TI Designs

Capacitor Bank Switching and HMI Subsystem Reference Design for Automatic Power Factor Controller

TI Designs

This TI Design demonstrates the working of various functional blocks of an automatic power factor controller used in mid- to low-voltage electrical distribution, including accurate measurement and computation of voltages, currents, power, and power factor; display of measured parameters using 4-digit 7-segment display; alarms and status indications using LEDs; switching outputs for driving contactor or thyristor for switching capacitor banks; and monitoring local and remote temperature using a breadth of products from TI's portfolio. An ambient light sensor is included for 7-segment LED display brightness control. The design is made modular with provision for expanding the system features including communication, harmonics computation, and storage of system alarms.

Design Resources

TIDA-00737	Design Folder
TLC5916	Product Folder
TLC59025	Product Folder
ISO7340C	Product Folder
TPL7407L	Product Folder
DRV8803	Product Folder
OPT3001	Product Folder
TPS7A4101	Product Folder
TMP451EVM	Product Folder
MSP430F67791A	Product Folder
TIDA-00454	Tools Folder

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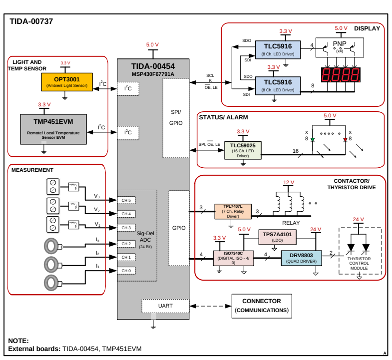
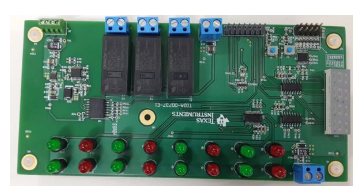


Design Features

- Accurate Measurement of 3 Φ Voltage, Current, Power, and Power Factor
- Accuracy < ±0.5% Achieved Using Simultaneous Sampling, 24-Bit Sigma-Delta ADCs
- 7-Segment LED Display (SSD)
  - Two Constant-Current Drivers are Cascaded to Drive Display With Decimal Point
- Relay and Transistor Output Switching
  - Three Channels (Expandable to Seven) for Controlling Relay Output (Contactors)
  - Two Channels (Expandable to Four), With Isolation for Controlling Transistor Output (Thyristors)
- Status Indication: 16 LEDs Controlled Using Constant-Current LED Sink Driver
  - Eight LEDs Indicate Phase, Parameter Being Displayed and Power Factor Direction (Lead/Lag)
  - Five LEDs Indicate Capacitor Bank Steps
  - Three LEDs Indicate Different Alarm Conditions
- Temperature and Ambient Light Sensors
  - Option to Measuring Remote (or Local) Temperature for Capacitor Bank Panel Temperature Measurement
  - Ambient Light Sensor to Control 4-Digit SSD Intensity
- Extended Features (TIDA-00454 Board)
  - Polyphase Metering System-on-Chip Library Tailored for Advanced Power Quality Analysis
  - Four Configurable Universal Asynchronous Receiver Transmitter Ports Connector (for Implementing RS-232 and RS-485 Interface)

Featured Applications

- Power Factor Controller (PFC)
- Reactive Power Control (RPC) Relay



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1 System Description

1.1 Active and Reactive Power

In any electric system, the phase difference between the voltage and current is dependent on the nature of the load as well as the type of current flowing through the system.

In direct current (DC) circuits, where current flows in one direction, the voltage and current are in phase and only dissipates "real" power, which is the product of voltage and current.

In alternating current (AC) systems, where the current reverses direction, the nature of the load introduces a phase difference between the voltage and current. The current, with respect to voltage, will be in phase for purely resistive loads, lead by 90° for purely capacitive loads, and lag by 90° for purely inductive loads. The effective load (vectorial combination of all load elements) introduces a net phase difference between voltage and current, which in turn results in two different types of power consumption in AC systems.

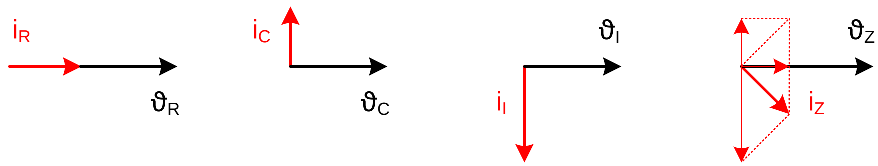


Figure 1. V, I Phasor (Resistive, Capacitive, Inductive, Combinational Loads in AC Systems)

In-phase current component ($i_Z \times \cos(\theta)$) results in the real component of power and the out-of-phase current ($i_Z \times \sin(\theta)$) results in imaginary component of power. The following summarizes various types of power in an AC system:

- *Active power (P)*: Active power ($\vartheta_Z \times i_Z \times \cos(\theta)$), expressed as watts (W), is the "real" power used by all electrical load to perform the work of heating, lighting, moving, and so on. The direction of energy flow is always in one direction. Resistive component of the transducers in the load use this energy for converting it into other forms or useful energy.
- *Reactive power (Q)*: Reactive power ($\vartheta_Z \times i_Z \times \sin(\theta)$), expressed as volt-amperes-reactive (var), is often referred to as "non-working" power. This power is used for storing and reversing energy as magnetic or electrostatic field in the reactive elements of the load. The direction of energy flow reverses as a portion of the energy stored is returned by the reactive elements.
- *Apparent power (S)*: Apparent power, expressed as volt-amperes (VA), is the vectorial combination of active and reactive power. The ratio between these two types of loads becomes important as more inductive equipment is added.

1.2 Power Factor

Power factor (PF) is the ratio of active power (P) to apparent power (S), expressed as W/VA. PF measures how effectively the current is being converted into useful work output and indicates the effect of the load current on the efficiency of the supply system.

Most of the commercial and industrial installations have heavy electrical loads such as motors, machines, air conditioners, drivers, and so on, which are inductive in nature. Introducing inductive loads results in a "lagging" PF. The reactive power results from the current and voltage waveforms being out of phase with each other.

1.3 Significance of Reactive Power

Reactive power increases the burden on the generation and transmission networks. Introduced by inductive and capacitive loads, higher reactive power translates to higher current for a given active power. This results in rise in temperature in the power cable, which leads to higher power losses in the distribution networks.

With proper matching, the reactive element of the load can be balanced, thereby minimizing the reactive power. Managing reactive power properly results in reduced energy consumption.

1.4 Improving PF

If inductors and capacitors are connected in parallel, then the inductive current will be out of phase with the capacitive current by 180°. With proper sizing of the capacitor, the leading capacitive current introduced can neutralize the lagging inductive current (and vice versa) thereby reducing the reactive current considerably in the circuit. This is the essence of improving the PF.

For residential customers, inductive loads such as motors or transformers found in common household appliances and air conditioners are compensated with built-in capacitors; therefore, no external PF correction is needed. However, for large industrial customers the PF could vary widely.

PF can be improved by using various methods: adding capacitor banks close to the inductive motors, filtering input to remove harmonics, running synchronous motors to provide capacitive loading, and so on. Capacitors are often used as they are readily available and can be installed at multiple points in an electrical system. There are two ways for capacitive compensation:

- *Fixed compensation*: If the load reactance profile is fixed and steady, then fixed compensation can be applied by using a known capacitance value. The reactive power supplied in this case is constant irrespective of any variations in the PF of the load. These capacitor banks are switched on either manually (using circuit breaker or switches) or semi-automatically by a remote-controlled contactor.
- *Automatic power factor correction (APFC)*: For loads that require varying reactive power, APFC is used. Also, under light load conditions, a fixed capacitor provides a leading power factor. APFC panels are used in industries or in the distribution network for APFC.

1.5 APFC Panel for Automatic Control of PF

- PFC: PFCs measure voltage and current, calculates the reactive and active power, and switches capacitors depending on the reactive power that needs to be corrected. APFCs have 6 to 16 relay steps for capacitor bank switching.
- External current transformer (CT): Due to large currents that are required to be measured, external CTs are used for monitoring industrial loads. CT steps down the primary current to a standardized 1- or 5-A secondary current. This secondary current is measured by the APFC to determine the primary current.
- Capacitor bank: The capacitor bank is a critical component of APFC panel. Each capacitor can be individually fused with an appropriately sized current limit fuse.
- Capacitor bank switching:
  - *Conventional switching — Contactor*: Contactors are electrically controlled switches for handling higher currents. They are used when the variation in reactive power is slow and the capacitor switching interval is in increments of seconds. Capacitors draw very large transient currents when they are switched in and out. Use caution as an oscillating inrush current can cause their failure, and too high currents can even fuse certain contacts. Capacitor duty contactors have additional auxiliary contacts with current limiting resistors (pre-charging resistors) in series. The auxiliary contacts come on first, and then the main contacts take over the steady state current of the capacitors. Also, the capacitor are completely discharged before reconnecting to avoid premature failure.
  - *Dynamic switching — Thyristor switching module (TSM)*: A TSM is used when the load variation is rapid for applications like presses, cranes, lifts, spot welding, plastic extrusion, and so on. They are also effective in eliminating inrush current of capacitors as they can be made to switch on when the voltage across the thyristor is zero.
- Auxiliary power supply: The APFC panel will have an auxiliary power supply that powers its various functional blocks.
- Exhaust fans: The APFC panel has a number of capacitor banks and busbars that carry large currents. Exhaust fans are used to maintain the temperature of the APFC panel.

1.6 TIDA-00737

This TI Design demonstrates the working of various blocks that are typically used in the APFC in an optimized way with flexibility to expand.

- Multiplexed 4-digit SSD with the decimal point (DP) controlled by two cascaded 8-bit constant-current LED sink drivers (with intensity control) with SPI
- 16 LEDs for status and alarm indication using a single 16-bit LED driver with SPI
- Low-side driver for switching relays (driver rated up to 40 V)
- Isolated transistor outputs to switch thyristors using digital isolator and low-side driver (driver rated up to 60 V)
- Ambient light sensor for intensity control of SSD
- Three-phase voltages and currents measurement and computation of active, reactive, and apparent power and PF
- Remote temperature sensor for temperature alarm

2 Key System Specifications

The various system specifications can derived by looking at different functional blocks of an APFC:

- Current and voltage measurement
- Computation of powers and PF
- Relay and transistor switching for capacitor bank control
- Display
- LED indications
- Communication
- Sensors (temperature and light)
- Keys for user interface

Table 1 lists the common specifications for each functional block.

Table 1. Design Specifications

NO	PARAMETERS	SPECIFICATION
1	7-segment LED display (SSD)	Four digits with DP
2	7-segment LED display brightness control (firmware controlled)	Depending on ambient light
3	Number of alarm and status monitoring LEDs	16 in total: • 5 for capacitor bank switching status • 3 for alarm • 8 for parameter selection
4	Light sensor	Ambient light sensor (ALS)
5	Temperature sensor	Remote and local temperature sensor
6	Relay output (for switching contactor)	Three
7	Transistor output (for switching thyristor module)	Two, open drain
8	Current inputs	Three with onboard CT
9	Voltage inputs	Three with onboard potential divider
10	Input frequency	50 or 60 Hz
11	Current measurement accuracy	< ±0.5% from 5% to 200% of rated current (In = 5 A)
12	Voltage measurement accuracy	< ±0.5% from 10% to 120% of rated voltage (Un = 230 V)
13	Power measurement accuracy	< ±0.5%
14	Number of ADC inputs, type, and sampling rate	Six sigma-delta ADC with 24-bit resolution, 4096 Hz
17	External DC power supply input	Isolated 24 V Non-isolated 5 V, 12 V

3 Block Diagram

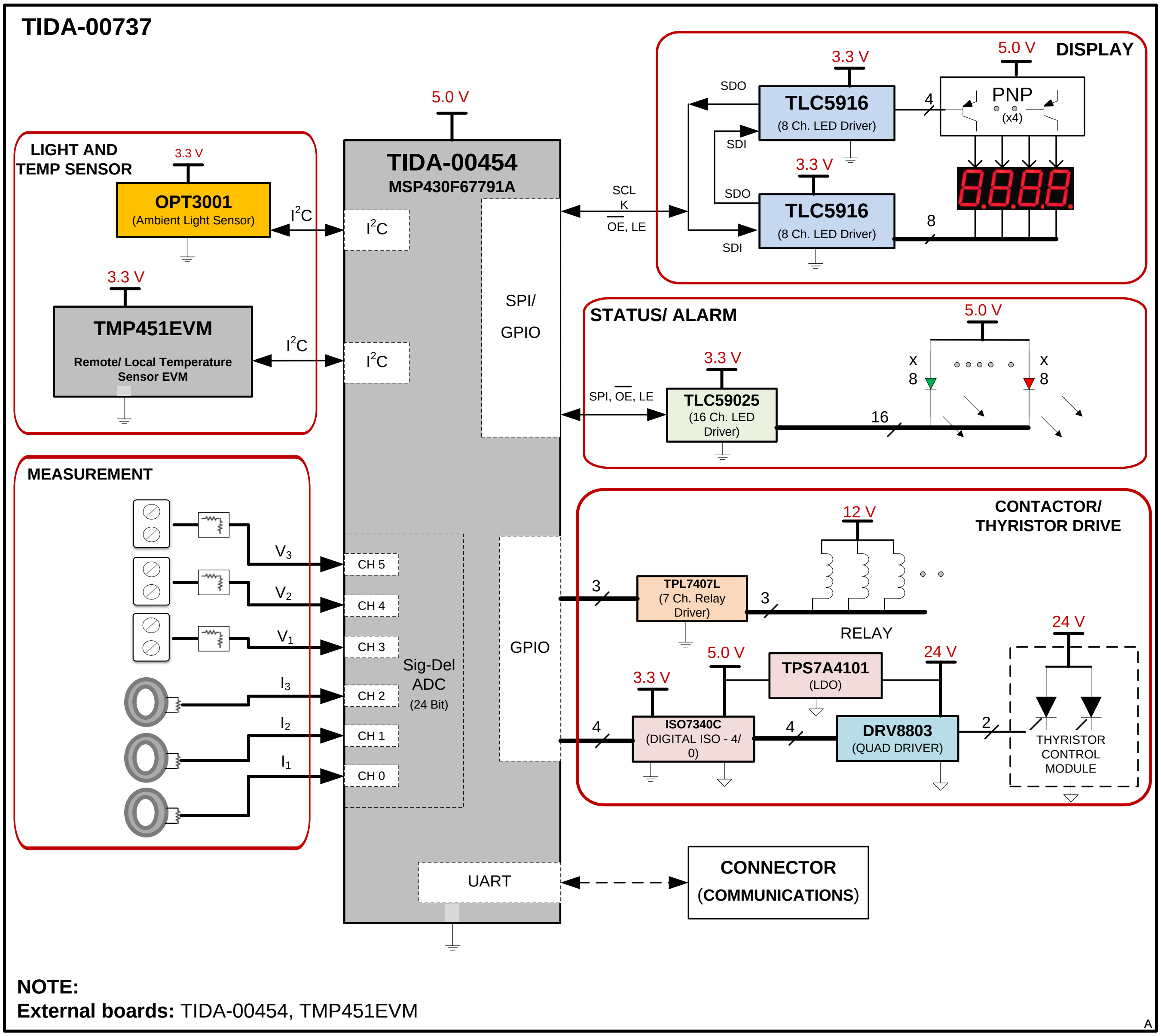


Figure 2. Functional Block Diagram for TIDA-00737

3.1 Highlighted Products

3.1.1 TLC5916—8-Channel Constant-Current LED Sink Driver

The TLC5916 contains an 8-bit shift register and data latches, which convert serial input data into parallel output format. Each output is independently controlled and can be programmed to be on or off by the user. The constant sink current for all channels is set through a single external resistor. The constant output current range is 3 to 120 mA. The TLC5916 is designed for up to 20 V at the output port. The high clock frequency (30 MHz) also satisfies the system requirements of high-volume data transmission.

The serial data is transferred into the TLC5916 through SDI, shifted in the shift register, and transferred out through SDO. Latch Enable (LE) latches the serial data in the shift register to the output latch. Output Enable (OE) enables the output drivers to sink current.

The TLC5916 is available in a 16-pin SOIC package and is specified to operate at temperatures from –40°C to 125°C.

