TI Designs

Analog Front End for Motor Electronic Overload Relays with Enhanced Current Range

TI Designs

TI Designs provide the foundation that you need including methodology, testing and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDA-00191	Design Files
PGA116	Product Folder
LM5017	Product Folder
LM62	Product Folder
CSD18537NKCS	Product Folder
LM4041B	Product Folder
TPS7A6533Q	Product Folder
TPS55010	Product Folder
ISO1176	Product Folder
LM293	Product Folder

TI E2E™ Community

ASK Our Analog Experts

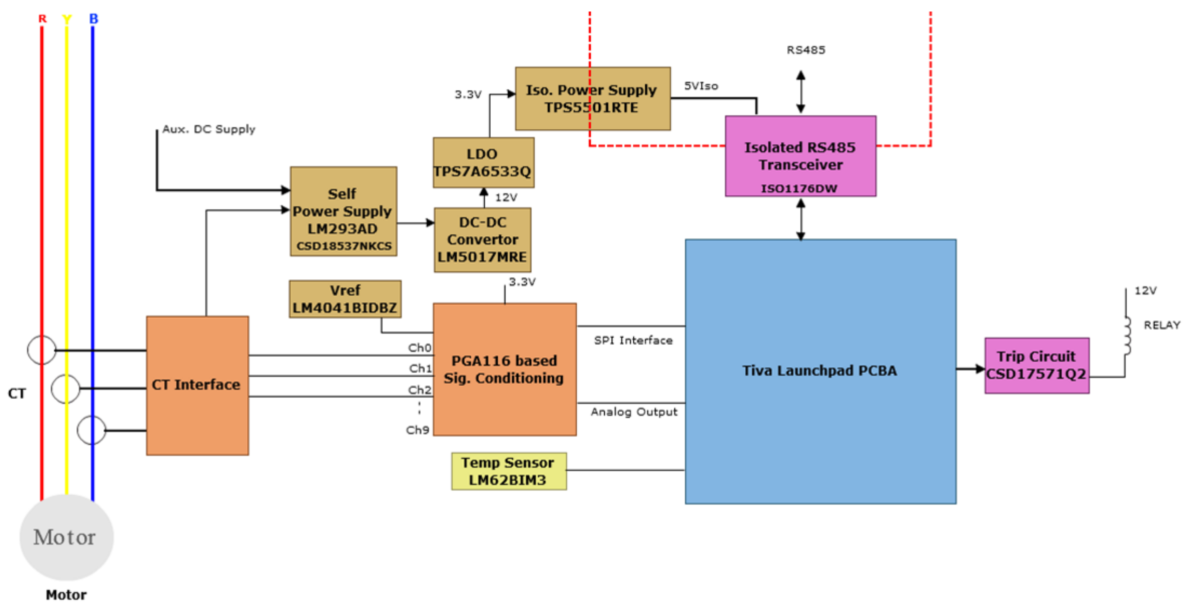
WebBench Calculator Tools

Featured Applications

- Electronic Overload Relays for Motors
- Overload Relays for Generators

Design Features

- Wide Full Load Ampere (FLA) of 10:1 Dramatically Reduces the Number of Units Required On-Hand
- Current Measurement Accuracies of < 2% Over Entire 10:1 Measurement Range From No Load to Locked Rotor Current
- Repeat Accuracy of 0.1%
- 0.01% Accuracy Between Channel-to-Channel Measurements
- Ambient Insensitivity From –10 to +70°C for Global Design and Worldwide Acceptance
- Better Trip Time Repeatability
- Reduced Component Count and Calibration Time
- Robust Design that Prevents Phase Reversal in Overdrive Conditions and High Electrostatic Discharge (ESD) Protection (3-kV HBM)



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

When an AC motor is energized, a high inrush current occurs. The starting current can be between 600 and 1000% of the rated current under given operating conditions. As a motor reaches running speed, the current subsides to its normal running level.

An overcurrent exists when the normal full load motor current is exceeded. Mechanical overload, locked rotor, short-circuit, and single-phasing are few of the situations when a motor can draw higher than its rated current. Leaving motors unprotected against these abnormal currents and conditions leads to overheat during continued operation. Overheat conditions cause the motor winding insulation to deteriorate and ultimately fail. Good motor overload protection can help in extending the life of the motor.

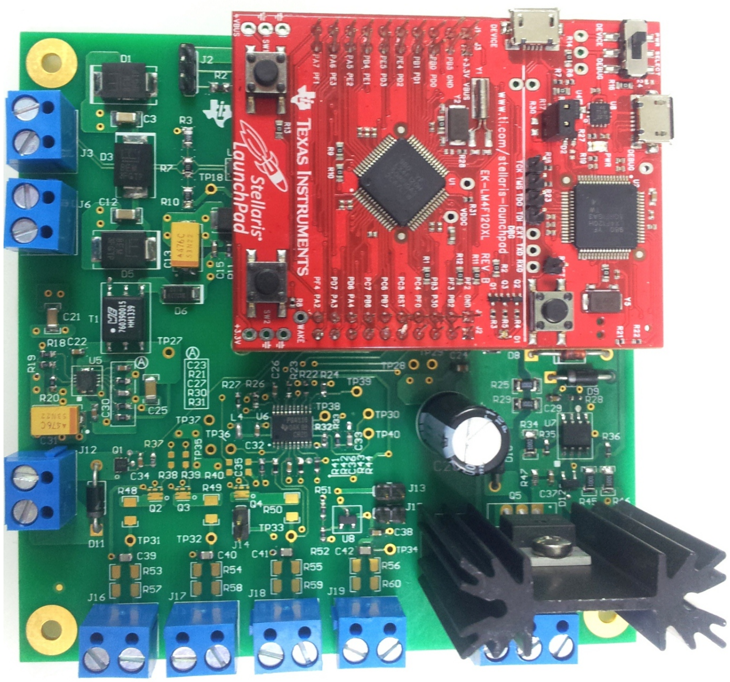


Figure 1. Analog Front End for Motor Electronic Overload Relays with Enhanced Current Range

Electronic overload relays are used to protect the motor from such situations by monitoring the motor current. When the current exceeds a preset condition, the device monitor will initiate a trip circuit or cause the contactor to trip and disconnect the motor from grid. Electronic overload relay offers reliable and fast protection for motors in the event of overload or phase failure.

The electronic overload relay can also be used to detect sudden drops in motor current arising out of many situations such as tool breakage and belt breakage. Monitoring of underload events also provides enhanced protection for motors.

Overload relay classifications include instantaneous over current relays and inverse time overload relays. Overload relays have contacts which are used to perform control functions, such as opening a motor controller or contactor. Inverse time overload relays are described by time current characteristics which are designated by a class number. The class number represents the maximum operating or tripping time that the device will operate within, carrying a current equal to 600% of its current rating. Classes 10, 20, or 30 will operate or trip within 10, 20, or 30 seconds or less, respectively.

Some of the advantages of electronic overload relays when compared to thermal overload relays are:

- Wide FLA range 10:1
- Accurate sensing
- Adjustable Ir (rated current) for continuous current settings
- Trip setting accuracy of around 5% (IEC 60947-4-1:2000 specifies ±10% of the value corresponding to the current setting)
- Repeat accuracies of less than 2%

The overload relays have a setting scale in amperes, which allows the direct adjustment of the setting current without any additional calculation. The setting current is the rated current of the motor. Relays trip when the motor current exceeds the set threshold after a predetermined time. Advanced electronic overload relays use digital sampling to determine the RMS value of sinusoidal and nonsinusoidal currents. To sense the current input, an amplifier with programmable gain is used for signal conditioning.

For set operating current, the motor current depends upon the fault condition. For example, a motor rated 9 A at full load may draw 45 A at locked rotor condition. Similarly, a motor rated 45 A may draw 270 A at locked rotor condition. This large swing in current from 9 A to 270 A limits the FLA ratio of relays. Some of the other limitations due to use of a general purpose operational amplifier for signal conditioning also leads to:

1. Higher DC output offset and low rail-to-rail output, which limits the ADC range
2. Setting accuracy variation overtemperature range of –10 to 70ºC
3. Phase reversal problems during short circuit resulting in pickup and trip timing repeatability issues
4. Higher input bias current causes loading on the input current transformer (CT) resulting in measurement nonlinearity
5. Needs more testing during manufacturing

This reference design provides a wide range analog front end amplifier solution that provide the following advantages:

1. Wide FLA range of 10:1 leading to reduced variants and inventory
2. Lower DC offset and improved rail-to-rail output voltage improves accuracy
3. Accurate and repeatable over -10 to 70°C (less variation in tripping accuracy)
4. Reduced Loading on the current transformers due to lower input bias current
5. Does not have phase reversal effects during saturation conditions, resulting in improved repeatability

Improvements also result in reduced manufacturing time, reduced testing time, and improved yield

The programmable gain amplifier (PGA)-based analog front end amplifier reference design is a platform for easy evaluation of the electronic overload trip characteristics. The design provides the following functionality:

- Current input measurement with programmable gains, based on PGA116
- TI MOSFET-based self-powered power supply
- DC-DC converter for FSD relay supply generation
- Isolated RS-485 communication
- Screw terminals for easy connection
- MCU interface for quick and easy evaluation

The complete design (or parts of the design) can be used in other self-powered or dual-powered (self-powered or 24-V auxiliary input-powered) applications like overcurrent, Earth fault, and other protection relays. The design files include PDF schematics, BOMs, PDF layer plots, Altium files, and Gerber Files.

2 Design Features

2.1 PGA with Low supply voltage (3.3-V DC)

Inputs:

- Programmable gain for R, Y, B inputs

Gain options:

- Binary gains (PGA116): 1, 2, 4, 8,16, 32, 64, and 128

Rail-to-rail operation up to 3.3 V – 50 mV

Low output DC offset voltage < 200 µV with highest gain

NOTE: The required gains for evaluation are configurable.

Two resistors have been provided as burden resistors for CT inputs.

2.2 Power Supply

POWER SUPPLY	VOLTAGE
Power supplies generated	> 12-V DC
	approximately 16-V DC
	3.3-V DC
Self-power supply regulation	39-V DC ± 5%
Input supply range for auxiliary input	20-V DC – 35-V DC

2.3 Measurement Reference (1.65-V DC with ±0.25%)

The reference for input current can be selected between 0 V and VCC/2 using jumpers. VCC/2 is generated using precision reference. The reference selected is 1.65 V with 0.1% tolerance. The maximum output error is expected to be less than ±0.25%.

2.4 Temperature Sensor

The temperature sensor has 0°C to 90°C temperature range, with accuracy of ±3.0°C at 25°C.

2.5 MOSFET Switch

The design has a MOSFET switch to control relay outputs, which in turn activates the motor contactors.

2.6 Communication

The design includes an isolated RS-485 communication interface to implement Modbus protocol. There is an option to mount a failsafe and termination resistor. Measured current can be used for metering purposes using the Modbus as well as to remotely control overload relay

3 Block Diagram

Figure 2 illustrates the blocks of the analog front end reference design of the electronic motor overload relay. The blocks are included in the following list:

1. Programmable gain amplifier, reference, temperature sensor, and current input
2. Self-power supply
3. Isolated RS-485 interface
4. Relay Control
5. Tiva C Series 32-Bit MCU

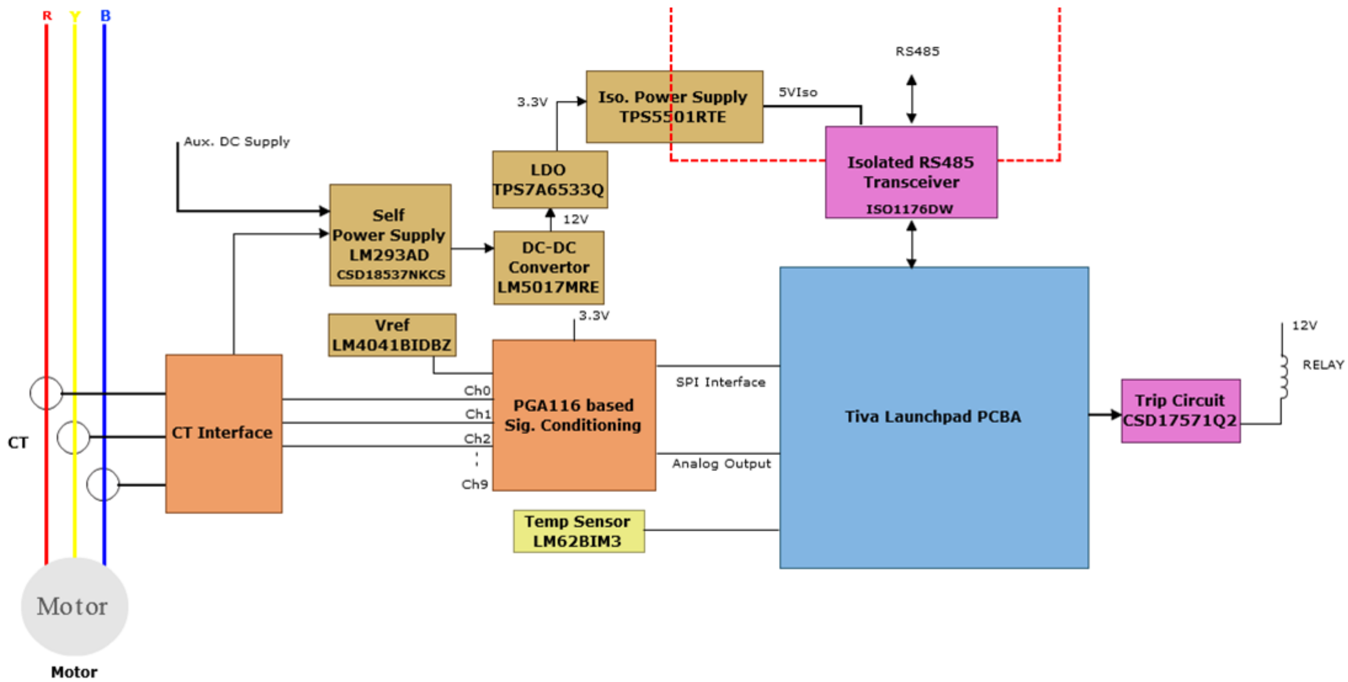


Figure 2. Block Level Diagram

3.1 *Programmable Gain Amplifier, Reference, and Current Input*

Programmable gain amplifiers are used to amplify the wide range of current inputs. Four input channels of the PGA are utilized for three-phase and neutral current inputs. The design provides a stable reference for highly accurate measurement over wide temperatures. The design provides screw type terminals to connect CT input. The design provides a highly accurate temperature sensor for calibration.

3.2 *Power Supply*

The overload relay is powered by auxiliary 24-V DC input, which is down-converted to 12 V and 3.3 V for relay operation and MCU functioning using a DC-DC convertor and regulator. The design provides an optional self-power supply circuit which can generate required output voltages from the CT secondary currents.

