TI Designs

Measurement Module for Branch Current Monitor

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Design Resources

TIDA-00221	Design Page
MSP430F6779	Product Folder
TPS7A6533-Q1	Product Folder
CSD17571Q2	Product Folder

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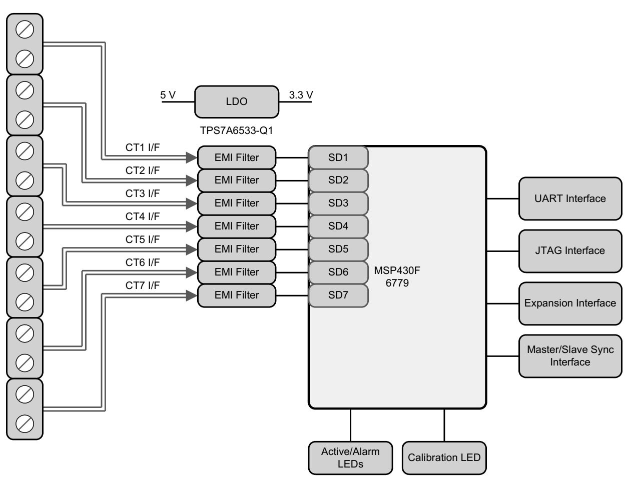
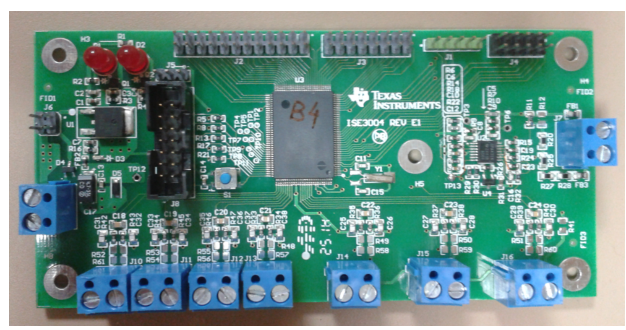
Design Features

- MSP430F6779 System-on-Chip (SOC) with 24-Bit Sigma-Delta Analog-to-Digital Converter (ADC) based system for higher accuracy
- Monitors up to 7 current channels
- Current Measurement accuracy < ±2% from 10-200% of rated current
- Sampling at 4096Hz
- UART Interface (TTL level) Connector for Communication
- True RMS measurement
- 3 LEDs for Indications

Featured Applications

- Data Centers
- Building automation
- Load Management





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1 System Description

Millions of dollars a year are invested in power-protection systems, such as UPSs and generators, but problems can still occur at the branch circuit level due to improper loading or inadequate monitoring. You might not be able to see trouble coming until a circuit breaker trips, and that is too late. Systems go down. Valuable data is lost, and business comes to a standstill. It can take hours to recover.

Branch Current Monitoring system monitors current on individual panel board branch circuits alerting users before the circuit current approaches the breakers trip point. Current alarm thresholds are programmable to match individual branch circuit breaker ratings. By receiving early notification of high current conditions, users can perform the required preventative maintenance to avoid unnecessary load drops making the Branch Current Monitor a giant step forward in enhancing system reliability.

The Branch Current Monitor (BCM) is a current sensing device that monitors multipoles on a Panelboard within a power distribution unit. Designed for use in multiple-location data centers, the BCM provides branch circuit amperage information and initiates alarm. The BCM enables the data center operator to manage Current/power by anticipating overloaded circuit breakers.

The Branch Current Monitor System continuously measures the current on all breaker levels and warns you of impending trouble, so you can take proactive steps. Armed with these insights, data center and facility managers can more effectively balance loads, prevent overload conditions, plan for future capacity needs and, where applicable, allocate energy cost among internal departments.

The BCM consists of a signal acquisition board with current sensor, RS485 for communication, and Visible/Audible Alarms.

1.1 Applications

- Circuit load monitoring
- Current limit alarming
- Load-based cost allocation
- Load management
- Load balancing
- Protecting against overload
- Managing and balancing loads
- Lighting circuits

1.2 BCM Product Requirements

1.2.1 Accuracy

- ±2% of reading
- Current input range
- Number of channels
- Frequency: 50/60 Hz
- Measurement resolution: >1280 Hz sampling
- Serial Communication - RS485 / RS232
- Connection: 2-wire or 4-wire*
- Protocol: Modbus
- Data rate: 2400, 4800, 9600, or 19200 bps*

1.2.2 Sub-Meter

Rising energy costs continue to pressure operators of commercial, industrial, institutional and multi-family residential facilities to leave “no stone unturned” in finding ways to reduce operating expenses. Users have turned to submetering to identify when and where energy is used in order to implement energy conservation measures and programs.

Building owners and facility managers are faced with ever increasing utility costs that eat away at the bottom line. In order to begin managing these costs, users need to know where the energy is being used and be able to allocate the costs appropriately. Submetering products and systems allow users to see specifically where and when energy is consumed within the building envelope. Meters are used to monitor actual usage by department, tenant or common area and report back to computerized systems for billing, allocation, analysis and management.

1.2.3 Cost Allocation

Building owners and facility managers face ever increasing utility costs that eat away at the bottom line. To manage these costs, users need to know where the energy is being used and to allocate the costs appropriately. Submetering products and systems allow users to see specifically where and when energy is consumed within the building envelope. Meters monitor actual usage by department, tenant or common area and report back to computerized systems for billing, allocation, analysis and management.

Metering individual departments, areas or buildings for cost center analysis, budgetary accountability and allocation allows visibility into energy consumption and usage trends. Armed with this critical information, managers can take advantage of energy savings opportunities that may be as simple as turning off lights or computers when rooms are not in use. When department budgets include energy consumption, users can take the necessary steps to ease the pressure on their budgets by reducing overall energy use.

1.2.4 Tenant Billing

In facilities where there are multiple tenants, monitoring actual consumption is a win-win situation for both the building manager and the tenants. Managers can allocate energy usage costs directly to the tenants. In addition, all common area usage can be monitored and distributed equitably between tenants. Both tenant billing and common area allocation allows building managers to recoup energy expenses. Tenants benefit from submetering of actual energy usage in two ways.