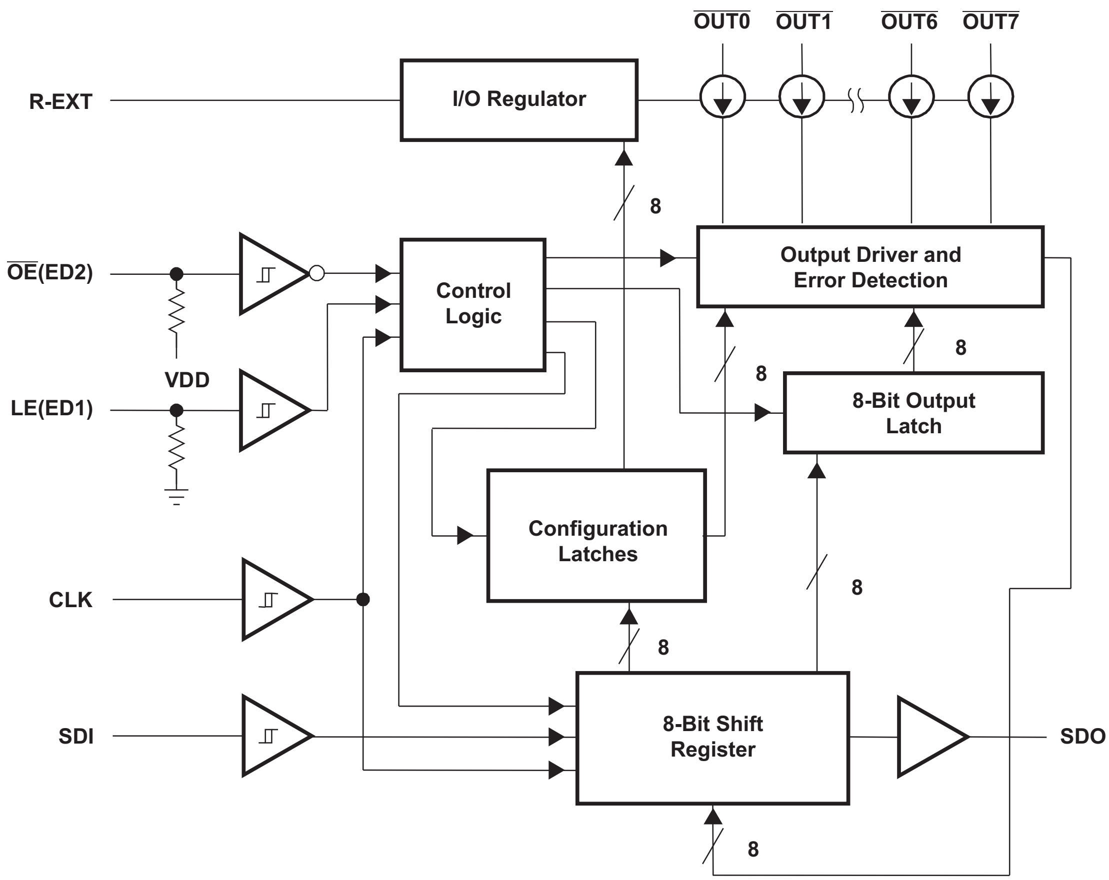
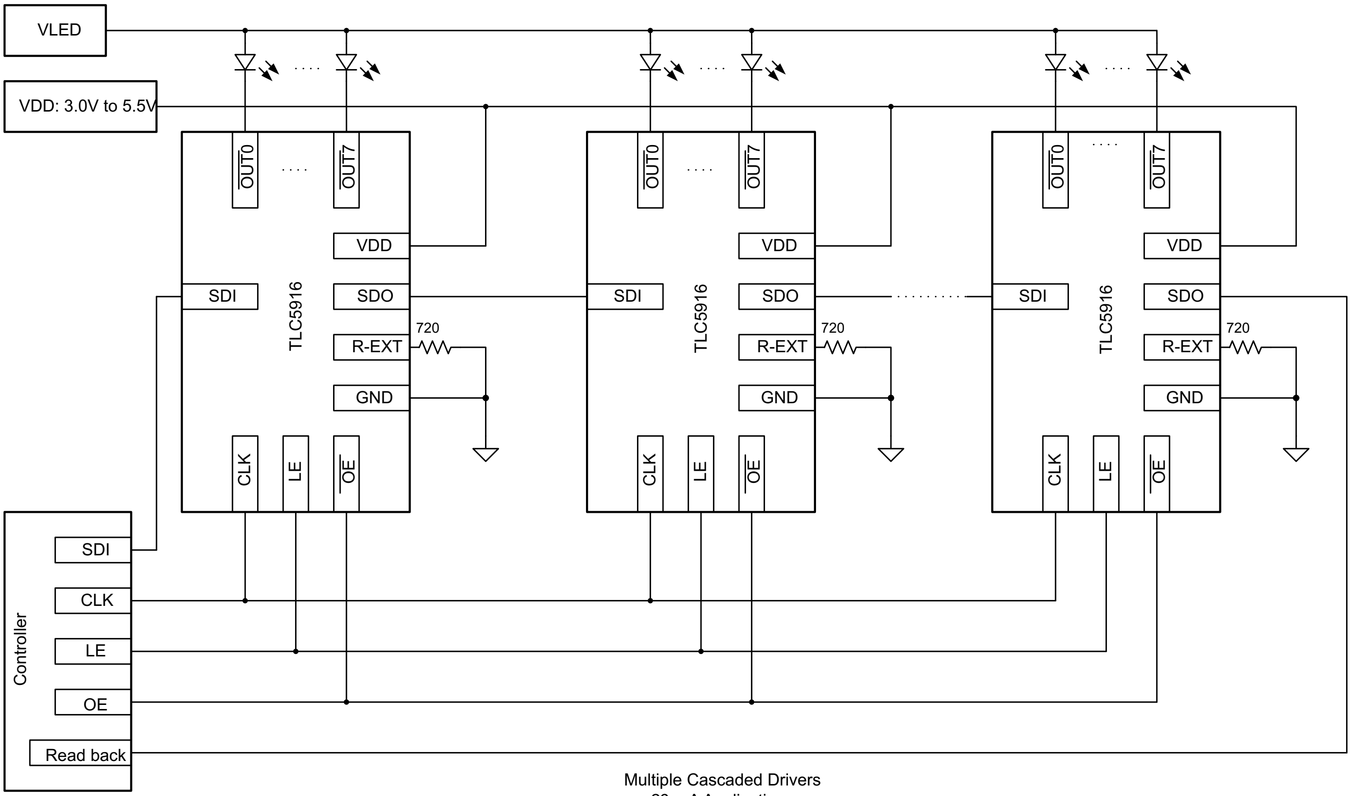


Figure 3. TLC5916 Functional Block Diagram

The TLC5916 is designed to work alone or cascaded. Figure 4 shows the cascading implementation of the TLC5916.



Multiple Cascaded Drivers
26-mA Application

Figure 4. Cascading of Multiple TLC5916 Drivers

3.1.2 TLC59025—16-Channel Constant-Current LED Sink Driver

The TLC59025 contains a 16-bit shift register and data latches, which convert serial input data into parallel output format. At the TLC59025 output stage, 16 regulated-current ports provide uniform and constant current for driving LEDs. Users can adjust the output current from 3 to 45 mA through an external resistor, R_{EXT}, which gives flexibility in controlling the intensity of LEDs. The TLC59025 is designed for up to 17 V at the output port. The high clock frequency, 30 MHz, also satisfies the system requirements of high-volume data transmission.

The serial data is transferred into the TLC59025 through SDI, shifted in the shift register, and transferred out through SDO. LE latches the serial data in the shift register to the output latch. OE enables the output drivers to sink current.

The TLC59025 is available in 24-pin SSOP package and is specified for operation at temperatures from –40°C to 125°C.

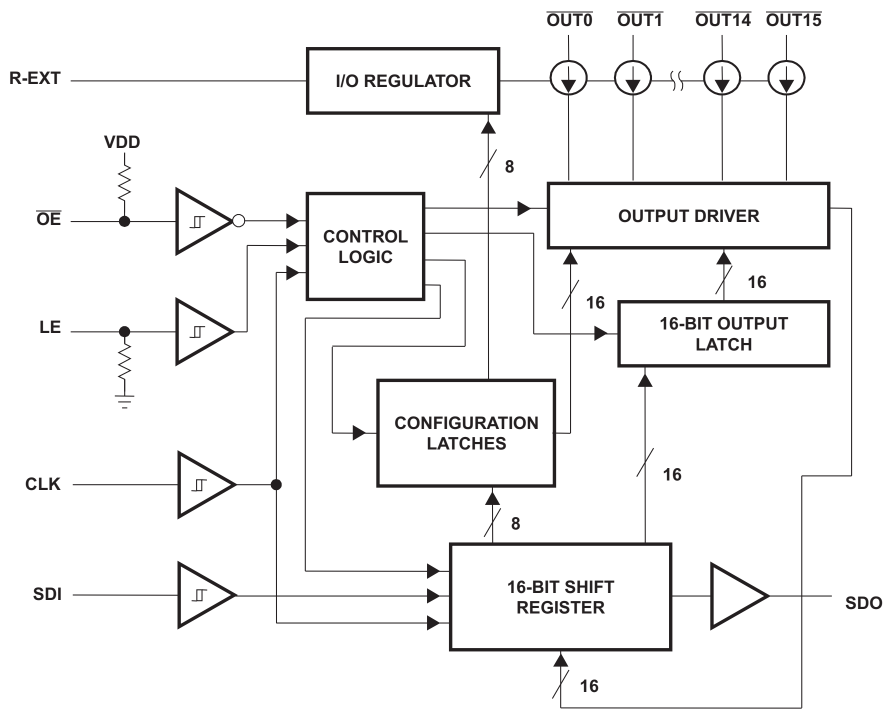


Figure 5. TLC59025 Functional Block Diagram

3.1.3 MSP430F67791A—Mixed Signal Microcontroller

The Texas Instruments MSP430F67xx1A family of polyphase-metering system-on-chips (SoCs) are powerful, highly-integrated solutions for revenue meters that offer accuracy and a low-system cost with few external components. The MSP430F67xx1A family of devices use the low-power MSP430™ MCU from TI with a 32-bit multiplier to perform all energy calculations, metering applications (such as tariff rate management), and communications with automatic meter reading (AMR) and advanced metering infrastructure (AMI) modules.

The MSP430F67xx1A features 24-bit sigma-delta converter technology from TI. Device family members include up to 512KB of flash, 32KB of RAM, and a LCD controller with support for up to 320 segments.

The ultralow-power nature of the MSP430F67xx1A family of devices means that the system power supply can be minimized to reduce the overall cost. Low standby power means that backup energy storage can be minimized, and critical data can be retained longer in case of a mains power failure.

The MSP430F67xx1A family executes the energy measurement software library from TI, which calculates all the relevant energy and power results. The energy measurement software library is available with the MSP430F67xx1A at no cost. Industry standard development tools and hardware platforms are available to hasten the development of meters that meet all of the American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) standards, globally.

This TI Design utilizes the MSP430F67791A. For cost optimization, the user can select another MSP430F67xx1A MCU-based device for design requirements such as flash, RAM, and so forth. Figure 6 shows the MSP430F67791A functional block diagram.

The MSP430F67791A is available in a 128-pin LQFP package and is specified to operate at temperatures from –40°C to 85°C.

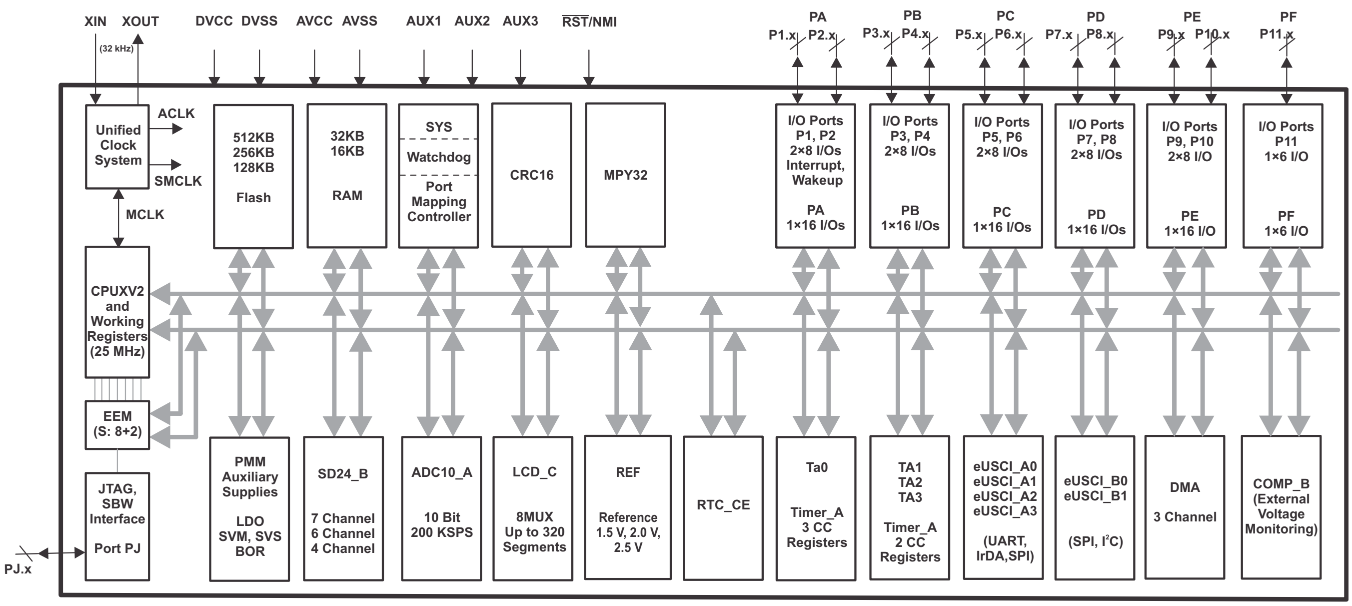


Figure 6. MSP430F67791A Functional Block Diagram

3.1.4 ISO7340C—Quad-Channel 4/0 Digital Isolator

The ISO7340C provides galvanic isolation up to 3000 V_{RMS} for 1 minute per UL and 4242 V_{PK} per VDE. The ISO7340C has four isolated channels comprised of logic input and output buffers separated by a silicon dioxide (SiO2) insulation barrier. The ISO7340C has four channels in forward direction. The suffix 'C' on the end of "ISO7340C" indicates that the default output is high, in case of input power or signal loss. Used in conjunction with isolated power supplies, the ISO7340C prevents noise current on a data bus or other circuits from entering the local ground and interfering with or damaging sensitive circuitry. The ISO7340C has an integrated noise filter for harsh industrial environments where short noise pulses may be present at the device input pins. The ISO7340C has transistor-transistor logic (TTL) input thresholds and operates from 3- to 5.5-V supply levels.

The ISO7340C is available in 16-pin SOIC package and is specified to operate at temperatures from –40°C to 125°C.

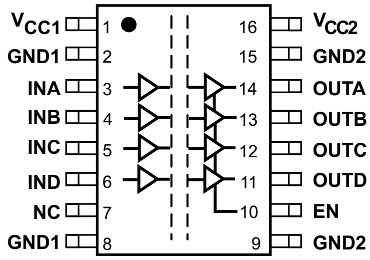


Figure 7. ISO7340C Pin Configuration and Function

3.1.5 TPL7407L—40-V, 7-Channel Low-Side Driver

The TPL7407L is a high-voltage, high-current NMOS transistor array. This device consists of seven NMOS transistors that feature high-voltage outputs with common-cathode clamp diodes for switching inductive loads. The maximum drain-current rating of a single NMOS channel is 600 mA. The user can set the transistors as parallel for higher-current capability.

The key benefit of the TPL7407L is its improved power efficiency and lower leakage than a bipolar Darlington implementation. With the lower VOL, the user dissipates less than half the power of traditional relay drivers with currents less than 250 mA per channel.

The TPL7407L is available in a 16-pin SOIC package and is specified to operate at temperatures from –40°C to 125°C.

Figure 8 shows the TPL7407L functional block diagram.

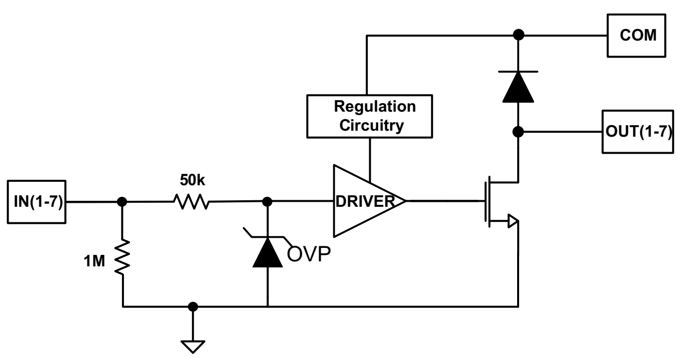


Figure 8. TPL7407L Functional Block Diagram

3.1.6 DRV8803 — 60-V, 4-Channel Low Side Driver

The DRV8803 provides a 4-channel low-side driver with overcurrent protection. It has built-in diodes to clamp turn-off transients generated by inductive loads. The DRV8803 is controlled through a parallel interface. Internal shutdown functions are available for overcurrent protection, short-circuit protection, over-temperature protection, and undervoltage lockout. Faults are indicated by a fault output pin.

The DRV8803 is available in a 16-pin HTSSOP package and is specified to operate at temperatures from –40°C to 150°C.

