

TI Designs: TIDA-01552

Reference Design of Eight-Channel, Parallel, 1-A, High-Side, Digital Output Module for PLC



Description

This eight-channel, parallel, 1-A, high-side, digital output reference design for PLC shows the diagnostic features and the power density of new Texas Instruments high-side driver components (such as TPS27S100). Each output can individually measure the output current in real time. This feature makes it possible to detect wire breaks and short circuits during operation. Modifications of the output load due to ageing or manipulation can be discovered as well.

Resources

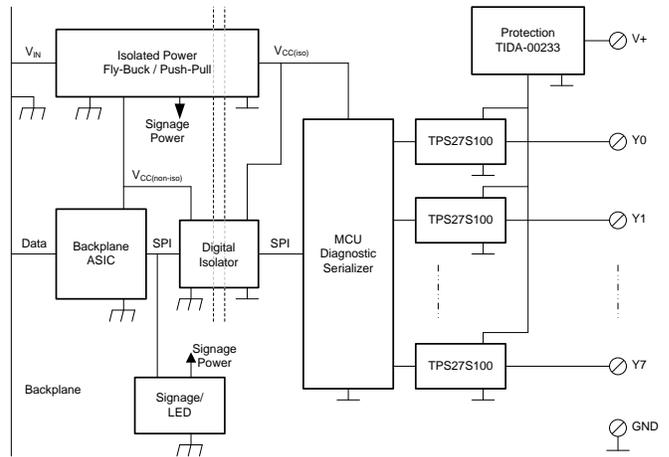
TIDA-01552	Design Folder
TIDA-00233	Design Folder
BeagleBone Black	Community
TPS27S100	Product Folder
ISO7141CC	Product Folder
ISO7141FCC	Product Folder
ISO7421	Product Folder
LM5009	Product Folder
LM5069-2	Product Folder
LM5050-1	Product Folder
MSP430F2132	Product Folder
SN74LV164A	Product Folder
Little Logic	Product Selector
NexFET™	Product Selector

Features

- High-Density, Eight-Channel, 24-V High-Side Output
- 1 A per Channel Unregulated (20%), 3-A Peak
- Four-Wire SPI MCU Interface
- Fast Switching of Inductive Loads
- LEDs to Indicate Output State
- BeagleBone Black Cape Form Factor for Easy Evaluation (Four Boards Stackable)

Applications

- Digital Outputs for
 - Programmable Logic Controllers (PLCs)
 - Distributed Control Systems (DCSs)
 - Process Automation Controllers (PACs)
 - Motor Control I/O Modules
 - Sensor Concentrators



Copyright © 2017, Texas Instruments Incorporated





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 reference design is a digital output (DO) module, which is a standard function in PLC or DCS systems. The DO module can energize or de-energize resistive, capacitive, or inductive loads or control them with pulse width modulation (PWM).

DO can be a high-side, low-side, or push-pull switch. This design uses the high-side principle, which means that the load is installed between the output of the module and ground. The switch connects the load with the 24-V field supply to energize the load.

An advantage of this principle is the intrinsic safe operation. If the isolation of the wire between output and load fails then the load can falsely connect to ground. The other side of the load is also connected to ground. Therefore, in this error case, the load has no energy and is off.

A high-side configuration is also less sensitive to corrosion because both sides of the load are permanently connected to ground when the load is off.

1.1 Key System Specifications

Table 1. Key System Specifications

SYMBOL	PARAMETER	CONDITIONS	SPECIFICATION			UNIT
			MIN	TYP	MAX	
$V_{IN(max, off)}$	Input voltage	Overvoltage protection stops local power supply, V_{IN} rising	—	32	—	V
$V_{IN(max, on)}$	Input voltage	Overvoltage protection stops local power supply, V_{IN} falling	—	30	—	V
$V_{IN(min, on)}$	Input voltage	Undervoltage protection starts local power supply at rising V_{IN}	—	12	—	V
$V_{IN(min, off)}$	Input voltage	Undervoltage protection stops local power supply at falling V_{IN}	—	11	—	V
I_{IN}	Input current	Normal operation	0.01 ⁽¹⁾	—	11 ⁽²⁾	A
V_{LOAD}	Load supply voltage	Normal operation	—	—	V_{IN}	—
I_{LOAD}	Load current	Per channel, $T_A = 85^\circ\text{C}$	—	1.2	3.5 ⁽³⁾	A
		Per channel, $T_A = 25^\circ\text{C}$	1.25	⁽⁴⁾	3.5 ⁽³⁾	A
t_{OVER}	Overcurrent time	All outputs on, $R_L = 18 \Omega$, $V_{IN} = 27 \text{ V}$, $T_A = 25^\circ\text{C}$	—	25	—	ms
I_{OVER}	Overcurrent limit	All outputs on, $R_L = 18 \Omega$, $V_{IN} = 27 \text{ V}$, $T_A = 25^\circ\text{C}$	9.6	11 ⁽²⁾	12.4	A
$P_{LOSS(25)}$	Power loss per channel	$R_L = 18 \Omega$, $V_{LOAD} = 21.6 \text{ V}$, $T_A = 25^\circ\text{C}$	—	150 ⁽⁵⁾	—	mW
$P_{LOSS(85)}$	Power loss per channel	$R_L = 18 \Omega$, $V_{LOAD} = 21.6 \text{ V}$, $T_A = 85^\circ\text{C}$	—	—	240 ⁽⁵⁾	mW
f_{SW}	Switching frequency (PWM)	Absolute maximum rating per TPS27S100 datasheet	—	—	2	kHz
$t_{ON(min)}$	Minimum on time	Guaranteed by design per TPS27S100 datasheet	50	—	—	μs
$t_{OFF(min)}$	Minimum off time	Guaranteed by design per TPS27S100 datasheet	50	—	—	μs
t_{RISE}	Load voltage rise time, 10% to 90%	$R_L = 18 \Omega$, $V_{LOAD} = 24 \text{ V}$, $T_A = 25^\circ\text{C}$, one load	27	45	135	μs
t_{FALL}	Load voltage fall time, 90% to 10%	$R_L = 18 \Omega$, $V_{LOAD} = 24 \text{ V}$, $T_A = 25^\circ\text{C}$, one load	27	45	135	μs
P_{IND}	Inductive power per output	—	—	70 ⁽⁶⁾	—	mJ/s

⁽¹⁾ Depends on the number of LEDs on and communication activity

⁽²⁾ Limited by overcurrent protection

⁽³⁾ Limited by current limit resistor designed into this reference design at TPS27S100

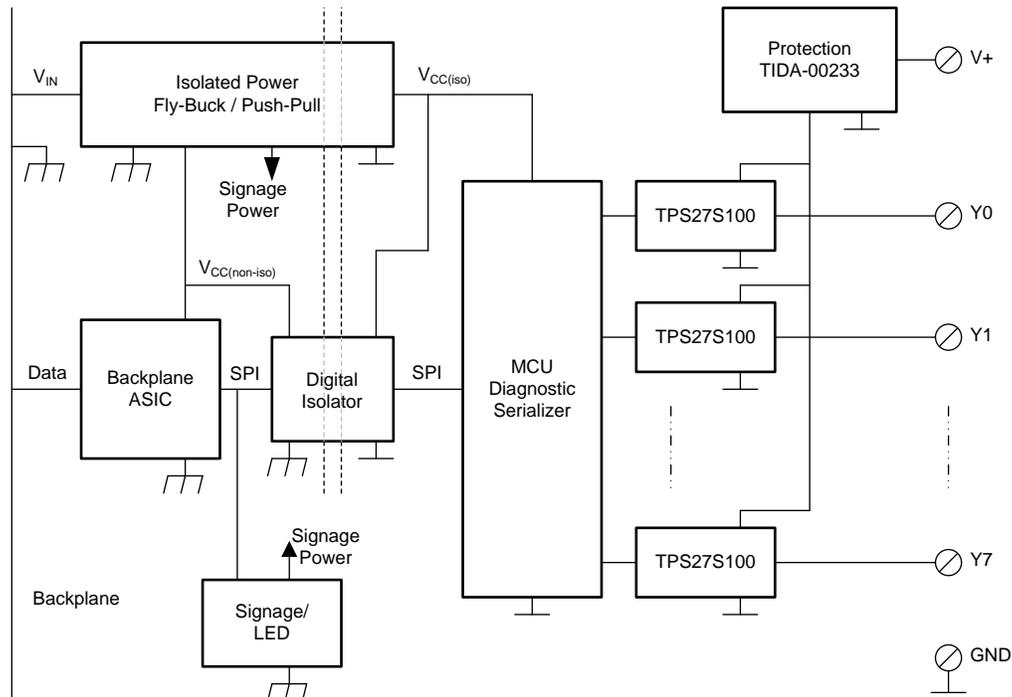
⁽⁴⁾ Protection limits total current to 10 A, load can be distributed for example $3 \times 3 \text{ A} + 5 \times 0.2 \text{ A}$