3.3 *Isolated RS-485 Interface*

The overload relay analog front end amplifier design can also communicate the measured data to the supervisory system through RS-485.

3.4 Relay Control

The design provides a MOSFET based switch for relay control. The design provides a 12-V supply to control the relay. The output of the DC-DC converter can be adjusted to 15 V or 18 V with programmable resistors.

3.5 Tiva C Series LaunchPad Interface

This reference design uses the Tiva C Series 32-bit CPU LaunchPad for measurement and transfer of the data to a PC-based GUI by USB interface. The PGA’s output is connected to the 12-bit ADC of the TM4C123G device. The gain and channel selection for the PGA is done using the SPI interface.

4 Circuit Design and Component Selection

4.1 Current Measurement Range

Table 1 provides approximate information on current drawn by three-phase 400 V and 50 Hz squirrel-cage induction motors rated for different powers. The ratio of starting current to full load current varies between 6.5 and 9.6. No load current is considered 30% of full load current.

Even though the ratio of full load currents in the followng table is approximately 10:1 (10.8 A to 98 A), the requirement on current measurement circuit is from 3 A (No load current) to 735 A (starting current or locked rotor current).

This wide measurement range can be designed using the programmable gain amplifier.

Table 1. Motor Currents for Different Power Ratings

MOTOR POWER (KW)	NOMINAL FULL LOAD CURRENT (I_n/A)	RATIO OF STARTING CURRENT TO NOMINAL CURRENT (I_s/I_n)	STARTING CURRENT (I_s/A)	NO LOAD CURRENT ($I_{no\ load}$/A)
5.5	10.8	6.5	70.2	3.24
7.5	14.3	6.5	92.95	4.29
11	21	7.9	165.9	6.3
15	28.5	9.6	273.6	8.55
18.5	35	7	245	10.5
22	40	8.5	340	12
30	55	8.2	451	16.5
37	68	6.6	448.8	20.4
45	83	6.7	556.1	24.9
55	98	7.5	735	29.4

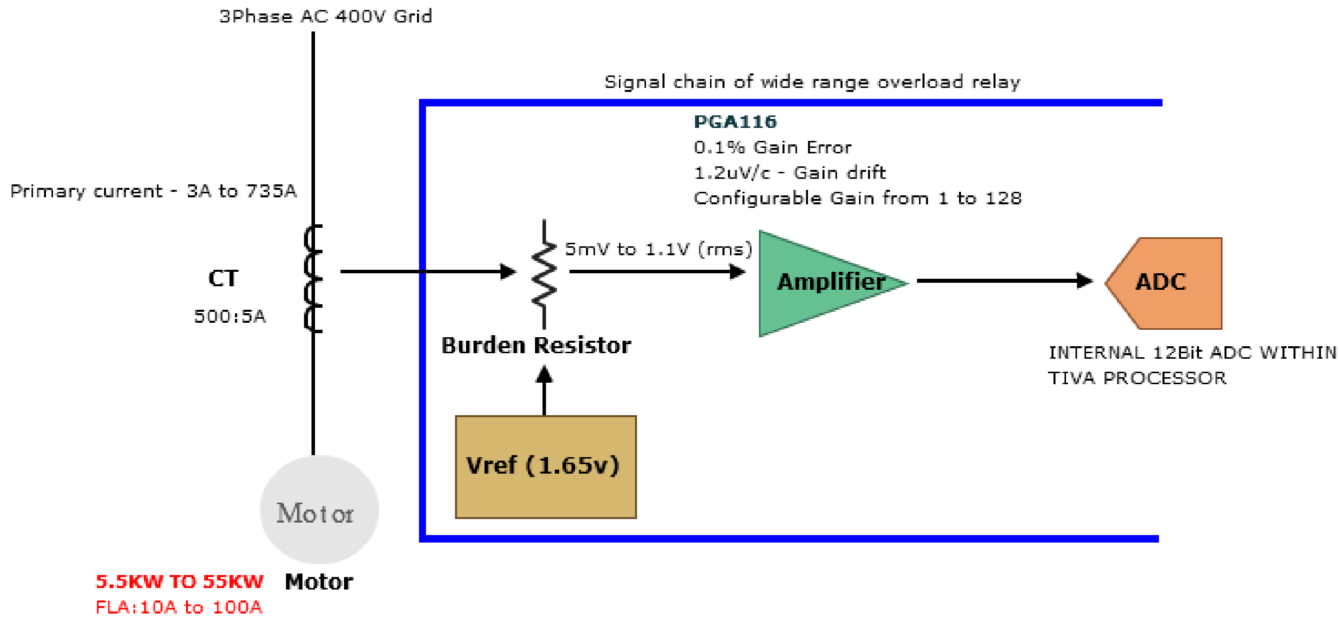


Figure 3. PGA116 Configuration in TIDA-00191

4.2 Current Transformer

Considering a wide measurement range, the CT with a ratio of 500:5 (5-A secondary current at 500-A primary current) can be used along with rating factor (RF) of at least 1.5. The RF is the number of times the name plate current can pass through the CT without overheating. With an RF of 1.5, the allowed primary current increases from 500 A to 750 A, which covers the requirement of measuring starting current from 70 A to 735 A.

Specification of the CT is typically of the form 500:5A RF 1.5 ACC CLASS 0.3S B 0.2, where 500:5 A specifies the current step down ratio, the Rating factor (RF) is 1.5, and the accuracy is 0.3% for the range from 5% to 150% of the primary current with a burden of less than 0.2 Ω.

4.3 Burden Resistor

The voltage developed across the burden resistor has to be level shifted by 3.3 V/2 in order to accommodate the negative swing of the sine wave output voltage across the burden resistor. With a 3.3-V measurement system, the peak-peak voltage across the burden resistor has to be limited to 3.2 V.

$$R_{burden} \leq \frac{\frac{3.2\text{ V}}{2}}{7.5\text{A} \times 1.414} \leq 0.15\ \Omega \tag{1}$$

When utilizing rectified output from the CT, the burden resistor can be increased to 0.3 Ω. For more information on different types of input, refer to Section 4.7.

4.4 Voltage Scaling

The voltage developed across the burden resistor varies between 6.87 mV and 1.558 V.

$$V_{min(pk)} = \frac{3.24}{500} \times 5 \times 0.15 \times 1.414 = \pm 6.87\text{ mV} \tag{2}$$

$$V_{max(pk)} = \frac{735}{500} \times 5 \times 0.15 \times 1.414 = \pm 1.558\text{ V} \tag{3}$$

Depending upon the selected motor power, gain of the PGA is configured to scale the voltage across the burden resistor to match the ADC input range (0 – 3.2 V).

4.5 Device Selection

Table 2 shows the specifications of application requirements along with multiple device parameters. PGA116 meets the requirement by having lowest offset voltage and gain error with sufficient input channels.

Table 2. Comparison Table of Different Op-Amps/PGAs with Critical Characteristics

CHARACTERISTICS	APPLICATION NEED	PGA116, PGA117	LMV824-N
Iq Total (Max)(µA)	Low	1.6 mA	1.2 mA
Number of Channels	≥ 8	10 (Muxed)	4
Rail-Rail	Rail-to-rail	In/Out	Out
Operating Temperature Range (°C) (Package dependent exceptions exist)	–40 to 125°C	–40 to 125°C	–40 to 125°C
V_{OS} (Offset Voltage at 25°C)(Max) (mV)	Min offset	0.1	3.5
Offset Drift (Typ) (µV/C)	Min offset drift	1.2	1
V_n at 1 kHz (Typ) (nV/rtHz)	Min noise	12	28
CMRR (Min) (dB)/PSRR	Max	100	90/85
Total Supply Voltage(Max) (+5 V = 5, ±5 V = 10)	3.3 V	5.5	5.5
Slew Rate (Typ) (V/us)	1	12	1.4
GBW (Typ)(MHz)	1	1.8	5
Pin/Package	14/20 pin SOIC	20 pin SOIC	14 SOIC, 14 TSSOP
Settling Time (0.1%) (Typ) (ns)	5-10 µs	10 µs for 0.01%	NA
ESD-Human model- kV	High	3	2
Gain Error	0.25%	0.10%	External resistors dependent
Gain Drift	< 100 PPM	2 PPM/ °C	External resistors dependent
V_O (Swing)	Rail-to-Rail	V_{CC} – 60 mV	V_{CC} – 100 mV

The PGA116 offers 10 analog inputs and a 4-terminal SPI Interface with daisy-chain capability in a TSSOP-20 package. The PGA versions provide internal calibration channels for system-level calibration. PGA116 can be programmed for Binary Gains: 1, 2, 4, 8, 16, 32, 64, and 128.

By using 10 analog input channels, the listed parameters can be measured:

1. Three channels for measuring three-phase motor currents
2. Three channels for measuring three-phase grid voltage
3. One channel to measure neutral current
4. One channel to measure ground fault current
5. One channel for temperature compensation (V_{ref} measurement)
6. One channel for motor temperature measurement

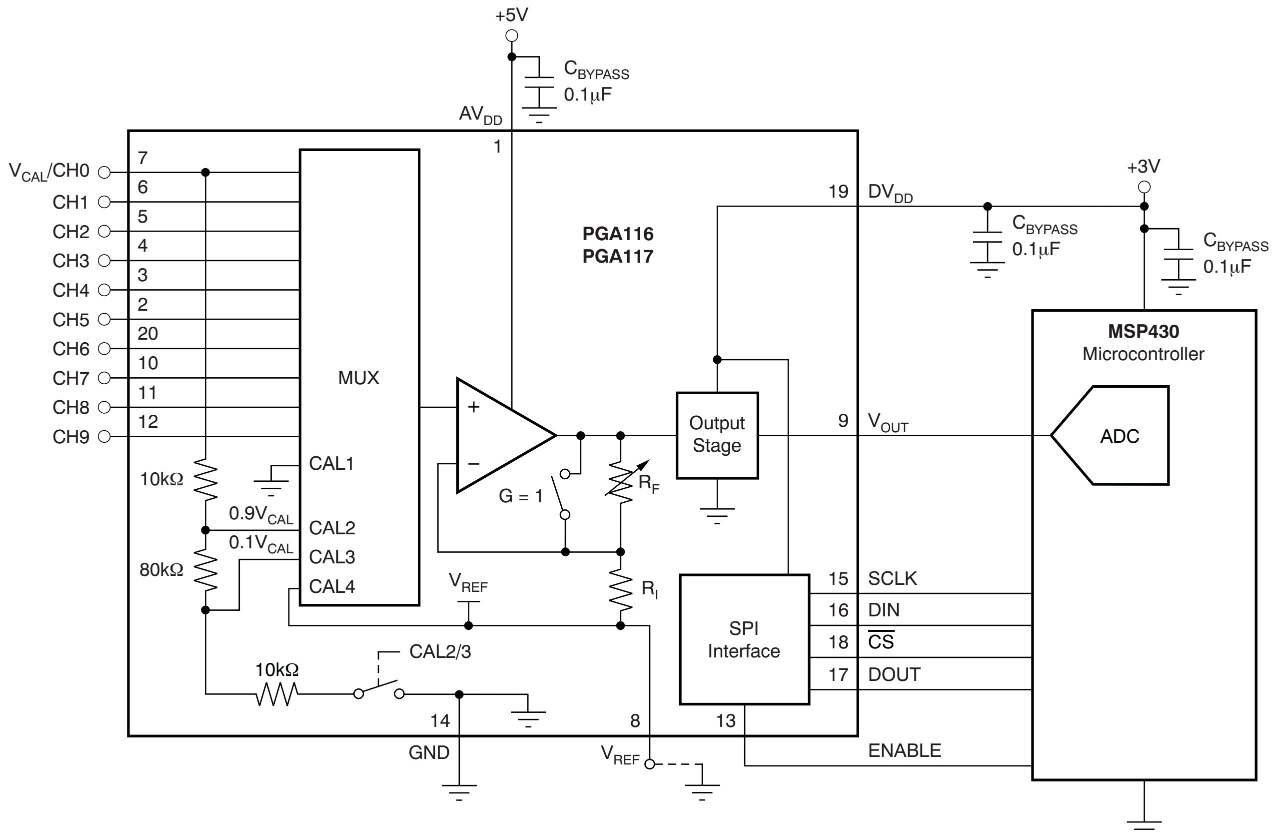


Figure 4. PGA116 Interface to MCU – Block Diagram

Some of the critical features of PGA116 are:

- Low noise: 12 nV/√Hz
- Low offset: 25 µV (typ), 100 µV (max)
- Offset drift: 1.2 µV/°C
- Amplifier gain drift: 6 PPM
- Low input offset current: ±5 nA max (25°C)
- SPI™ Interface (10 MHz) with Daisy-Chain capability.
- Gain switching time: 200 ns
- Extended temperature range: –40°C to 125°C

PGA116 offers less than a 0.01% gain error between the channels, which makes PGA116 ideal for detecting current imbalances (asymmetry) between the motor phase currents.

4.6 Gain Selection

Each output of each CT is connected to one PGA channel. The voltage developed across the burden resistor varies from a few millivolts to approximately 1.5-V peak. The gains of the PGA can be configured though the SPI interface based on the set full load current. Programming of the PGA is done through the SPI interface. Each channel has to be read with two different gains for a particular set FLA. The channel reading scales the voltage developed across the burden resistor appropriately based on measured current.

Alternatively, the output of each CT can be connected to 2 channels of PGA with two different gains. Using two different gains provides the flexibility of using the higher gain to measure the no load to full load current on one channel and a lower gain to measure currents up to several multiples of full load current.

Table 3. PGA Gain Setting Based on Motor Power

MOTOR POWER	PGA GAIN TO MEASURE UNTIL FLA	PGA GAIN TO MEASURE FROM FLA TO LOCKED ROTOR CURRENT
5.5 kW, 7.5 kW	32	8
11 kW	32	4
15 kW, 18.5 kW, 22 kW	16	2
30 kW, 37 kW, 45 kW	8	1
55 kW	4	1

The current design configures Channel 0 - Channel 3 (designated CH0, CH1, CH2, and CH3) to measure three-phase input current along with Neutral as optional.

4.7 Interface to PGA

The PGA can accept AC input or rectified half-wave input. The reference design uses LM4041-N/LM4041-N-Q1 Precision Micropower Shunt Voltage Reference for providing the level shifting when the PGA is configured for AC input.

Key LM4041-N/LM4041-N-Q1 1.2 Specifications:

- 0.1% Output voltage tolerance
- 20-µV RMS Output noise
- Low temperature coefficient of < 100 PPM/°C

Using LM4041-N/LM4041-N-Q1 Precision Micropower Shunt Voltage Reference with the PGA guarantees the trip accuracy over a wide temperature range.