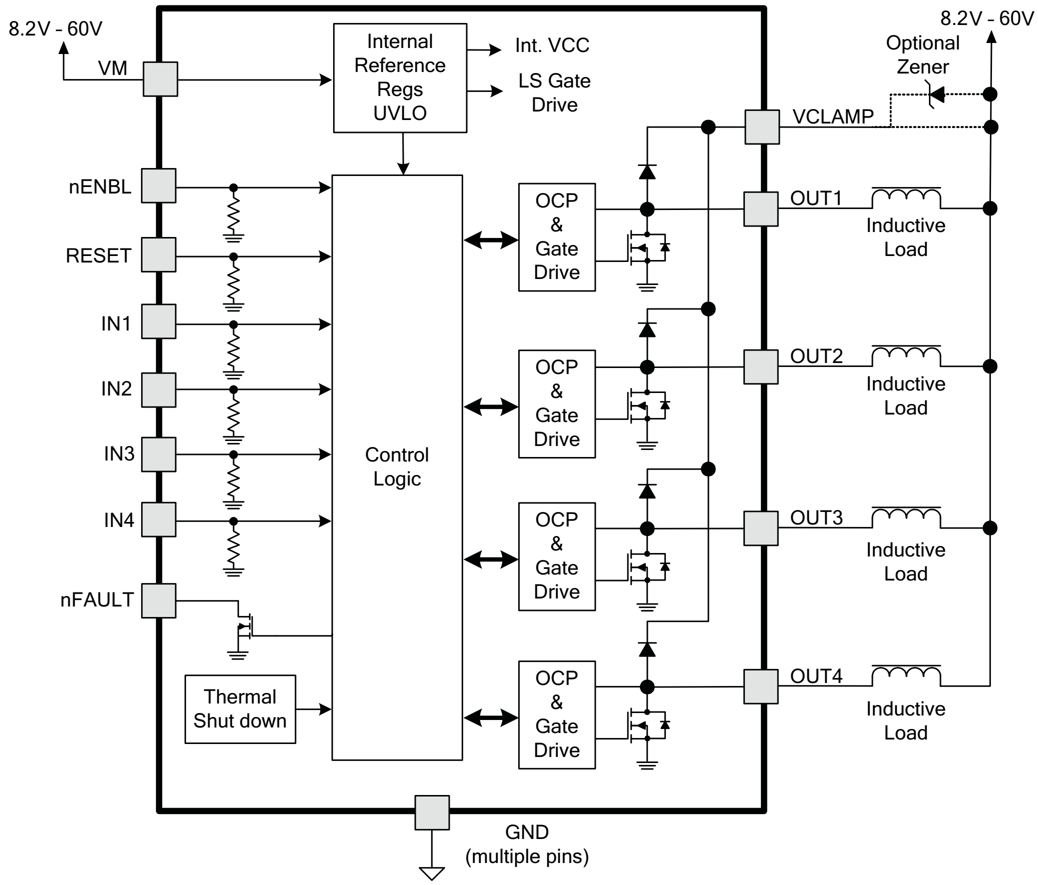


Figure 9. DRV8803 Functional Block Diagram

3.1.7 TPS7A4101 — LDO

The TPS7A41 is a high voltage-tolerant linear regulator that offers the benefits of a thermally-enhanced package (MSOP-8) and is able to withstand continuous DC or transient input voltages of up to 50 V.

The TPS7A41 is stable with any output capacitance greater than 4.7 µF and any input capacitance greater than 1 µF (over temperature and tolerance). Thus, implementations of this device require minimal board space because of its miniaturized packaging (MSOP-8) and a potentially small output capacitor. In addition, the TPS7A41 offers an enable pin (EN) compatible with standard CMOS logic, to enable a low-current shutdown mode.

The TPS7A41 has an internal thermal shutdown and current limiting to protect the system during fault conditions. The MSOP-8 packages has an operating temperature range of T_J = –40°C to 125°C.

In addition, the TPS7A41 is ideal for generating a low-voltage supply from intermediate voltage rails in telecom and industrial applications. The linear regulator can not only supply a well-regulated voltage rail, but can also withstand and maintain regulation during fast voltage transients. These features translate to simpler and more cost-effective electrical surge-protection circuitry for a wide range of applications.

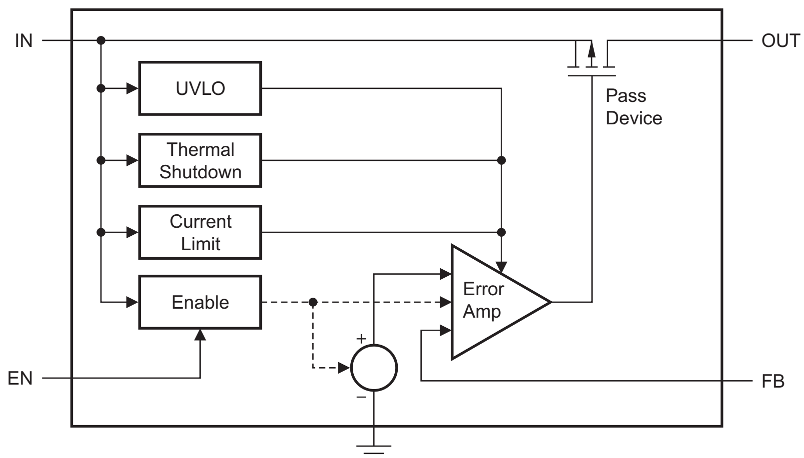


Figure 10. TPS7A41 Functional Block Diagram

3.1.8 OPT3001 — Digital ALS

The OPT3001 is a sensor that measures the intensity of visible light. The digital output is reported over an I^2C, two-wire serial interface. Measurements can be either continuous or single-shot.

The OPT3001 is available in 6-pin small form factor USON-6 package and is specified to operate at temperatures from –40°C to 85°C.

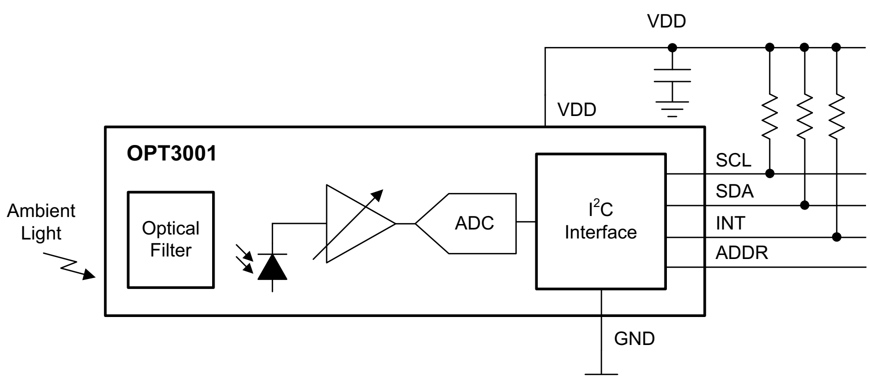


Figure 11. OPT3001 Functional Block Diagram

3.1.9 TMP451— Remote Temperature Sensor

The TMP451 is a high-accuracy, low-power remote temperature sensor monitor with a built-in local temperature sensor. The temperature is represented as a 12-bit digital code for remote sensors, giving a resolution of 0.0625°C. The temperature accuracy is ±1°C (maximum) in the typical operating range for the local and the remote temperature sensors. The two-wire serial interface accepts the SMBus communication protocol.

The TMP451 is ideal for high-accuracy temperature measurements in multiple locations and in a variety of industrial subsystems. The device is specified for operation over a supply voltage range of 1.7 to 3.6 V and a temperature range of –40°C to 125°C.

4 System Design Theory

4.1 Display

4.1.1 7-Segment LED Display (SSD)

The working of SSD is showcased using four digits. Each digit patten has seven segments and a decimal point LED that can be turned ON depending on the number that needs to be displayed. In order to reduce the number of control lines required to control four digits, multiplexing is used. At any given instant only one digit is enabled and driven for 250 µs, followed by subsequent digits. The pattern is cycled at a rate greater than persistence of vision (POV) so that all digits are visible at a time.

4.1.1.1 Multiplexing

Figure 12 shows the internal connection diagram for a multiplexed 4-digit SSD.

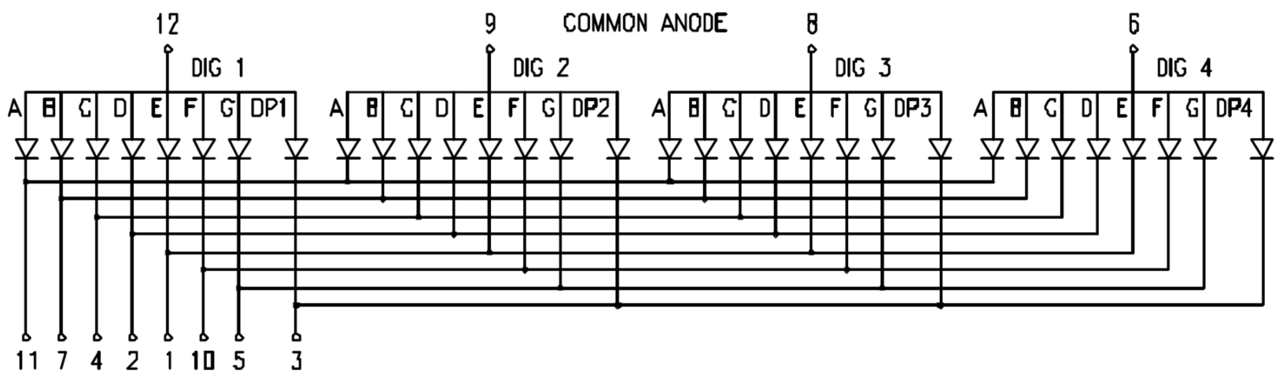


Figure 12. Multiplexed 4-Digit SSD

Each digit in the module has a common anode pin. However, all the digits across the display module share cathode connections. This allows each digit to be controlled independently.

The LDQ-M286RI (D18 in Figure 13) is a 4-digit SSD. The anode of each digit is connected to the supply through the PNP switch (time multiplexed). Only one digit receives supply at a time. At any given instant, only one PNP switch is turned ON using one of the two TLC5916.

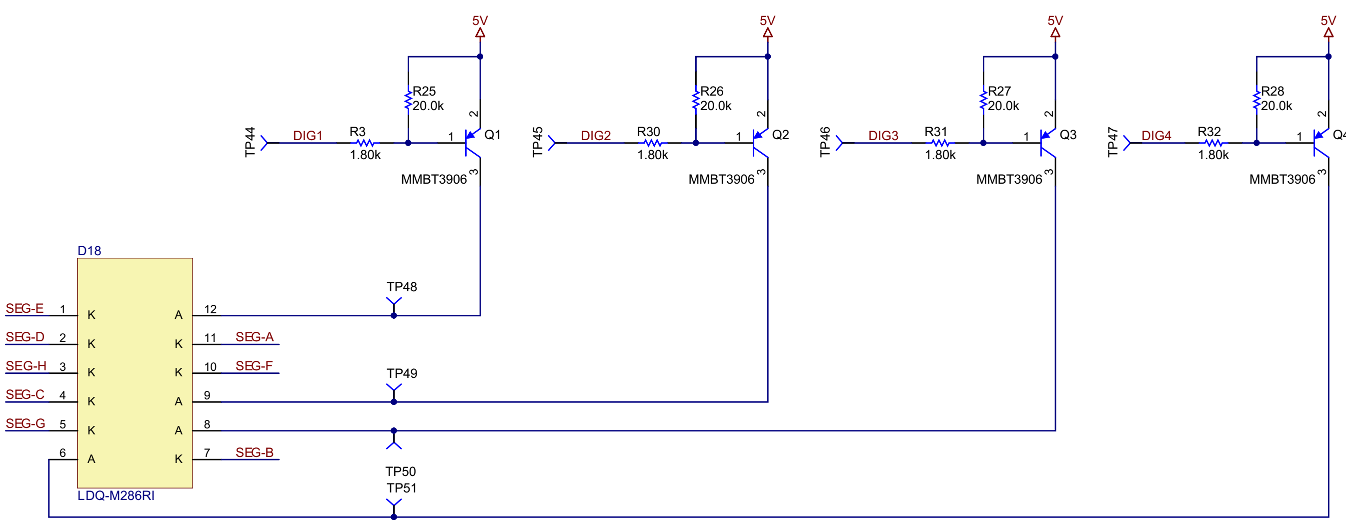


Figure 13. Interface for Multiplexing 4-Digit SSD

The TIDA-00737 has 4-digit SSD implementation for auto-cyclic display with scrolling time of 4 seconds for displaying nine parameters, namely three voltages, three currents, and three PFs.

4.1.1.2 Cascading

Two TLC5916 are used in this design: one for selecting the digit and other for driving SSD. The TLC5916 contains an 8-bit shift register and latches data, which converts serial input data into parallel output format. At the output stage, eight regulated current ports are designed to provide uniform and constant current for driving LEDs.

The TLC5916 constant-current LED sink driver is designed to work alone or cascaded. Cascaded configuration is useful when more number of outputs are required and MCU pins are limited.

The cascading of the two devices is done by:

- Connecting the same SPI clock from MCU to both TLC5916 drivers
- SDO of MCU is connected to SDI of Device 1. SDO of Device 1 is connected to SDI of Device 2
- SDO of Device 2 is connected to SDI of MCU
- Connecting two GPIOs from the MCU to LE_SEG and OE_SEG of both the devices

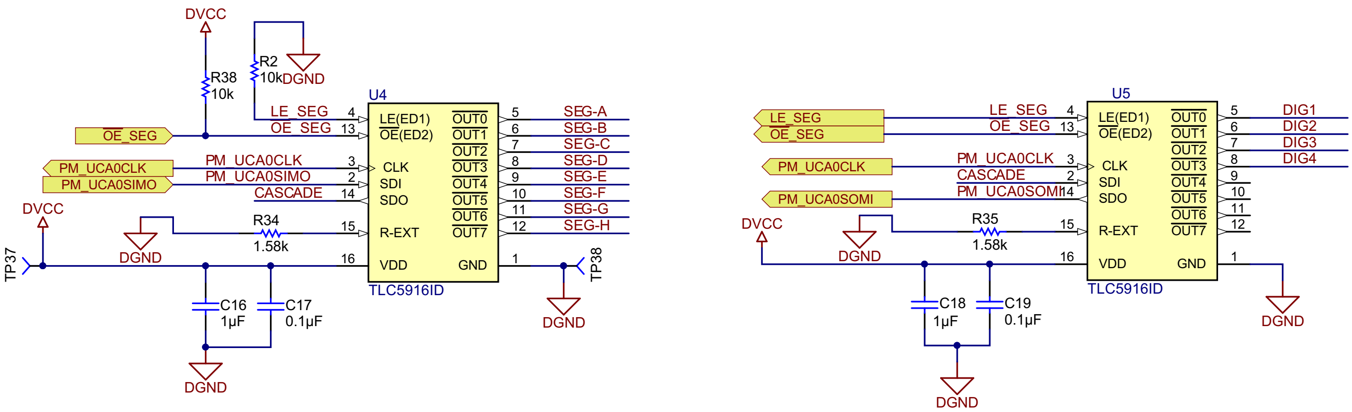


Figure 14. SSD Driver Interface

4.1.1.3 Current Control

SSD intensity can be controlled depending on the ambient light for better visibility when the APFC is mounted into a panel. The LED sink current of the TLC5916 can be controlled by external resistor R_{EXT} and also by a 256-step programmable global current gain using firmware.

The TLC5916 scales up the reference current, I_{REF}, set by the external resistor R_{EXT} to sink a current, I_{OUT}, at each output port. The procedure to calculate the target output current $I_{OUT,TARGET}$ in the saturation region is as follows.

Firmware control of $I_{OUT,TARGET}$ uses a bit definition of the configuration code. This bit definition of the code in the configuration latch is shown in Table 2.

Table 2. Bit Definition of 8-Bit Configuration Code

	0	1	2	3	4	5	6	7
MEANING	CM	HC	CC0	CC1	CC2	CC3	CC4	CC5
DEFAULT	1	1	1	1	1	1	1	1

Bits 1 to 7 {HC, CC [0:5]} determine the voltage gain (VG) that affects the voltage at R_{EXT} and indirectly affects the reference current, I_{REF}, flowing through the external resistor at R_{EXT}. Bit 0 is the current multiplier (CM) that determines the ratio $I_{OUT,TARGET}/I_{REF}$. Each combination of VG and CM gives a specific current gain (CG).

VG is the relationship between {HC,CC[0:5]} and the voltage gain, which is calculated as shown in Equation 1 and Equation 2:

$$VG = \frac{(1 + HC) \times \left(1 + \frac{D}{64}\right)}{4} \tag{1}$$

$$D = CC0 \times 25 + CC1 \times 24 + CC2 \times 23 + CC3 \times 22 + CC4 \times 21 + CC5 \times 20 \tag{2}$$

The maximum possible value of the configuration code is {CM, HC, CC[0:5]} = {1,1,111111}.

Using the values in Equation 2, D = 63.

Placing D = 63 and HC = 1 in Equation 1, VG = 127/128 = 0.992.

R_{EXT} is the external resistor connected between the R-EXT terminal and ground (R34 and R35 shown in Figure 14) and VR-EXT is the voltage of R-EXT, which is controlled by the programmable voltage gain (VG). VG is defined by the configuration code.

To calculate VR-EXT,

$$VR-EXT = 1.26\ V \times VG \tag{3}$$

$$= 1.26 \times \frac{127}{128} = 1.25\ V$$

To calculate current gain (CG):

$$CG = VG \times 3^{(CM-1)} \tag{4}$$

$$= VG \times 3^{(1-1)} = VG = \frac{127}{128}$$

To calculate the reference current (I_{REF}):

$$I_{REF} = \frac{VR-EXT}{R_{EXT}} \tag{5}$$

Considering R_{EXT} = 1580 Ω (used in this design),

$$I_{REF} = \frac{1.25\ V}{1580\ \Omega} = 0.791\ mA$$

$$I_{OUT,TARGET} = I_{REF} \times 15 \times CG \tag{6}$$

$$= 0.791 \times 15 \times \frac{127}{128} = 11.87\ mA$$

Hence, each output port is set to sink a current of 11.87 mA in this design.

