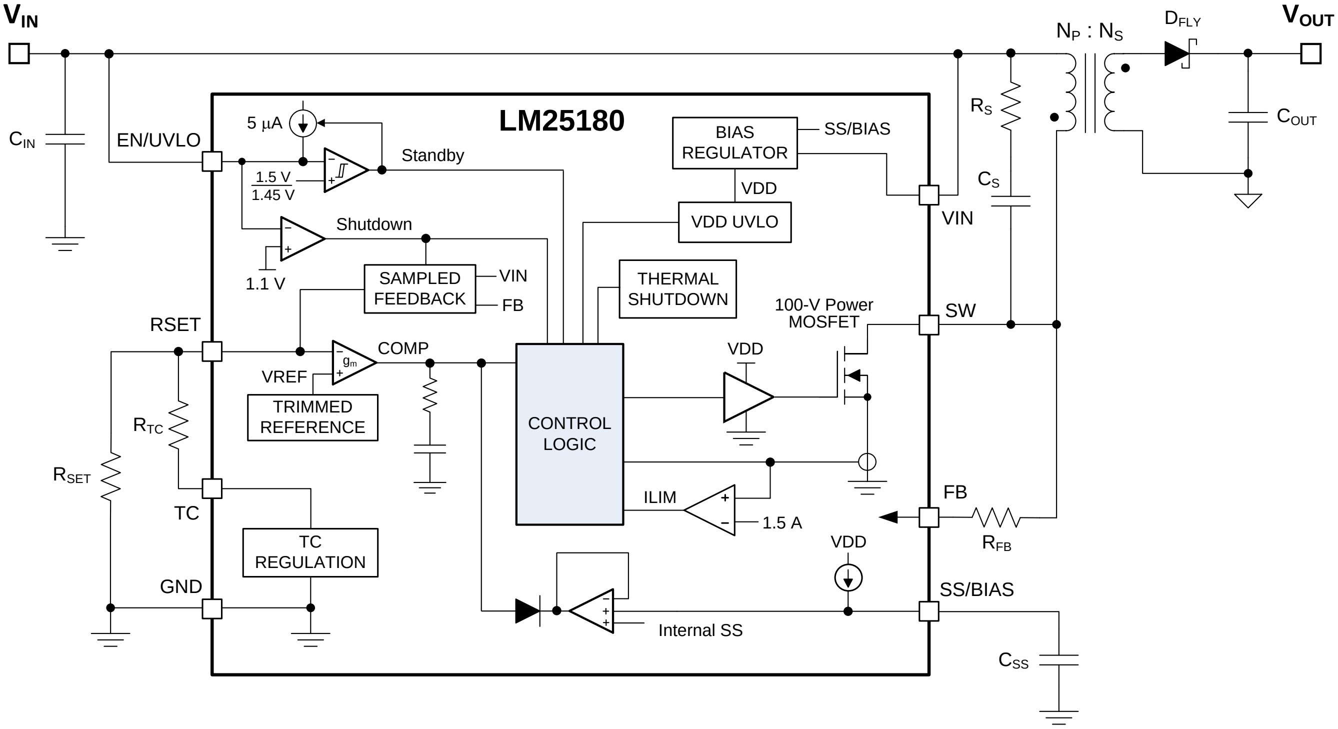


Figure 5. LM25180 Functional Block Diagram

2.3.3 ISO77x1

The ISO774x isolators provide multiple-channel digital isolation that prevents external circuitry interfering with the local ground. These devices feature 100-Mbps signaling, 2500-V_{RMS} isolation, and low power consumption. In this design, the ISO7741 device is used for SPI isolation and the ISO7721 device is used to isolate the alarm and reset signals.

Figure 6 shows the ISO7741 functional block diagram.