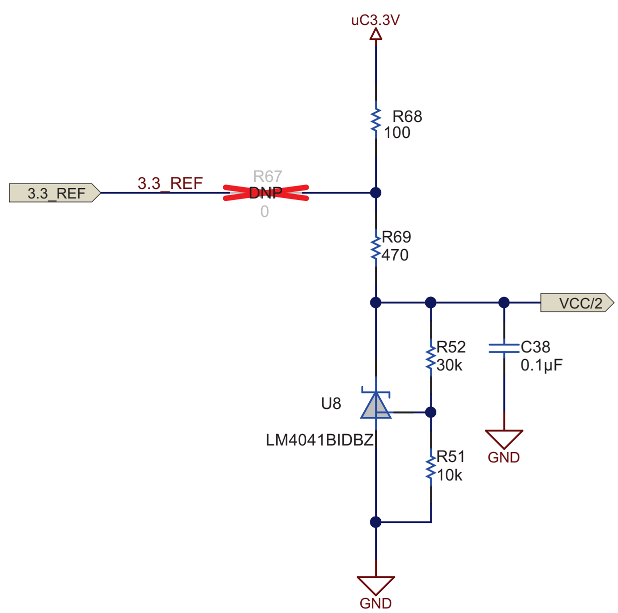


Figure 5. Voltage Reference for Level Shifting

The input (AC or rectified) is configured with the jumper settings in Figure 6 and is explained in Table 4. Figure 7 illustrates the input waveform of PGA based on the configuration.

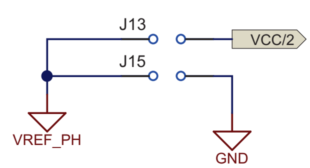


Figure 6. PGA116 Input Jumper Configuration

Table 4. Input Jumper Configuration for PGA116

Test Condition 1	Jumper J13 is mounted	PGA accepts AC input (J14 must be removed)
Test Condition 2	Jumper J15 is mounted	PGA accepts rectified input (J14 is removed)[1][2]

(1) In case the neutral CT output is not rectified output J14 must be mounted to level shift the neutral CT output in condition 2.
(2) Do not mount both the jumpers together.

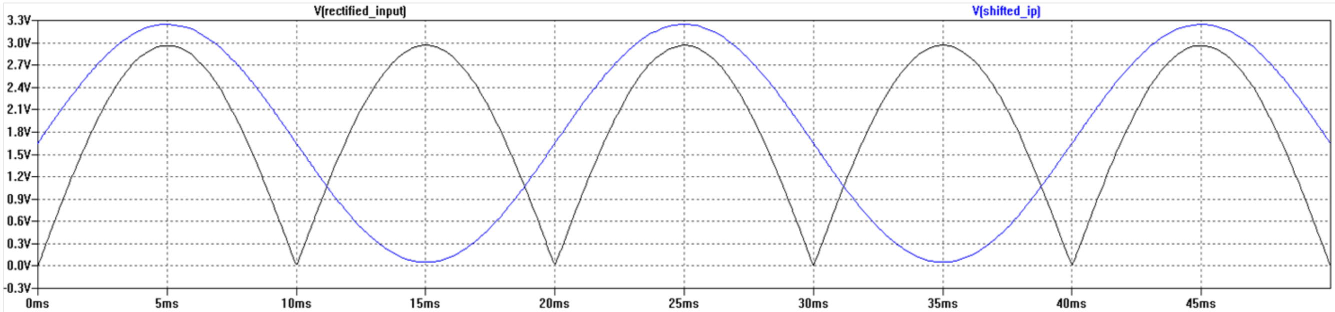


Figure 7. Input Signal to PGA

A temperature sensor has been provided for thermal overload trip and gain compensation functions as required. The temperature sensor is rated for a 0°C to 90°C Range.

4.8 Current Inputs

The board is designed to connect up to four current inputs. The current input can be AC or half-wave rectified input. The design provides the abilitiy to mount two 300-mΩ burdens. Screw-type terminals are provided to connect the current input. Based on the secondary current and transformer performance, the burden resistor can be changed by the user.

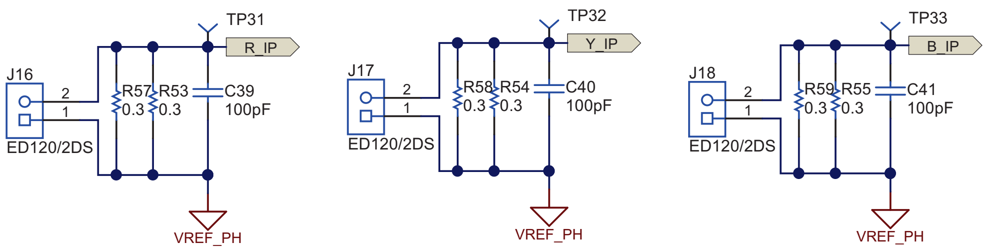


Figure 8. CT Burden

The design provides an option to switch the burden resistor using MOSFETs. The designer can use the option to switch the burden resistor when the burden resistor value has to be reduced while measuring high currents. The option to switch the burden resistor along with gain switching can be used to enhance the current measuring range. Increasing the current measuring range is for future enhancements and is currently not used in this design. The Rogowski coil cannot be connected directly. The integrator output has to be applied at the current inputs. When the integrator output is applied, the burden resistors should not be populated.

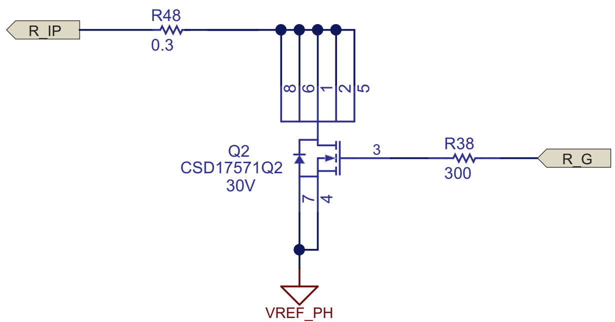


Figure 9. Option for Burden Switching

> **CAUTION**
>
> Do not leave the current terminal open and apply current during testing. Ensure the current inputs are connected and the terminal screws are tightened before applying current for testing.

4.9 Power Supply

This power supply section is designed to power the overload relay from CT inputs, emulating MCCB functionality.

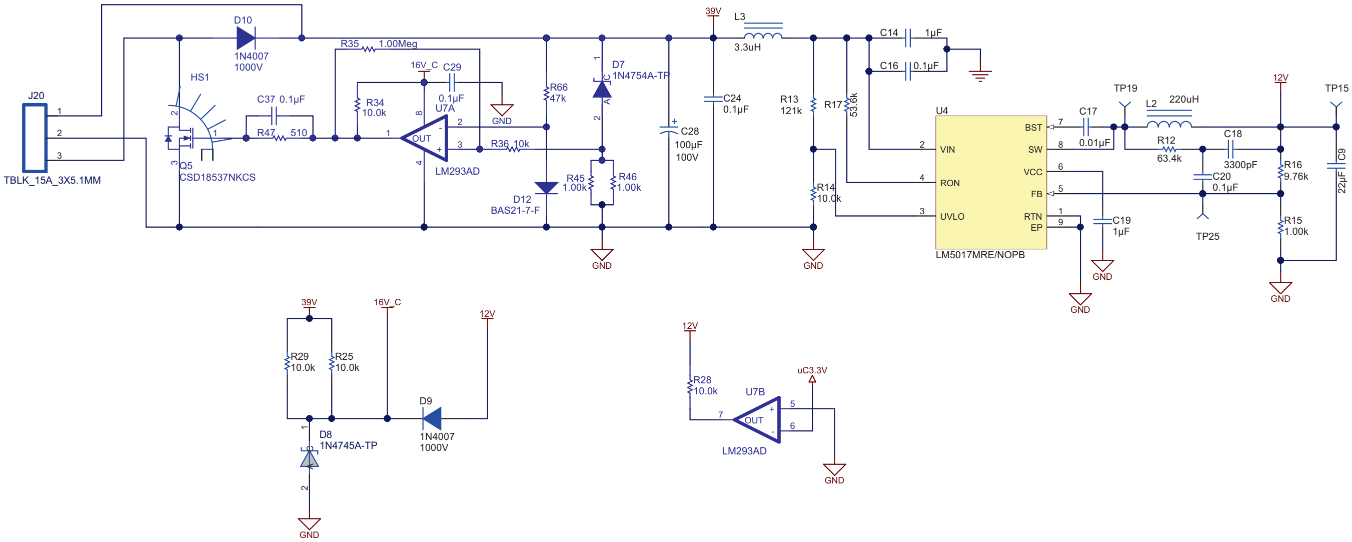


Figure 10. Self-Power Supply Using LM5017

The Self-Power section has provision for two inputs:

- Half wave rectified current inputs
- Auxiliary DC voltage inputs

The Self-Power supply generates output voltage from the input currents. The input to the Self-Power generation circuit is half-wave recited output from current transformers. The rectifier diodes have to be connected externally. Optionally, the overload relay can be powered by an auxiliary 24-V input. The Self-Power output is regulated to 39 V by the Zener diode reference. If the output voltage exceeds 39 V, the comparator switches the MOSFET to ON and the MOSFET shunts the input current. When the output voltage reduces, the comparator switches the MOSFET to OFF and the input current charges the output capacitor. 39-V Self-Power output is converted to 12 V and 3.3 V for relay operation and electronic circuit functioning using DC-DC converters and LDO .**The advantage of the Self-Power circuit is reduction in the CT loading.** The critical component in the Self-Power circuit is the shunt regulation MOSFET. A wide range of MOSFETs are available and are listed in Table 5.

Table 5. TI MOSFETs with Current Shunting

CSD18537NKCS	60-V, N-Channel NexFET™ Power MOSFET
CSD18534KCS	60-V, N-Channel NexFET Power MOSFET
CSD19506KCS	80-V, N-Channel NexFET Power MOSFET
CSD19503KCS	80-V, 7.6 mΩ, N-Channel TO-220 NexFET Power MOSFET
CSD19535KCS	100-V, N-Channel NexFET Power MOSFET
CSD19531KCS	100-V, 6.4 mΩ, TO-220 NexFET Power MOSFET

See Figure 11, which indicates the power loss in a typical Self-Power supply.

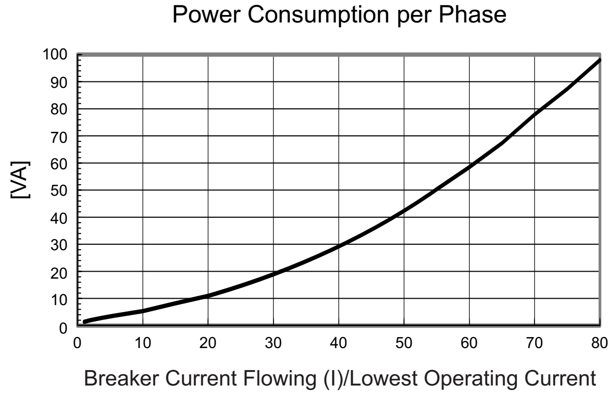


Figure 11. Typical Power Consumption for Current or Lowest Operating Current

> **CAUTION**
>
> Do not leave the current terminal open and apply current for testing.
>
> Ensure the current inputs are connected and the terminal screws are tightened before applying current for testing.

By using the LM5017 device, the clamping voltage can be increased as the device input is rated up to 100 V. The shunt clamping with the LM5017 device configured in nonisolated output configuration is detailed in TIDU224 High Precision Analog Front End Amplifier and Peripherals for MCCB - Electronic Trip Unit.

4.10 Isolated RS-485 Communication Interface

This reference design provides an EMC compliant isolated 1-Mbps, 3.3 to 5-V RS-485 interface using the ISO1176 transceiver and the TPS55010 device. This board provides signal and power isolation with reduced board space and power consumption. The TPS55010 device has higher efficiency and better regulation accuracy, since the Fly-Buck™ topology uses primary side feedback that provides excellent regulation over line and load. The TPS55010 device provides 3.3 to 5-V and isolation levels using off-the-shelf Fly-Buck transformers. The design uses a transformer that has 475 µH primary inductance and dielectric strength of 2500-V AC. The ISO1176 transceiver is an ideal device for long transmission lines, since the ground loop is broken to provide for operation with a much larger common mode voltage range. The symmetrical isolation barrier provides 2500 VRMS of isolation between the line transceiver and the logic level interface. The RS-485 bus is available on screw-type terminals or connectors.

The design provides an external fail safe biasing option on an RS-485 bus that uses external resistor biasing to ensure failsafe operation during an idle bus. If none of the drivers connected to the bus are active, the differential voltage (VAB) approaches zero ±250 mV, allowing the receivers to assume random output states. To force the receiver outputs into a defined state, the design introduces failsafe biasing resistors with terminating resistors of 120 Ω. The RS-485 bus is also protected against EFT, ESD, and surges with the help of transient voltage suppressor diodes (SMCJ15CA, 1500-W series).

4.11 Relay Control

TI has a wide range of MOSFETs that can be used for driving relay, FSD, Alarms, and LEDs. A wide range of MOSFETs with a tiny SON2x2 package is available. The reference design uses CSD17571Q2.

Table 6. Relay Control MOSFETS

CSD17571Q2	30-V, N-Channel NexFET Power MOSFETs
CSD13202Q2	N-Channel Power MOSFET, CSD13202Q2, 12-V Vds, 9.3 mΩ, $R_{ds(on)}$ 4.5 V (max)
CSD15571Q2	20-V, N-Channel NexFET Power MOSFET
CSD17313Q2Q1	Automotive 30-V, N-Channel NexFET Power MOSFET
CSD17313Q2	30-V, N-Channel NexFET Power MOSFET
CSD16301Q2	N-Channel NexFET™ Power MOSFET

4.12 Tiva C Series LaunchPad Interface

The Tiva™ C Series LaunchPad (EK-TM4C123GXL) is a low-cost evaluation platform for ARM® Cortex™-M4F-based microcontrollers. The Tiva C Series LaunchPad design highlights the TM4C123GH6PMI microcontroller USB 2.0 device interface, hibernation module, and motion control pulse-width modulator (MC PWM) module. The Tiva C Series LaunchPad also features programmable user buttons and an RGB LED for custom applications. The stackable headers of the Tiva C Series LaunchPad BoosterPack XL interface demonstrate how easy it is to expand the functionality of the Tiva C Series LaunchPad when interfacing to other peripherals on many existing Booster Pack add-on boards as well as future products. Figure 12 shows a photo of the Tiva C Series LaunchPad.