⁽⁵⁾ Based on calculations derived from TPS27S100 datasheet

⁽⁶⁾ Based on inductive power capabilities of TPS27S100. If the clamping value of TVS diode D89 is set to a voltage level smaller than the clamping level of TPS27S100, then D89 takes all inductive energy. In this case, the total inductive power for all outputs together can be 1 J/s irrespective how the energy is distributed among the outputs. More copper area can increase the inductive power. Up to 3 J/s is possible

2 System Overview

2.1 Block Diagram



Copyright © 2017, Texas Instruments Incorporated

Figure 1. Block Diagram

2.2 Highlighted Products

Find more details about these devices in [Section 2.3](#).

2.2.1 TPS27S100

The TPS27S100 is a fully protected high-side power switch with integrated NMOS power FET and a charge pump, targeted for the intelligent control of the variable kinds of resistive, inductive, and capacitive loads. The device has an accurate current sense, a programmable current limit, and overtemperature protection.

2.2.2 MSP430F2132

The MSP430F2132 is an ultra-low-power microcontroller unit (MCU) with two built-in 16-bit timers, a fast 10-bit A/D converter with integrated reference, and a data transfer controller (DTC), a comparator, built-in communication capability using the universal serial communication interface, and up to 24 I/O pins.

2.2.3 ISO7141CC and ISO7141FCC

The ISO7141CC and ISO7141FCC devices provide galvanic isolation up to 2500 V_{RMS} for 1 minute per UL and 4242 VPK per VDE. The ISO7141 has three forward and one reverse-direction channels. These devices are capable of a 50-Mbps maximum data rate with 5-V supplies and a 40-Mbps maximum data rate with 3.3-V or 2.7-V supplies, with integrated filters on the inputs for noise-prone applications. The devices have TTL input thresholds. CC indicates that the output is high when the input side is not powered. FCC indicates that the output is low when the input side is not powered.

2.2.4 ISO7421

The ISO7421 has the same isolation capabilities as the ISO7141 above. The device has two channels, one forward and one back channel and operates at maximum 1 Mbps with 3.3-V and 5-V supplies. The device has TTL input threshold.

2.2.5 TLC5928

The TLC5928 is a 16-channel, constant-current sink LED driver. Each channel can be turned on or off by writing serial data to an internal register. The constant-current value of all 16 channels is set by a single external resistor. The TLC5928 has two error detection circuits: one for LED open detection (LOD) and one for a pre-thermal warning (PTW). LOD detects a broken or disconnected LED and LEDs shorted to GND while the constant-current output is on. PTW indicates a high temperature condition.

2.2.6 SN74LV164A

The SN74LV164A devices are 8-bit parallel-out serial shift registers designed for 2-V to 5.5-V VCC operation.

2.2.7 Little Logic

These devices from TI's Little Logic family are in the design for address decoding, SPI chip select, and reset generation: SN74LVC1G07, SN74LVC2G86, SN74LVC1G332, SN74LVC1G19, SN74LVC1G58, and SN74LVC1G125.

Little Logic gates have all the features of their bigger cousins but in single, double, and triple gate functions. They cover the full range of voltages from 0.8 to 5.5 V. They come in tiny packages making them excellent for handheld and any other equipment where space is a concern.

2.2.8 SN6501

The SN6501 is a monolithic oscillator and power driver, specifically designed for small form factor, isolated power supplies in isolated interface applications. The device drives a low-profile, center-tapped transformer primary from a 3.3-V or 5-V DC power supply. The secondary can be wound to provide any isolated voltage based on transformer turns ratio.

2.2.9 LM5009

The LM5009 features all of the functions needed to implement a low-cost, efficient, buck regulator. This device is capable of driving a 150-mA load current from a 9.5-V to 95-V input source. The output voltage can be 2.5 V to 85 V. The regulator has an N-Channel buck switch and internal startup regulator. With its much smaller power loss, it is a perfect replacement for high-voltage LDOs. The control scheme requires no loop compensation, resulting in an ultra-fast transient response. An intelligent current limit is implemented with forced OFF time, which is inversely proportional to V_{OUT} . This scheme ensures short circuit protection while providing minimum foldback. Other features include thermal shutdown, V_{CC} undervoltage lockout, gate drive undervoltage lockout, and maximum duty cycle limiter.

2.2.10 LM5050-1

The LM5050-1 operates in conjunction with an external MOSFET as an ideal diode rectifier when connected in series with a power source. This ORing controller allows MOSFETs to replace diode rectifiers in power distribution networks, thus reducing both power loss and voltage drops.

2.2.11 LM5069

The LM5069 positive hot swap controller provides intelligent control of the power supply connections during insertion and removal of circuit cards from a live system backplane or other "hot" power sources. The LM5069 provides in-rush current control to limit system voltage droop and transients. The current limit and power dissipation in the external series pass N-Channel MOSFET are programmable, ensuring operation within the safe operating area (SOA). The POWER GOOD output indicates when the output voltage is within 1.25 V of the input voltage. The input undervoltage and overvoltage lockout levels and hysteresis are programmable as well as the initial insertion delay time and fault detection time. The LM5069-1 latches off after a fault detection, while the LM5069-2 automatically restarts at a fixed duty cycle.

2.3 System Design Theory

This reference design has a BeagleBone Black Cape form factor. The BeagleBone Black is an open source, low-cost microcomputer with Linux operating system. This makes the evaluation of our featured components very easy. With this methodology, it is possible to test all components in the target environment, which is an industrial switching cabinet for factory automation. The DO module reference design has all necessary components for safe operation in noisy industrial environment.

This design uses digital isolators and an isolated power supply to separate the 24-V field side and the BeagleBone Black. Therefore, the microprocessor (MPU) in BeagleBone Black continues operation even when a lightning strike happens in the field. A ground shift of 500 V between BeagleBone Black and field side has no impact on the correct operation.

The MPU on the BeagleBone Black talks to the design through a four-wire SPI. Therefore, only one isolation component with four channels is necessary for SPI. A second isolation component isolates a reset signal and an interrupt signal.

An MCU works as the isolated SPI slave within the reference design. The MCU also connects to eight high-side switches, one switch per load. Through the isolated SPI, the MCU receives and decodes the data from the BeagleBone Black. This data tells the MCU which load to energize or de-energize. The MCU can also measure all load currents and calculate the power loss in all high-side switches. If the total power loss is more than permitted by the thermal budget of this DO module reference design, then the MCU can de-energize outputs.

The MCU can also use the measured output currents to implement electronic fuses. If the current of a certain output is more than a programmed threshold (optionally for more than a programmed time), then the MCU can de-energize the load on this output. A programmable current limit and the thermal limit function of the high-side switch do the protection (first line of defense) until the MCU responds.

A smart diode protects the reference design from reverse polarized field supply voltage and from reverse currents. The reverse currents can come from a short circuit of the field supply. In this case, the stored local energy or stored output energy (capacitive loads or brushed DC motors) wants to flow back into the field supply. This can destroy the high-side switches. The reverse current protection effectively prevents this potential destruction. A smart diode has less of a voltage drop than a Schottky diode. This is important because of the power loss. At a 10-A total load current, a Schottky diode has a loss of typical 5 W. The smart diode only has a typical 0.5-W power loss.

An in-rush current limiter and electronic fuse protect the reference design from these effects:

- Surges
- Fast transients
- Overvoltage
- Undervoltage
- Overcurrent
- Short circuit

Surges can come from lightning strikes nearby, and fast transient can come from inductive loads. The electronic fuse protects the reference design also from too high load currents. If the sum of all load currents is higher than 10 A, the electronic fuse stops the local power supply within a typical 45 μ s (overcurrent protection). If the sum of all load currents is higher than 30 A, the local power supply stops instantly within a typical 450 ns and maximum 1.2 μ s (circuit breaker). Through the isolated power from the BeagleBone Black, the MCU has still auxiliary power in this error case. It then can report the error to the BeagleBone Black.