4.1.1.4 Layout Guidelines

See Section 12 Layout of the datasheet for layout guidelines and layout example.

4.1.2 Status and Alarm Indication LEDs

16 LEDs are used in this design for indicating alarm, capacitor bank status, and parameter selected:

- 8 LEDs indicate phase, parameter selected and lead/lag information
- 5 LEDs indicate the capacitor bank status
- 3 LEDs indicate the alarm condition

4.1.2.1 LED Current Configuration

The TLC59025 has 16 output ports. The forward current of each LED is set around 10 mA. External resistor REXT is used to set sink current, I_{OUT}, at each output port.

To calculate the R_{EXT} for target output current $I_{OUT,TARGET}$ in the saturation region:

$$R_{EXT} = \left(\frac{1.21\ \text{V}}{I_{OUT,TARGET}}\right) \times 15.5 \tag{7}$$

Placing $I_{OUT,TARGET}$ = 10 mA,

$$R_{EXT} = \left(\frac{1.21\ \text{V}}{10\ \text{mA}}\right) \times 15.5 = 1875\ \Omega$$

1800 Ω is used in this design.

Calculating $I_{OUT,TARGET}$ with R_{EXT} = 1800 Ω,

$$I_{OUT,TARGET} = \left(\frac{1.21\ \text{V}}{1800\ \Omega}\right) \times 15.5 = 10.4\ \text{mA}$$

Each output port of the TLC59025 is set to sink a current of 10.4 mA in this design.

4.1.2.2 Parameter Indication LEDs

The TIDA-00737 displays multiple parameters like voltages, currents, and PF of each phase. The LEDs associated with the parameter being displayed will be turned ON. Table 3 shows the LEDs that are assigned for the parameter being displayed.

Table 3. LEDs Indicating Parameter Being Displayed on 7-Segment LED

D14	D15	D11	D12	D13	D16	D10	D7
VOLTAGE	CURRENT	PF	PHASE R	PHASE Y	PHASE B	LAG	LEAD

4.1.2.3 Capacitor Bank Status LEDs

The selective capacitor from the bank will be switched ON/OFF based on reactive power being compensated. This design shows the switching of the capacitor bank in five steps for improving the lagging PF (towards unity). This is implemented by switching three relays and two transistor outputs. Further details on relay and transistor output switching are covered in Section 4.2. Associated five LED functionalities for capacitor bank switching status are shown in Table 4.

Table 4. Capacitor Bank Status LED States Proportional to Reactive Power

<table>
<tr><th>D9</th><th>D8</th><th>D5</th><th>D4</th><th>D1</th><th>COMMENTS</th></tr>
<tr><td>ON</td><td colspan="4">OFF</td><td>var ≥ 200</td></tr>
<tr><td>ON</td><td>ON</td><td colspan="3">OFF</td><td>var ≥ 400</td></tr>
<tr><td>ON</td><td>ON</td><td>ON</td><td colspan="2">OFF</td><td>var ≥ 600</td></tr>
<tr><td>ON</td><td>ON</td><td>ON</td><td>ON</td><td>OFF</td><td>var ≥ 800</td></tr>
<tr><td>ON</td><td>ON</td><td>ON</td><td>ON</td><td>ON</td><td>var ≥ 1000</td></tr>
</table>

4.1.2.4 Alarm Indication

Three LEDs are assigned to indicate alarm conditions for voltage, temperature, and low lighting conditions.

Table 5. LEDs to Indicate Alarms

D2	D3	D6	COMMENTS
ON	X	X	Input voltage: > 110% of 230-V AC
X	ON	X	Remote temperature: > 50°C
X	X	ON	Ambient light: < 100 lux

NOTE:

- LED1 to LED16 are represented as D1 to D16 in the schematic.
- Red and green LEDs are used in alternate rows for easy identification.

4.1.2.5 Layout Guidelines

See Section 11 Layout of the datasheet for layout guidelines and layout example.

4.2 Output Drive

4.2.1 Relay Output Drive

This TI Design provides three high-current output drivers for switching relays. It features the TPL7407L, a low-side relay driver. The COM pin is the power supply pin of the TPL7407L that powers the gate drive circuitry. This design ensures a full-drive potential with any GPIO above 1.5 V. The gate drive circuitry is based on low-voltage CMOS transistors that can only handle a max gate voltage of 7 V. An integrated LDO reduces the COM voltage of 8.5 to 40 V to a regulated voltage of 7 V. Though TI recommends an 8.5-V minimum for VCOM, the device still functions with a reduced COM voltage, a reduced gate drive voltage, and a resulting higher $R_{DS(ON)}$.

To prevent overvoltage on the internal LDO output because of a line transient on the COM pin, the COM pin must be limited to below 3.5 V/µs. TI recommends using a bypass capacitor that limits the slew rate to below 0.5 V/µs.

Three single-pole, single-throw–normally open (SPST-NO) contact form type relays are installed on the board. The TPL7407L drives these relays. The contact rating of each relay is 12 A at 250-V AC. The TPL7407L relay driver outputs are controlled by the MSP430F67791A GPIO pins.

Figure 15 shows the TPL7407L relay driver switching control and Figure 16 shows relay control.

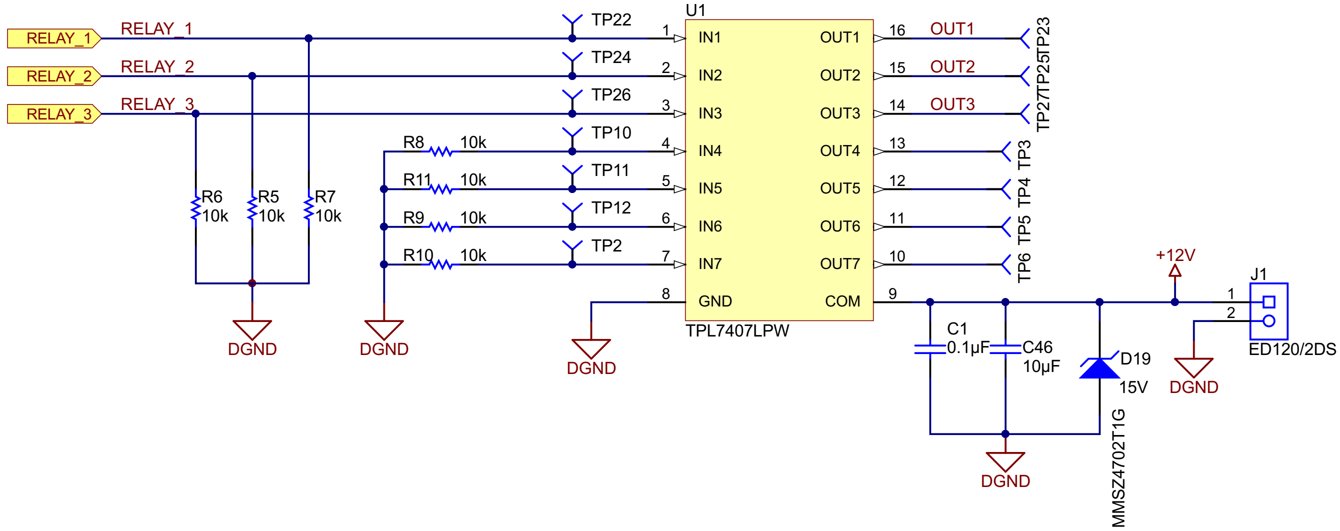


Figure 15. Relay Driver

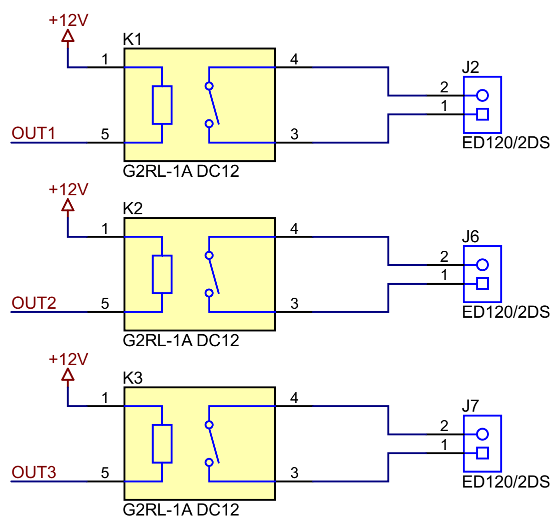


Figure 16. Relay Control

4.2.1.1 Layout Guidelines

See Section 11 Layout of the datasheet for layout guidelines and layout example.

4.2.2 Transistor Output Drive

4.2.2.1 Output Driver

This TI Design provides two high-current output driver for switching transistors. It features the DRV8803, a low-side driver that is protected. Each output has an integrated clamp diode connected to a common pin, VCLAMP. The per channel rated output current capacity of the DRV8803 is up to 2-A (one channel on) or 1-A (four channels on) continuous output current per channel, at 25°C with proper PCB heatsinking.

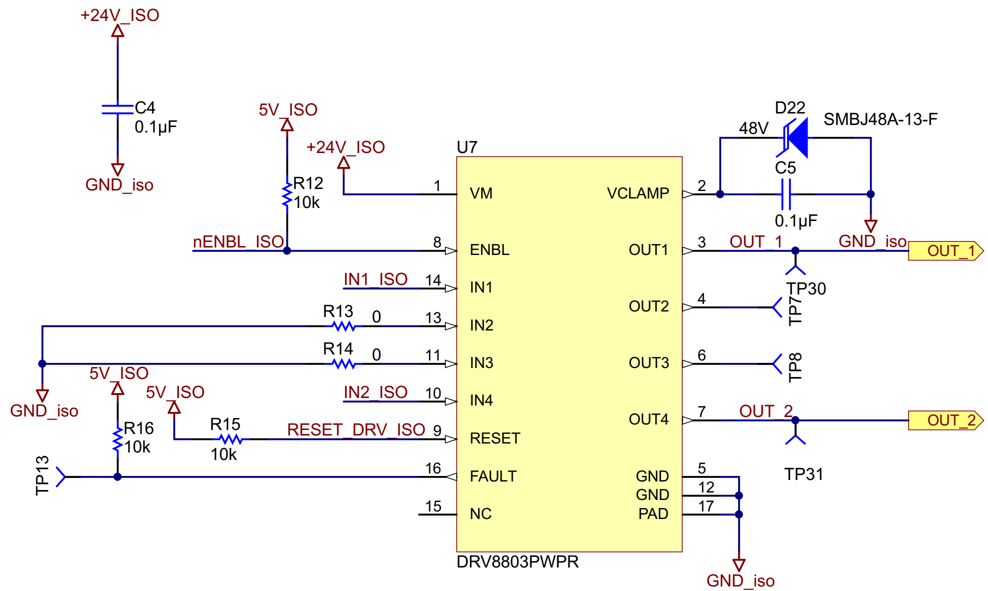


Figure 17. Driver for Transistor Output

4.2.2.1.1 nENBL and RESET Operation

The nENBL pin enables or disables the output drivers. nENBL must be low to enable the outputs The RESET pin, when driven active high, resets internal logic. All inputs are ignored while RESET is active.

4.2.2.1.2 Protection Circuits

The DRV8803 is protected against undervoltage, overcurrent, and over-temperature events.

4.2.2.1.3 Overcurrent Protection (OCP)

An analog current limit circuit on each FET limits the current through the FET by removing the gate drive. If this analog current limit persists for longer than the t_{OCP} deglitch time (approximately 3.5 µs), the driver will be disabled and the nFAULT pin will be driven low. The driver will remain disabled for the t_{RETRY} retry time (approximately 1.2 ms), then the fault will be automatically cleared. The fault will be cleared immediately if either RESET pin is activated or VM is removed and re-applied.

4.2.2.1.4 Thermal Shutdown (TSD)

If the die temperature exceeds safe limits (approximately 150°C), all output FETs will be disabled and the nFAULT pin will be driven low. Once the die temperature has fallen to a safe level, operation will automatically resume. Any tendency of the device to enter TSD is an indication of either excessive power dissipation, insufficient heatsinking, or too high ambient temperature.

4.2.2.1.5 Undervoltage Lockout (UVLO)

If at any time the voltage on the VM pin falls below the UVLO threshold voltage, all circuitry in the device will be disabled, and internal logic will be reset. Operation will resume when VM rises above the UVLO threshold.

4.2.2.1.6 Layout Guidelines

The DRV8803PWP package used in this design is an HTSSOP package with an exposed PowerPAD™. The PowerPAD package uses an exposed pad to remove heat from the device. For proper operation, this pad must be thermally connected to copper on the PCB to dissipate heat. On PCB without internal planes, copper area can be added on either side of the PCB to dissipate heat. If the copper area is on the opposite side of the PCB from the device, thermal vias are used to transfer the heat between top and bottom layers.

For details about how to design the PCB, see the TI Application Report *PowerPAD Thermally Enhanced Package* (SLMA002) and TI Application Brief *PowerPAD Made Easy* (SLMA004), both available at www.ti.com.

4.2.2.2 Digital Isolator

The DRV8803 is isolated from the MCU using digital isolator. The ISO7340C digital isolator supports data rates up to 25 Mbps. To control two outputs of the DRV8803, a total of four outputs are required. To provide these essential outputs, one ISO7340C is used and features four output channels.

Figure 18 shows all four signals interfacing:

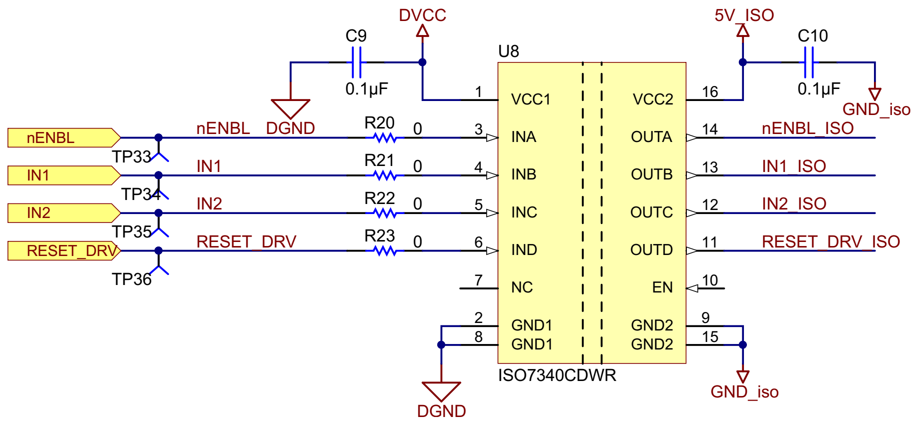


Figure 18. Digital Isolator Interface for Transistor Output Control

Associated five (three relays + two transistor outputs) digital outputs for capacitor bank switching are shown in Table 6.

Table 6. Capacitor Bank Switching States Proportional Reactive Power

RELAY K3	RELAY K2	RELAY K1	TRANSISTOR OUT_1	TRANSISTOR OUT_2	COMMENTS
ON	OFF				var ≥ 200
ON	ON	OFF			var ≥ 400
ON	ON	ON	OFF		var ≥ 600
ON	ON	ON	ON	OFF	var ≥ 800
ON	ON	ON	ON	ON	var ≥ 1000

4.2.2.2.1 Layout Guidelines

See Section 11 Layout of the datasheet for layout guidelines and layout example.

4.3 Sensor Input

4.3.1 ALS

SSD intensity can be controlled depending on the ambient light for better visibility when the APFC is mounted in a panel. This design features the ALS OPT3001 to sense ambient light. It measures the intensity of visible light and reports recorded digital output over I^2C, two-wire serial interface. Figure 19 shows the OPT3001 interfacing:

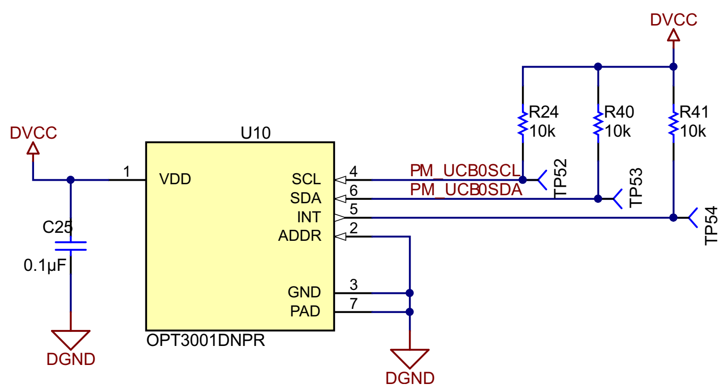


Figure 19. Ambient Light Sensor OPT3001 Interfacing

Currently, the ALS is mounted on the PCB and is accessible to test different ambient light conditions. In practical applications, the board is mounted inside an enclosure, and the ALS is not accessible or visible. For ALS to function in these conditions, a window must be provided in the enclosure for ambient light to fall on the sensor. See OPT3001 application report (SBEA002) for details on designing the window.

4.3.1.1 Layout Guidelines

See Section 10: Layout of the datasheet for layout guidelines and layout example.

4.3.2 Remote Temperature Sensor EVM

The TMP451EVM is used as a remote temperature sensor. The TMP451EVM is an evaluation module that uses the TMP451, a 1.8-V remote temperature sensor. The TMP451 has the capability of measuring remote temperatures. The TMP451EVM consists of two printed circuit boards (PCBs). One board (USB_DIG_Platform) generates the digital signals required to communicate with the TMP451. The second PCB (TMP451_Test_Board) contains the TMP451 as well as support and configuration circuitry. TMP_Test_Board is used in this design to measure remote temperature and to communicate with TMP451 over I^{2}C, two-wire serial interface.