1. Tenants only pay for what they use. They are not burdened with the overflow cost of large users as they would be if billed a flat rate per square foot of space rented.
2. Tenants gain control over their usage allowing them to conserve energy and benefit financially for their efforts.

Whether metering a commercial or residential tenant, department or common area, cost allocation and accurate billing practices help reduce costs, recoup energy expenses and promote energy conservation.

1.2.5 Commercial - Office and Retail

In today’s commercial office, retail and mixed-use facility environments, submeter-based energy monitoring solutions benefit parties on both sides of the electric bill. At the enterprise level, submeters help facility managers track everything from common area usage and HVAC system performance to monitoring after-hours energy usage for recovering and allocating costs back to the using tenant. From the tenant’s perspective, submeters eliminate problems associated with arbitrary ratio-based measures like square-footage that favor high-volume users over low use tenants. Tenants are also able to benefit financially from any energy conservation practices they implement. Submeters provide the usage data that allows managers to generate electric bills that put tenant fairness concerns to rest by including proof of exact use with every billing statement.

1.2.6 Multi-Family Residential

Rising energy rates are driving multi-family property owners to allocate utility costs back to tenants, recover revenue and promote resource conservation. Arbitrary square-footage cost allocation and other ratio billing measures do little to encourage energy conservation. Alternatively, tenants in high-rises, condos, co-operatives, and mixed-use buildings have been shown to use up to 25% less energy when submeters hold them accountable for the power they use. Wireless meters and accessories, is the perfect cost-effective solution for tenant metering and common area allocation.

1.2.7 Industrial/Manufacturing

With the industrial sector consuming more than one-third of all U.S. energy, it is easy to see why facilities are seeking ways to reduce energy costs without compromising production. As part of the facility energy picture, plant operators need accurate, real-time data to evaluate the performance of individual processes, pieces of equipment and departments.

1.3 Critical Requirements for BCM

In any type of industrial facility, whether process or discrete manufacturing, critical requirements for the BCM are:

- Number of channels monitored
- Measurement accuracy
- Communication capability

This TI design demonstrates the Current Measurement capabilities using Sigma-Delta ADC required for BCM. With this design, customers will be able to measure the current much more accurately compared to many of the current solutions.

All the relevant design files like Schematics, BOM, Layer plots, Altium files, Gerber, MSP430F6779 MCU software and executable for easy-to-use Graphical User Interface (GUI) have also been provided to the user.

2 Design Specification

Table 1. Design Specification

SI Number	Features	Descriptions
1	Current Inputs and Measurement Range	7 ΣΔ ADC Current channel Range: 10–200% of Rated Current (50A)
2	Input Frequency	50 / 60 Hz
3	Current Measurement Accuracy	< ±2%
4	Sampling Rate	4096 Hz
5	MCU	MSP430F6779
6	Power Supply	Input: < 5 Vdc Output: 3.3 Vdc
7	LED Indication	3 LEDs
8	Communication Interface Options	Interface Connectors for: 1. UART 2. SPI 3. I2C

3 Block Diagram

The Measurement Module has the following blocks in Figure 1.

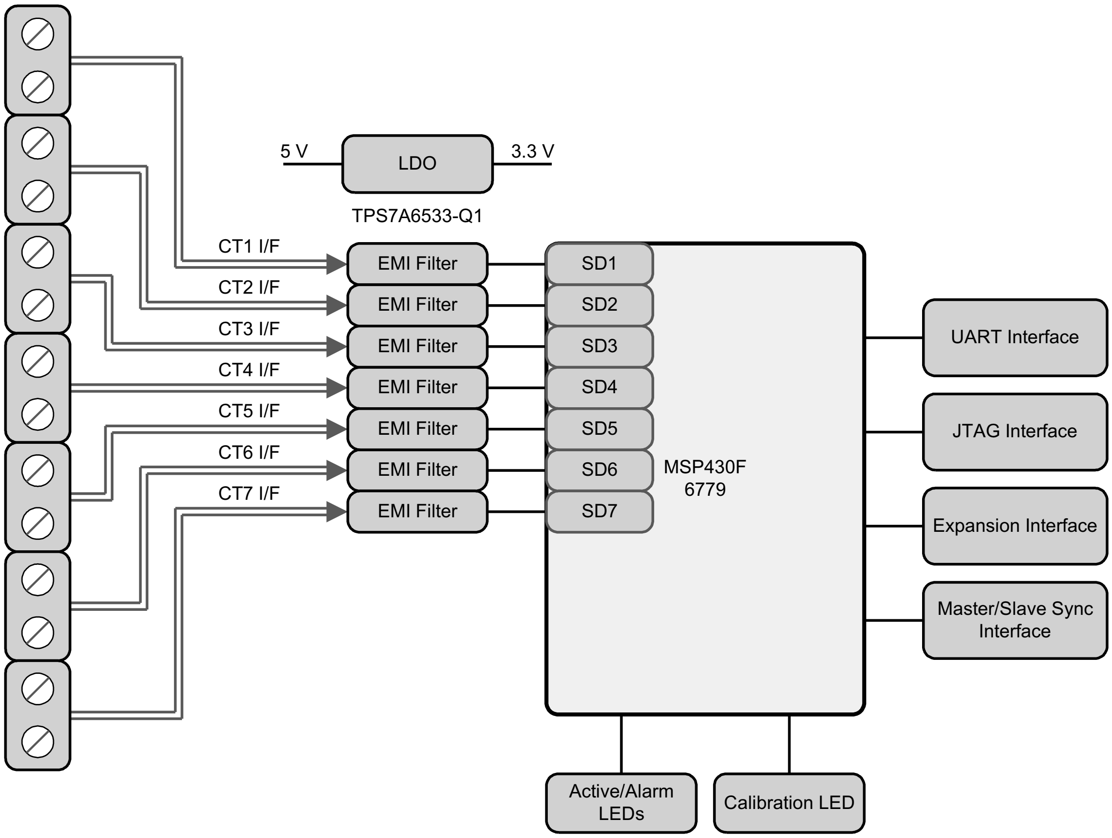


Figure 1. Block Diagram of BCM Module

3.1 MCU

The MCU MSP430F6779 is used in the current design. This MCU has 7 channels of 24-bit ΣΔ ADC based on a second-order sigma-delta architecture for current measurement, which has a large dynamic range. The availability of Software Modules and integration of the 24-bit ADC lead to the selection of the MSP430F6779 MCU.