A power good signal from the electronic fuse tells the MCU that the field supply is present and within specification. The MCU also measures the local 24-V power supply. With this information, the MCU can detect miss-wiring. If 24 V is available on the local supply but the power good signal is not there, then this is an index for the field supply connected to an output (instead of the 24-V field supply connector). In this case, the protection from electronic fuse is not effective and the MCU must not energize any loads.

Up to four DO module design boards can work together with one BeagleBone-Black. All share the same SPI bus. Discrete logic chips with single-gate functions do the necessary address decoding. With this address decoding the BeagleBone Black can talk to individual reference design boards on the same SPI bus.

An isolated debug port is necessary to debug the MCU on the field side when the field side is in operation. Otherwise, a ground shift on the field side can cause unwanted current flow into the debugger PC. This current flow can be dangerous for the operator, stop the correct operation of the PC or destroy the PC. With the debug port isolation, there is no current flow into the PC and the debug operation is safe.

2.3.1 High-Side Switch

The main task of the DO module reference design is to switch on and off electric loads, which are connected to ground on the machine side. For this task, it uses the high-side switch principle. The TPS27S100 is a device for this purpose. The TPS27S100 can switch resistive, inductive, and capacitive loads. Examples for load types are in [Table 2](#).

Table 2. Examples for Loads

TYPE OF LOAD	LOAD PROPERTIES	LOAD EXAMPLE
Resistive load	Current nearly constant over time	Resistors, heaters
Inductive load	Current starts at zero and increases over time, wants to continue flow when output switches off, causes high-voltage spike	Inductors, relays, magnetic valves, electric magnets
Capacitive load	Current starts high (inrush) and decreases over time	Capacitors, lamps, brushed DC motors, electric equipment which is energized from this output

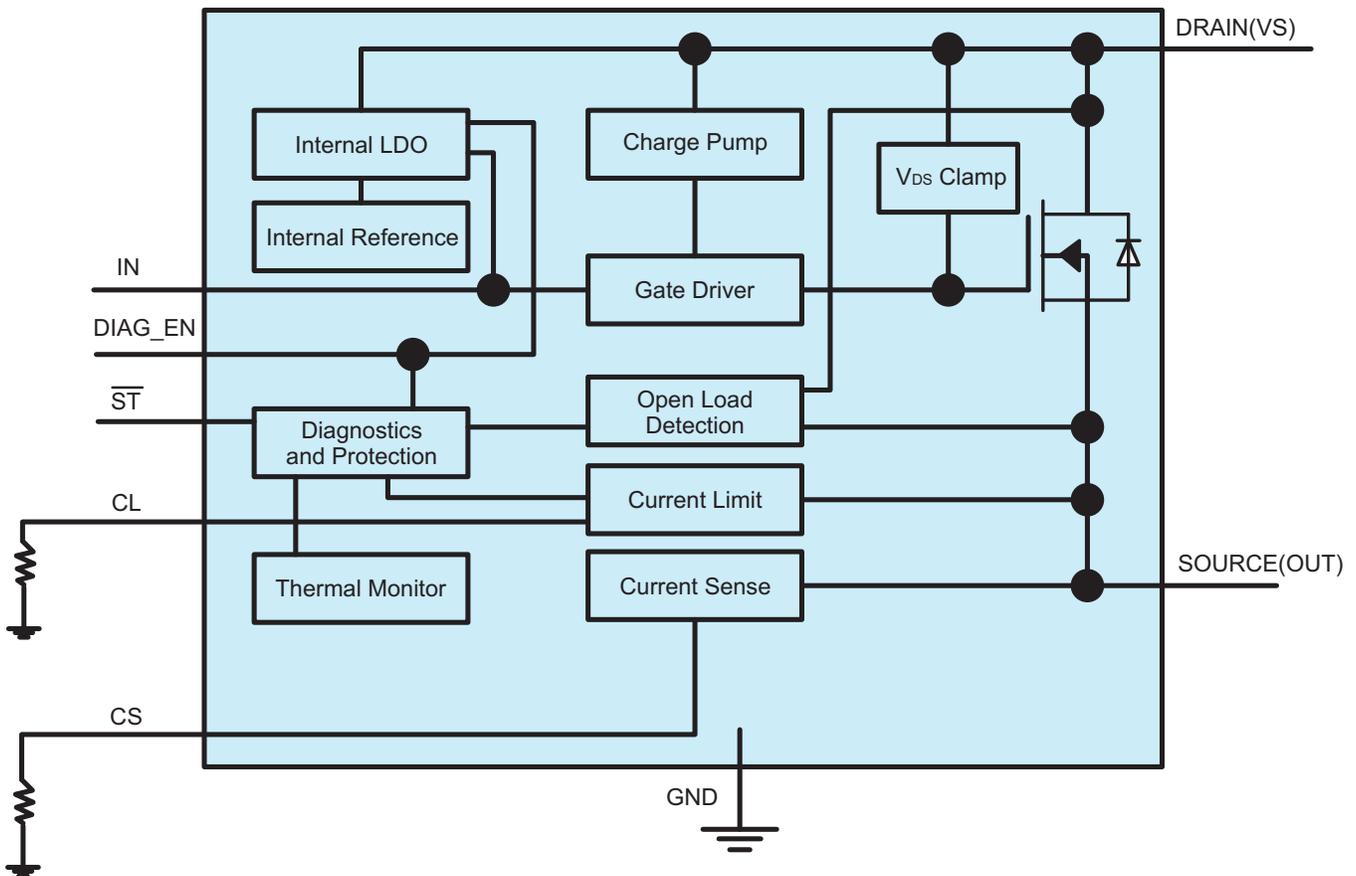


Figure 2. TPS27S100 Block Diagram

The TPS27S100 has protection against voltage spikes from inductive loads. The device can limit the output current and slowly charge capacitive load. If the die temperature is more than 150°C, then the load is de-energized until the die has cooled down to 125°C. A current mirror and scaler drives a current through the CL pin to ground. This current is proportional to the output current. A sense resistor can convert this current to a voltage. In this design, the MCU measures this voltage and gets information about the load current.

The TPS27S100 comes in a PWP package at a 5-mm×7-mm board space and can drive 1.2 A simultaneously at each output with only PCB cooling. An area of about 30 cm² copper for all TPS27S100 together is sufficient for operation at ambient temperatures of 85°C. The design provides around the 32-cm² copper area.

The TPS27S100s have internal clamping for inductive loads. The clamping voltage is more than 50 V below the 24-V power supply voltage and enables fast inductive discharge. The design considerations are in more detail in [Section 2.3.6](#).

2.3.2 Digital Isolators

This reference design uses the ISO7141 devices for SPI bus isolation and for the debug port. The ISO7141 isolates three signals in one direction and one signal in opposite direction. For the SPI bus, the three signals from BeagleBone Black towards the MCU are:

- SCLK
- CS
- MOSI

The one signal back from MCU towards BeagleBone Black is MISO.

For the reset signal from the BeagleBone Black to the reference design MCU, use an ISO7421 two-channel isolator. The isolator has one channel in each direction. The back channel carries an interrupt signal from the reference design MCU to the BeagleBone Black.

When the debugger is not connected to the debug port then the power on that side of the digital isolator is missing. This is the normal operation mode. When the debug tool is not connected, these signals need to default to high:

- TDI/TCLK
- nRST
- RXD

When the debug tool is not connected, these signals need to default to low:

- TCK
- TMS
- TEST

For the debug port, use the digital isolators in two different configurations:

- ISO7141CC outputs default to high when the input side is not powered
- ISO7141FCC outputs default to low when the input side is not powered

The ISO7141 isolators support up to 50 Mbps. This limit is well above the communication speed used in the design. The ISO7421 supports 1 Mbps, which is fast enough for reset and interrupt signals in this design.