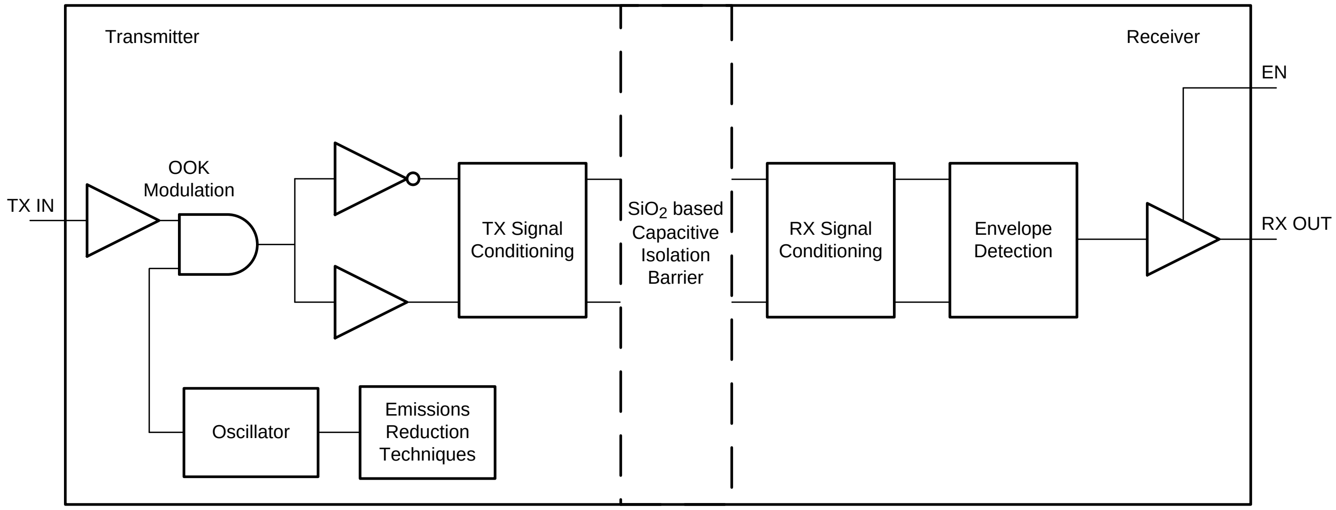


Figure 6. ISO7741 Functional Block Diagram

3 Hardware, Software, Testing Requirements, and Test Results

3.1 *Required Hardware and Software*

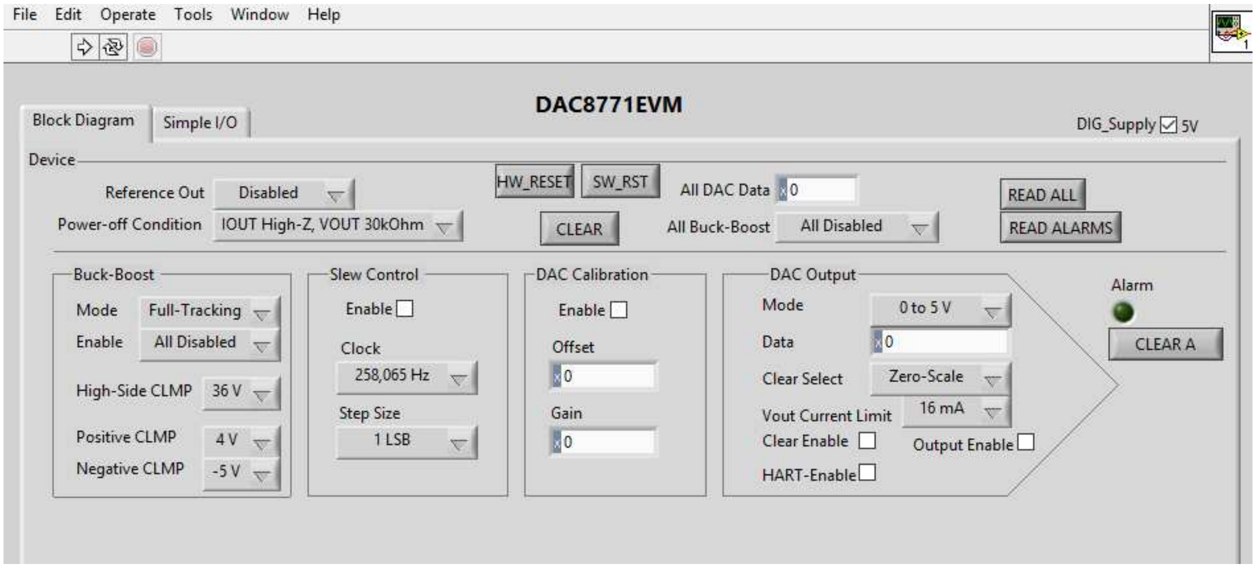
3.1.1 Hardware

For testing, this reference design was connected to a computer USB port through the SM-USB-DIG platform. This connection allows commands to be sent to the DAC from a computer. This process is the same as connecting the DAC8771 evaluation module. Figure 7 shows an image of the test setup connections. For more details, see *DAC8771 Evaluation Module User's Guide*.

Figure 7. SM-USB-DIG Connected to TIDA-01535

3.1.2 Software

The software used for testing was the evaluation module (EVM) software. Figure 8 shows a screenshot of the graphical user interface (GUI).



DIG_Supply ☑ 5V

Reference Out: Disabled
Power-off Condition: IOUT High-Z, VOUT 30kOhm
All DAC Data: 0
All Buck-Boost: All Disabled

Buck-Boost
Mode: Full-Tracking
Enable: All Disabled
High-Side CLMP: 36 V
Positive CLMP: 4 V
Negative CLMP: -5 V

Slew Control
Enable ☐
Clock: 258,065 Hz
Step Size: 1 LSB

DAC Calibration
Enable ☐
Offset: 0
Gain: 0

DAC Output
Mode: 0 to 5 V
Data: 0
Clear Select: Zero-Scale
Vout Current Limit: 16 mA
Clear Enable ☐
Output Enable ☐
HART-Enable ☐

Figure 8. EVM Software GUI

3.2 Testing and Results

3.2.1 Test Results

The total unadjusted error (TUE) was measured across the output range of the DAC8771 device. This measurement ensures that the DAC output is accurate across the code range. The TUE was measured in both current and voltage mode outputs across four boards.Figure 9 shows the voltage mode TUE. For this measurement, the output was connected to a 1-kΩ load and swept from –10 V to +10 V. Figure 10 shows the TUE measurement across the code range when the DAC8771 device is in current mode. In this measurement, the DAC output was connected to a 300-Ω load and swept from 0 mA to 20 mA. These TUE plots show that the design has much less than 0.1% TUE across all codes.