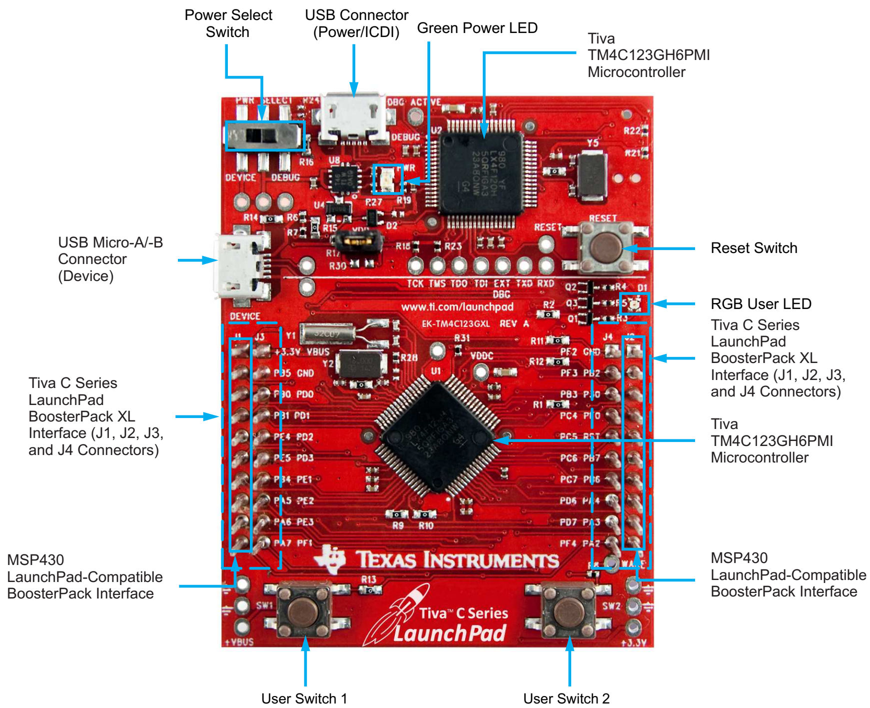


Figure 12. Tiva C Series LaunchPad

For further details, see EK-TM4C123GXL.

> **CAUTION**
>
> Care has to be taken while aligning the Tiva C Series LaunchPad with the reference design board.

Table 7. Mapping Tiva C Series LaunchPad and Reference Design Connectors

Tiva C SERIES LaunchPad CONNECTOR	REFERENCE DESIGN CONNECTOR
J1, J3	J1
J4, J2	J11

5 Test Results

5.1 CT Supply Rail

Table 8 lists the voltage measured on different rails present in the system.

Table 8. Self-Power Supply Rail Measured Results

RAILS	MEASURED
39 V	39.8 V
16 V	16.12 V
12 V	12.2 V
3.3 V	3.301 V
V_{ref} (VCC/2)	1.6554 V

5.2 Accuracy Testing

This section contains test results including the test setup, DC offset, 12-bit ADC measurement results, offset variation over temperature, gain drift over temperature, gain error before saturation, and a summary of the test results.

5.2.1 Test Setup

Figure 13 and Figure 14 illustrate TIDA-00191 test setup.

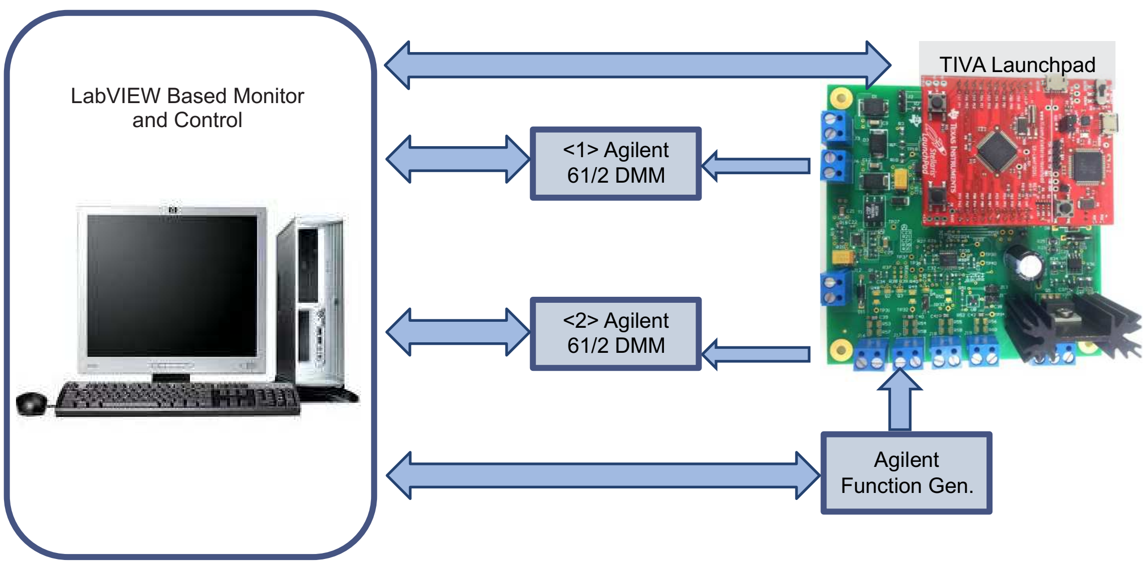


Figure 13. TIDA-00191 Test Setup Diagram

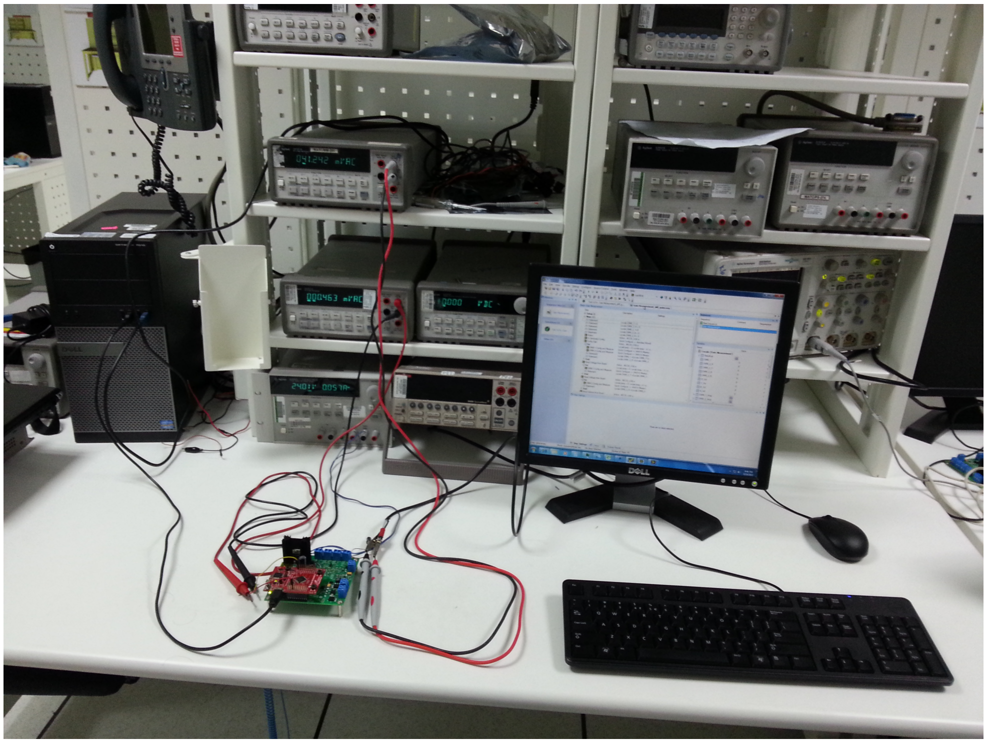


Figure 14. TIDA-00191 Test Setup

Setup Description:

The measurement and characterization setup is controlled by LabVIEW™. The test program executes the following steps:

1. Variable AC (60 Hz) input is provided to the amplifier through J16 to J19.
2. The gain and channel selection for each measurement is configured by an SPI Interface using Tiva LaunchPad.
3. The input voltage to amplifier and amplifier output voltages are measured using a multimeter.
4. The measurement is repeated for multiple steps.

The tests were performed for different PGA gains.

High Gain is used to measure low level signals.

Low Gain is used for higher current inputs so that the PGA output does not saturate.

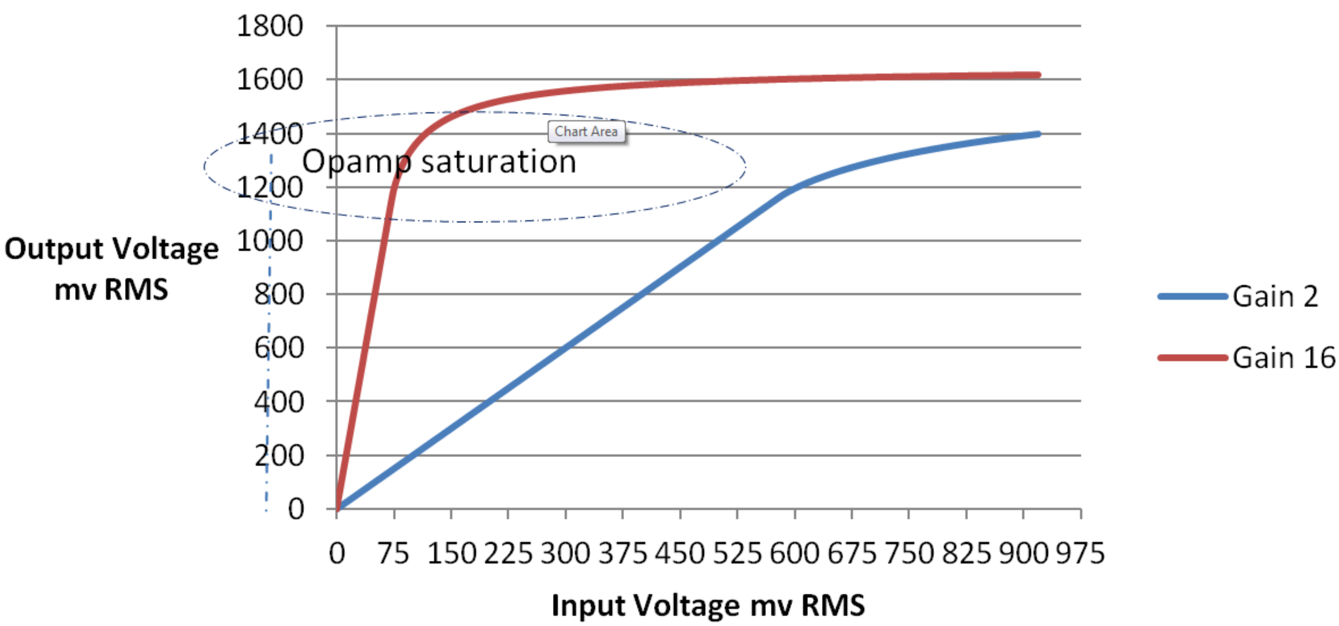


Figure 15. PGA116 Saturation for TIDA-00191

The TIVA LaunchPad sets the gain and channel on the PGA by using configurations in Table 9.

Table 9. PGA116 Configuration Set by TIVA LaunchPad

AMPLIFIER	GAIN	GAIN AND CHANNEL REGISTER SETTING	INPUT CHANNEL	DELAY BEFORE MEASURING	SPI SPEED	TOTAL CONVERSION TIME PER SAMPLE FOR EACH CHANNEL [(1)]
PGA116	2	0x2A10	0	>10 µs	1 Mbps	35 µs
		0x2A11	1			
		0x2A12	2			
		0x2A13	3			
	8	0x2A30	0			
		0x2A31	1			
		0x2A32	2			
		0x2A33	3			
	128	0x2A70	0			
		0x2A71	1			
		0x2A72	2			
		0x2A73	3			

(1) Conversion Time per Sample = Channel and Gain Setting Time – SPI (16.2 µs) + PGA Settling Time (10 µs) + ADC Conversion Time – 125 ksps (8 µs) + Software Overhead (0.8 µs)

5.2.2 DC Offset

Table 10 output DC offset results measured with Gain 1.

Table 10. PGA116 DC Offset Test Results

PGA TYPE	CHANNEL NUMBERS	OFFSET µV
PGA116	Ch0	< 20 µV
	Ch1	< 20 µV
	Ch2	< 20 µV

5.2.3 12- Bit ADC Measurement Results

Figure 16 through Figure 17 indicate the error in percentage with respect to theoretical value when measured by the 12-bit ADC of the Tiva MCU using PGA116 for different gains.

All the voltages in Figure 16 through Figure 20 are Root Mean Square Values (RMS).

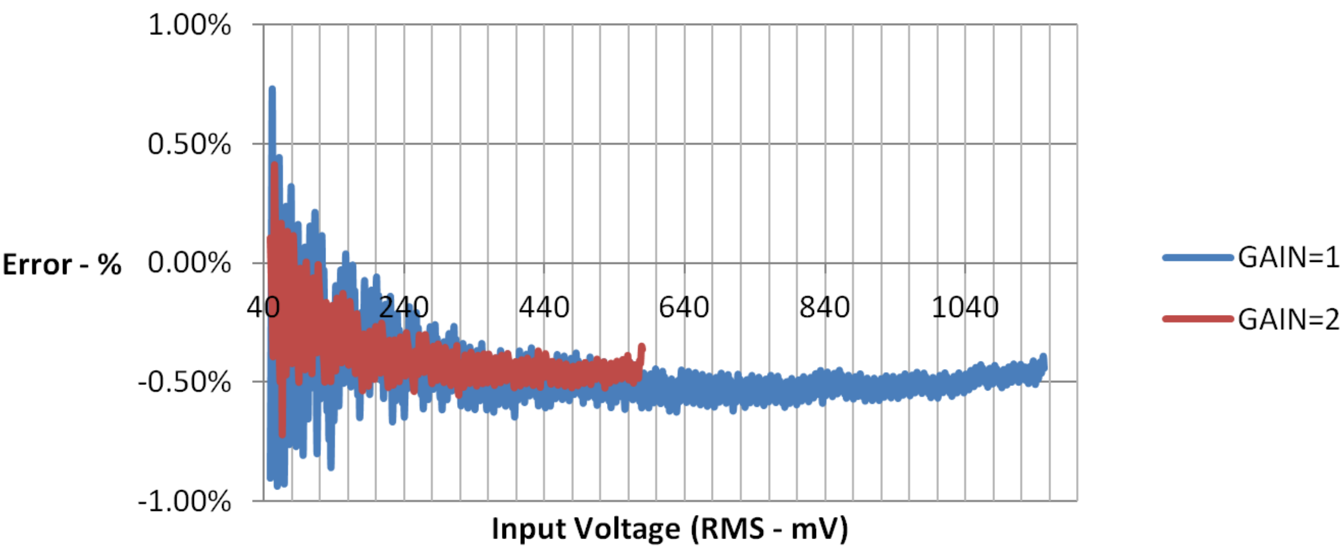


Figure 16. Measured Error of PGA116 and TIVA MCU ADC

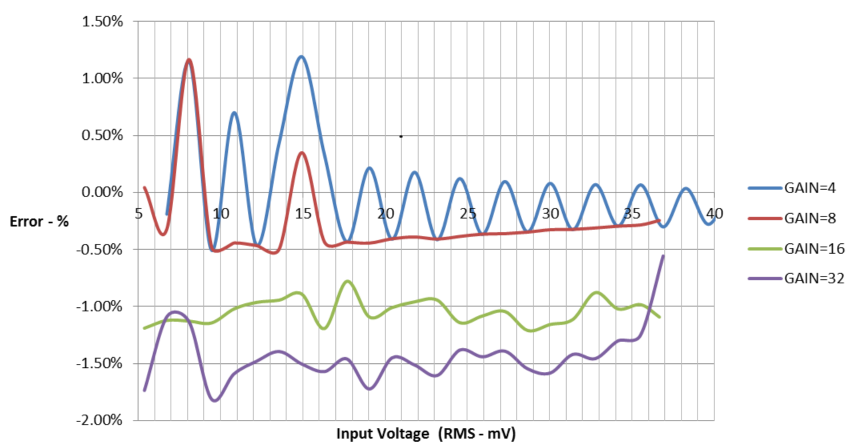


Figure 17. Measured Error of PGA116 and TIVA MCU ADC (Gain Variations)

5.2.4 Offset Variation over Temperature

The output offset voltage of the PGA116 varies with temperature. The offset voltage was measured by keeping the PCB in an chamber set to different temperatures. Table 11 shows the results.