2.3.3 MCU

The MCU in the DO module reference design comes from the MSP430™ family of ultra-low-power MCUs. The MSP430F2132 works at temperatures up to 105°C and has 8KB of Flash memory for program storage. 512 bytes are available as RAM working memory. If the control routines for the MCU need less memory, these controllers are available with less memory:

- MSP430F2122 with 4KB Flash and 512-Byte RAM
- MSP430F2112 with 2KB Flash and 256-Byte RAM

In this reference design, use these features of this MCU family:

- 10-bit A/D converter
- Timer
- SPI
- UART
- GPIO
- Temperature sensor

The A/D converter measures the output currents in the high-side switches and the local 24-V power supply voltage. The GPIOs energize the load through the high-side switches. The timer functions control the measurement intervals for the output currents and optional the fuse function. The UART can send live status information about the health of the reference design when the user evaluates the function. The temperature sensor can measure the ambient temperature before the evaluation and the board temperature profile during the evaluation.

The MCU core has enough performance to protect the SPI data stream with error detection and correction codes. The device can also start an emergency program if the data connection to the BeagleBone Black is lost. The MCU can then energize and de-energize the loads to a pre-defined safe state.

2.3.4 Power Supply

The MCU on the reference design and the high-side switches need a stable power supply for correct operation. The 24-V field supply voltage can have destructive conditions for the high-side switches and for the MCU. Therefore, a filter is necessary to remove these destructive conditions. The filter has two stages.

In the first stage, the filter reduces surge voltages from 500 V down to 85 V. The filter also uses smart diode technology to protect the reference design against wrong polarized power supplies. The smart diode function comes from an LM5050 OR-ing controller and a NexFET.

The second stage involves an LM5069 and a NexFET and protects against these conditions:

- Overcurrent
- Undervoltage
- Overvoltage
- Short circuit

The second stage also breaks the current-flow when the input voltage is more than 45 V during a surge pulse. The output voltage of the power filter is never higher than 45 V.

The MCU has a dual power supply and can receive power from the BeagleBone Black through an isolating power supply. This supply is the auxiliary power and it is based on an SN6501 push-pull driver with an integrated oscillator. A forward converter transformer does the isolation and voltage conversion from 5 V to 3.3 V. The transformer powers the MCU to start a diagnostic process before the start of normal operation. This diagnostics includes these tests:

- Miss-wiring test
- 24-V field supply test for specification compliance
- Host communication test

With miss-wiring or if the field supply voltage is out of specification, it can happen that no 24-V local power supply is available. In this case, the auxiliary power can help the MCU to do diagnostics and give the BeagleBone-Black detailed information about the source of the problem.

The auxiliary power has a second purpose. The field supply can have an intermittent failure or the surge protection can briefly interrupt the power supply. With the auxiliary power, the MCU can preserve the actual working state. The MCU can resume correct operation once the 24-V supply is stable again.

When a correct 24-V local power is available, then the 3.3 V for the MCU come from a buck regulator. Then the MCU has power for initialization and diagnostics even if the BeagleBone Black is not working. In this case, the MCU can bring the DO module reference design with all connected loads into a safe state.

This buck regulator uses an LM5009. The LM5009 is a high-voltage buck regulator and can operate at up to 100-V input voltage. When a surge happens, then the LM5009-based regulator can still supply stable 3.3 V to the MCU.

2.3.5 Thermal Management

The thermal management budget has been calculated based on the following design considerations:

- The junction temperature must not be above 150°C.
- The thermal resistance of the package is 2.7°K/W junction to bottom plate.
- Board space provides thermal resistance to air of around 900°K/W per cm² (see formula 23 in *Thermal Considerations for Surface Mount Layouts* [2]).

The $R_{DS(ON)}$ of the TPS27S100 is always smaller than 0.166 Ω . With an output current of 1.2 A the total power dissipation is 0.24 W per device. The accumulated power is then 1.92 W.

2.3.6 Switch Off an Inductive Load

This reference design can switch inductive loads. Such loads are stepper motors, valves, or relays. An inductive load has the property that it stores energy. When the switch wants to de-energize the inductive load, this energy is released. The inductor tries to keep the current flowing, which could result in a high voltage spike at the output of the switch. A free-wheeling diode is a typical method to block the spike. This diode limits the voltage at the inductor to 0.7 V. The resulting voltage at the output of the switch is 0.7 V negative. The method is simple and used for non-timing-critical switching processes. A free-wheeling voltage of more than 0.7 V releases the energy faster. The release time is reverse proportional to the free-wheeling voltage. High-speed actuators (for example, injection valves in process control systems) need a high free-wheeling voltage. The TPS27S100 clamps at 50 V below the 24-V power supply. This reduces the energy release time by a factor of 30 compared to a 0.7-V free-wheeling voltage.

2.3.7 Switching Light Bulbs and Brushed DC Motors

The reference design can switch conventional light bulbs. Such a load has typically a 10 times higher cold current than continuous current. A 24 V, a 5-W light bulb can have an in-rush current of 2 A, which is within the operating range of the TPS27S100. Larger light bulbs trigger the current limit of the TPS27S100. This does not harm the TPS27S100 but it takes longer for the light bulb to light up.

Brushed DC motors can have a similar start-up behavior. Here the ratio between the start-up current and the continuous current can be even higher. A factor of more than 30 is possible. Motors with a high efficiency have a high current ratio. Here the current limit of the TPS27S100 helps with a controlled start of the motor. There is a high-voltage drop in the TPS27S100 when it does current limit. This can heat up the TPS27S100 until it thermally shuts down its operation. A PWM control for motor start is more power effective. It reduces the risk of thermal shutdown of TPS27S100. The MCU can use PWM for outputs, which are configured to drive a motor.

2.3.8 EMI

Each output connector pin has a 10-nF capacitor connected to earth nearby. This reduces ESD sensitivity and EMI. There are also two steering diodes connected to each output. One diode guides positive surges into the local 24-V power supply where they are clamped to 45 V. The other diode guides negative surges into a transient protection diode with a clamping voltage of 45 V below ground. This diode becomes effective if the clamping capability of the TPS27S100 switch is not sufficient for the strength of the negative surge pulse.

2.3.9 Output Signage and Output Connector

All TPS27S100 outputs are connected to blue LEDs. The LED current is set to 2.2 mA at 24 V. The LEDs show the output state. They have light guides so that they are visible even if multiple capes are stacked. The board connector is a low profile type so that it is possible to stack capes and still have access to each of the boards.

3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

This reference design can be used either as cape with the BeagleBone Black evaluation platform or as a standalone card. For the connection to the BeagleBone Black, connectors J20 and J21 handle the communication. If standalone operation is planned, there exist two options:

- SPI communication through the BeagleBone Black connector
- UART communication through the MSP430 isolated debug port

3.1.1 Pin Assignment

Table 3. Pin Assignments

TIDA-01552 FUNCTION	TIDA-01552 HEADER	BBB HEADER	SOFTWARE	DIRECTION
Address A0	J2, Pin 11	P9_11	UART4_RXD	OUT
Address A1	J2, Pin 13	P9_13	UART4_TXD	OUT
Address A2	J1, Pin 22	P8_22	MMC1_DAT5	OUT
SPI0_CS	J2, Pin 17	P9_17	SPI0_CS	OUT
SPI0_D0	J2, Pin 21	P9_21	SPI0_D0	OUT
SPI0_D1	J2, Pin 18	P9_18	SPI0_D1	IN
SPI0_SCLK	J2, Pin 22	P9_22	SPI0_SCLK	OUT
XRST_n	J2, Pin 15	P9_15	GPIO1_16	OUT
/XSDRDY	J2, Pin 23	P9_23	GPIO1_17	IN
I2C2_SCL	J2, Pin 19	P9_19	I2C2_SCL	OUT
I2C2_SDA	J2, Pin 20	P9_20	I2C2_SDA	IN/OUT

3.1.2 Initialization and Control

In this test version, the control of the board is limited to a simple ASCII terminal control. With this, it is possible to switch on and off outputs in any combination. The control scheme is sufficient to test and evaluate the TPS27S100 high-side driver and the power section of the DO module reference design.

A separate, future software reference design will cover the BeagleBone Black software and the MSP430 SPI communication software.

3.1.3 Power Supply

The board is connected to a 24-V field supply. The 3.3 V for the isolators are coming from this supply as well as the voltage VS for the TPS27S100 parts. A combination of 33-V TVS diodes and an electronic fuse is used as protection against surge pulses of 500 V 1.2/50 μ s (250 A, 8/20 μ s). This protection scheme is available as a separate reference design, the [TIDA-00233](#). The electronic fuse also limits the maximum current into all outputs together to 10 A. It resets when the short-circuit or overcurrent condition disappears.