3.2 Current Inputs and EMI Filter

There is provision to connect up to seven current inputs in this Measurement Module. The current transformers (CT) secondary input is interfaced to the Measurement Module through the 2-pin connectors. The required CT burden has been provided on the board. The required input filters for the current input is also provided.

NOTE: Current transformer (CT) is not provided on board. Based on the accuracy of the current transformers, there may be a requirement for calibration to meet the required accuracy.

Seven current channels are sensed through 24-bit ΣΔ ADC. Distributed current is measured through current transformers (CT). Interfacing of CT on board is through the 2-pin terminal block for each current channel. Output of current transformer is in the form of current. Burden resistor is used to convert current to voltage. Voltage is passed through RF / EMI filter. The RF / EMI filter is used for common mode and differential mode noise rejection; hence, improved performance.

3.3 Power Supply

An external DC voltage input has to be applied for the Measurement Module to operate. The DC input is connected using a 2-pin screw type connector . An input voltage of 5V must be applied.

3.4 RS232 (TTL Level) Communication Interface

Communication capabilities have been provided on the Measurement Module. Communication interface is required to set Alarm Functions and read the currents measured. An RS232 (TTL level) Communication interface has been provided on a connector for interface. An external level converter has to be used to communicate with external devices like a desktop computer.

3.5 LED Indication

Three LEDs are available on the Measurement Module. These LEDs can be used for different functions like indicating Current, Alarm, or to indicate the Measurement Module health.

3.6 JTAG Programming

JTAG interface connector has been provided on the Measurement Module for programming and debugging of the MCU MSP430F6779.

3.7 Expansion Options

Different expansion options are available in the Measurement Module:

- SPI, UART, and I2C Interface – for feature enhancements/External Communication/connecting multiple Measurement Modules
- GPIO Interface connector – for future feature enhancements

4 Circuit Design

4.1 MCU

The MSP430F6779 devices are the latest metering SoC that belongs to the MSP430F67xx family of devices. This family of devices belongs to the powerful 16-bit MSP430F6xx platform, which brings in many new features and provides flexibility to support robust metrology solutions. These devices find their application in energy measurement and have the necessary architecture to support them.

The F6779 has a powerful 25-MHz CPU with MSP430CPUX architecture. The analog front end consists of up to seven independent 24-bit ΣΔ ADC based on a second-order Sigma Delta architecture that supports differential inputs. The sigma-delta ADCs (ΣΔ24_B) operate independently and are capable of 24-bit results. They can be grouped together for simultaneous sampling of 7 currents on the same trigger. In addition, it also has an integrated gain stage to support gains up to 128 for amplification of low-output current sensors.

Availability of 24-bit resolution and seven simultaneous channels makes it suitable for the applications like BCM.

4.2 Current Inputs and EMI Filter

There are seven current input channels on the Measurement Module. The CT burden depends on the current transformer selected and the current input range that is expected to be measured. The value of the burden resistor used in the current configuration is approximately 13Ω. The filter circuit consisting of resistors and capacitors, follows the burden resistor. Differential input signal with a voltage swing of ±919 mV can be applied. The Gain configuration depends on the input. The method to calculate the burden value is shown in Figure 2.

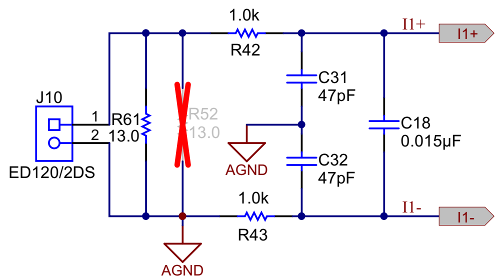


Figure 2. Current Input Schematic

The following calculation can be used to calculate burden resistor value:

NOTE: Pri = Primary

Sec = Secondary

Maximum Primary Sensing Current → Imax (pri)	= 100Arms
Maximum Peak Primary Current → Imax_pk (pri)	= Imax (pri) × 1.414 = 141A
Turns ratio of CT (Np(Primary turns - 1 / Ns (Secondary turns - 2000))	= 1 / 2000 Turns
Maximum Secondary Peak Current → Imax_pk (sec)	= Imax_pk (pri) × Np / Ns = (141 × 1000) mA / 2000 (turns) = 70.5 mA
Maximum allowable swing of SD ADC → V (Adc , Max)	= ± 919 mV
Max permissible Burden resistor value → Rburden	= V (Adc , Max) / Imax_pk (sec) = 919/70.5 = 13.03Ω

So, 13Ω burden is used in measurement module design. However, burden resistor value may vary depending on CT ratio and maximum current measurement. Sometimes, it is difficult to find exact value of burden or it is very costly. To overcome this limitation, design is equipped with two burden resistors.

NOTE: The errors due to DC offset or CT gain is compensated by calibration.

NOTE: Do not make the CT connections with the Current flowing on the primary side of the CT. Make sure the current source is switched Off before connecting.

4.3 Power Supply

An external DC supply should be connected on the 2-pin terminal block to power the Measurement Module. TPS7A6533-Q1 LDO is used in the design. A maximum of 12V DC input must be applied. DVCC for the Measurement Module is 3.3V. The power supply is protected for reverse Polarity and Over Voltage. There is an LED to indicate the power supply health.