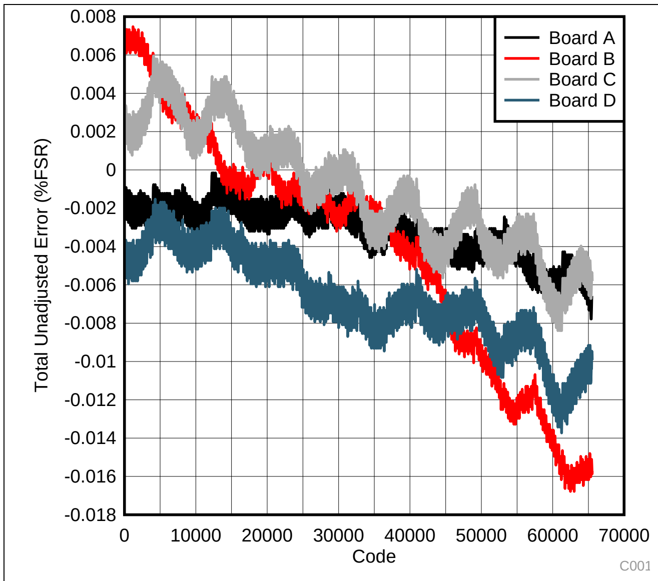


Figure 9. TUE in Voltage Mode Swept From –10 V to +10 V and Driving a 1-kΩ Load

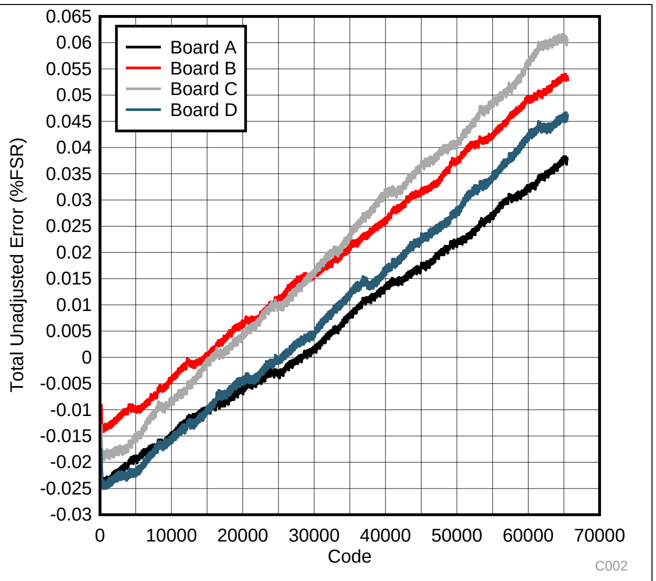


Figure 10. TUE in Current Mode Swept From 0 mA to 20 mA Driving a 300-Ω Load

The DAC8771 output was also examined for noise that can originate from the isolated switching power supply. The output was directly connected to an oscilloscope through a coaxial cable to prevent environmental noise from coupling. A 200-MHz bandwidth limit was set on the oscilloscope to remove any high frequency. Figure 11 shows the output ripple in voltage mode with the voltage set to 10 V to drive a 10-V load. The measured peak-to-peak voltage output ripple was approximately 3 mV. The current output ripple was also measured with the output set to 20 mA driving a 300-Ω load. The voltage was measured and then divided by the load resistance to determine the current ripple. The current ripple was 3.2 mV / 250 Ω = 11 $\mu A_{PK\text{-}PK}$. Figure 12 shows the current mode output ripple. These results show that noise on the output is low for both voltage and current modes.

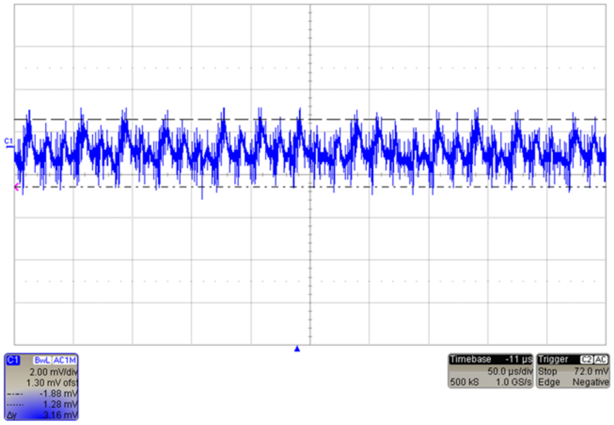


Figure 11. Output Ripple in Voltage Mode (3 $mV_{PK\text{-}PK}$)

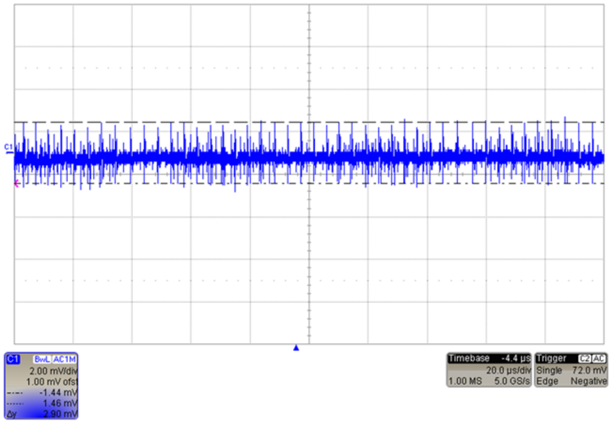


Figure 12. Output Ripple in Current Mode (3.2 mV / 300 Ω = 11 $\mu A_{PK\text{-}PK}$)