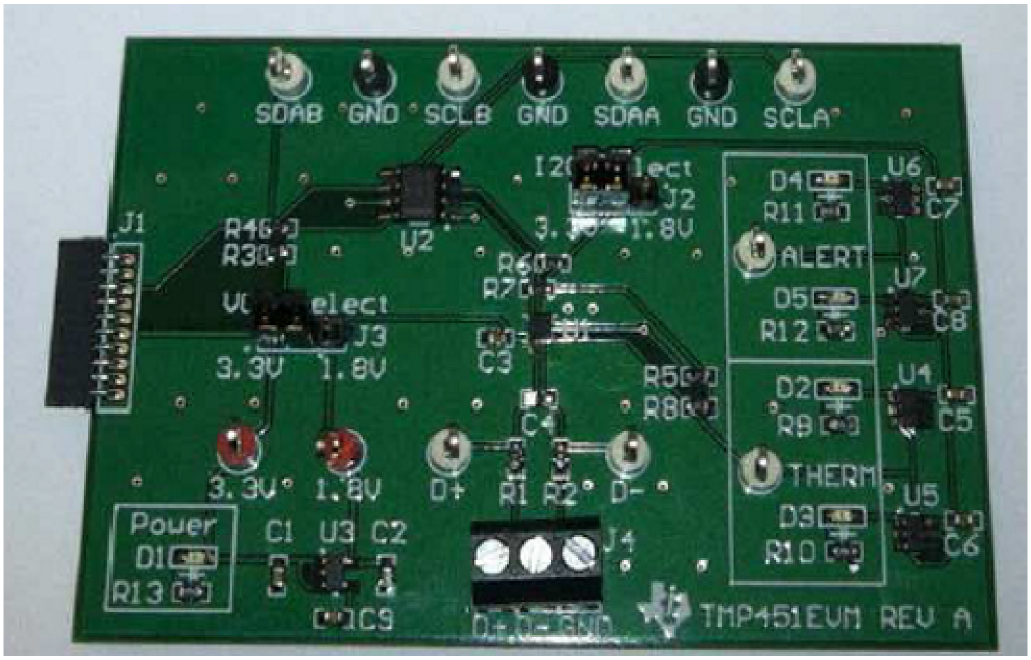


Figure 20. TMP451EVM — Remote Temperature Sensor EVM

4.4 AC Input

AC input parameters are measured using the TIDA-00454 MCU AFE board. The TIDA-00454 MCU AFE is interfaced with the TIDA-00737 board to measure AC input.

The following key features of the TIDA-00454 MCU AFE are used in this design:

- MSP430F67791A SoC with six simultaneous sigma-delta ADCs for three-current and three-voltage measurement
- AC input voltage measurement range: 10% to 120% of the rated voltage (230 V)
- AC input current measurement range: 5% to 200% of the rated current (5 A)
- AC input measurement accuracy < ±0.5%
- Provides expansion option for UART interface
- Onboard CTs and potential dividers provided for direct measurement of voltages and currents

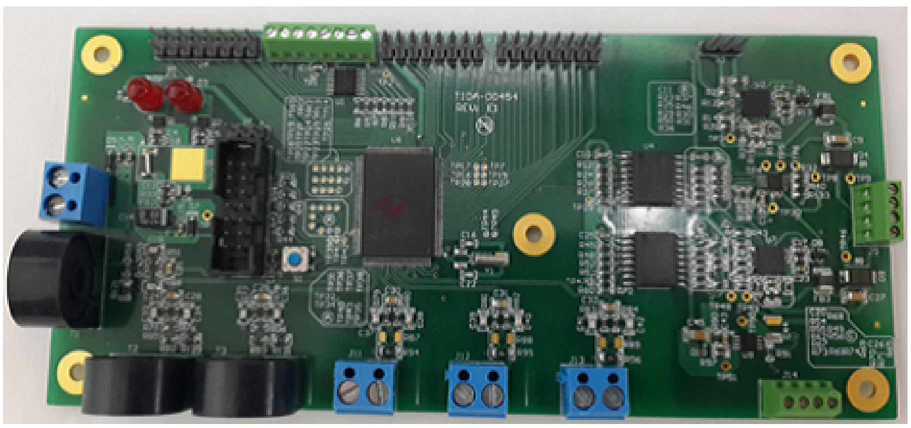


Figure 21. TIDA-00454 MCU AFE Board

The following sections describe key subsystems of the TIDA-00454. See the TIDA-00454 design guide (TIDUAH1) for more information.

4.4.1 AC Input Measurement

4.4.1.1 Current Measurement

Three-phase current is measured using an onboard CT followed by a burden resistor. The voltage drop across the burden resistor is connected to the ADC inputs. The user can change the input current range by changing CTs and burden resistor value. Ensure the input to the MSP430F67791A SD24_B ADC is less than the differential input range ±919 mV for the maximum input current expected to be measured.

4.4.1.2 Voltage Measurement

Three-phase voltage is measured using onboard voltage divider (resistor divider). The divided voltage is connected to the ADC inputs. The user can change the input voltage range by changing the voltage divider ratio (or changing resistor value). Ensure the input to the MSP430F67791A SD24_B ADC is less than the differential input range ±919 mV for the maximum input voltages expected to be measured.

4.4.2 MCU

The TIDA-00454 board has MSP430F67791A MCU. The user can interface three current and three voltage channels to the ΣΔ ADC available on the MSP430F67791A. Figure 22 shows the MSP430F67791A MCU schematic.

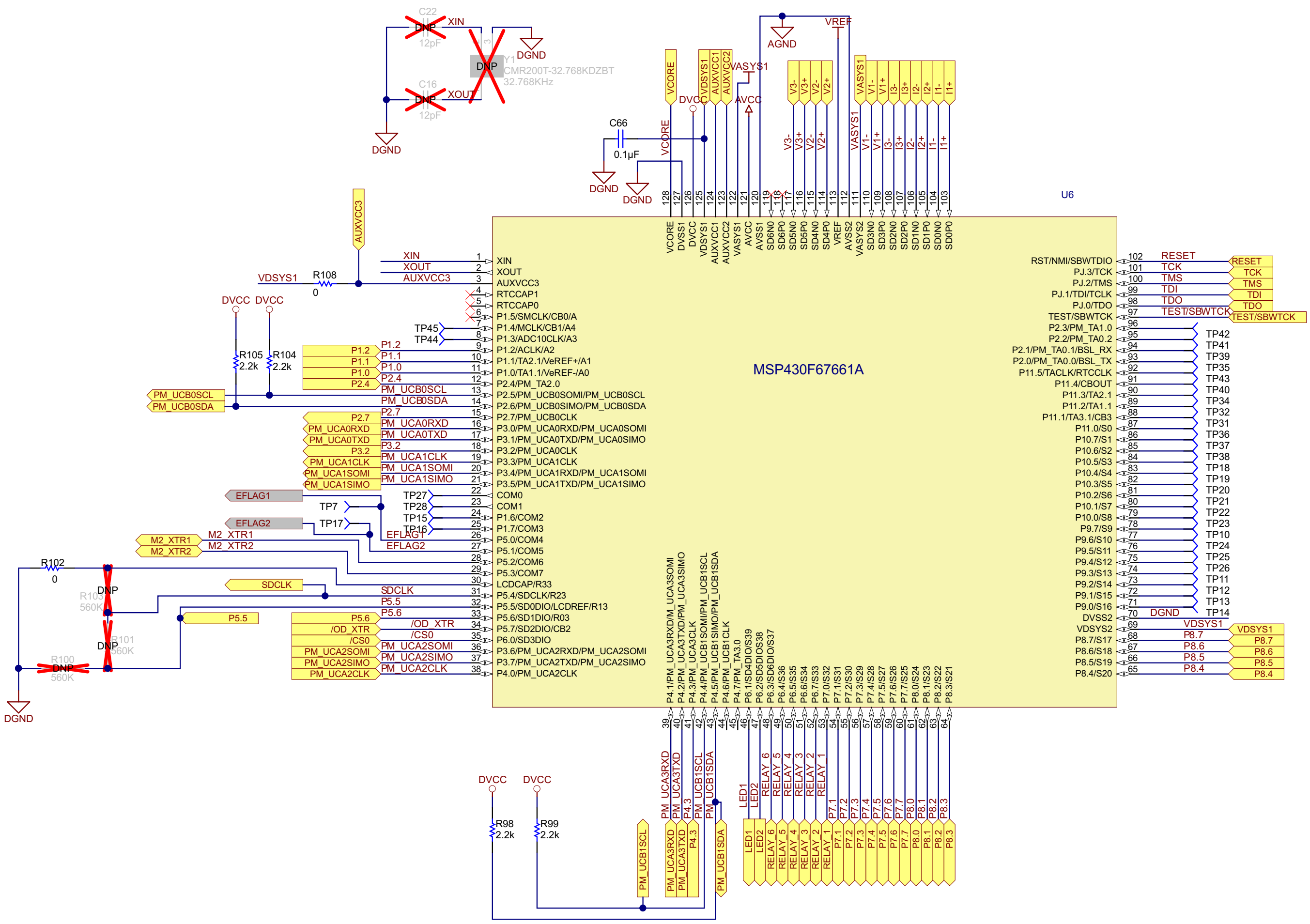


Figure 22. MSP430F67791A MCU Schematic

4.4.2.1 MCU Programming

The TI MSP430 family of MCUs supports the standard JTAG interface, which requires four signals for sending and receiving data. The JTAG signals are shared with the GPIO. The TEST/SBWTCK signal is used to enable the JTAG signals. In addition to these signals, the RESET signal is required to interface with the MSP430 development tools and device programmers. Figure 23 shows the JTAG programming connector. For further details on interfacing to development tools and device programmers, see the MSP430 Hardware Tools User's Guide (SLAU278).

For a complete description of the features of the JTAG interface and its implementation, consult the MSP430 Programming through the JTAG Interface User's Guide (SLAU320).

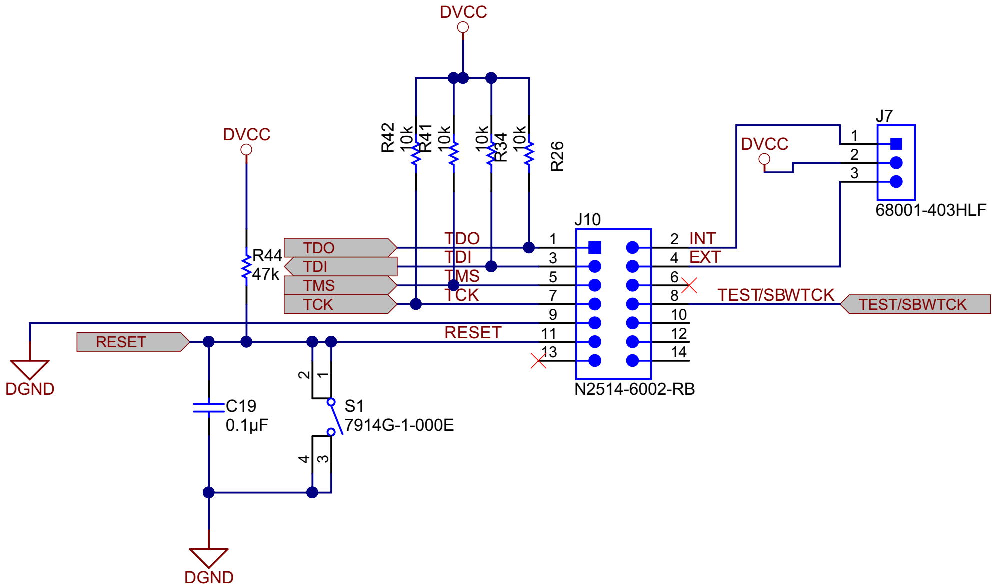


Figure 23. JTAG Programming Connector

4.5 Power Supply

The following DC power supply have to be connected externally:

- Isolated power supply: 24 V; used to drive low-side driver for transistor output
- Non-isolated power supply: 5 V; used to drive 4-digit SSD and 16 LEDs
- Non-isolated power supply: 12 V; used to drive low-side driver for relay output

The following DC supplies are generated using LDO:

- Isolated power supply: 5 V from 24 V; used to drive digital isolator
- Non-isolated power supply: 3.3 V from 5 V; used for
  - MCU and AFE section of the TIDA-00454
  - 4-digit SSD and LED sink driver
  - Sensors for temperature and ambient light

4.5.1 Isolated Power Supply

The user must connect the external 24-V DC supply on the 4-pin terminal block J8 to power the isolated transistor output section of the TIDA-00737 board (see Figure 24). The power supply is protected from reverse polarity and overvoltage.

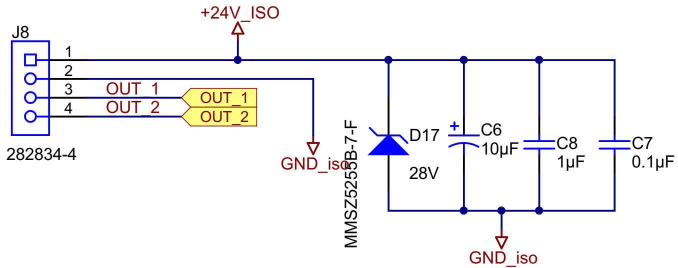


Figure 24. 24-V Input Connection

The DRV8803 and ISO7340C isolated supply side require a 5-V supply voltage. The TPS7A4101 LDO, which is a very high voltage-tolerant linear regulator, is used to step down 24 V to 5 V.

Figure 25 shows the LDO circuit diagram.

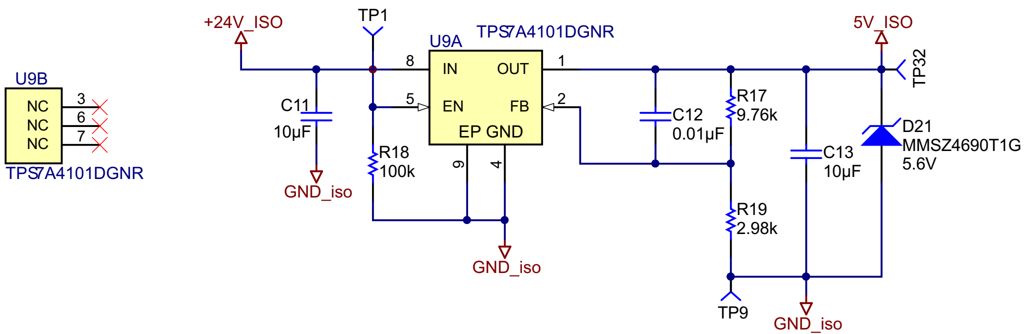


Figure 25. 24- to 5-V Power Supply

4.5.1.1 Layout Guidelines

See Section 11 Layout of the datasheet for layout guidelines.

4.5.2 Non-Isolated Power Supply

4.5.2.1 Power Supply for Driving Relays

An external 12-V DC supply must be connected on a two-pin terminal block J1 to power the relay driver TPL7407L. The power supply is protected for reverse polarity and overvoltage.

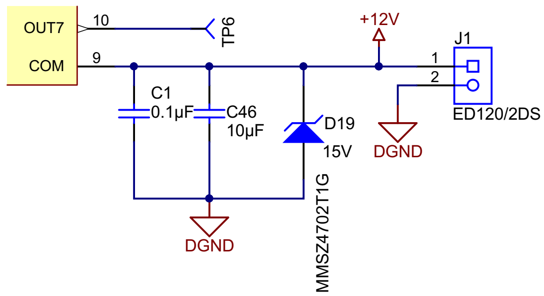


Figure 26. 12-V Input Connection

4.5.2.2 Power Supply for LED Operation

An external 5-V DC supply must be connected on a two-pin terminal block J9 to power the 4-digit SSD and indication LEDs. The power supply is protected for reverse polarity and overvoltage.

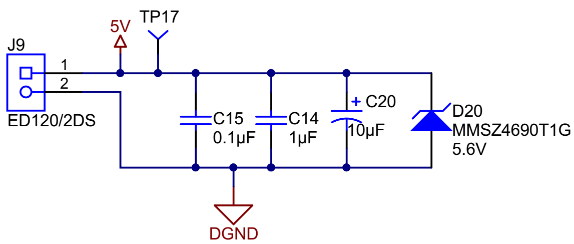


Figure 27. 5-V Input Connection

5 Firmware Description

For a firmware description and code examples for the TIDA-00737, see this design's firmware guide (TIDCBV2).

6 Getting Started Hardware

This section provides details of different connectors that are provided on the TIDA-00737 and TIDA-00454 boards and their applications.

6.1 Connectors

Table 7 provides connection information for the following sections.

The **OUTPUTS** section covers three relay and two transistor outputs available on TIDA-00737 board. Connector column shows pin number. Example J2.1 means pin 1 of connector J2 on TIDA-00737 board.