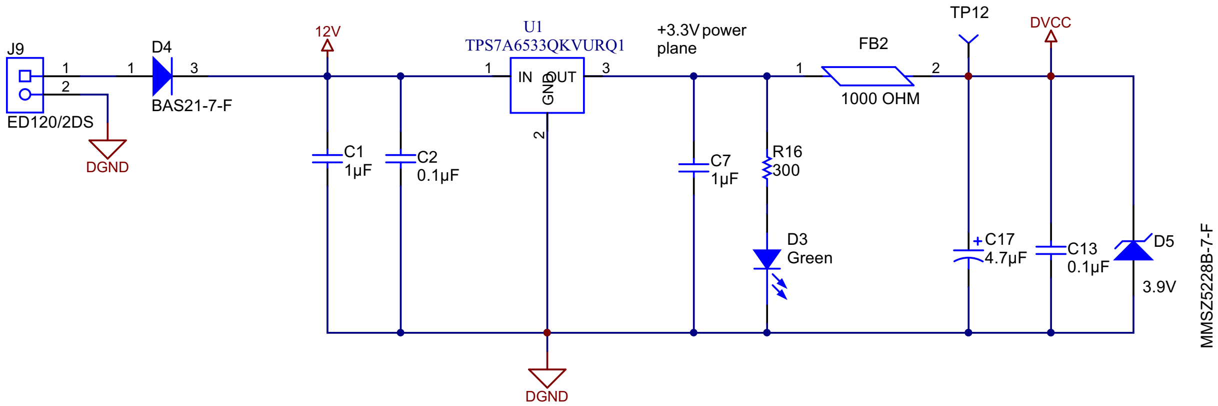


Figure 3. Power Supply

4.4 RS232 (TTL Level) Communication Interface

UART0 signals of MSP430F6779 is routed to the interface connector. The interface has transmit, receive, 3.3 V power and ground pins. One additional GPIO is also connected. In most of the BCPM applications, RS485 interface is preferred and when an external RS485 module is connected, this port pin can be used for data direction control. No fuse is connected to the 3.3 V output supply and care has to be taken when power is taken out for the communication module.

RS232 (TTL level) communication interface is available on connector J1. UART A0 of MSP430F6779 is extended on connector. To achieve RTS/DTE functionality, 1 digital port pin P2.7 is extended on J1 connector. DVCC and DGND power pins are available on J1 connector.

NOTE: This interface is used to View the measurement results on GUI.

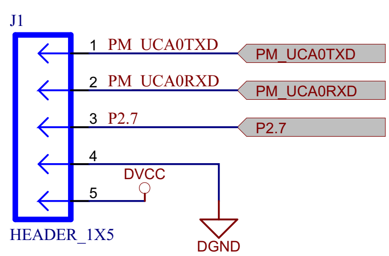


Figure 4. RS232 (TTL Level) Communication Interface

NOTE: The Power Supply on the Interface connector and all other signals are not protected. Care has to be taken while using this Interface connector.

4.5 LED Indication

Three LEDs are available on Measurement Module and can be programmed by the user for some of the following functions:

1. Alive LED – Can be used to indicate that the Measurement Module functioning is Normal.
2. Metrology LED – Can be used to indicate magnitude of current flowing.
3. Alarm LED - Can be used to indicate any abnormal conditions of current during measurement.

NOTE: These features have not been implemented as part of software.

4.6 JTAG Programming

The MSP430 family supports the standard JTAG interface that requires four signals for sending and receiving data. The JTAG signals are shared with general-purpose I/O. The TEST/SBWTCK pin is used to enable the JTAG signals. In addition to these signals, the RST/NMI/SBWTDIO is required to interface with MSP430 development tools and device programmers. 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, see MSP430 Programming Via the JTAG Interface User's Guide (SLAU320).

Connector J8 is the JTAG programming interface connector.

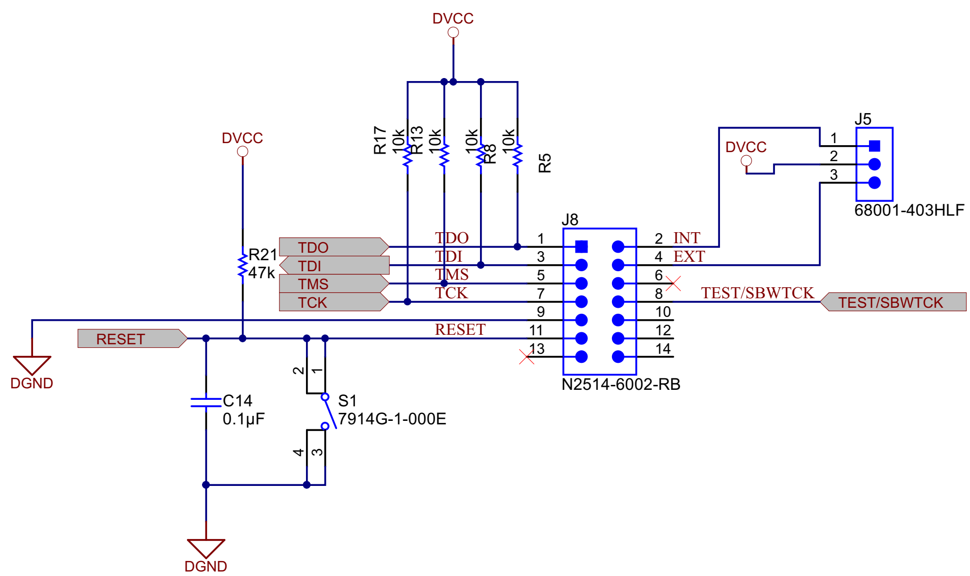


Figure 5. JTAG Programming Interface

4.7 Expansion Options

Different expansion options are available in the measurement module: SPI, UART, and I2C interface.

- **SPI:** SPI can be used for synchronizing multiple measurement modules to configure them for more number of channels or for three-phase measurement.
- **I2C:** There may be a need to calibrate the inputs based on accuracy of the CT. In this case, an EEPROM can be connected to the I2C interface to store the calibration values. This I2C interface can be used to interface to the temp sensor, RTC or any other I2C interface-based peripherals.
- **GPIO:** The GPIO inputs can be used as I/O, Timer inputs or PWM outputs. These I/Os can be used when feature enhancements are required.