The output ripple of the isolated power supply was also measured. This task was accomplished by measuring directly across the output capacitors of the isolated supplies. This measurement was taken at a full load (24 mA, 1 kΩ) and also at a light load with the output of the DAC8771 disabled. Figure 13 and Figure 14 show these measurements, respectively. The output ripple increases at a full load. This ripple is not observable at the output of the DAC8771 device.

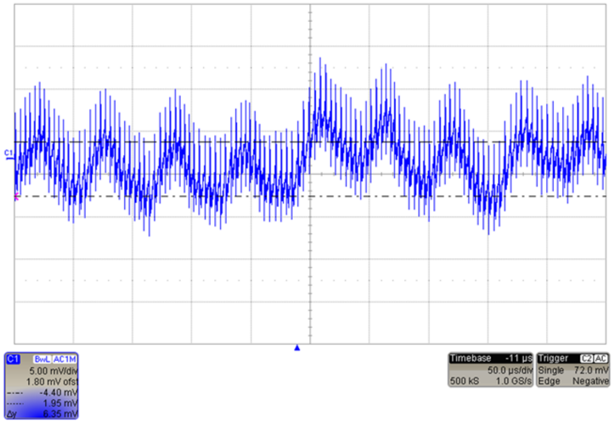


Figure 13. Isolated Power Supply Output Ripple at Full Load

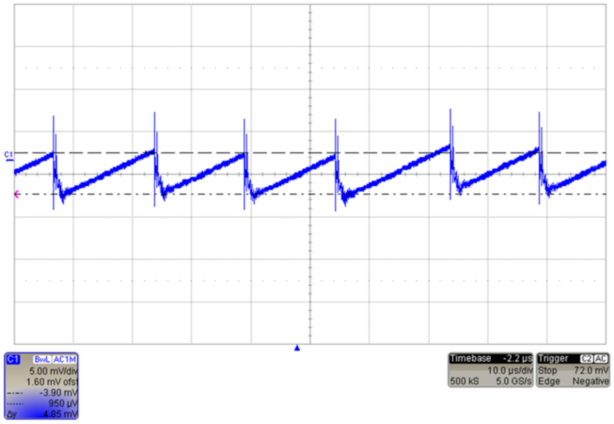


Figure 14. Isolated Power Supply Output Ripple at Light Load

The onboard power dissipation was measured for three different resistive loads at different current outputs, as Figure 15 shows. The power dissipation includes powering the two onboard digital isolators that are responsible for much of the power dissipation at 0-mA load.