Under **INTERFACE CONNECTORS**, TIDA-00737 and TIDA-00454 boards are interfaced through two connectors. One connector is a 16 pin (2 x 8) and another is a 10 pin (2 x 5). Pin number 1 to 16 of J5 of TIDA-00737 are connected to pin number 1 to 16 of J2 of TIDA-00454, respectively. Pin number 1 to 10 of J3 of TIDA-00737 are connected to pin number 1 to 10 of TIDA-00454, respectively. The remote temperature sensor TMP451EVM interface section covers interfacing of temperature sensor with the TIDA-00454.

The **POWER SUPPLY** section covers isolated and non-isolated power supply connections.

The **MCU – TIDA-00454** section covers about MCU JTAG programming interface connector.

The **INPUTS – TIDA-00454** section covers three phase AC voltage input connection of TIDA-00454. Current input is through CT, which is shown in subsequent images.

Table 7. TIDA-00737 and TIDA-00454 Connectors

INPUT OR OUTPUT TYPE	SPECIFICATION	CONNECTOR
OUTPUT — TIDA-00737		
Relay output	Relay K1	J2.1 – J2.2
	Relay K2	J6.1 – J6.2
	Relay K3	J7.1 – J7.2
Transistor output	OUT1	J8.3 – J8.2
	OUT2	J8.4 – J8.2
INTERFACE CONNECTORS — TIDA-00737 WITH TIDA-00454		
Interface connectors (with TIDA-00454 board)	2 × SPI, 1 × I^2C, 5 × GPIO and DVCC, DGND	J5 of TIDA-00737 – J2 of TIDA-00454 (pin 1-pin1 to pin16-pin16)
	8 × GPIO	J3 of TIDA-00737 – J4 of TIDA-00454 (pin 1-pin1 to pin10-pin10)
Remote temperature sensor TMP451EVM interface (with TIDA-00454 board)	1 × I^2C, DVCC, GND	J5 of TIDA-00454 – Test point of TMP451EVM
		J5.12 – SCLA
		J5.13 – SDAA
		J5.15 – GND
		J5.16 – DVCC
POWER SUPPLY — TIDA-00737 AND TIDA-00454		
Non-isolated power supply input	5-V DC	J9.1 wrt J9.2 [TIDA-00737] J8.1 wrt J8.2 [TIDA-00454]
	12-V DC	J1.1 wrt J1.2
Isolated power supply input	24-V DC	J8.1 wrt J8.2
MCU — TIDA-00454		
MCU programming	JTAG	J10
INPUTS — TIDA-00454		
Voltage input	Channel 1	J11.1 – J11.2
	Channel 2	J12.1 – J12.2
	Channel 3	J13.1 – J13.2

NOTE: The current inputs have to be applied across the CTs and no connectors have been provided.

Figure 28 shows the interface connectors of the TIDA-00737 board.

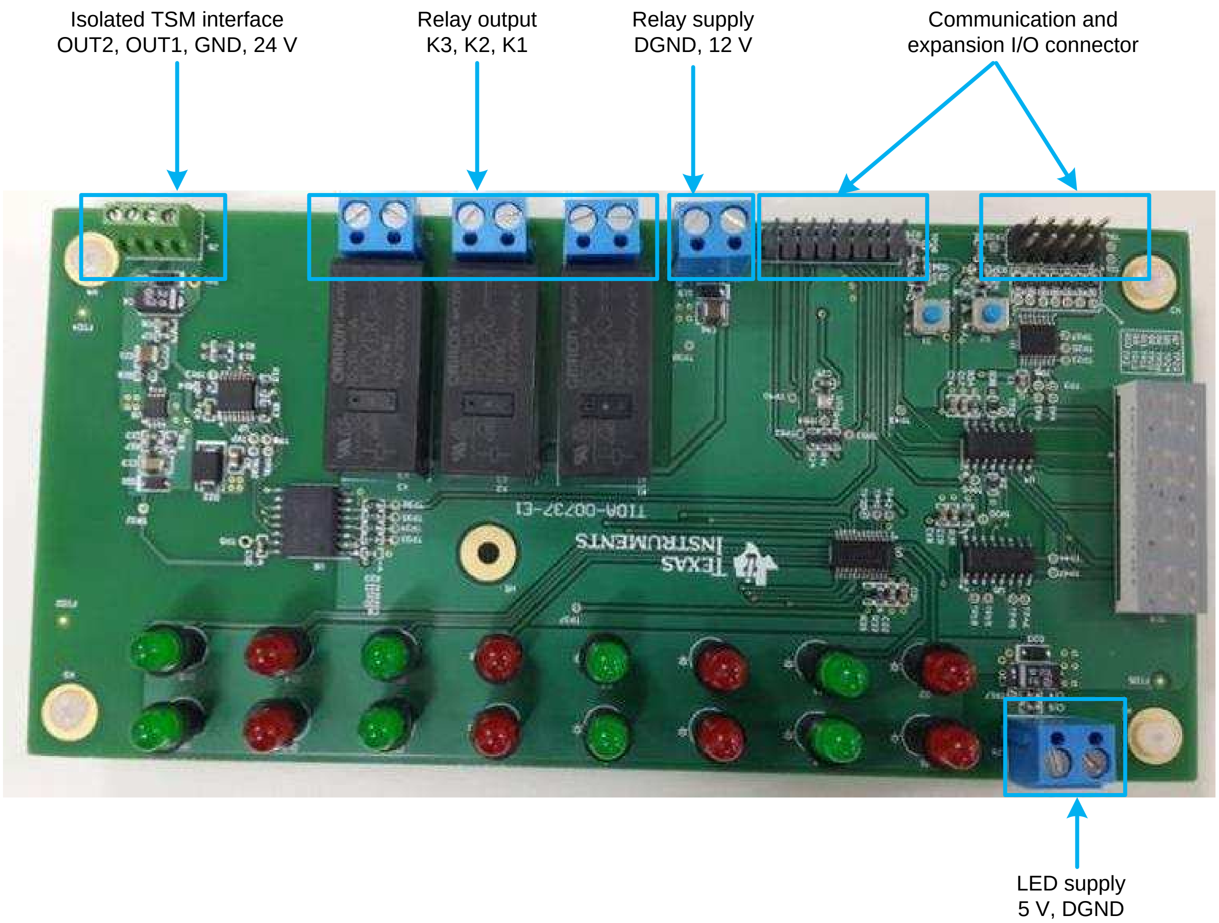


Figure 28. TIDA-00737 Interface Connectors

Figure 29 shows the interface connectors of the TIDA-00454 board.

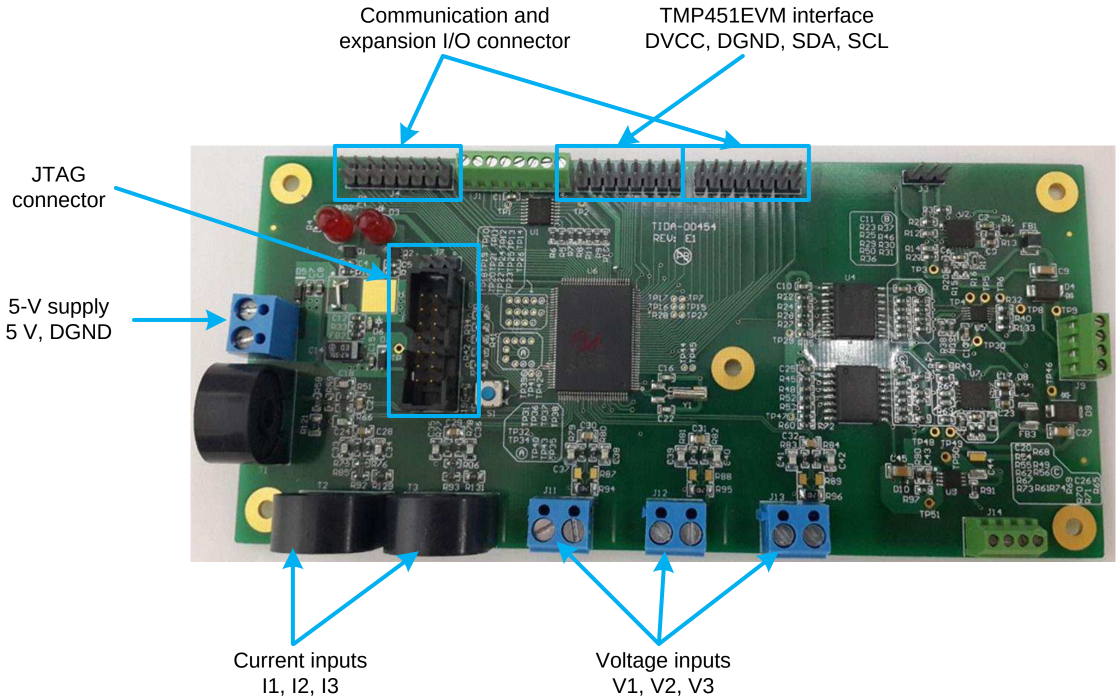


Figure 29. TIDA-00454 Interface Connectors

The current input wires are taken through the CT and do not have connectors (see Figure 30). The wires are connected externally as flying leads. An external terminal block can be used to connect the current inputs.

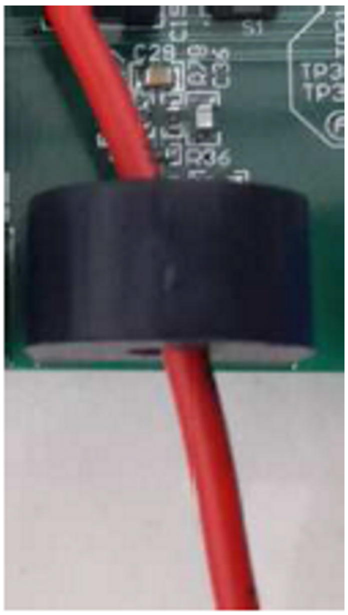


Figure 30. Current Input Wire Through CT

Figure 31 shows the interface for the remote temperature sensor TMP451EVM board.

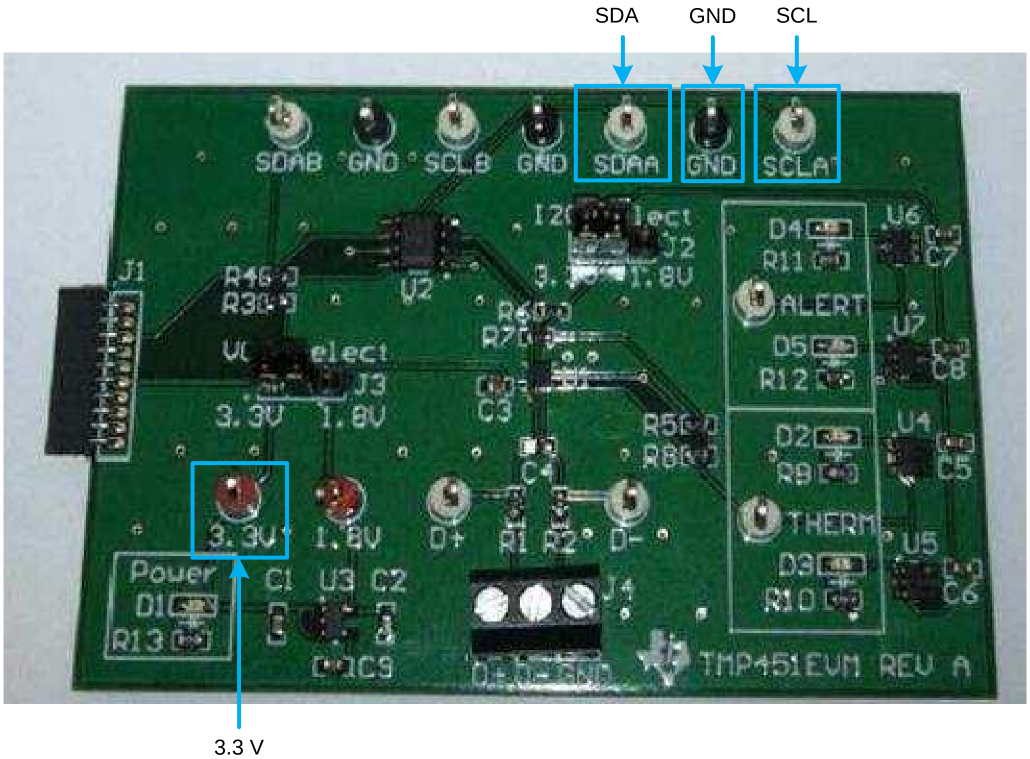


Figure 31. TMP451EVM Interface

6.2 External DC Power Supply

The following external power supplies are connected:

- Non-isolated: 5 V and 12 V
- Isolated: 24 V

NOTE: Consider the current limit setting.

See Section 4.5 for more details.

6.3 AC Input Range

The current input range for this design is 0.25 to 10 A. The voltage input range for this design is 23 to 320 V.

7 Test Setup

7.1 Test Setup Connection

Figure 32 shows test setup for the TIDA-00737 board. The TIDA-00454 board is interfaced with the TIDA-00737 board. A programmable three-phase current and voltage source (PTS3.3C) is used for applying three-phase voltages and currents to the TIDA-00454 board. The remote temperature sensor TMP451EVM is interfaced with the TIDA-00454 board through I^2C serial communication. 5-V, 12-V, and 24-V power supply connections are shown. A three-phase contactor is connected on the relay output of the TIDA-00737 board. The contactor consists of a contactor coil, main contacts, and auxiliary contacts. The contactor coil is used to control main contacts and are controlled through the relay output. Auxiliary contacts are used for auxiliary indication of main contacts position.

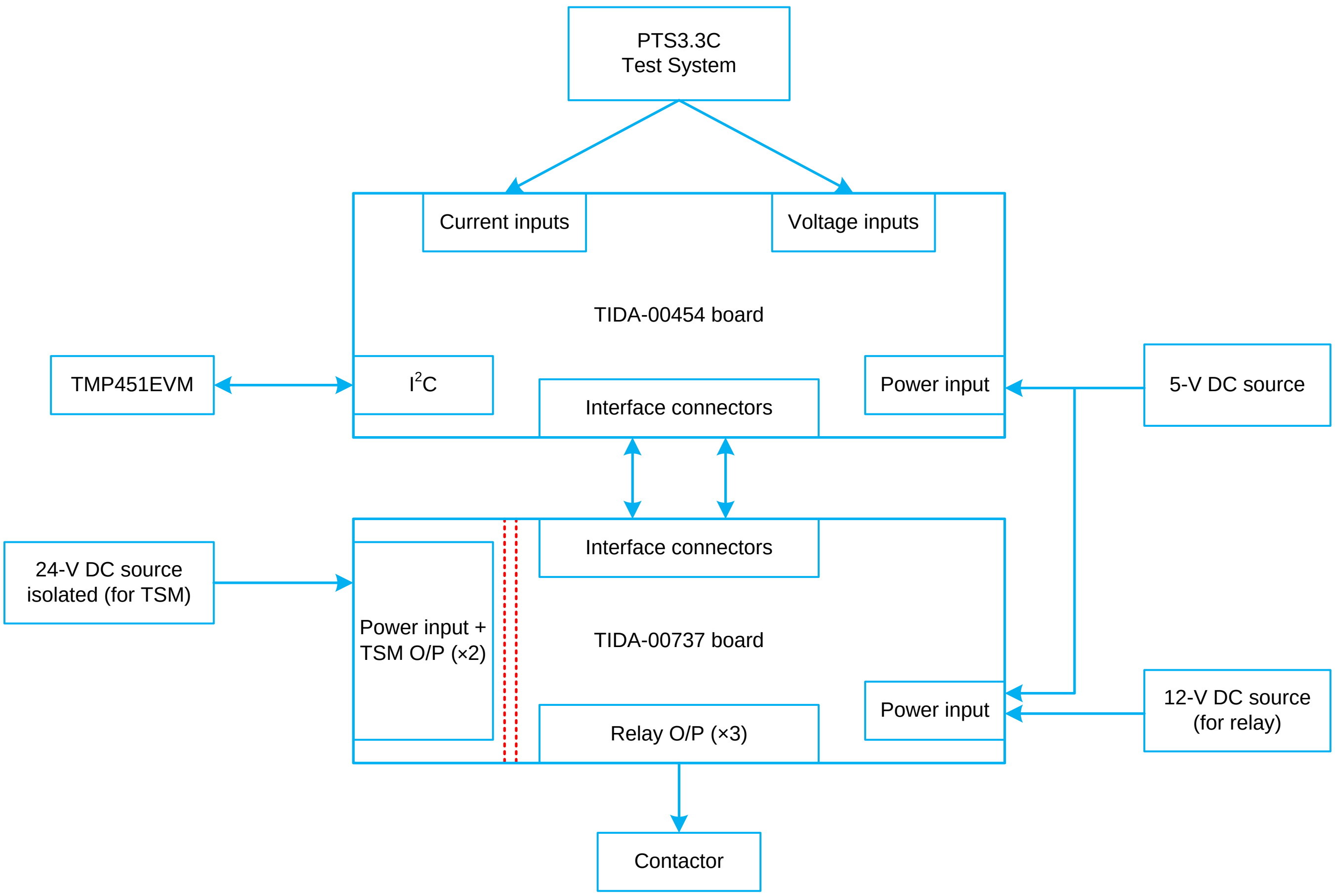


Figure 32. Test Setup to Connect TIDA-00737 With TIDA-00454

7.2 Test System

PTS3.3C with a 0.05% accuracy class is used for measurement. Using PTS3.3C provides minimum uncertainty during measurement.