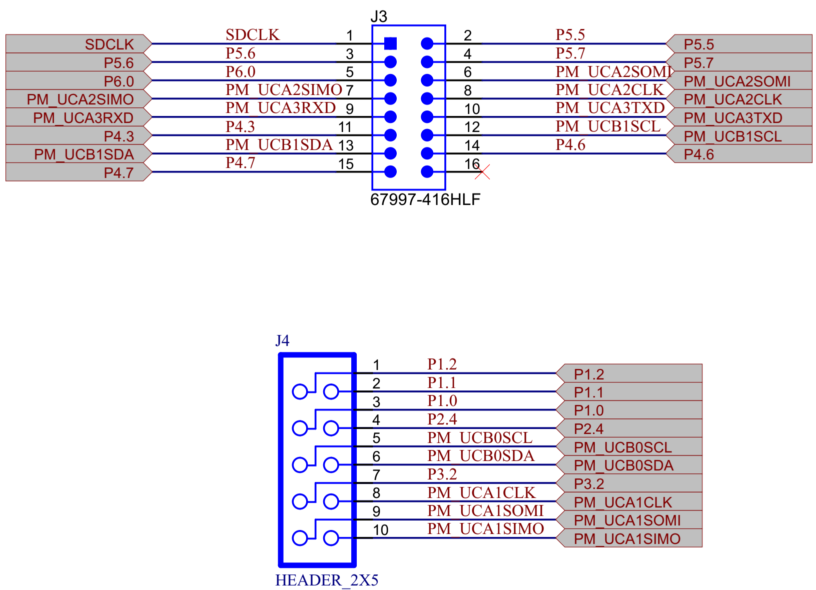


Figure 6. SPI / I2C / UART Expansion Interface

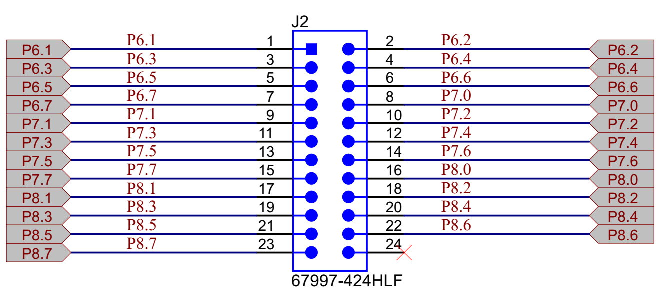


Figure 7. I/O Expansion Interface

5 Software Description

In this design, the software has three projects:

- mathematical routines
- metrology (current calculation)
- an application wrapper that deals mainly with application-processor functionality or communication

In the following subsections, the software is described. The first subsection describes the setup of various peripherals of the MSP430. Subsequently, the entire metrology software is described as two major processes: the foreground process and background process.

5.1 ΣΔ24 Initialization

The F677x family has seven independent sigma delta data converters. The clock to the ΣΔ24 (fM) is derived from system clock, which is configured to run at 25 MHz. The sampling frequency is defined as fs = fM/OSR, the OSR is chosen to be 256 and the modulation frequency fM, is chosen as 1.048576 MHz, resulting in a sampling frequency of 4.096 ksps. The ΣΔ24 is configured to generate regular interrupts every sampling instance. The following are the ΣΔ channels associations:

- A0.0+ and A0.0- → Current I1
- A1.0+ and A1.0- → Current I2
- A2.0+ and A2.0- → Current I3
- A3.0+ and A3.0- → Current I4
- A4.0+ and A4.0- → Current I5
- A5.0+ and A5.0- → Current I6
- A6.0+ and A6.0- → Current I7

5.2 Foreground Process

The foreground process includes the initial setup of the MSP430 hardware and software immediately after a device RESET. Figure 8 shows the flowchart for this process.

The initialization routines involve the setup of the analog to digital converter, clock system, general purpose input/output (port) pins, RTC module for 1-second interrupts and timekeeping, and the USCI_A0 for UART functionality. After the hardware is setup, any received frames from the GUI are processed. Subsequently, the foreground process checks whether the background process has notified it to calculate new metering parameters. This notification is done through the assertion of a status flag whenever a frame of data is available for processing. This data frame consists of the processed current dot products that were accumulated in the background process. These dot products are used by the foreground process to calculate the corresponding RMS current in real-world units. Each processed current dot product is accumulated in separate 64-bit registers to further process and obtain the RMS.

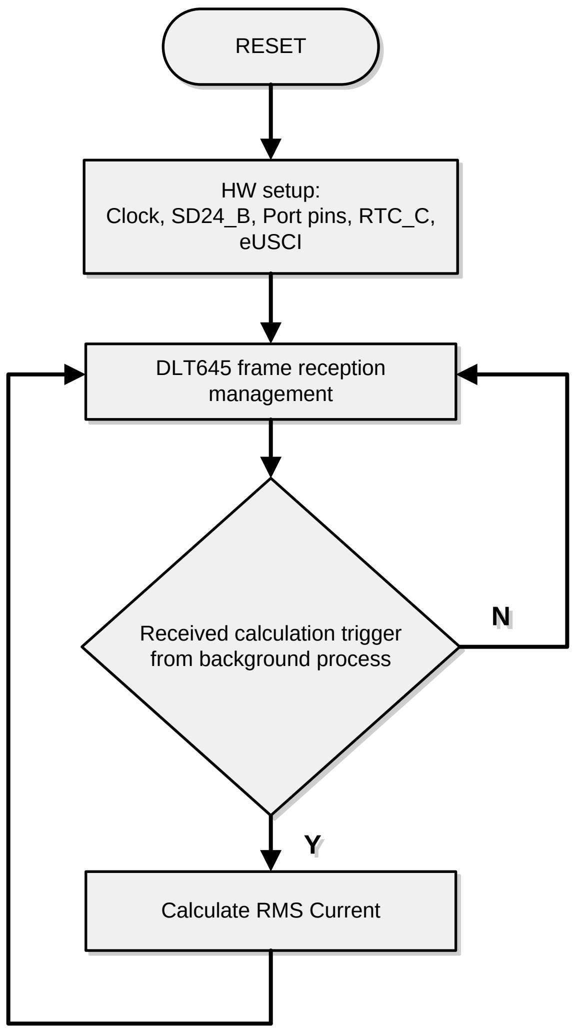


Figure 8. Foreground Process

The formula used to calculate RMS current is:

$$I_{RMS,ch} = K_{i,ch} \cdot \sqrt{\frac{\sum_{n=1}^{Sample\ count} i_{ch}(n) \cdot i_{ch}(n)}{Sample\ count}} - i_{offset,ch} \quad (1)$$

Where,

Ch = Current channel whose parameters are being calculated [that is, Channel A(=1), Channel B(=2), Channel C(=3), Channel D(=4), Channel E(=5), Channel F(=6), or Channel G(=7)]

$I_{ch}(n)$ = Each current sample of channel n at a sample instant n

$i_{offset,\ ch}$ = Offset used to subtract effects of the Additive White Gaussian Noise from the current converter

Sample count = Number of samples in one second

$K_{i,ch}$ = Scaling factor for each current

5.3 Background Process

The background function deals mainly with timing critical events in software. It uses the ΣΔ interrupt as a trigger to collect current samples. A ΣΔ interrupt is generated when the first current channel's (converter 0) sample is ready. Once the interrupt for the first current channel's sample is generated, sample processing is done by the "per_sample_dsp()" function.