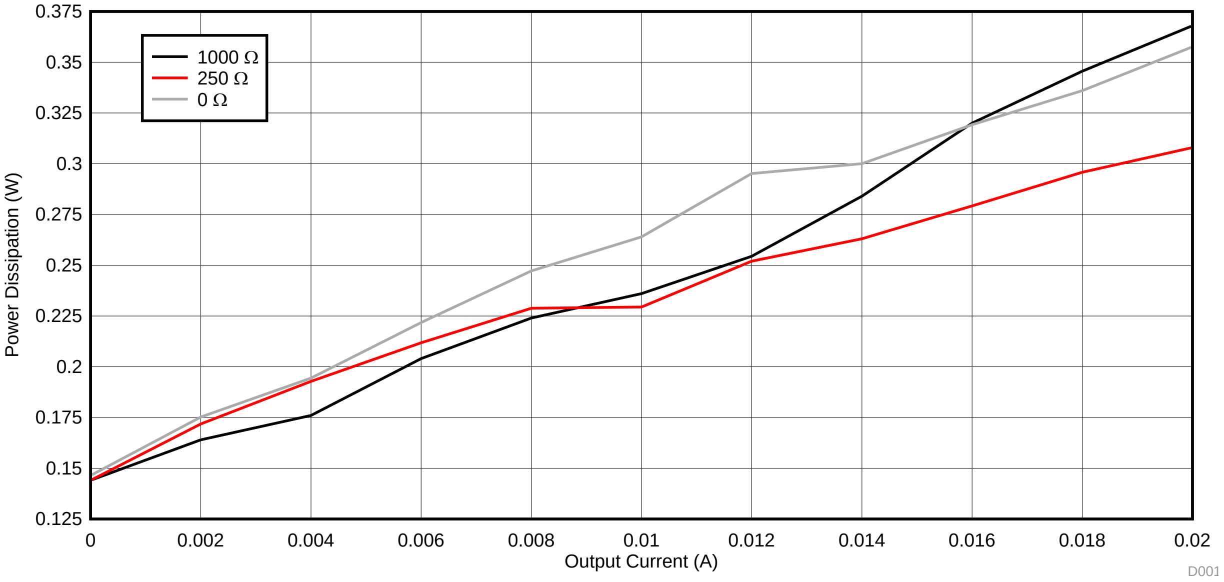


Figure 15. Onboard Power Dissipation vs Output Current

Figure 16 shows the power dissipation at the three load conditions without the digital isolators. This power dissipation only includes the DAC8771 and LM25180 circuitry, because not all applications require digital isolation. To make these measurements, the isolators were removed from the board, and the digital communication was interfaced directly with the DAC8771. This plot shows a significant reduction in power dissipation without digital isolation.

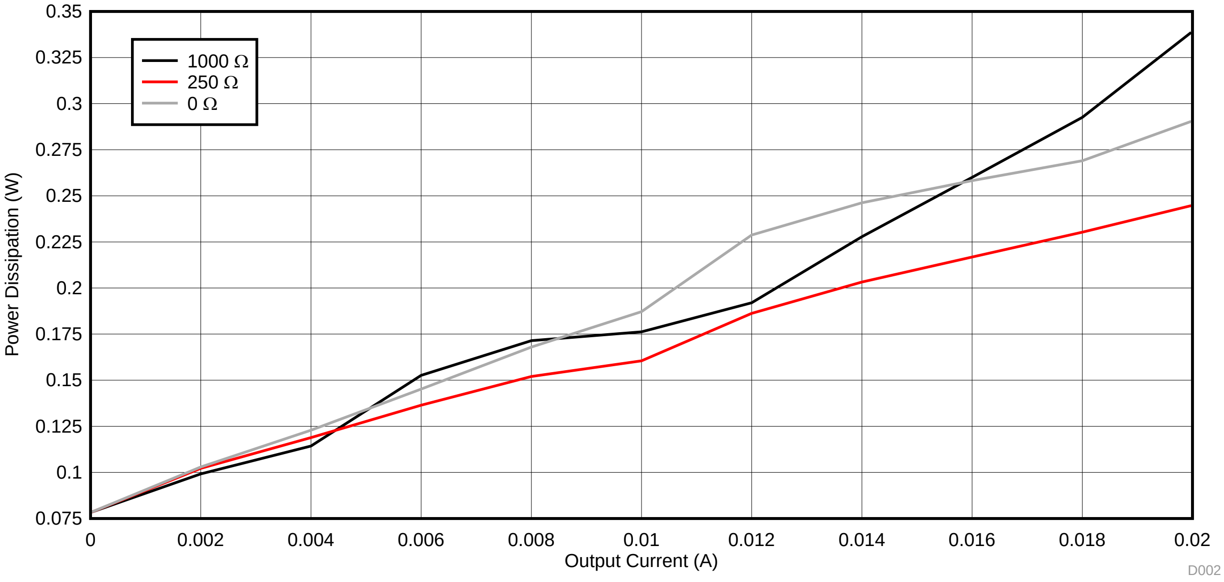


Figure 16. Onboard Power Dissipation vs Output Current (without digital isolators)

The efficiency of the isolated supply was measured across the designed load range of 0 mA to 150 mA. Figure 17 shows the plotted efficiency results for the isolated supply. These efficiency results only include the LM25180 isolated supply design.