3.2 Testing and Results

3.2.1 Test Setup

3.2.1.1 Undervoltage and Overvoltage Lockout

Table 4. Equipment

DEVICE TYPE	DESCRIPTION
Power supply	GW instek GPS4303
Voltmeter	Fluke 45

Prerequisite

- Connect the 24-V input connector to power supply

Test 1—Undervoltage Lockout

1. Start power supply at 0 V
2. Increase V_{IN} until LED D95 is on
3. Measure and protocol V_{IN}
4. Decrease V_{IN} until LED D95 is off
5. Measure and protocol V_{IN}

Test 2—Overvoltage Lockout

1. Start V_{IN} at 0 V
2. Increase V_{IN} until LED D95 is on
3. Further increase V_{IN} until LED D95 is off
4. Measure and protocol V_{IN}
5. Decrease supply voltage until LED D95 is on
6. Measure and protocol V_{IN}

3.2.1.2 Overcurrent Timing

Table 5. Equipment

DEVICE TYPE	DESCRIPTION
Power supply	GW instek GPS4303 and 2229 Statron
Oscilloscope	Tektronix TDS 3034
Load	Wirewound resistor Dale RH-50 50 W

Prerequisite

- Connect the 24-V input connector to power supply.
- Connect the second power supply in parallel to first power supply.

Test—Overload Test

1. Connect all outputs Y0 to Y7 to 18- Ω , 50-W resistors.
2. Connect the oscilloscope to Y0.
3. Set the oscilloscope to trigger on the rising edge of the signal with trigger level set to 2.4 V.
4. Use normal trigger mode, one shot.
5. Set VIN to 27 V on both power supplies.
6. Set the oscilloscope to "ready".
7. Set all outputs simultaneously to "on".
8. Measure the time from the trigger point to the falling edge of the signal at Y0.

3.2.1.3 Output Current Capability

Table 6. Equipment

DEVICE TYPE	DESCRIPTION
Power supply	GW instek GPS4303 and 2229 Statron
Ampere meter	Built into power supply (2% gain accuracy, zero offset)
Load	Wirewound resistor Dale RH-50 50 W

Prerequisite

- Connect the 24-V input connector to power supply.
- Connect the second power supply in parallel to first power supply.

Test—Standard Load Test at 1.2 A per Output, All Outputs Loaded

1. Connect all outputs Y0 to Y7 to 18- Ω , 50-W resistors, Y0 with Ampere measurement.
2. Set the supply voltage to a value that the load current is 1.2 A per output (21 to 22 V).
3. Take a thermal image and take the maximum temperature rise.

3.2.1.4 Rise and Fall Times

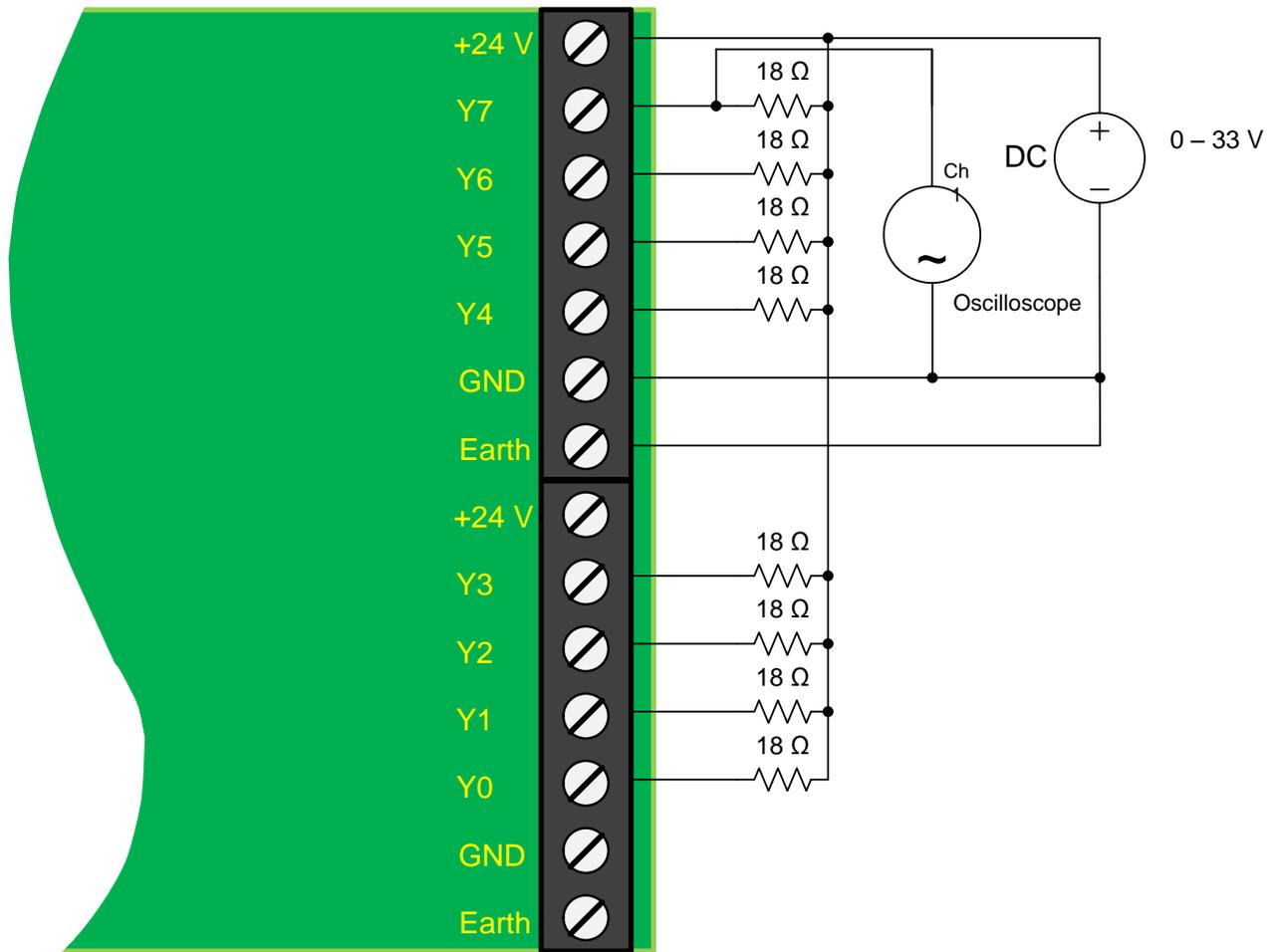


Figure 3. Measurement Setup for Rise and Fall Times

Table 7. Equipment

DEVICE TYPE	DESCRIPTION
Power supply	GW instek GPS4303
Oscilloscope	Tektronix TDS 3034
Ampere meter	Built into power supply (2% gain accuracy, zero offset)
Load	Wirewound resistor Dale RH-50 50 W

Prerequisite

- Connect loads and power supply according to [Figure 3](#).

Test 1—Rise Time Single Output Switching, One Output Loaded

1. Connect any single output (example Y7) to 18- Ω , 50-W resistor.
2. Connect the oscilloscope to this output (example Y7).
3. Set the oscilloscope to trigger on the rising edge with trigger level set to 2.4 V.
4. Use normal trigger mode, single shot o Set VIN to 24 V.
5. Set the oscilloscope to 'ready' o Set output (example Y7) to "on".
6. Measure the time from 10% output voltage to 90% output voltage.

Test 2—Fall Time Single Output Switching, One Output Loaded

1. Connect any single output (example Y7) to 18- Ω , 50-W resistor.
2. Connect the oscilloscope to this output (example Y7).
3. Set the oscilloscope to trigger on the falling edge with trigger level set to 21.6 V.
4. Use normal trigger mode, one shot o Set VIN to 24 V.
5. Set the output to "on".
6. Set the oscilloscope to "ready".
7. Set the output to "off".
8. Measure the time from 90% output voltage to 10% output voltage.