The flowchart for the per_sample_dsp function is shown in Figure 9. In this function, the per_sample_dsp function is used to calculate intermediate current dot product results that are fed into the foreground process for the calculation of RMS current. Since 24-bit current samples are used, the current samples are processed and accumulated in dedicated 64-bit registers.

The output of each ΣΔ converter is a signed integer and any stray dc or offset value on these converters is removed using a dc tracking filter. Separate dc estimates for all currents are obtained using the filter and current samples. These estimates are then subtracted from each current sample. The resulting instantaneous current samples are used to generate the intermediate RMS dot product.

After sufficient samples (approximately one second's worth) have been accumulated, then the foreground function is triggered to calculate the final IRMS values. In the software, there are two sets of dot products: at any given time, one is used by the foreground for calculation and the other used as the working set by the background. After the background process has sufficient samples, it swaps the two dot products so that the foreground uses the newly acquired dot products that the background process just calculated and the background process uses a new empty set to calculate the next set of dot products.

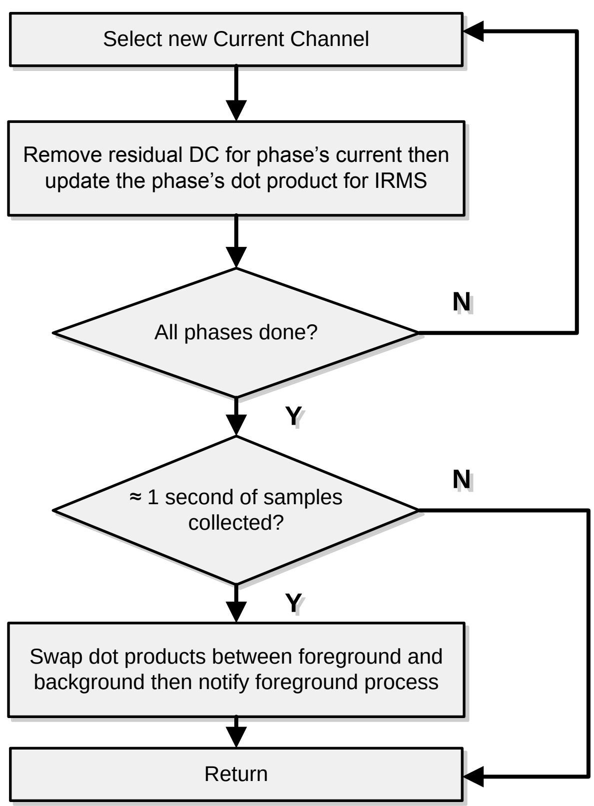


Figure 9. per_sample_dsp() Function

6 Test Setup

A GUI is provided with this TI Design for calibration and result display. To run the GUI, the eUSCIA0 UART TX/RX pins must be connected to an isolated UART to RS-232 adapter, such as:

http://www.ti.com/tool/TIDA-00163

6.1 Viewing Results

To run the GUI:

1. Connect the Measurement Module to a PC via an RS-232 cable and the isolated UART to RS-232 adapter.
2. Open the /Source/GUI folder and open calibration-config.xml in a text editor.
3. Change the "port name" field within the "meter" tag to the COM port connected to the meter. In step 4, this field is changed to COM7.

```
            </correction>
        </phase>
        <temperature/>
        <rtc/>
    </cal-defaults>
    <meter position="1">
        <port name="com7" speed="9600"/>
    </meter>
    <reference-meter>
        <port name="USB0::0x0A69::0x0835::A66200101281::INSTR"/>
        <type id="chroma-66202"/>
        <log requests="on" responses="on"/>
        <scaling voltage="1.0" current="1.0"/>
    </reference-meter>
```

Figure 10. GUI Configuration File Changed to Communicate With Meter

4. Run calibrator.exe in the /Source/GUI folder. If the COM port in calibration-config.xml was changed in the previous step to the com port connected to the Measurement Module, the GUI opens (see Figure 11).

If the GUI connects properly to the Measurement Module, the top left button is green. If there are problems with connections or if the code is not configured correctly, the button is red. Click the green button to view the results.