Figure 33. Three-Phase Test System with Programmable Power Source

8 Test Data

8.1 Power Supply Testing

The following external power supplies are connected:

- Isolated: 24 V
- Non-isolated: 12 V, 5 V

The following supplies are generated on board using LDOs:

- Isolated: 5 V
- Non-isolated: 3.3 V

See Section 4.5 for more details.

Externally connected and generated power supply voltage levels measured are shown in Table 8.

Table 8. Functional Test Results

PARAMETERS	ACTUAL VALUE (VDC)	MEASURED VALUE (VDC)
Non-isolated power supply	5	4.98
	12	12.01
	3.3	3.29
Isolated power supply	24	24.01
	5	5.05

8.2 Accuracy Testing

Three-phase voltages and currents are applied using the PTS3.3C. Accuracy of voltages, currents, active powers, and reactive powers for three phases are observed. Measurements were adjusted for gain, offset, and phase angle as required.

8.2.1 AC Input Voltage Measurement

For measurement at 50 Hz:

Table 9. Input Voltage versus Measurement Error at 50 Hz

% OF NOMINAL	APPLIED VOLTAGE INPUT (V)	MEASURED PHASE VOLTAGE (V)			MEASUREMENT ERROR (%)			MEASURED FREQ (Hz)
		R	Y	B	R	Y	B	
5	11.5	11.471	11.472	11.470	–0.25	–0.24	–0.26	49.99
10	23.0	22.951	22.952	22.949	–0.21	–0.21	–0.22	
20	46.0	45.918	45.920	45.914	–0.18	–0.17	–0.19	
50	115.0	114.871	114.891	114.879	–0.11	–0.09	–0.11	
100	230.0	229.773	230.005	229.984	–0.10	0.00	–0.01	
120	276.0	275.753	275.855	276.103	–0.09	–0.05	0.04	

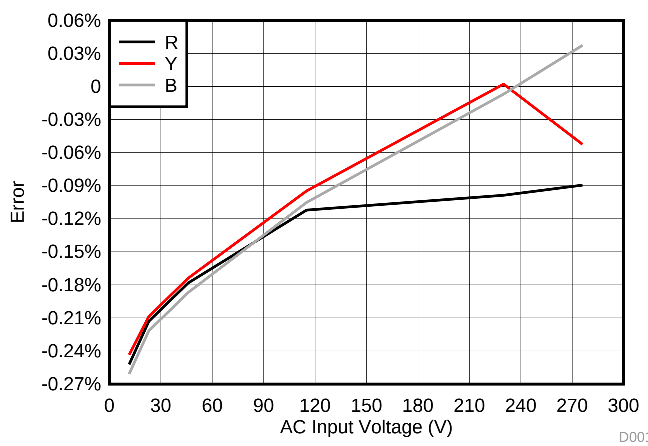


Figure 34. AC Input Voltage versus Measurement Error at 50 Hz

For measurement at 60 Hz,

Table 10. Input Voltage versus Measurement Error at 60 Hz

% OF NOMINAL	APPLIED VOLTAGE INPUT (V)	MEASURED PHASE VOLTAGE (V)			MEASUREMENT ERROR (%)			MEASURED FREQ (Hz)
		R	Y	B	R	Y	B	
5	11.5	11.470	11.469	11.468	–0.26	–0.27	–0.28	59.98
10	23.0	22.943	22.944	22.941	–0.25	–0.24	–0.26	
20	46.0	45.898	45.900	45.895	–0.22	–0.22	–0.23	
50	115.0	114.817	114.832	114.817	–0.16	–0.15	–0.16	
100	230.0	229.713	229.916	229.887	–0.12	–0.04	–0.05	
120	276.0	275.753	275.999	275.952	–0.09	0.00	–0.02	

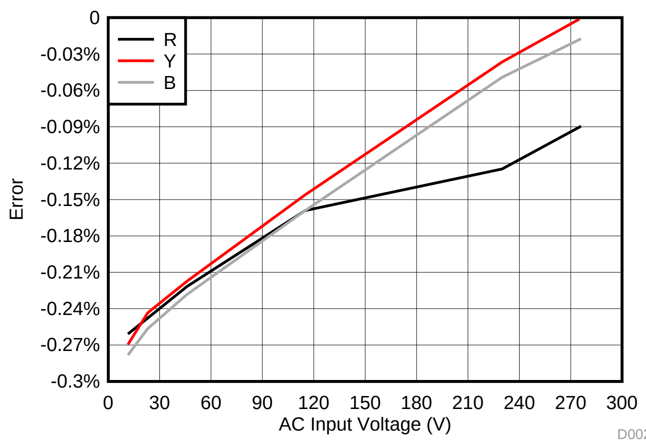


Figure 35. AC Input Voltage versus Measurement Error at 60 Hz

8.2.2 AC Current Input Measurement

For measurement at 50 Hz,

Table 11. Input Current versus Measurement Error at 50 Hz

% OF NOMINAL	APPLIED CURRENT INPUT (A)	PHASE CURRENT MEASURED (A)			MEASUREMENT ERROR (%)			MEASURED FREQ (Hz)
		R	Y	B	R	Y	B	
5	0.25	0.250	0.2500	0.2498	0.04	0.00	–0.08	49.99
10	0.50	0.500	0.4998	0.4996	0.02	–0.04	–0.08	
20	1.00	1.000	0.9990	0.9994	0.00	–0.10	–0.06	
50	2.50	2.500	2.4990	2.4980	0.00	–0.04	–0.08	
100	5.00	4.996	4.9940	4.9920	–0.08	–0.12	–0.16	
200	10.00	9.998	9.9920	9.9890	–0.02	–0.08	–0.11	

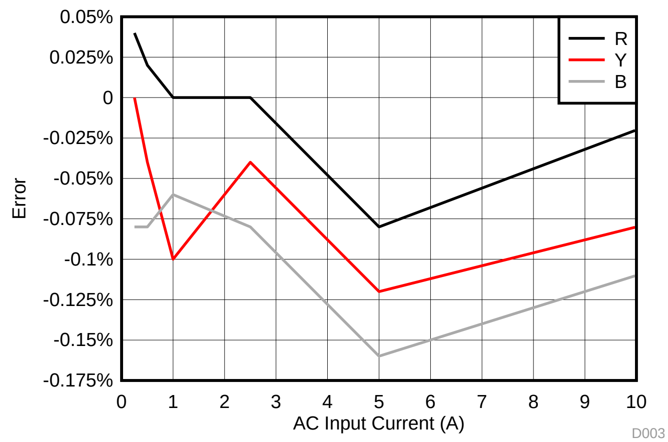


Figure 36. AC Input Current versus Measurement Error at 50 Hz

For measurement at 60 Hz,

Table 12. Input Current versus Measurement Error at 60 Hz

% OF NOMINAL	APPLIED CURRENT INPUT (A)	PHASE CURRENT MEASURED (A)			MEASUREMENT ERROR (%)			MEASURED FREQ (Hz)
		R	Y	B	R	Y	B	
5	0.25	0.2500	0.2499	0.2497	0.00	–0.04	–0.12	59.98
10	0.50	0.4998	0.4996	0.4994	–0.04	–0.08	–0.12	
20	1.00	1.0001	0.9995	0.9990	0.01	–0.05	–0.10	
50	2.50	2.5000	2.4962	2.4979	0.00	–0.15	–0.08	
100	5.00	4.9990	4.9960	4.9930	–0.02	–0.08	–0.14	
200	10.00	9.9940	9.9820	9.9840	–0.06	–0.18	–0.16	

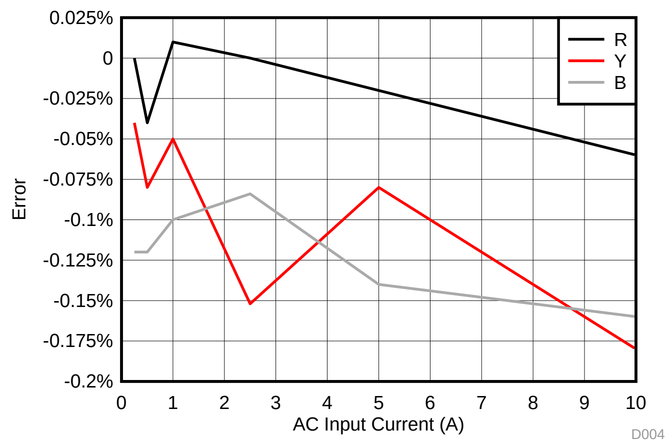


Figure 37. AC Input Current versus Measurement Error at 60 Hz

8.2.3 Power (Reactive and Active) Measurement

The following inputs were applied and powers were observed for the following conditions:

- AC voltage: 230 V
- Current: 5 A
- Frequency: 50 Hz
- PF: Performed between 0 to 1 (lead or lag)

Table 13. Power Measurement: R-Phase

PF TYPE	APPLIED PHASE ANGLE BETWEEN CURRENT AND VOLTAGE	EXPECTED W	MEASURED W	EXPECTED var	MEASURED var
LAG	45	813.05	812.73	813.05	813.35
ZPF	90	N/A		1150	1149.58
UPF	0	1150	1150.24	N/A	
LEAD	45	813.05	813.85	813.05	812.44

Table 14. Power Measurement: Y-Phase

PF TYPE	APPLIED PHASE ANGLE BETWEEN CURRENT AND VOLTAGE	EXPECTED W	MEASURED W	EXPECTED var	MEASURED var
LAG	45	813.05	813.02	813.05	813.51
ZPF	90	N/A		1150	1149.96
UPF	0	1150	1150.34	N/A	
LEAD	45	813.05	813.73	813.05	812.23

Table 15. Power Measurement: B-Phase

PF TYPE	APPLIED PHASE ANGLE BETWEEN CURRENT AND VOLTAGE	EXPECTED W	MEASURED W	EXPECTED var	MEASURED var
LAG	45	813.05	812.13	813.05	813.36
ZPF	90	N/A		1150	1149.17
UPF	0	1150	1149.91	N/A	
LEAD	45	813.05	814.28	813.05	811.46

8.3 Functional Testing: SSD Display and LED Indications

An AC voltage of 230 V and AC current of 1 A are applied and the following were observed:

- Display of parameters like voltage, current, and PF
- LED indications
- Display updated every 4 seconds between the selected parameters
- Cyclic display of selected parameters

Table 16. SSD Display and LED Indications

INPUT PARAMETER	PARAMETERS (OBSERVED)			PHASES (OBSERVED)			PF (OBSERVED)		DISPLAY (SSD)	
	D14	D15	D11	D12	D13	D16	D10	D7	EXPECTED	OBSERVED
Voltage Phase R (V)	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF	230.3	230.3
Voltage Phase Y (V)	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	230.4	230.4
Voltage Phase B (V)	ON	OFF	OFF	OFF	OFF	ON	OFF	OFF	230.4	230.4
Current Phase R (A)	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	1.001	1.001
Current Phase Y (A)	OFF	ON	OFF	OFF	ON	OFF	OFF	OFF	1.001	1.001
Current Phase B (A)	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	1.001	1.001
PF Phase R (LAG)	OFF	OFF	ON	ON	OFF	OFF	ON	OFF	0.707	0.707
PF Phase Y (LAG)	OFF	OFF	ON	OFF	ON	OFF	ON	OFF	0.707	0.707
PF Phase B (LAG)	OFF	OFF	ON	OFF	OFF	ON	ON	OFF	0.707	0.707
PF Phase R (LEAD)	OFF	OFF	ON	ON	OFF	OFF	OFF	ON	0.707	0.707
PF Phase Y (LEAD)	OFF	OFF	ON	OFF	ON	OFF	OFF	ON	0.707	0.707
PF Phase B (LEAD)	OFF	OFF	ON	OFF	OFF	ON	OFF	ON	0.707	0.707

8.4 Capacitor Bank (Simulated Reactive Power) Switching Test

The design provides:

- Three relay outputs for contactor switching. A three-phase contactor with a main contacts rating of 220 V, 25 A is used for the test. Each relay is connected with a separate contactor. The relay output is connected to the contactor coil. Auxiliary contact of contactor is monitored for main contact's switching status – ON/OFF.
- Two transistor outputs for thyristor switching.

The output switching is simulated by increasing and reducing the reactive power (applying constant current and voltage and varying the PF).

When multiple relay and transistor output status needs to be changed. the relay and transistor outputs are switched ON or OFF sequentially with a delay of 4 seconds (See Section 3 of the firmware design guide (TIDCBV2) for more details).

8.4.1 Increase of Reactive Power

Table 17. Relay and Transistor Switching

INPUT	RELAY K3		RELAY K2		RELAY K1		TRANSISTOR OUT_1		TRANSISTOR OUT_2	
var (V = 230 V, I = 5 A)	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED
< 200	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
≥ 200	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
≥ 400	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
≥ 600	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF
≥ 800	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
≥ 1000	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

Table 18. LEDs to Indicate Switching Steps

INPUT	D9		D8		D5		D4		D1	
var (V = 230 V, I = 5 A)	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED
< 200	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
≥ 200	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
≥ 400	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
≥ 600	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF
≥ 800	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
≥ 1000	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON

8.4.2 Reduction of Reactive Power

Table 19. Relay and Transistor Switching

INPUT	RELAY K3		RELAY K2		RELAY K1		TRANSISTOR OUT_1		TRANSISTOR OUT_2	
var (V = 230 V, I = 5 A)	EXPECTED	OBSERVED	EXPECTED	OBSERVED	Expected	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED
≥ 1000	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
≥ 800	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
≥ 600	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF
≥ 400	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
≥ 200	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
< 200	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

Table 20. LEDs to Indicate Switching Steps

INPUT	D9		D8		D5		D4		D1	
var (V = 230 V, I = 5 A)	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED	EXPECTED	OBSERVED
≥ 1000	ON	ON	ON	ON	ON	ON	ON	ON	ON	ON
≥ 800	ON	ON	ON	ON	ON	ON	ON	ON	OFF	OFF
≥ 600	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF
≥ 400	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
≥ 200	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
< 200	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

8.5 ALS Test

Alarm LED D6 indicates ambient light intensity level. The following tests were performed.

Table 21. Ambient Light Status

AMBIENT LIGHT	EXPECTED LIGHT ALARM LED (D6) STATUS	OBSERVED LIGHT ALARM LED (D6) STATUS
Bright	OFF	OFF
Dim (below 100 lux)	ON	ON

8.6 Remote Temperature Sensor Test

An environment chamber with the capability to program temperature is used to perform this test. The TMP451EVM is placed inside the environment chamber. The following temperatures were set and the temperature alarm LED indication was tested.

Table 22. Remote Temperature Sensor Status

SET TEMPERATURE (°C)	EXPECTED TEMPERATURE ALARM LED (D3) STATUS	OBSERVED TEMP ALARM LED (D3) STATUS
25	OFF	OFF
51	ON	ON

8.7 AC Input Voltage — Overvoltage Test

The overvoltage alarm LED D2 indicates the overvoltage level. The following tests were performed.

Table 23. Overvoltage Test

VOLTAGE INPUT (V)	EXPECTED OVER VOLTAGE ALARM LED (D2) STATUS	OBSERVED OVER VOLTAGE ALARM LED (D2) STATUS
230	OFF	OFF
255 (> 110% of 230 V)	ON	ON

8.8 Summary of Test Results

Table 24. Test Result Summary

SERIAL NUMBER	PARAMETERS	RESULT
1	Power supply testing	OK
2	AC input measurement accuracy for current, voltage, and powers	OK
3	LEDs alarm and status indication	OK
4	Relay and transistor output testing to indicate switching of capacitor bank (simulated reactive power)	OK
5	ALS performance	OK
6	Remote temperature sensor performance	OK
7	Scrolling and cyclic display of parameters	OK
8	AC input voltage — overvoltage test	OK

9 Design Files

9.1 Schematics

To download the schematics, see the design files at TIDA-00737.