3.2.2 Test Results

Table 8. Test Results

SYMBOL	PARAMETER	CONDITIONS	SPECIFICATION			MEAS	UNIT
			MIN	TYP	MAX		
$V_{IN(max, off)}$	Input voltage	Overvoltage protection stops local power supply, V_{IN} rising	—	32	—	32.07	V
$V_{IN(max, on)}$	Input voltage	Overvoltage protection stops local power supply, V_{IN} falling	—	30	—	30.05	V
$V_{IN(min, on)}$	Input voltage	Undervoltage protection starts local power supply at rising V_{IN}	—	12	—	12.01	V
$V_{IN(min, off)}$	Input voltage	Undervoltage protection stops local power supply at falling V_{IN}	—	11	—	11.05	V
I_{IN}	Input current	Normal operation	0.01 ⁽¹⁾	—	11 ⁽²⁾	10 ⁽²⁾	A
V_{LOAD}	Load supply voltage	Normal operation	—	—	V_{IN}	—	—
I_{LOAD}	Load current	Per channel, $T_A = 85^\circ\text{C}$	—	1.2	3.5 ⁽³⁾	3.15	A
		Per channel, $T_A = 25^\circ\text{C}$	1.25	⁽⁴⁾	3.5 ⁽³⁾	3.15	A
t_{OVER}	Overcurrent time	All outputs on, $R_L = 18 \Omega$, $V_{IN} = 27 \text{ V}$, $T_A = 25^\circ\text{C}$	—	25	—	25.4	ms
I_{OVER}	Overcurrent limit	All outputs on, $R_L = 18 \Omega$, $V_{IN} = 27 \text{ V}$, $T_A = 25^\circ\text{C}$	9.6	11 ⁽²⁾	12.4	10	A
$P_{LOSS(25)}$	Power loss per channel	$R_L = 18 \Omega$, $V_{LOAD} = 21.6 \text{ V}$, $T_A = 25^\circ\text{C}$	—	150 ⁽⁵⁾	—	—	mW
$P_{LOSS(85)}$	Power loss per channel	$R_L = 18 \Omega$, $V_{LOAD} = 21.6 \text{ V}$, $T_A = 85^\circ\text{C}$	—	—	240 ⁽⁵⁾	—	mW
f_{SW}	Switching frequency (PWM)	Absolute maximum rating per TPS27S100 datasheet	—	—	2	—	kHz
$t_{ON(min)}$	Minimum on time	Guaranteed by design per TPS27S100 datasheet	50	—	—	—	μs
$t_{OFF(min)}$	Minimum off time	Guaranteed by design per TPS27S100 datasheet	50	—	—	—	μs
t_{RISE}	Load voltage rise time, 10% to 90%	$R_L = 18 \Omega$, $V_{LOAD} = 24 \text{ V}$, $T_A = 25^\circ\text{C}$, one load	27	45	135	42.8	μs
t_{FALL}	Load voltage fall time, 90% to 10%	$R_L = 18 \Omega$, $V_{LOAD} = 24 \text{ V}$, $T_A = 25^\circ\text{C}$, one load	27	45	135	38	μs
P_{IND}	Inductive power per output	—	—	70 ⁽⁶⁾	—	—	mJ/s

- (1) Depends on number of LEDs on and communication activity
- (2) Limited by overcurrent protection
- (3) Limited by current limit resistor designed into this reference at TPS27S100
- (4) Protection limits total current to 10 A, load can be distributed for example $3 \times 3 \text{ A} + 5 \times 0.2 \text{ A}$
- (5) Based on calculations derived from the TPS27S100 datasheet
- (6) Based on inductive power capabilities of TPS27S100. If the clamping value of TVS diode D89 is set to a voltage level smaller than the clamping level of TPS27S100, then D89 takes all inductive energy. In this case, the total inductive power for all outputs together can be 1J/s irrespective how the energy is distributed among the outputs. More copper area can increase the inductive power. Up to 3 J/s is possible.

Figure 4 shows the measurement results for the timing of the overcurrent protection. Overcurrent is the condition when the total input current into the connector 24 V is above 10 A and below 20 A. When an overcurrent event occurs, then for a period of 200 ns the current can flow according to Ohm's law. After the period of 200 ns, the total current gets limited to 10 A. If the overcurrent condition is longer than 25 ms, the local power supply is set to zero. This sets also all outputs to zero.

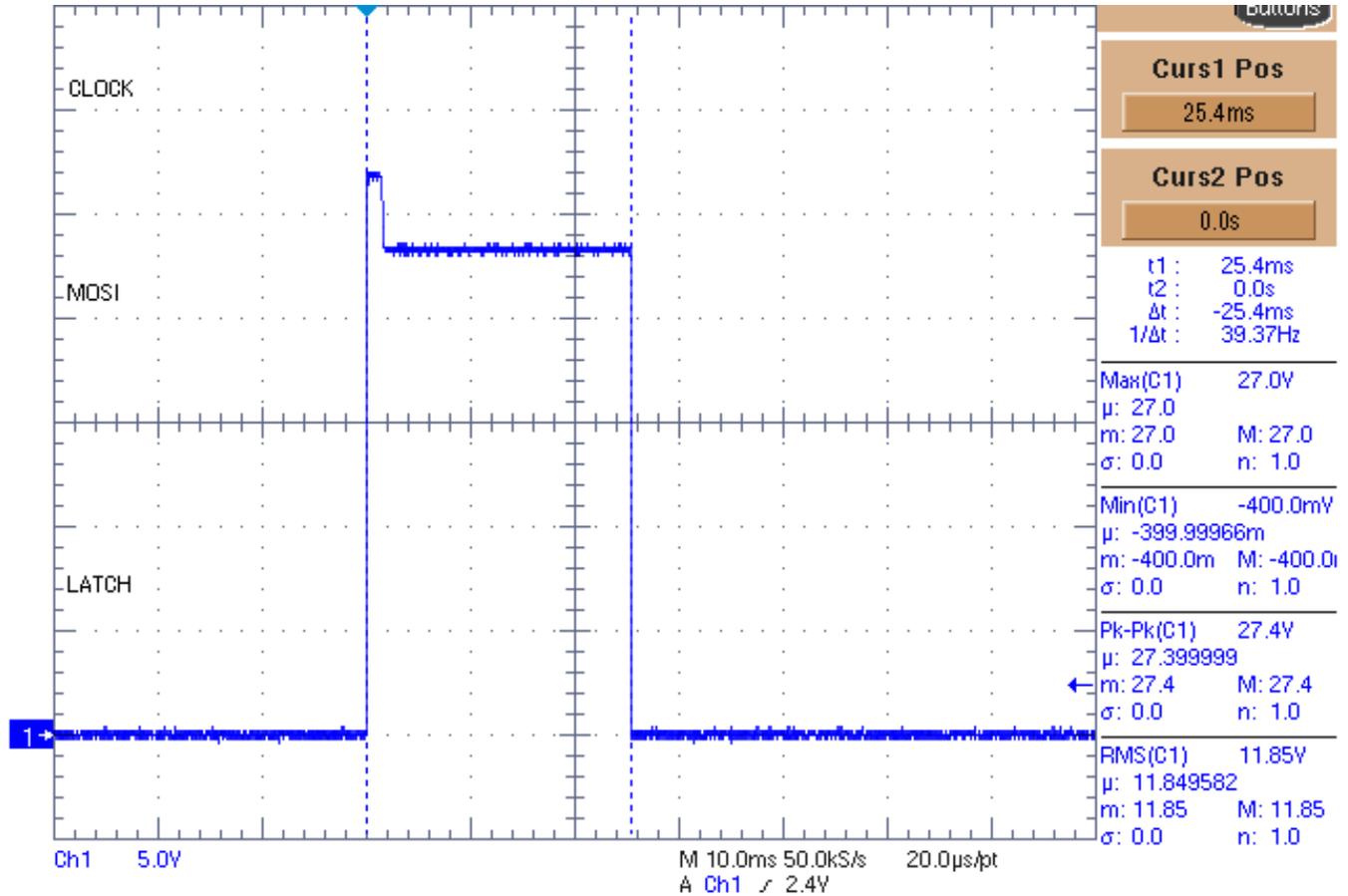


Figure 4. Overcurrent Time

Figure 5 shows the measurement results for the fall time. The TPS27S100 controls the slew such that the fall time is in the range of 40 μ s. This is necessary to prevent EMI.