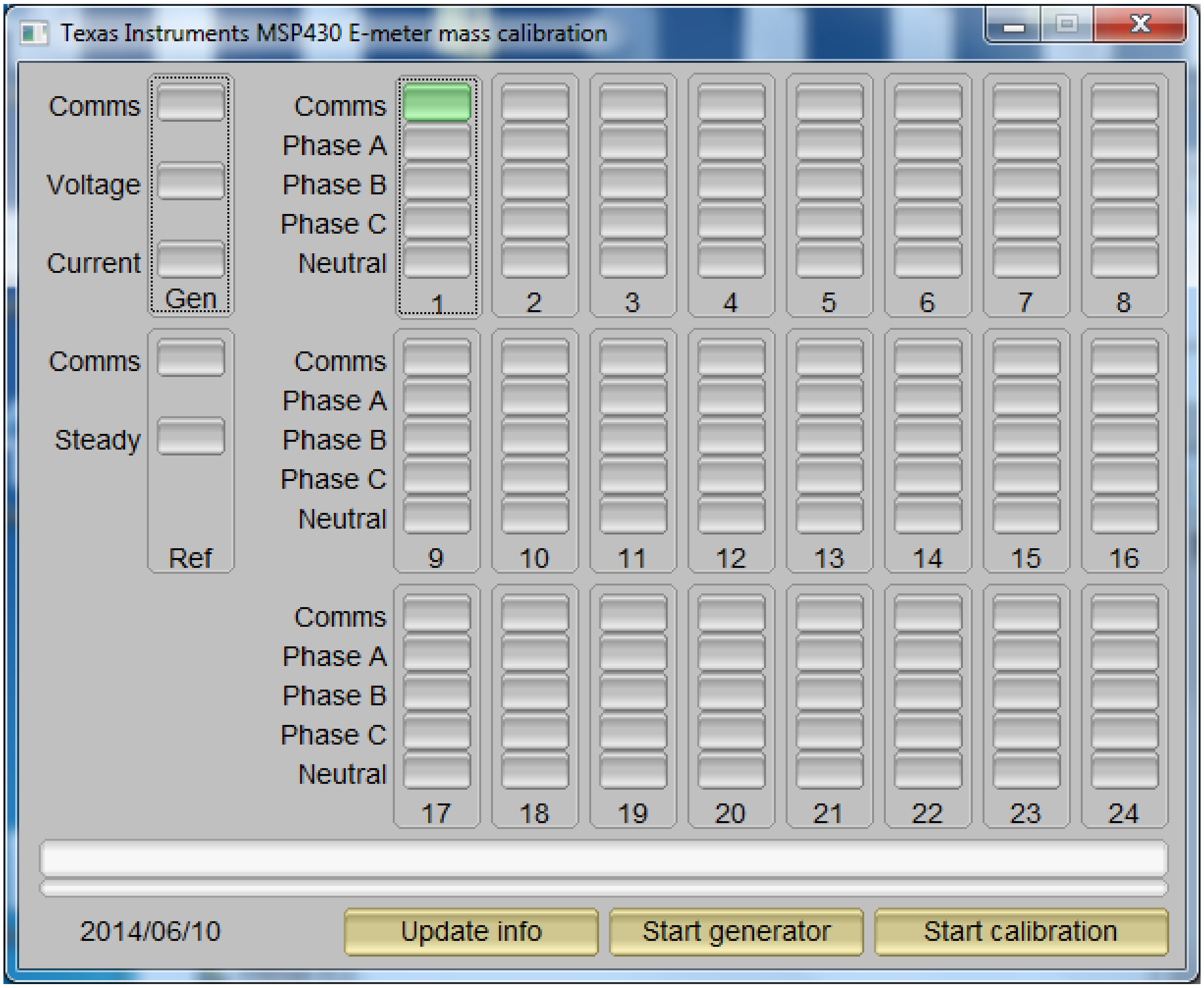


Figure 11. GUI Startup Window (Snapshot of GUI Screen)

When you click on the green button, the results window opens (see Figure 12).

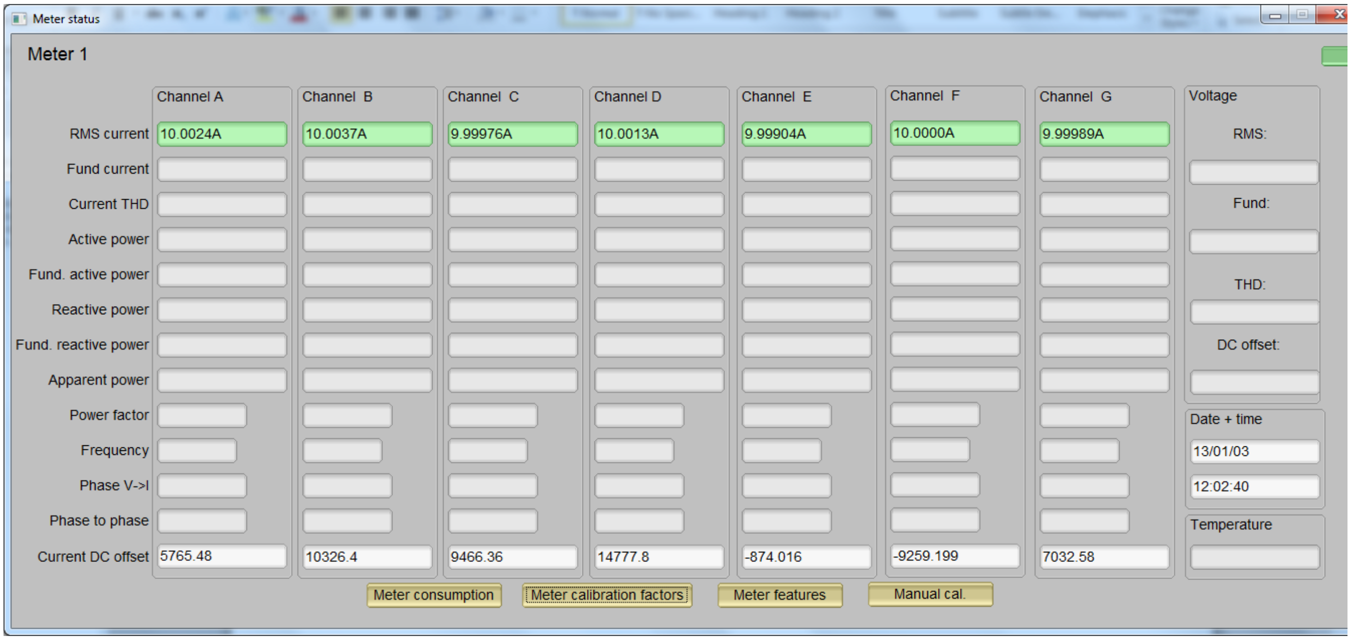


Figure 12. Results Window (Snapshot of GUI Screen)

The configuration of the meter can also be viewed by clicking Meter features to open the screen shown in Figure 13.