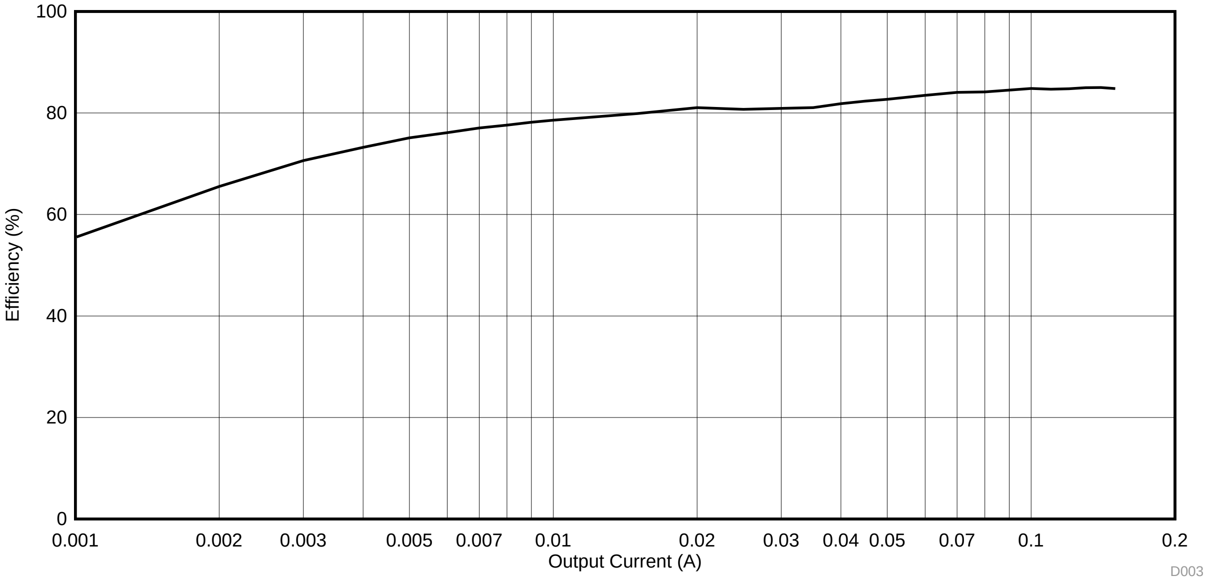


Figure 17. LM25180 Isolated Supply Efficiency vs Output Current

Figure 18 shows a thermal image of the board providing 24 mA into a 1-kΩ load.