Table 11. Offset Variation over Temperature

AMPLIFIER	GAIN	INPUT CHANNEL	OFFSET DRIFT AT –10ºC (mV)	EXPECTED DRIFT IN mV	OFFSET DRIFT AT +60 ºC (mV)	EXPECTED DRIFT IN mV
PGA116	128	1	–4.16	9	3.834	9
		2	–5.83		5.32	
		3	–5.12		4.05	
	2		1.52			
			1.55			

5.2.5 Gain Drift over Temperature

The gain variation of the PGA116 is very low with change in temperature. The gain drift was measured by keeping the PCB in a chamber set to different temperatures. Table 12 shows the results.

Table 12. Gain Variation Over Temperature

AMPLIFIER	INPUT CHANNEL	GAIN	MEASUREMENT COUNT AT EACH TEMPERATURE	ALLOWED DRIFT IN PPM	AVERAGE GAIN DRIFT IN PPM/ºC INCLUDING REFERENCE OFFSET AND REFERENCE DRIFT (25 TO 60°C)	AVERAGE GAIN DRIFT IN PPM/ºC INCLUDING REFERENCE DRIFT (25 TO –10 °C)
PGA116	1	2	5	> 102	30	–27.9
		8	5	> 102	–45	41
		16	5	> 102	–38	44
PGA116	2	2	5	> 102	30	–45
		8	5	> 102	–42	41
		16	5	> 102	–55	58
PGA116	3	2	5	> 102	28	–37
		8	5	> 102	–43	40
		16	5	> 102	–60	58

5.2.6 Gain Error

The PGA116 has been tested at 25°C by varying the input. Figure 18, Figure 19, and Figure 20 show the gain error plots with respect to input.

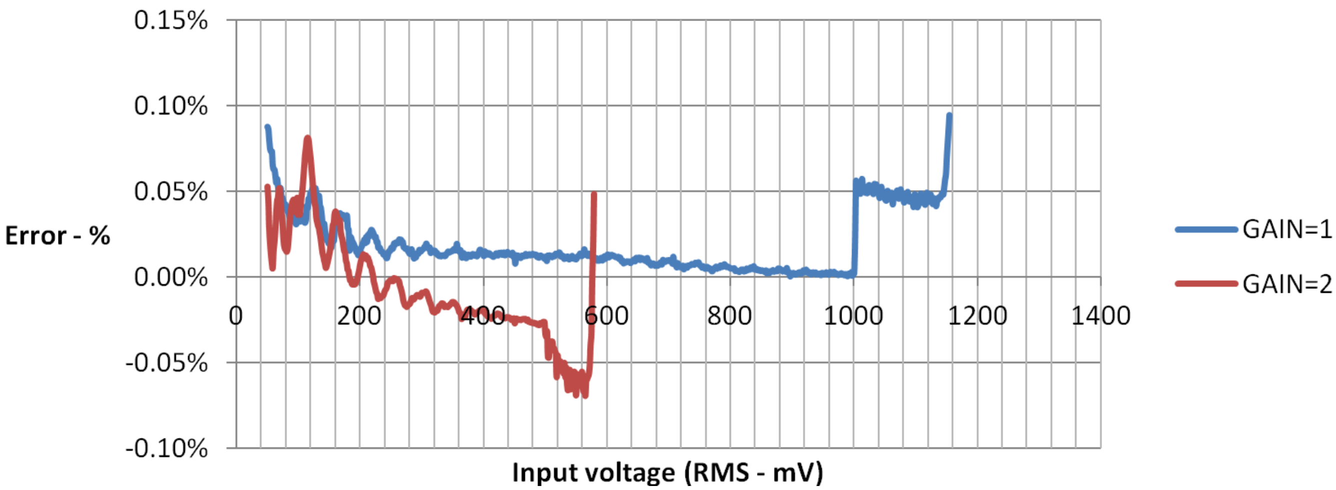


Figure 18. PGA116 Gain Error over Input Range (25ºC)

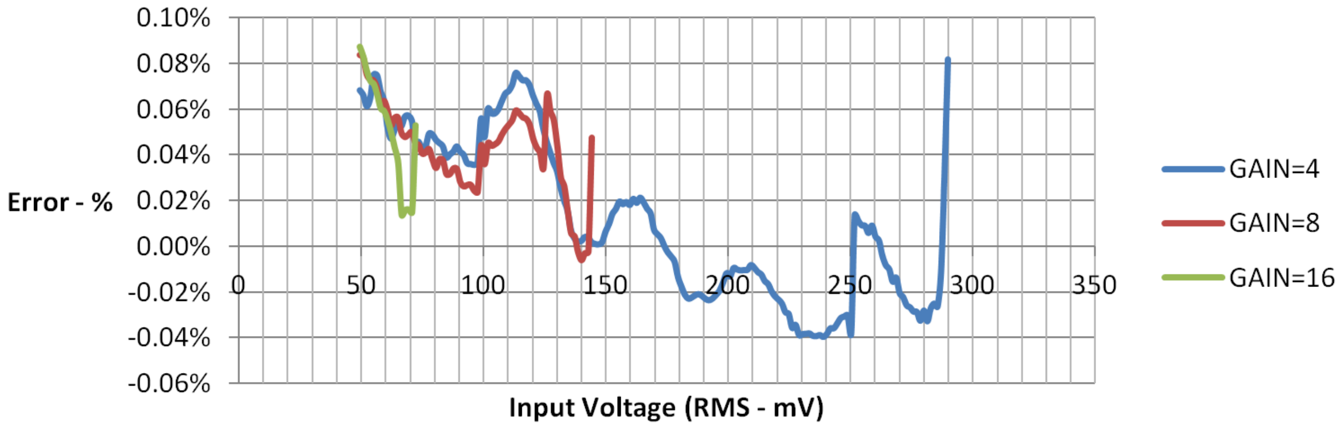


Figure 19. PGA116 Gain Error over Input Range (25ºC)

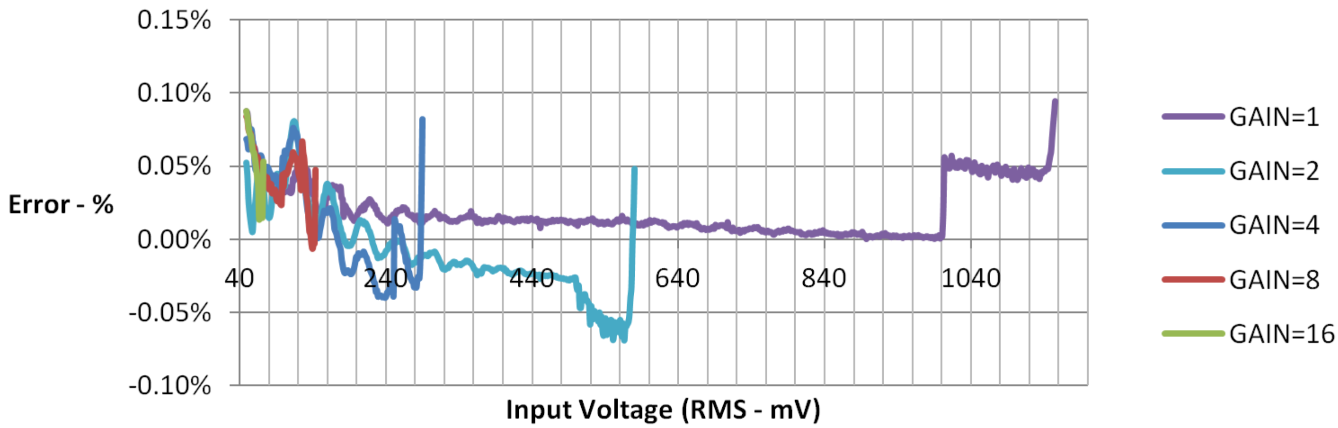


Figure 20. PGA116 Gain Error Over Input Range (25ºC)

5.2.7 Test Results Summary

The total measurement error including PGA and ADC is well within 2% over the entire measurement range of 3 A to 735 A. The accuracy can be further improved by measuring voltage reference and temperature input to compensate the drift.

6 Design Files

6.1 Schematics

The schematics are presented in the following order:

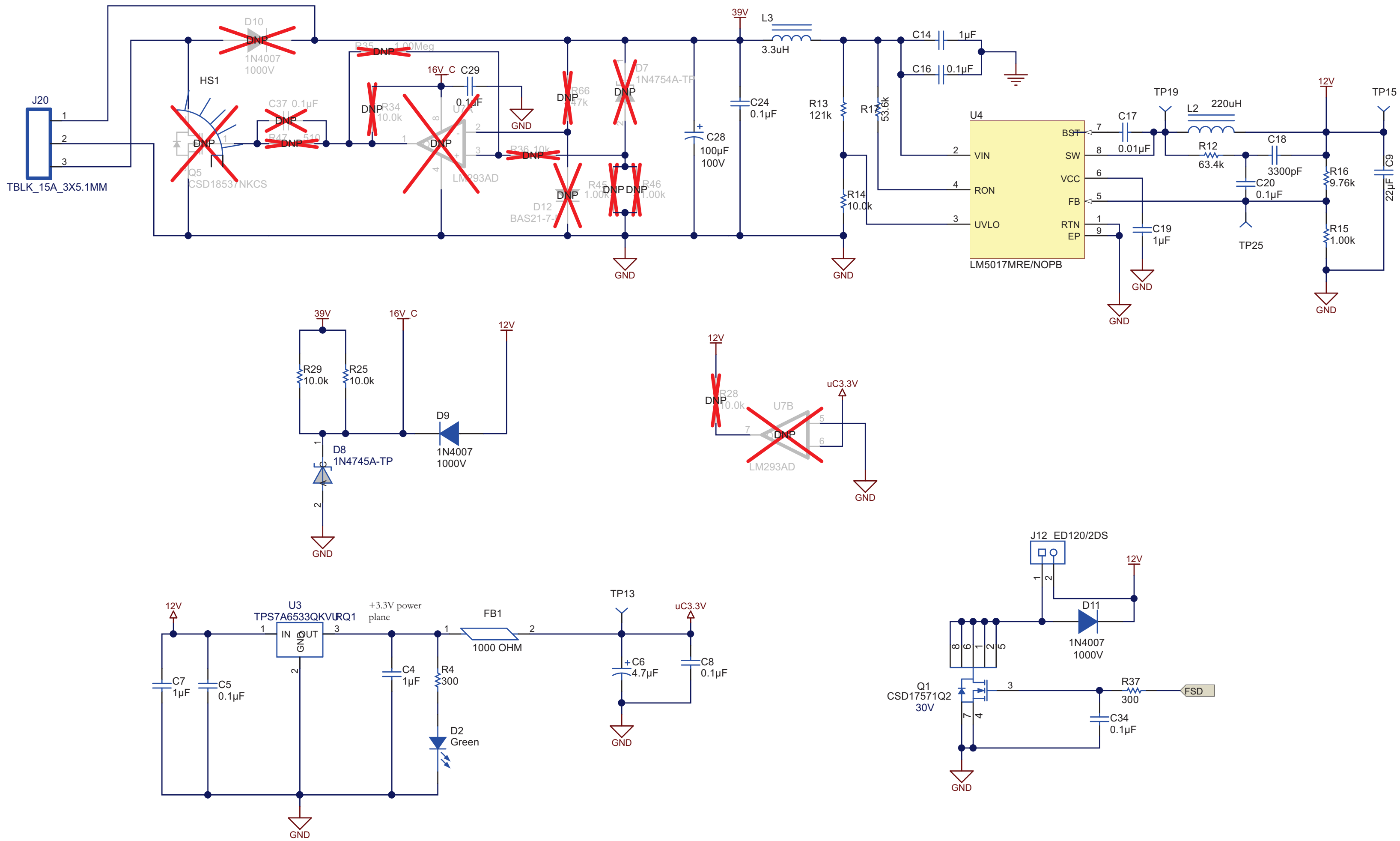


Figure 21. TIDA-00191 Schematic Page 3 (LM5017)