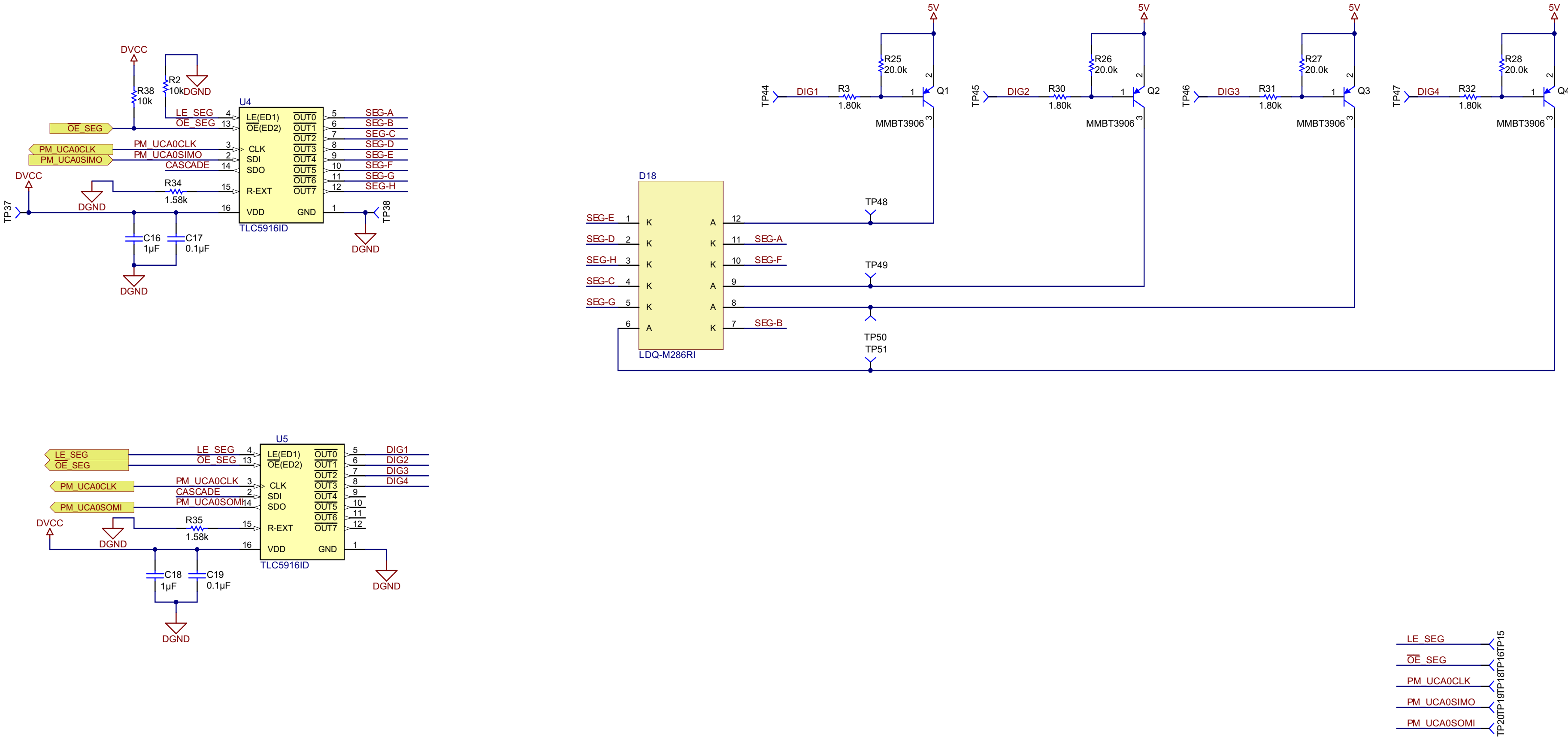


Figure 38. 7-Segment LED Display + Driver Schematic

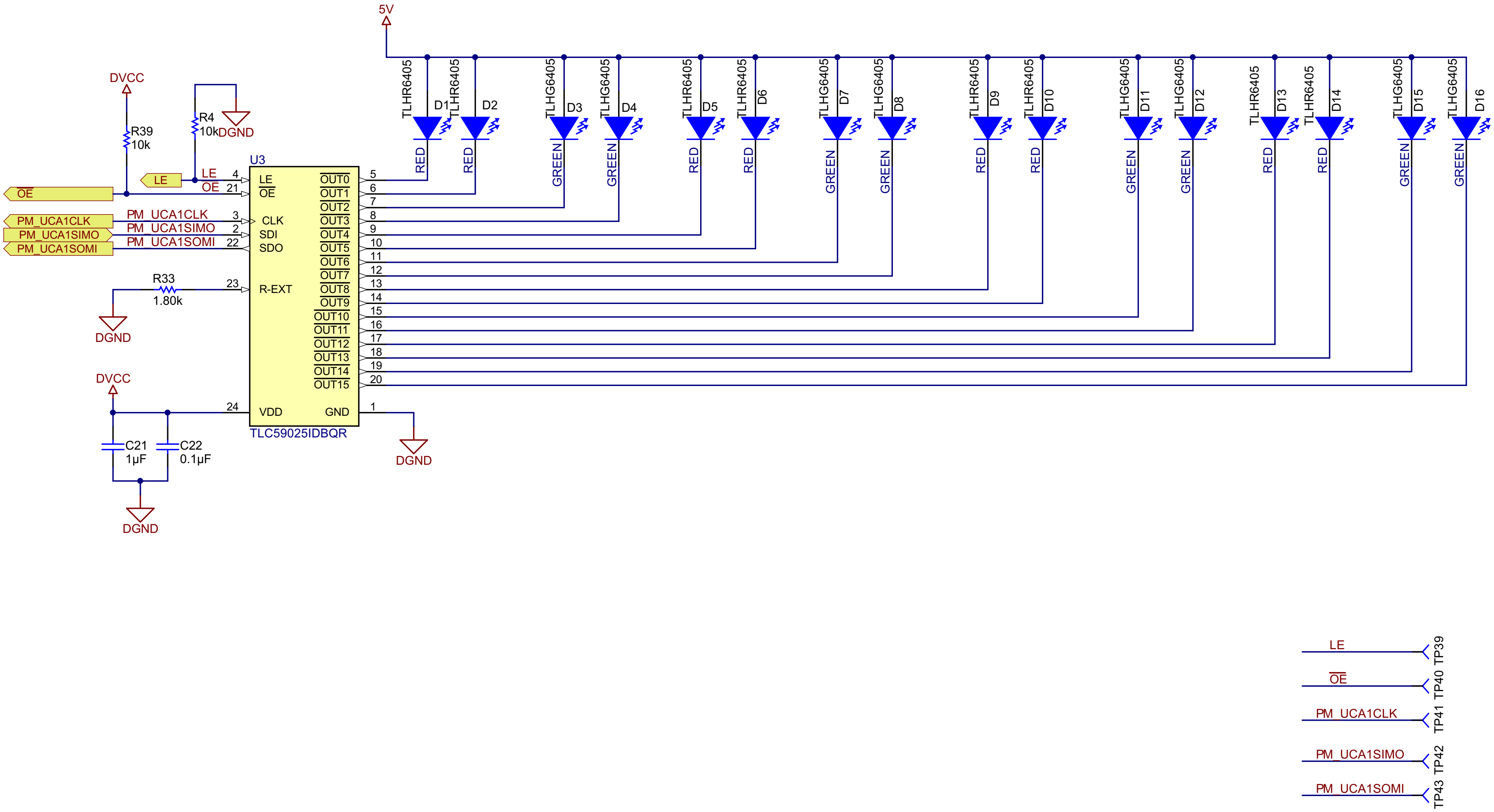


Figure 39. 16 LEDs + Driver Schematic

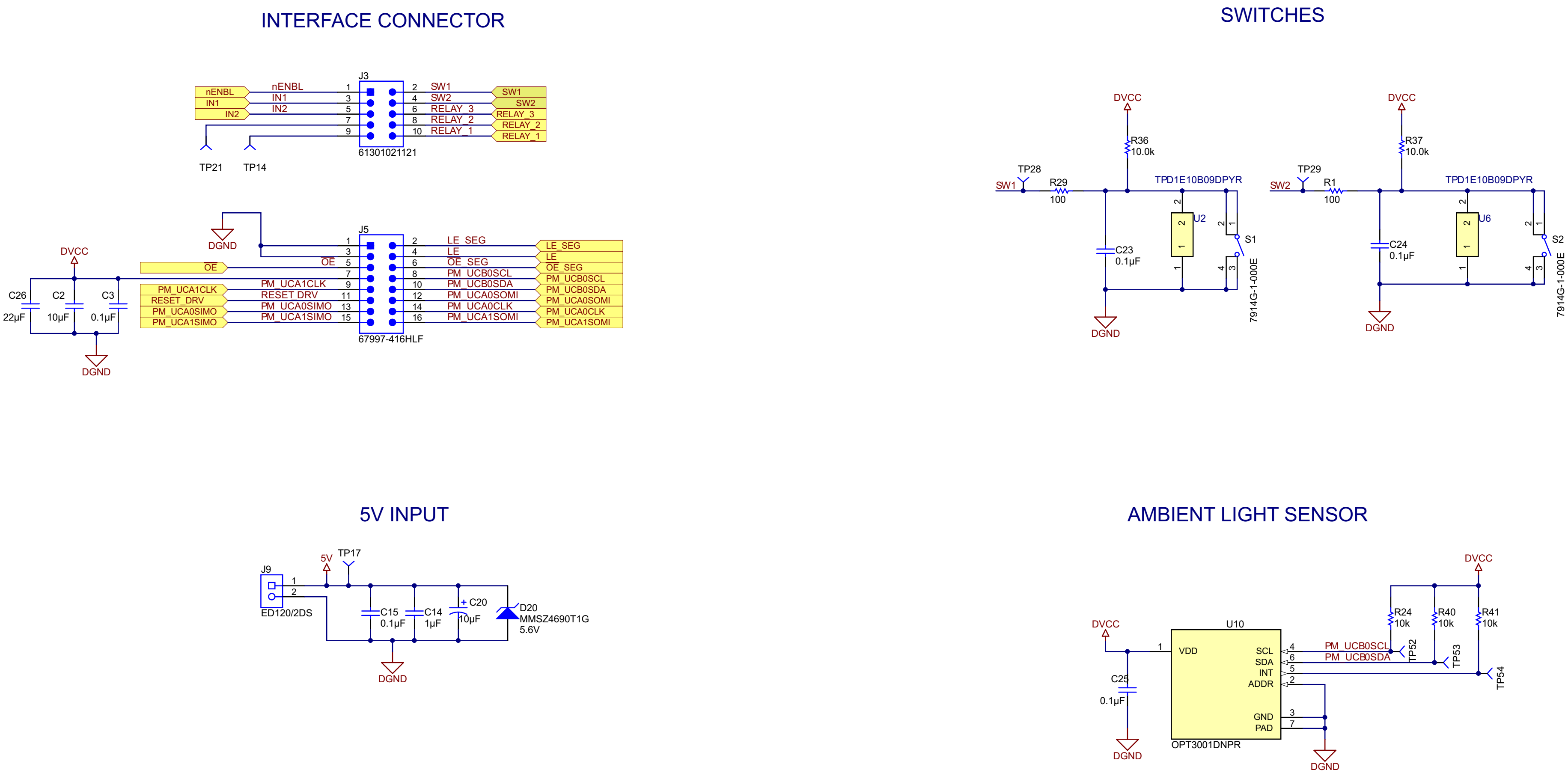


Figure 40. Interface Connectors + Ambient Light Sensor Schematic

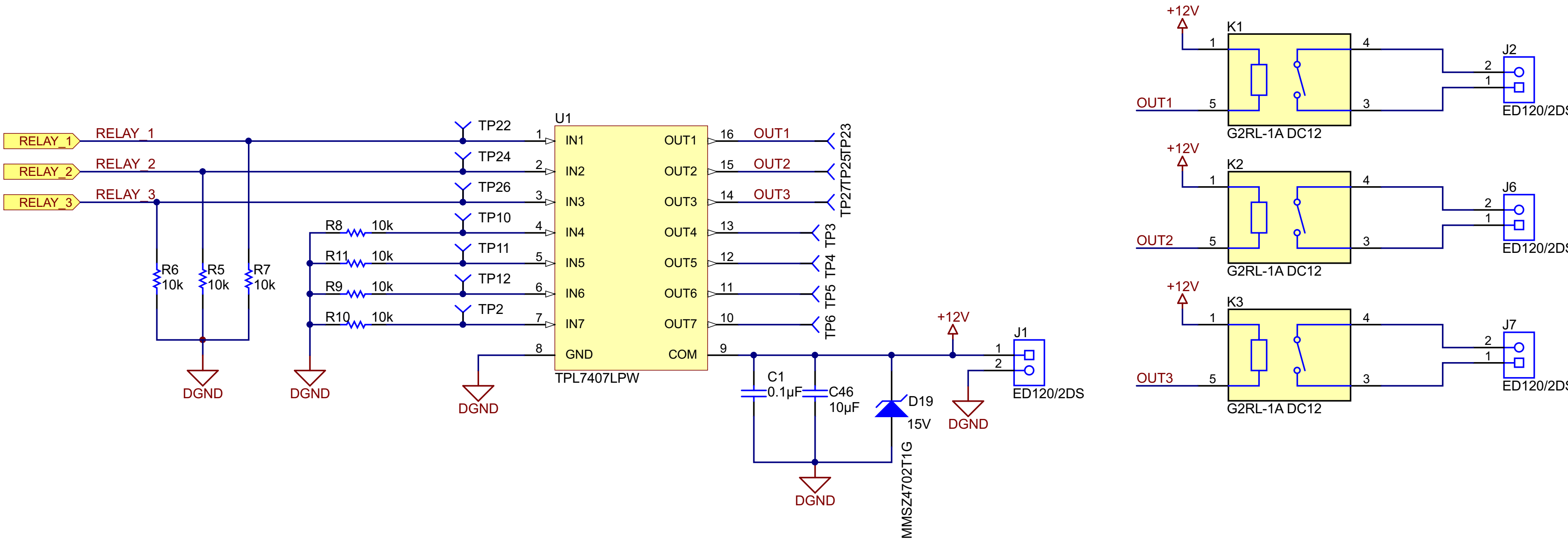


Figure 41. Relay Output Schematic

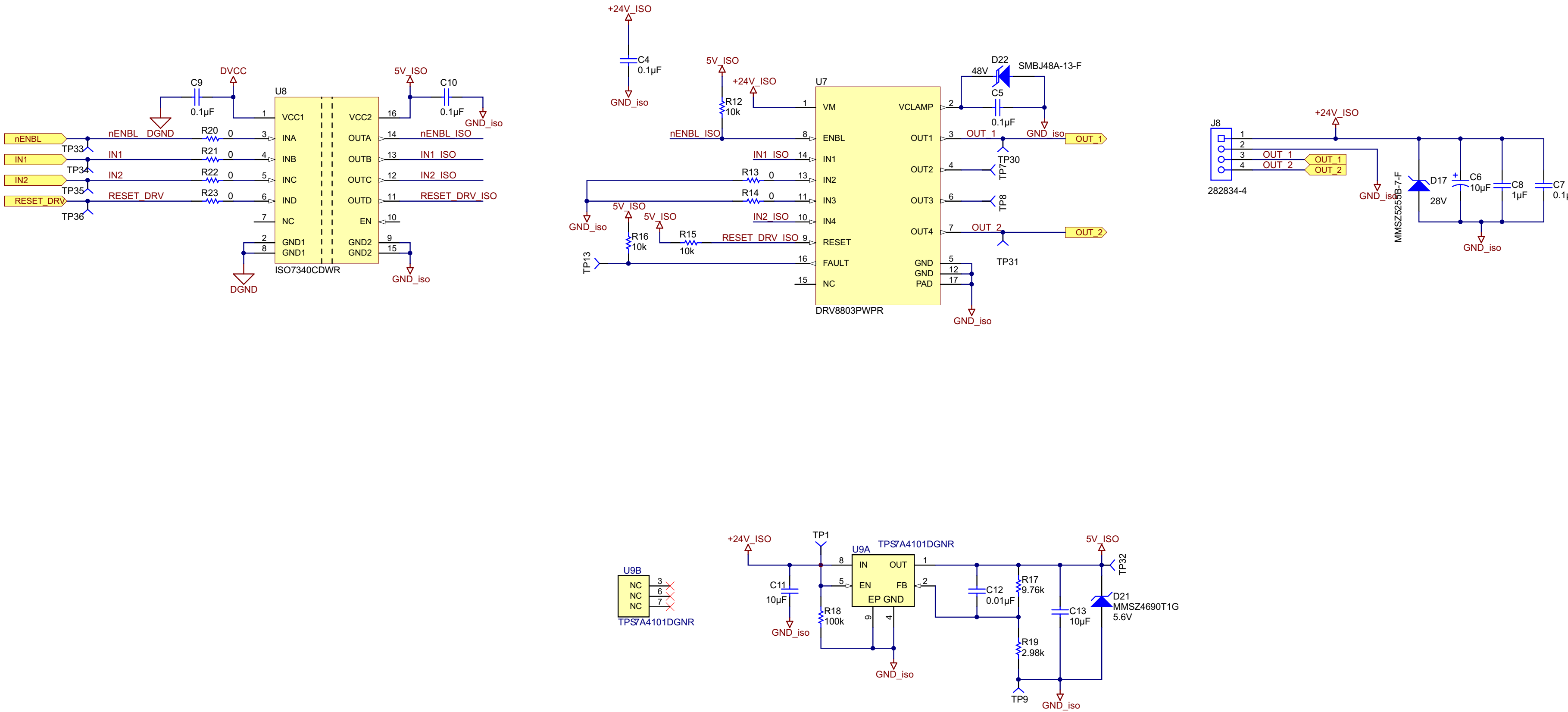


Figure 42. Transistor Output + Digital Isolator 5 V Schematic

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00737.

9.3 PCB Layout Prints

To download the layout prints, see the design files at TIDA-00737.

9.4 Altium Project

To download the Altium project files, see the design files at TIDA-00737.

9.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00737.

9.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00737.

10 References

1. Texas Instruments, *AC Voltage and Current Transducer With DC Analog Outputs and Digital Output Drivers*, TIDA-00454 Design Guide (TIDUAH1)
2. Texas Instruments, *Three-Phase Metrology With Enhanced ESD Protection and Tamper Detection*, TIDM-3PHMTR-TAMP-ESD Design Guide (TIDU817)
3. Texas Instruments, WEBENCH® Design Center (http://www.ti.com/webench)

11 Terminology

CT— Current transformer

ALS— Ambient light sensor

PFC— Power factor controller

APFC— Automatic power factor correction

LED— Light emitting diode

NO— Normally open

NC— Normally closed

TSM— Thyristor switching module

12 About the Authors

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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