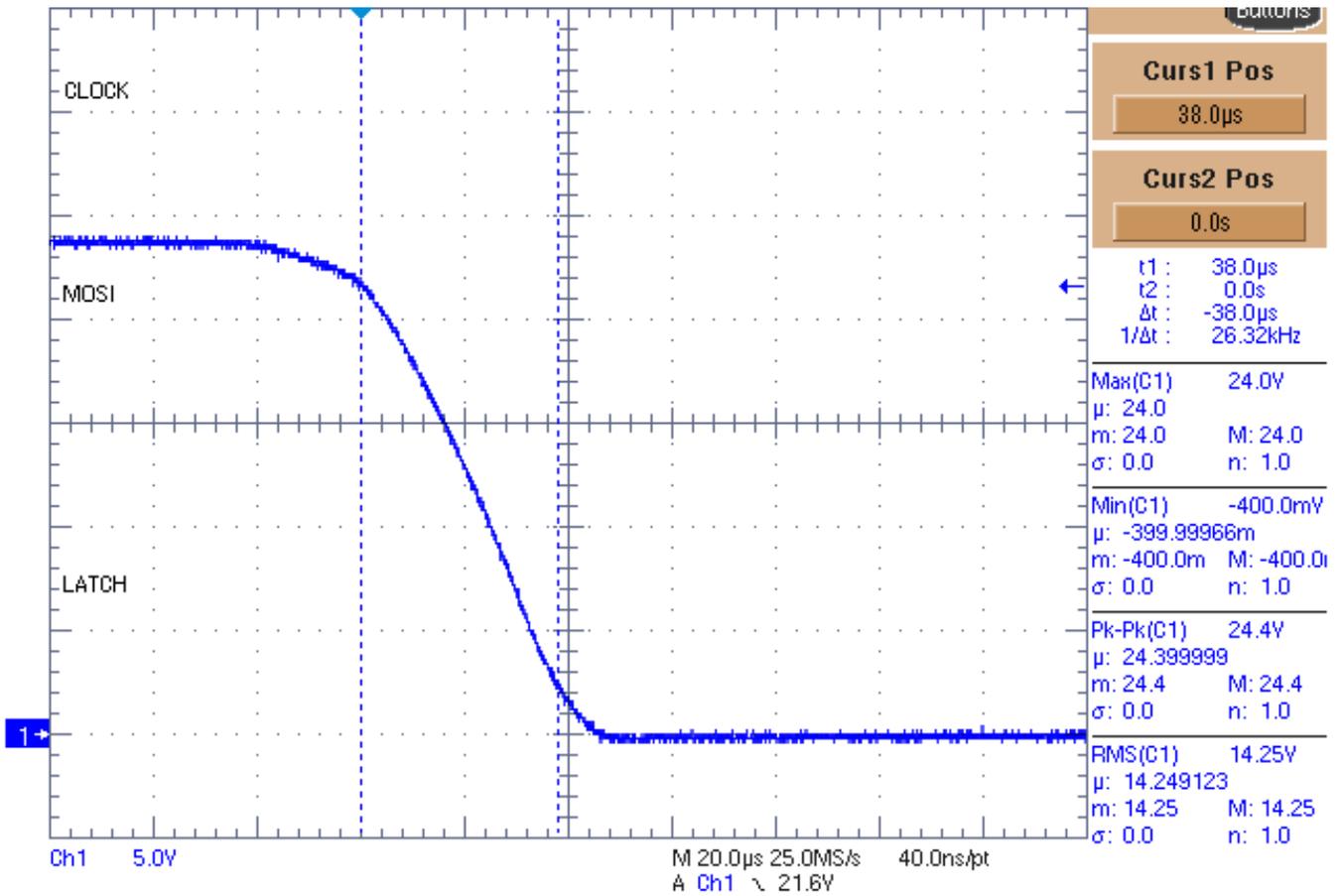


Figure 5. Fall Time

Figure 6 shows the measurement results for the rise time. The TPS27S100 controls the slew such that also the rise time is in the range of 40 μ s. This is necessary to prevent EMI.

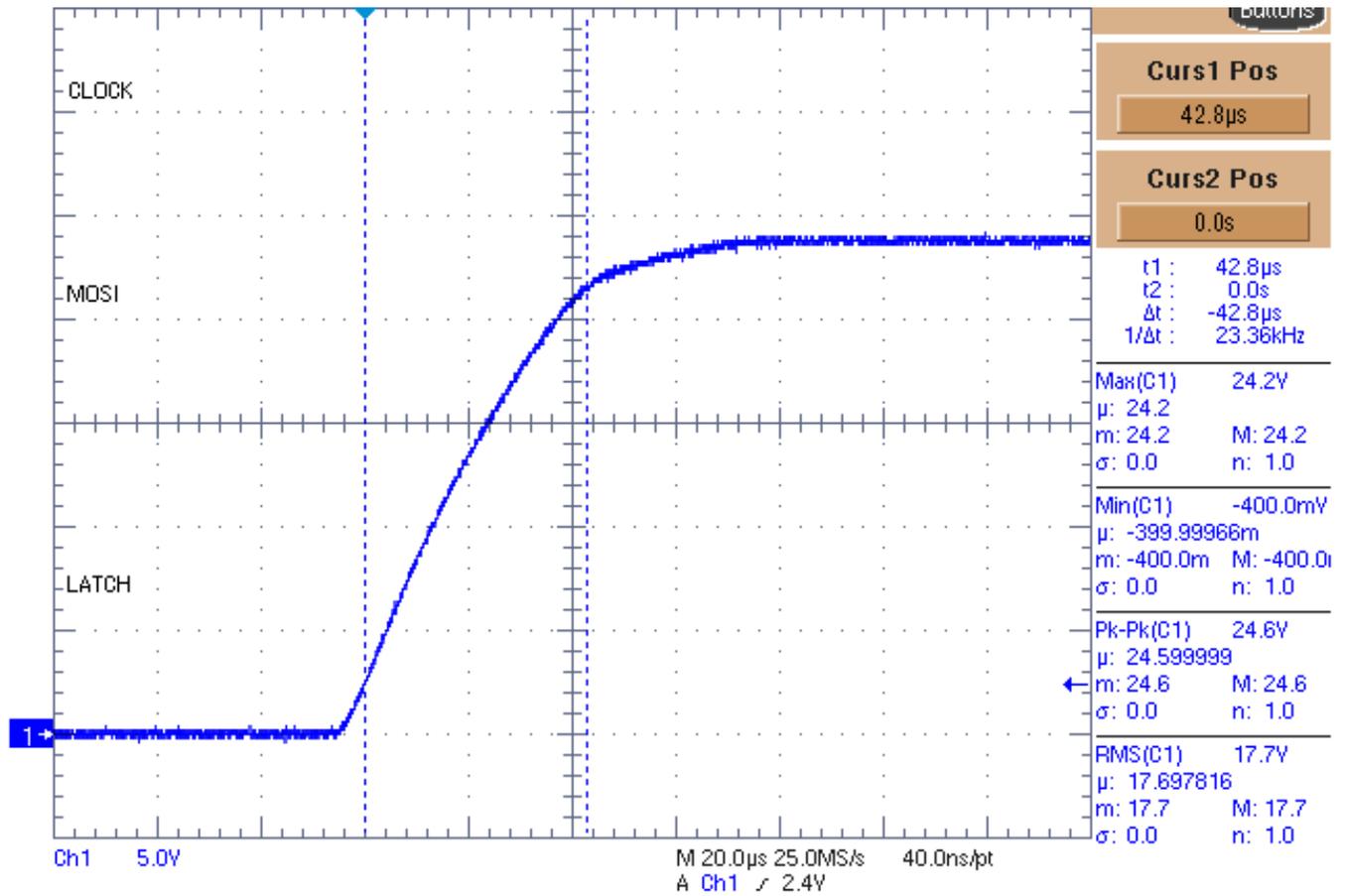


Figure 6. Rise Time

The thermoscan shows the board operating at full load with an 8×1.2-A output current. The result of the heat management verification is visible in [Figure 7](#) for the top of the PCB and in [Figure 8](#) for the bottom of PCB. The bottom side reaches 78°C on the top surface of the TPS27S100 devices and the top-side peaks at 76°C on the top surface of the TPS27S100 switches. This corresponds to a temperature rise of 50K in the silicon above the ambient temperature. Based on the heat distribution on thermal images with all eight TPS27S100 devices active, the temperature rise is small enough for operation at ambient temperatures of 85°C. Assuming a maximum silicon temperature of 150°C, an ambient temperature of 100°C is the absolute maximum. 85°C leaves sufficient guard band for safe operation.