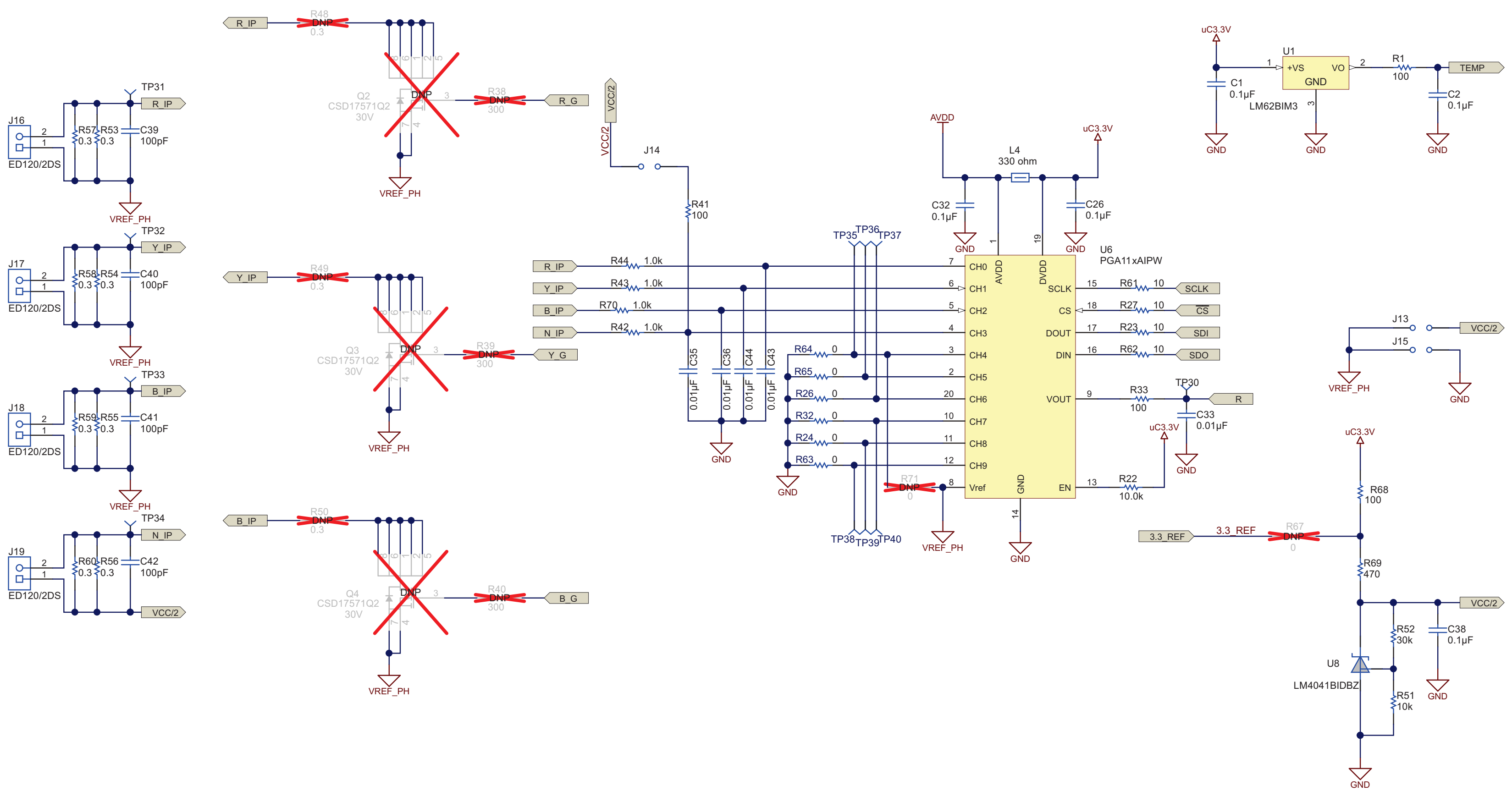


Figure 22. TIDA-00191 Schematic Page 4 (PGA116)

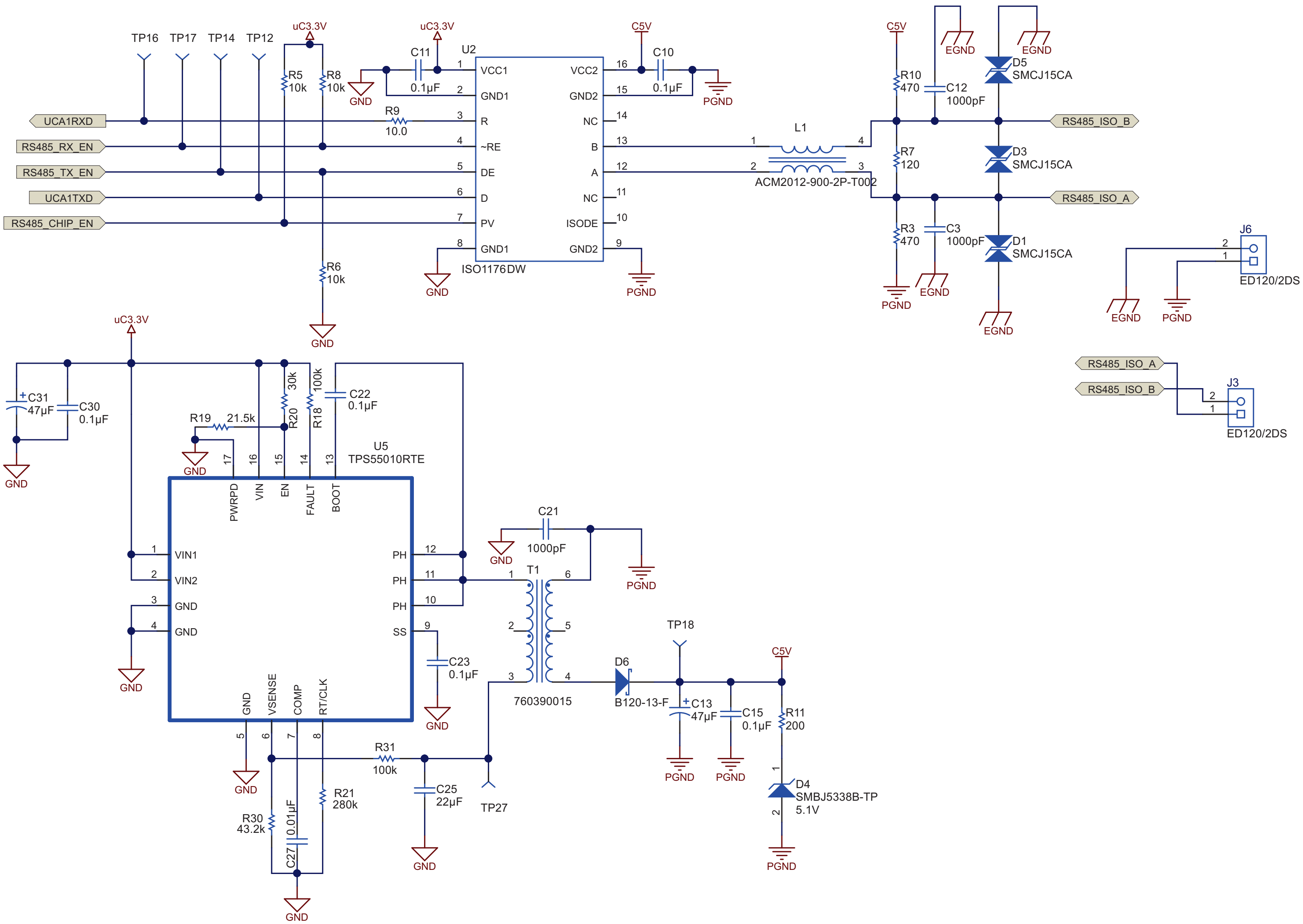


Figure 23. TIDA-00191 Schematic Page 5 (TPS5501 + ISO1176)

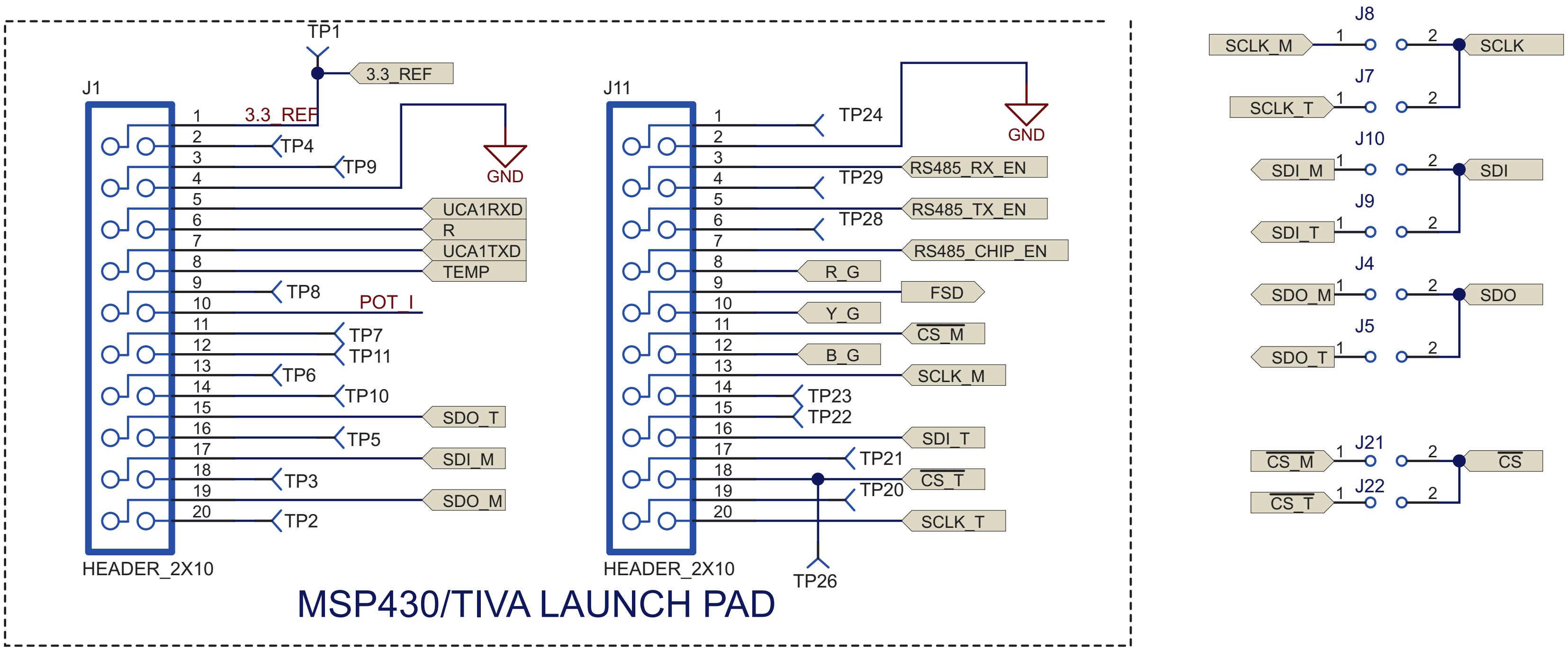


Figure 24. TIDA-00191 Schematic Page 6 (MSP430 LaunchPad)

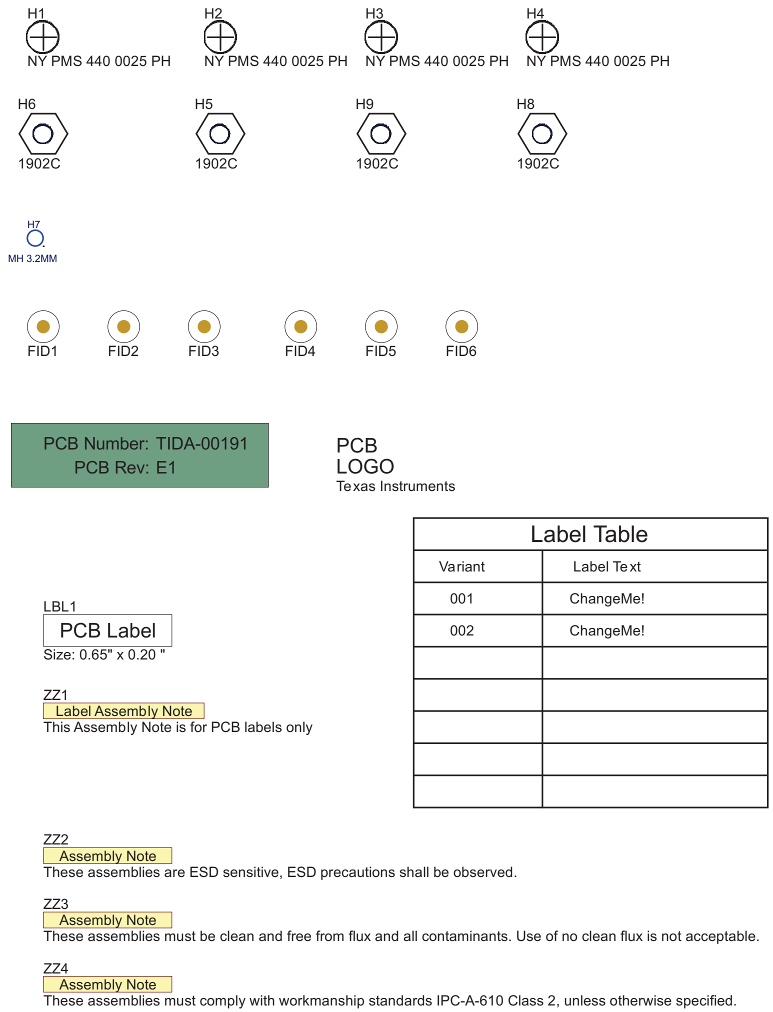


Figure 25. TIDA-00191 Schematic Page 7 (Assembly Notes)

6.2 Bill of Materials

Table 13 shows the BOM for the TIDA-00191.