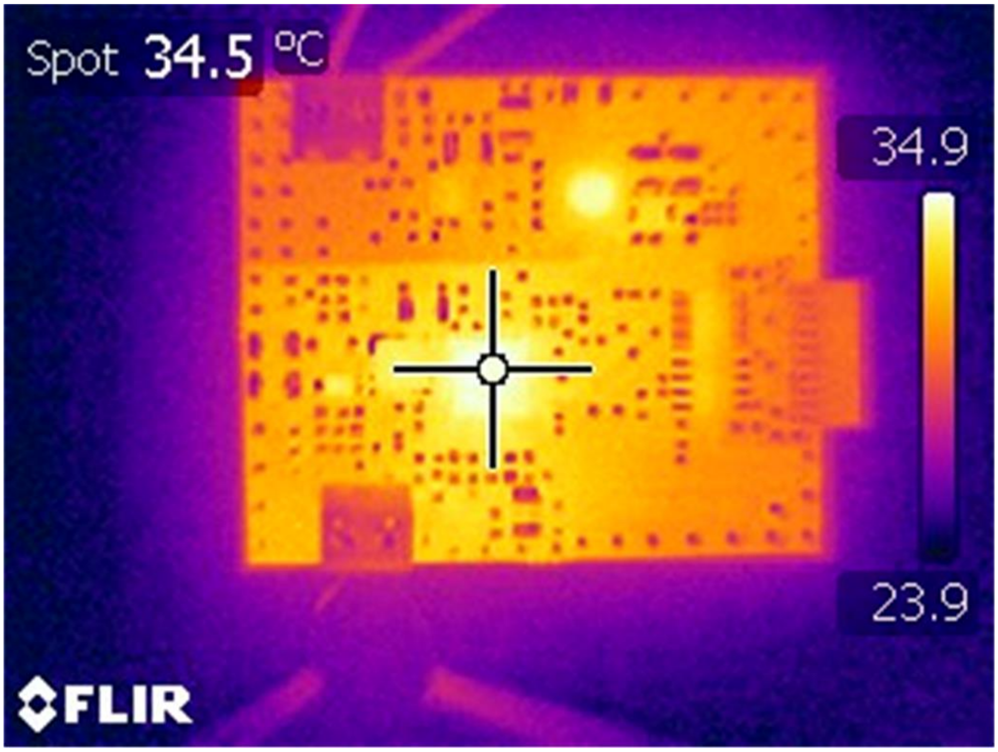


Figure 18. Board Thermal Image: 24 mA into a 1-kΩ Load

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01535.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01535.

4.3 PCB Layout Recommendations

TI recommends to follow standard printed-circuit board (PCB) layout guidelines such as proper decoupling and ground connections with large copper pours. The EMI and EMC protection circuit elements must be placed as close to the output connectors as possible. Use wide traces along the path of the output signal to provide a low impedance path for the analog signals. Via stitching must be used to tie the ground planes together. When possible, use copper pours instead of traces. The inductor for the integrated power supply of the DAC8771 must be placed as close to the device as possible and wide traces must be used to minimize parasitics.

Note that the isolated power supply circuitry requires a few additional guidelines. Placement of the input bypass capacitor for the LM25180 must be as close as possible to the device pin, which is critical. This capacitor provides switching current and must have a direct path to minimize impedance. Minimizing high di/dt loops in a switch-mode power supply design is also important. The input loop from V_{IN} to GND through the bypass capacitor must be minimized. The loop from the switch node through the inductor and output capacitors must also be made as short as possible. Be sure to remove the copper layers (GND, PWR) between the input isolated ground planes for isolation. If possible, remove the thermal reliefs on the power components to further reduce impedance in the power path

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01535.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01535.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01535.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01535.

5 Software Files

To download the software files, see the design files at TIDA-01535.

6 Related Documentation

1. Texas Instruments, *LM5180 EVM user's guide*
2. Texas Instruments, *DAC8771 evaluation module user's guide*
3. Texas Instruments, *Quad-channel industrial voltage and current output driver reference design (EMC/EMI tested)*
4. Texas Instruments, *Less than 1-W, quad-channel, analog output module with adaptive power management reference design*

6.1 Trademarks

All trademarks are the property of their respective owners.

7 Terminology

BOM— Bill of materials

CCM— Continuous conduction mode

COT— Constant on time

DAC— Digital-to-analog converter

DCIO— Discrete input/output module

DNL— Differential nonlinearity

EMC— Electromagnetic compatibility

EMI— Electromagnetic interference

EVM— Evaluation module

FET— Field-effect transistor

FSR— Full-scale range

GUI— Graphical user interface

LSB— Least significant bit

PFM— Pulse frequency modulation

RMS— Root mean square

SIMO— Single inductor multiple output

SPI— Serial peripheral interface

TUE— Total unadjusted error

UVLO— Undervoltage lockout

8 About the Author

GARRETT SATTERFIELD is an applications engineer in the Precision Digital-to-Analog Converters group at Texas Instruments, where he supports industrial products. Garrett received his BSEE from The Georgia Institute of Technology in 2016.

Revision History

Changes from Original (March 2018) to A Revision **Page**

- Changed design guide to use new LM25180 device and associated content 1

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2022, Texas Instruments Incorporated