Figure 7. Thermal Scan of PCB Top Under Full Load

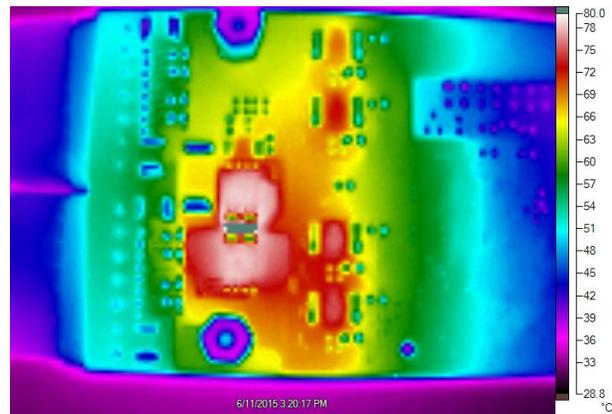


Figure 8. Thermal Scan of PCB Bottom Under Full Load

One area of potential improvement on the top layer is the trace marked with 75.2°C in [Figure 7](#). When it is made wider, the temperature goes down. This has also a positive effect on the ambient temperature for the protection circuit with the two NexFETs on the bottom side and on the two hottest TPS27S100 devices.

Another area of improvement is the cooling of the shunt resistors R98 and R99 between the two NexFETs Q1 and Q2. When the two NexFETs are set apart by 1 cm more, then the temperature of the shunt resistors goes down by 20 K. The hot trace on the top layer also benefits from this change.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01552](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01552](#).

4.3 PCB Layout Recommendations

Sufficient cooling of the TPS27S100 devices is critical to the design and requires thermal vias under the devices and contiguous copper area. In this reference design, thermal vias are also used to transfer the heat between the layers if traces break the cooling area.

Surges can cause high-current flow transients in excess of 200 A. The impedance of the power supply traces must be low. Therefore, they must be optimized to wide and short. The protective devices must be located close to the connector. This stops the high-current transients before the sensitive inner part of the design.

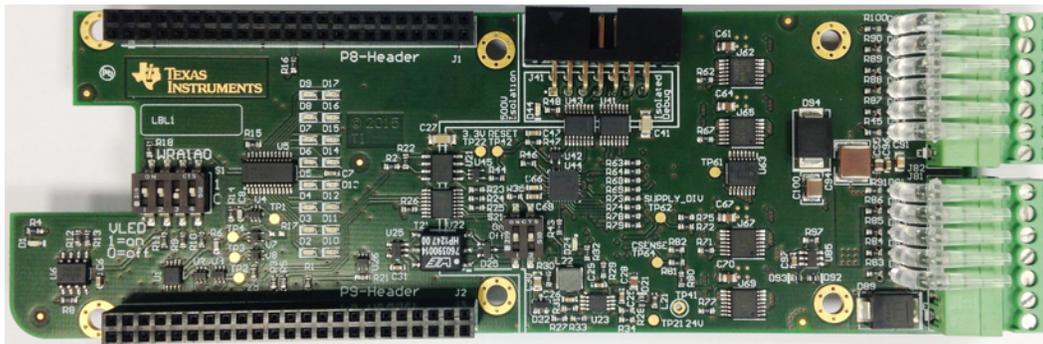


Figure 9. Top View

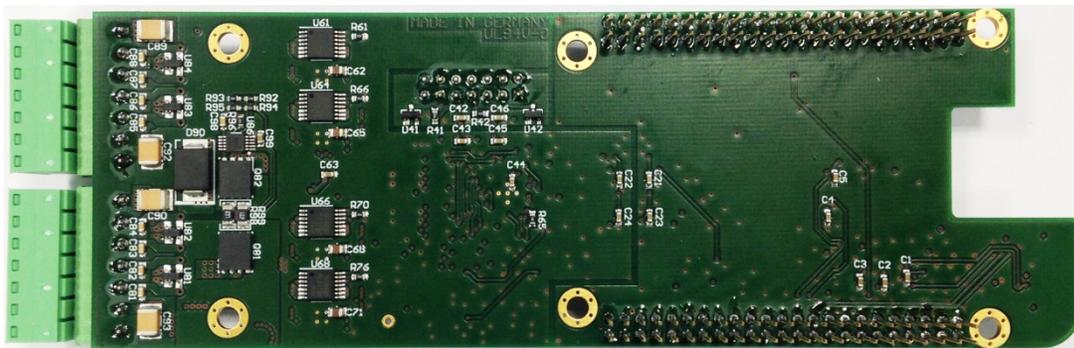


Figure 10. Bottom View

4.3.1 Layer Plots

To download the layer plots, see the design files at [TIDA-01552](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01552](#).

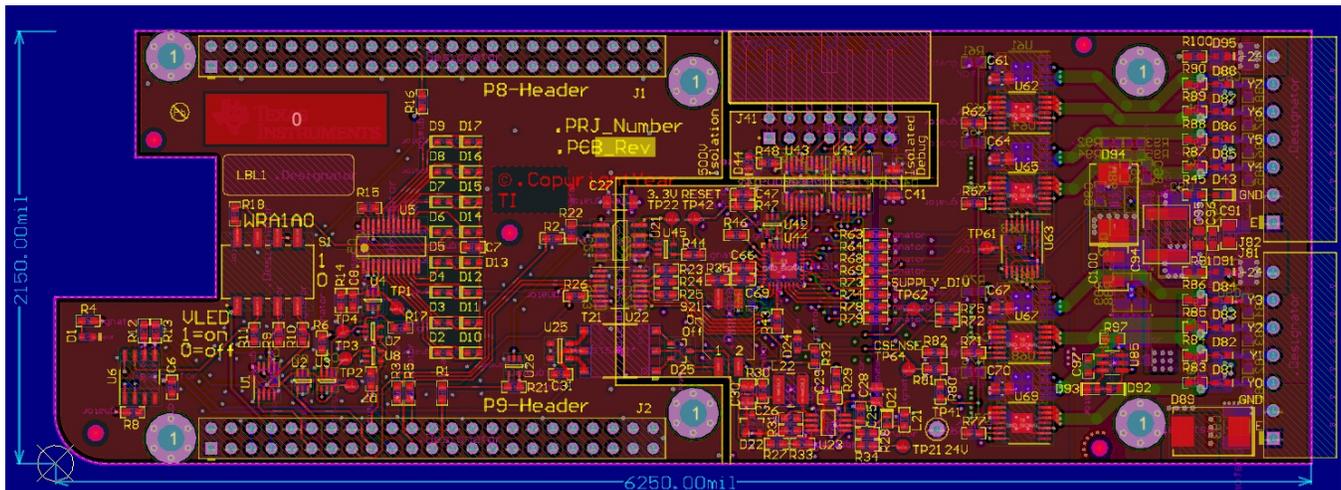


Figure 11. Altium Project Image

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01552](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01552](#).

5 Related Documentation

1. Texas Instruments, [TIDA-00233 24-V DC, 10-A eFuse and Protection Circuit for Programmable Logic Controllers \(PLC\) Design Guide](#)
2. Texas Instruments, [Thermal Considerations for Surface Mount Layouts Seminar](#)
3. Texas Instruments, [TIDA-00320 8-Ch Parallel 0.5-A Low-Side Digital Output Module for Programmable Logic Controllers \(PLCs\) Design Guide](#)

5.1 Trademarks

NexFET, E2E, MSP430 are trademarks of Texas Instruments.
All other trademarks are the property of their respective owners.

6 About the Author

INGOLF FRANK is a systems engineer in the Texas Instruments Factory Automation and Control team, focusing on programmable logic controller I/O modules. Ingolf works across multiple product families and technologies to leverage the best solutions possible for system level application design. Ingolf earned his electrical engineering degree (Dipl. Ing. (FH)) in the field of information technology at the University of Applied Sciences Bielefeld, Germany in 1991.

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated ("TI") technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, "TI Resources") are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI's provision of TI Resources does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include; without limitation, TI's standard terms for semiconductor products (<http://www.ti.com/sc/docs/stdterms.htm>), [evaluation modules](#), and [samples](http://www.ti.com/sc/docs/sampterm.htm) (<http://www.ti.com/sc/docs/sampterm.htm>).

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2017, Texas Instruments Incorporated