Table 13. Bill of Materials

DESCRIPTION	DESIGNATOR	FITTED	FOOTPRINT	MANUFACTURER	PARTNUMBER	QTY
Printed Circuit Board	!PCB1	Fitted		Any	TIDA-00191	1
CAP, CERM, 0.1uF, 25V, +/-5%, X7R, 0603	C1, C2, C10, C11, C15, C16, C20, C22, C23, C26, C30, C32, C34, C38	Fitted	0603	AVX	06033C104JAT2A	14
CAP, CERM, 1000pF, 1000V, +/-10%, X7R, 1206	C3, C12, C21	Fitted	1206	Yageo America	CC1206KKX7RCBB102	3
CAP, CERM, 1uF, 16V, +/-10%, X7R, 0603	C4, C7	Fitted	0603	TDK	C1608X7R1C105K	2
CAP, CERM, 0.1uF, 50V, +/-10%, X7R, 0603	C5, C8, C29	Fitted	0603	Kemet	C0603C104K5RACTU	3
CAP, TA, 4.7uF, 35V, +/-10%, 1.9 ohm, SMD	C6	Fitted	6032-28	Vishay-Sprague	293D475X9035C2TE3	1
CAP, CERM, 22uF, 16V, +/-10%, X5R, 1206	C9	Fitted	1206	MuRata	GRM31CR61C226KE15L	1
CAP, TA, 47uF, 35V, +/-10%, 0.3 ohm, SMD	C13, C31	Fitted	7343-43	Kemet	T495X476K035ATE300	2
CAP, CERM, 1uF, 100V, +/-10%, X7R, 1206	C14	Fitted	1206	MuRata	GRM31CR72A105KA01L	1
CAP, CERM, 0.01uF, 25V, +/-5%, C0G/NP0, 0603	C17, C27, C33, C35, C36, C43, C44	Fitted	0603	TDK	C1608C0G1E103J	7
CAP, CERM, 3300pF, 50V, +/-10%, X7R, 0603	C18	Fitted	0603	Kemet	C0603C332K5RACTU	1
CAP, CERM, 1uF, 25V, +/-10%, X5R, 0603	C19	Fitted	0603	TDK	C1608X5R1E105K080AC	1
CAP, CERM, 0.1uF, 100V, +/-10%, X7R, 0805	C24	Fitted	0805_HV	Kemet	C0805C104K1RACTU	1
CAP, CERM, 22uF, 16V, +/-20%, X5R, 1206	C25	Fitted	1206	AVX	1206YD226MAT2A	1
CAP, AL, 100uF, 100V, +/-20%, 0.12 ohm, TH	C28	Fitted	YXJ_1000x2000	Rubycon	100YXJ100M10X20	1
CAP, CERM, 100pF, 25V, +/-10%, X7R, 0603	C39, C40, C41, C42	Fitted	0603	AVX	06033C101KAT2A	4
Diode, TVS 15V 1500W BIDIR 5% SMC	D1, D3, D5	Fitted	SMC	Littelfuse Inc	SMCJ15CA	3
LED SmartLED Green 570NM	D2	Fitted	LED0603AA	OSRAM	LG L29K-G2J1-24-Z	1
Diode, Zener, 5.1V, 5W, SMB	D4	Fitted	SMB	Micro Commercial Components	SMBJ5338B-TP	1
Diode, Schottky, 20V, 1A, SMA	D6	Fitted	SMA	Diodes Inc.	B120-13-F	1
Diode, Zener, 16V, 1W, DO41	D8	Fitted	DO-41	Micro Commercial Co	1N4745A-TP	1
Diode, P-N, 1000V, 1A, TH	D9, D11	Fitted	DO-41	Fairchild Semiconductor	1N4007	2
FERRITE CHIP 1000 OHM 300MA 0603	FB1	Fitted	0603	TDK Corporation	MMZ1608B102C	1
Fiducial mark. There is nothing to buy or mount.	FID1, FID2, FID3, FID4, FID5, FID6	Fitted	Fiducial10-20	N/A	N/A	6
Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	H1, H2, H3, H4	Fitted	NY PMS 440 0025 PH	B&F Fastener Supply	NY PMS 440 0025 PH	4
Standoff, Hex, 0.5"L #4-40 Nylon	H5, H6, H8, H9	Fitted	Keystone_1902 C	Keystone	1902C	4
Mountin hole, NPTH Drill 3.2mm	H7	Fitted	MH3.2_H5_W6_KO8_STARHEAD			1
HEATSINK TO-220 W/PINS 1.5"TALL	HS1	Fitted	HEATSINK_513201	Aavid Thermalloy	513102B02500G	1
Header, Male 2x10-pin, 100mil spacing	J1, J11	Fitted	HEADER_2X10P	Sullins	PEC10DAAN	2
TERMINAL BLOCK 5.08MM VERT 2POS, TH	J3, J6, J12, J16, J17, J18, J19	Fitted	CONN_ED120-2DS	On-Shore Technology	ED120/2DS	7
Header, Male 2-pin, 100mil spacing,	J4, J5, J7, J8, J9, J10, J13, J14, J15, J21, J22	Fitted	HDR100_1X2	Sullins	PEC02SAAN	11
Terminal Block, 3-pin, 15-A, 5.1mm	J20	Fitted	TB_3X5.1MM	OST	ED120/3DS	1
Inductor, Common Mode Filter SMD	L1	Fitted	IND_0805-4P	TDK	ACM2012-900-2P-T002	1
Inductor, 220uH .30A SMD	L2	Fitted	SRR7045	Bourns	SRR7032-221M	1
Inductor, Chip, 3.3uH 770MA 1210 10%	L3	Fitted	1210	EPCOS Inc	B82422H1332K	1
1.5A Ferrite Bead, 330 ohm @ 100MHz, SMD	L4	Fitted	0603	MuRata	BLM18SG331TN1D	1

Table 13. Bill of Materials (continued)

DESCRIPTION	DESIGNATOR	FITTED	FOOTPRINT	MANUFACTURER	PARTNUMBER	QTY
Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	LBL1	Fitted	Label_650x200	Brady	THT-14-423-10	1
MOSFET, N-CH, 30V, 22A, SON 2X2 MM	Q1	Fitted	SON_CSD17571Q2	TEXAS INSTRUMENTS	CSD17571Q2	1
RES, 100 ohm, 1%, 0.1W, 0603	R1, R33, R41, R68	Fitted	0603	Vishay-Dale	CRCW0603100RFKEA	4
RES, 470 ohm, 1%, 0.125W, 0805	R3, R10	Fitted	0805_HV	Vishay-Dale	CRCW0805470RFKEA	2
RES, 300 ohm, 5%, 0.1W, 0603	R4, R37	Fitted	0603	Vishay-Dale	CRCW0603300RJNEA	2
RES, 10k ohm, 5%, 0.1W, 0603	R5, R6, R8	Fitted	0603	Vishay-Dale	CRCW060310K0JNEA	3
RES, 120 ohm, 5%, 0.125W, 0805	R7	Fitted	0805_HV	Vishay-Dale	CRCW0805120RJNEA	1
RES, 10.0 ohm, 1%, 0.1W, 0603	R9	Fitted	0603	Vishay-Dale	CRCW060310R0FKEA	1
RES, 200 ohm, 1%, 0.1W, 0603	R11	Fitted	0603	Vishay-Dale	CRCW0603200RFKEA	1
RES, 63.4k ohm, 1%, 0.1W, 0603	R12	Fitted	0603	Vishay-Dale	CRCW060363K4FKEA	1
RES, 121k ohm, 0.1%, 0.125W, 0805	R13	Fitted	0805_HV	Yageo America	RT0805BRD07121KL	1
RES, 10.0k ohm, 1%, 0.1W, 0603	R14, R22	Fitted	0603	Vishay-Dale	CRCW060310K0FKEA	2
RES, 1.00k ohm, 1%, 0.1W, 0603	R15	Fitted	0603	Yageo America	RC0603FR-071KL	1
RES, 9.76k ohm, 1%, 0.1W, 0603	R16	Fitted	0603	Vishay-Dale	CRCW06039K76FKEA	1
RES, 53.6k ohm, 0.1%, 0.125W, 0805	R17	Fitted	0805_HV	Susumu Co Ltd	RG2012P-5362-B-T5	1
RES, 100k ohm, 1%, 0.1W, 0603	R18, R31	Fitted	0603	Vishay-Dale	CRCW0603100KFKEA	2
RES, 21.5k ohm, 1%, 0.1W, 0603	R19	Fitted	0603	Vishay-Dale	CRCW060321K5FKEA	1
RES, 30k ohm, 5%, 0.1W, 0603	R20, R52	Fitted	0603	Vishay-Dale	CRCW060330K0JNEA	2
RES, 280k ohm, 1%, 0.1W, 0603	R21	Fitted	0603	Vishay-Dale	CRCW0603280KFKEA	1
RES, 10 ohm, 5%, 0.1W, 0603	R23, R27, R61, R62	Fitted	0603	Vishay-Dale	CRCW060310R0JNEA	4
RES, 0 ohm, 5%, 0.1W, 0603	R24, R26, R32, R63, R64, R65	Fitted	0603	Vishay-Dale	CRCW06030000Z0EA	6
RES, 10.0k ohm, 1%, 0.25W, 1206	R25, R29	Fitted	1206	Vishay-Dale	CRCW120610K0FKEA	2
RES, 43.2k ohm, 1%, 0.1W, 0603	R30	Fitted	0603	Vishay-Dale	CRCW060343K2FKEA	1
RES, 1.0k ohm, 5%, 0.1W, 0603	R42, R43, R44, R70	Fitted	0603	Vishay-Dale	CRCW06031K00JNEA	4
RES, 10k ohm, 0.01%, 0.063W, 0603	R51	Fitted	0603	Stackpole Electronics Inc	RNCF0603TKY10K0	1
RES, 0.3 ohm, 1%, 0.5W, 1206	R53, R54, R55, R56, R57, R58, R59, R60	Fitted	1206	Stackpole Electronics Inc	CSR1206FKR300	8
RES, 470 ohm, 5%, 0.1W, 0603	R69	Fitted	0603	Vishay-Dale	CRCW0603470RJNEA	1
Transformer 475uH SMD	T1	Fitted	760390015	Wurth Electronics Midcom	760390015	1
Test Point, O.040 Hole	TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14, TP15, TP16, TP17, TP18, TP19, TP20, TP21, TP22, TP23, TP24, TP25, TP26, TP27, TP28, TP29, TP30, TP31, TP32, TP33, TP34, TP35, TP36, TP37, TP38, TP39, TP40	Fitted	TP-040_RND	STD	STD	40
2.7V, 15.6mV/°C, Temperature Sensor, 3-pin SOT-23	U1	Fitted	MF03A_N	National Semiconductor	LM62BIM3	1
IC, ISOLATED RS-485 PROFIBUS TRANSCEIVER	U2	Fitted	DW0016A_N	TI	ISO1176DW	1
IC, 300-mA 40-V LOW-DROPOUT REGULATOR WITH 25-uA QUIESCENT CURRENT	U3	Fitted	KVU_1	TI	TPS7A6533QKVURQ1	1
100V, 600mA Constant On-Time Synchronous Buck Regulator, DDA0008B	U4	Fitted	DDA0008B_N	Texas Instruments	LM5017MRE/NOPB	1
IC, DC-DC Converter	U5	Fitted	RTE-16	TI	TPS55010RTE	1
ZerØ-Drift Programmable Gain Amplifier with MUX	U6	Fitted	PW0020A_L	Texas Instruments	PGA11xAIPW	1
IC, Micropower Shunt Voltage Reference 100 ppm/°C, 45µA-12mA, Adjustable	U8	Fitted	SOT-23	TI	LM4041BIDBZ	1
CAP, CERM, 0.1uF, 25V, +/-5%, X7R, 0603	C37	Not Fitted	0603	AVX	06033C104JAT2A	0
Diode, Zener, 39V, 1W, DO41	D7	Not Fitted	DO-41	Micro Commercial Co	1N4754A-TP	0

Table 13. Bill of Materials (continued)

DESCRIPTION	DESIGNATOR	FITTED	FOOTPRINT	MANUFACTURER	PARTNUMBER	QTY
Diode, P-N, 1000V, 1A, TH	D10	Not Fitted	DO-41	Fairchild Semiconductor	1N4007	0
Diode, Switching, 200V, 0.2A, SOT-23	D12	Not Fitted	SOT-23	Diodes Inc.	BAS21-7-F	0
Header, Male 3-pin, 100mil spacing,	J2	Not Fitted	HDR100_1X3	Sullins	PEC03SAAN	0
MOSFET, N-CH, 30V, 22A, SON 2X2 MM	Q2, Q3, Q4	Not Fitted	SON_CSD17571Q2	TEXAS INSTRUMENTS	CSD17571Q2	0
MOSFET, N-CH, 60V, 50A, TO-220AB	Q5	Not Fitted	TO-220AB	Texas Instruments	CSD18537NKCS	0
RES, 1.00k ohm, 1%, 0.125W, 0805	R2	Not Fitted	0805_HV	Vishay-Dale	CRCW08051K00FKEA	0
RES, 10.0k ohm, 1%, 0.1W, 0603	R28	Not Fitted	0603	Vishay-Dale	CRCW060310K0FKEA	0
RES, 10.0k ohm, 1%, 0.25W, 1206	R34	Not Fitted	1206	Vishay-Dale	CRCW120610K0FKEA	0
RES, 1.00Meg ohm, 1%, 0.1W, 0603	R35	Not Fitted	0603	Vishay-Dale	CRCW06031M00FKEA	0
RES, 10k ohm, 0.01%, 0.063W, 0603	R36	Not Fitted	0603	Stackpole Electronics Inc	RNCF0603TKY10K0	0
RES, 300 ohm, 5%, 0.1W, 0603	R38, R39, R40	Not Fitted	0603	Vishay-Dale	CRCW0603300RJNEA	0
RES, 1.00k ohm, 1%, 0.25W, 1206	R45, R46	Not Fitted	1206	Vishay-Dale	CRCW12061K00FKEA	0
RES, 510 ohm, 0.1%, 0.1W, 0603	R47	Not Fitted	0603	Susumu Co Ltd	RG1608P-511-B-T5	0
RES, 0.3 ohm, 1%, 0.5W, 1206	R48, R49, R50	Not Fitted	1206	Stackpole Electronics Inc	CSR1206FKR300	0
RES, 47k ohm, 5%, 0.125W, 0805	R66	Not Fitted	0805_HV	Panasonic	ERJ-6GEYJ473V	0
RES, 0 ohm, 5%, 0.1W, 0603	R67, R71	Not Fitted	0603	Vishay-Dale	CRCW06030000Z0EA	0
IC, Dual Differential Comparators, 2-36 Vin	U7	Not Fitted	SO8	TI	LM293AD	0

6.3 PCB Layout

This design implements in 2 layers in the PCB. For optimal performance of the design, follow standard PCB layout guidelines, including providing decouple capacitors close to all IC's. Also, include adequate power and ground connections with large copper pours. Additional considerations must be made for providing robust EMC and EMI immunity. All protection components should be placed as close to the output connectors as possible to provide a controlled return path for transient currents that does not cross sensitive components. For best performance, use low impedance thick traces along the protection circuits. Pour copper wherever possible.

6.3.1 Layout Recommendations

In order to achieve a high performance, follow the layout guidelines as recommended:

1. Ensure that protection elements such as TVS diodes and capacitors are placed as close to connectors as possible.
2. Use large and wide traces to ensure a low-impedance path for high-energy transients.
3. Place the decoupling capacitors close to the IC supply terminal.
4. Use multiple vias for power and ground for decoupling caps.
5. Place the reference capacitor close to the voltage reference.

7 Layer Plots

To download the layer plots for each board, see the design files at TIDA-00191. Figure 26 through Figure 33 show the layer plots for TIDA-00191.

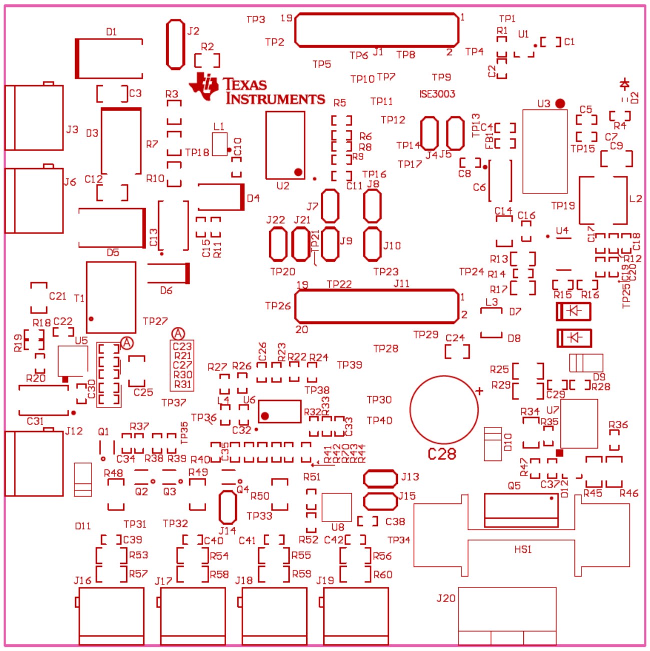


Figure 26. TIDA-00191 — Top Overlay

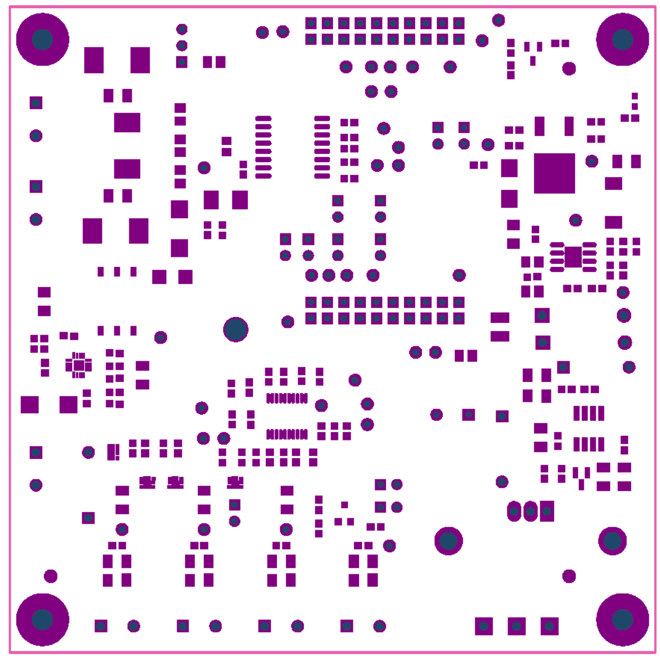


Figure 27. TIDA-00191 — Top Solder Mask

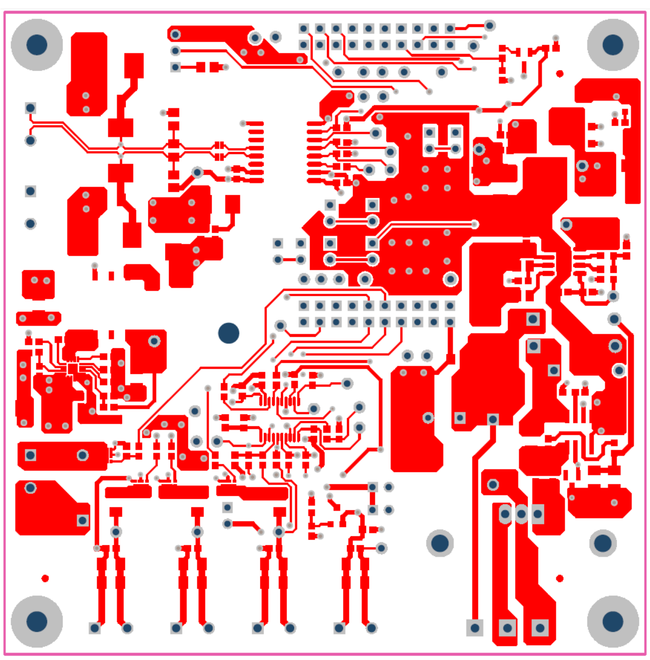


Figure 28. TIDA-00191 — Top Layer

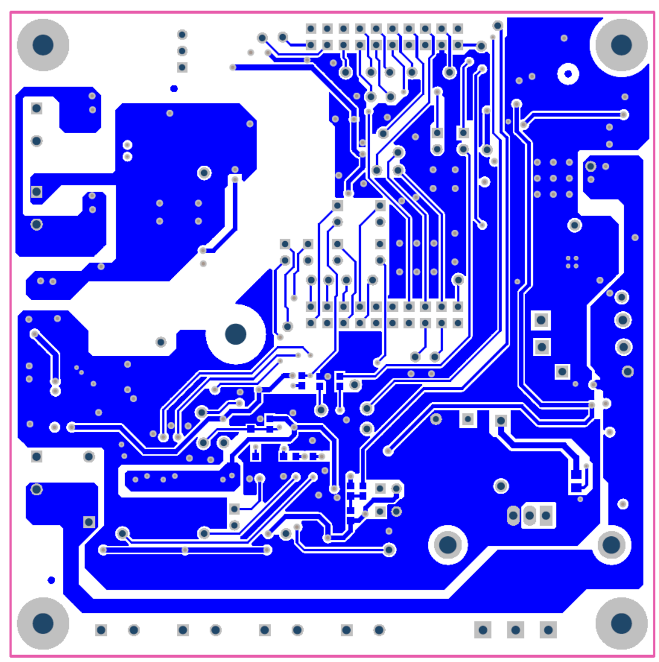


Figure 29. TIDA-00191 — Bottom Layer

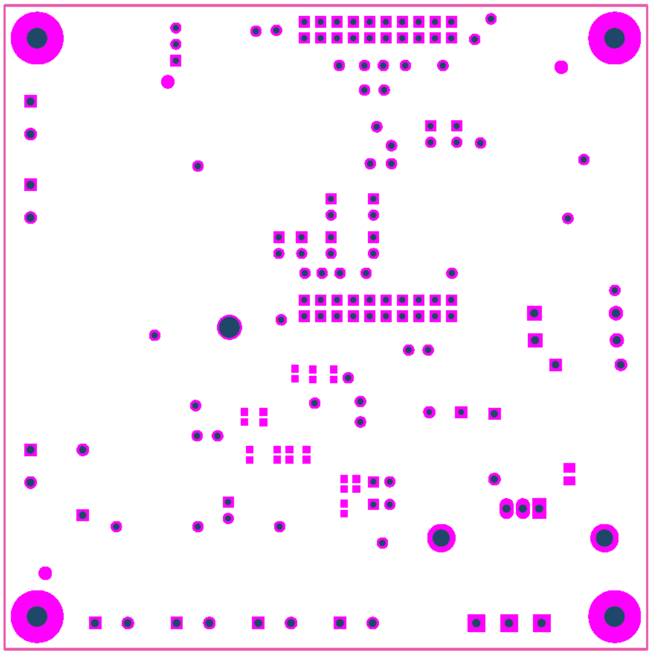


Figure 30. TIDA-00191 — Bottom Solder Mask

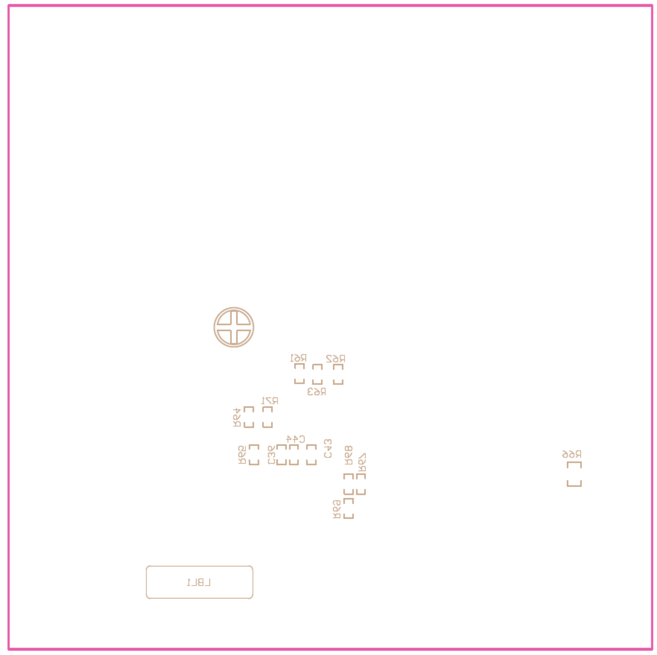
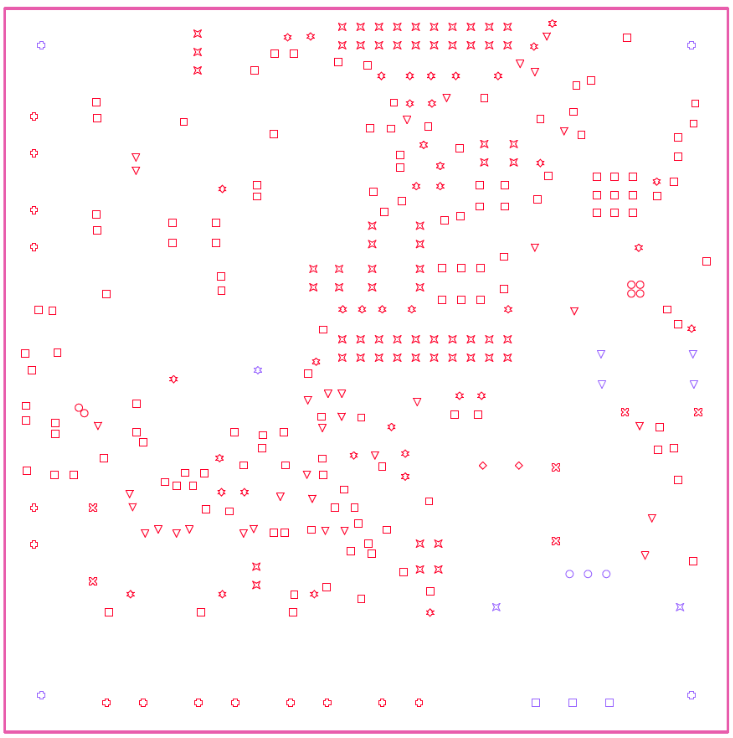


Figure 31. TIDA-00191 — Bottom Overlay



Symbol	Hit Count	Tool Size	Plated	Hole Type
○	6	12mil (0.305mm)	PTH	Round
▽	34	16mil (0.406mm)	PTH	Round
□	134	20mil (0.508mm)	PTH	Round
◇	2	36mil (0.914mm)	PTH	Round
⌑	65	38mil (0.965mm)	PTH	Round
✡	40	40mil (1.016mm)	PTH	Round
⊠	6	45.276mil (1.15mm)	PTH	Round
⬡	14	49.213mil (1.25mm)	PTH	Round
○	3	50mil (1.27mm)	PTH	Round
▽	4	51mil (1.295mm)	PTH	Round
□	3	52mil (1.321mm)	PTH	Round
⌑	2	106.5mil (2.705mm)	PTH	Round
⊕	4	125.984mil (3.2mm)	PTH	Round
✡	1	128mil (3.251mm)	NPTH	Round
	318 Total			

Drill Table

DRILL TOLERANCES: FOR PTH +/−3MILS
FOR NPTH +/−2MILS

Figure 32. TIDA-00191 — Drill Drawing

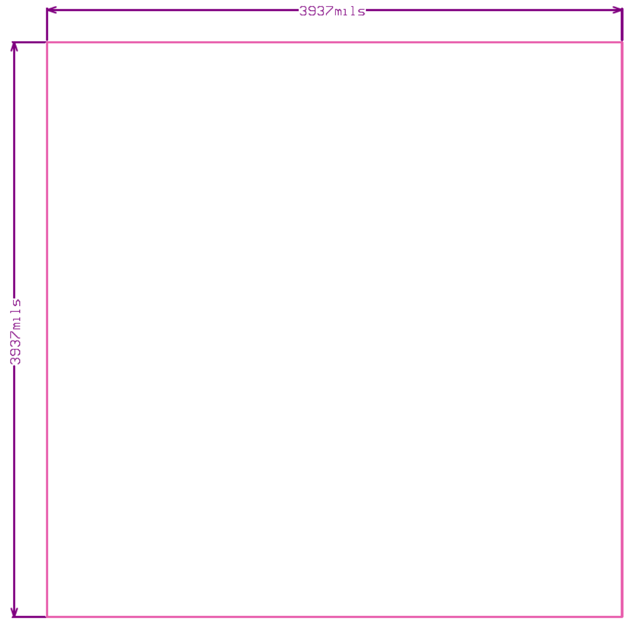


Figure 33. TIDA-00191 — Board Dimensions

8 Altium Project

To download the Altium project files for each board, see the design files at TIDA-00191.

9 Gerber Files

To download the Gerber files for each board, see the design files at TIDA-00191.

10 Software Files

To download the software files for the reference design, see the design files at TIDA-00191.

11 About the Author

N. NAVANEETH KUMAR is a Systems Architect at Texas Instruments, where he is responsible for developing subsystem solutions for motor controls within Industrial Systems. N. Navaneeth brings to this role his extensive experience in power electronics, EMC, analog, and mixed signal designs. He has system-level product design experience in drives, solar inverters, UPS, and protection relays. N. Navaneeth earned his Bachelor of Electronics and Communication Engineering from Bharathiar University, India and his Master of Science in Electronic Product Development from Bolton University, UK.

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated ("TI") reference designs are solely intended to assist designers (“Buyers”) who are developing systems that incorporate TI semiconductor products (also referred to herein as “components”). Buyer understands and agrees that Buyer remains responsible for using its independent analysis, evaluation and judgment in designing Buyer’s systems and products.

TI reference designs have been created using standard laboratory conditions and engineering practices. **TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design.** TI may make corrections, enhancements, improvements and other changes to its reference designs.

Buyers are authorized to use TI reference designs with the TI component(s) identified in each particular reference design and to modify the reference design in the development of their end products. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY THIRD PARTY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT, 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 components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of such information 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 REFERENCE DESIGNS ARE PROVIDED "AS IS". TI MAKES NO WARRANTIES OR REPRESENTATIONS WITH REGARD TO THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, EXPRESS, IMPLIED OR STATUTORY, INCLUDING ACCURACY OR COMPLETENESS. TI DISCLAIMS ANY WARRANTY OF TITLE AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, QUIET ENJOYMENT, QUIET POSSESSION, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS WITH REGARD TO TI REFERENCE DESIGNS OR USE THEREOF. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY BUYERS AGAINST ANY THIRD PARTY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON A COMBINATION OF COMPONENTS PROVIDED IN A TI REFERENCE DESIGN. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, SPECIAL, INCIDENTAL, CONSEQUENTIAL OR INDIRECT DAMAGES, HOWEVER CAUSED, ON ANY THEORY OF LIABILITY AND WHETHER OR NOT TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, ARISING IN ANY WAY OUT OF TI REFERENCE DESIGNS OR BUYER’S USE OF TI REFERENCE DESIGNS.

TI reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques for TI components are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

Reproduction of significant portions of TI information in TI data books, data sheets or reference designs is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards that anticipate dangerous failures, monitor failures and their consequences, lessen the likelihood of dangerous failures and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in Buyer’s safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed an agreement specifically governing such use.

Only those TI components that TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have ***not*** been so designated is solely at Buyer's risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265