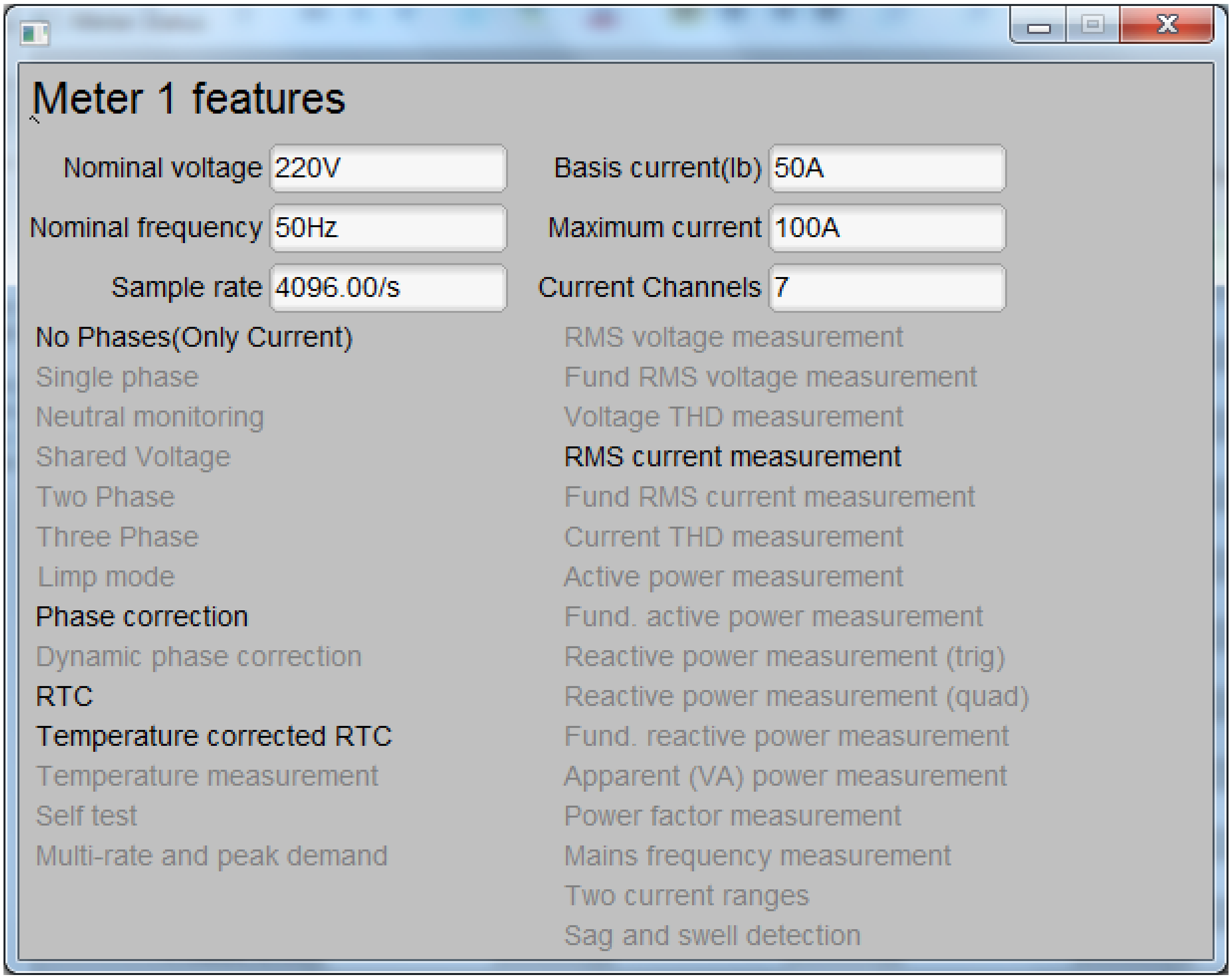


Figure 13. Meter Features Window (Snapshot of GUI Screen)

6.2 Calibration

Calibration is key to any meter's performance and it is absolutely necessary for every meter to go through this process. Initially, every meter exhibits different accuracies due to silicon-to-silicon differences, sensor accuracies, and other passive tolerances. To nullify the effects of these differences, every meter must be calibrated. For this Measurement Module, the GUI that is used for viewing results can also be used to calibrate the Measurement Module. During calibration, parameters called calibration factors are modified in software to give least error in measurement. For this design, there are two main calibration factors for each current channel: current scaling factor and current AC offset. The current scaling factors translate measured current in metrology software to real-world values represented in Amps. The current AC offset is used to eliminate the effect of Additive White Gaussian Noise associated with each current channel.

When the meter software is flashed with the code (available in the zip file), default calibration factors are loaded into these calibration factors. These values will be modified via the GUI during calibration. The calibration factors are stored in INFO_MEM, and therefore, would remain the same if the meter is restarted. The calibration factors can be viewed by pressing the "Meter calibration factors" button shown in Figure 14. The meter calibration factors window displays the latest values and this could be used to directly replace the macro definition of these factors in the source code.

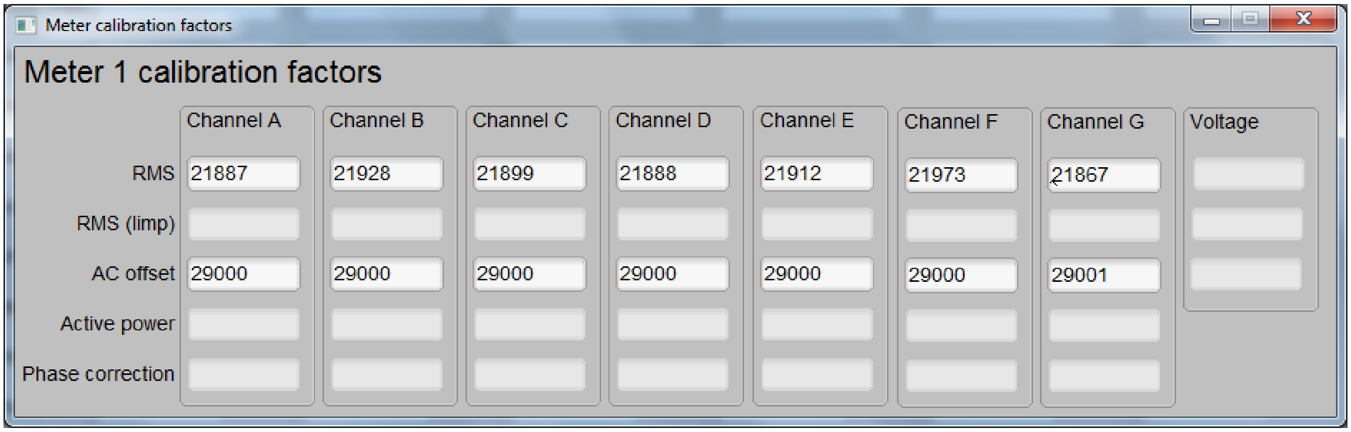


Figure 14. Calibration Factors Window (Snapshot of GUI Screen)

To calibrate the current readings:

1. Connect the GUI to view result for current.
2. Configure the test source to supply the desired current for all channels. Make sure that these are the current calibration points. Typically, these values are the same for every channel.
3. Click the Manual cal. button in the Results Window (see Figure 12) to open the window shown in Figure 15.

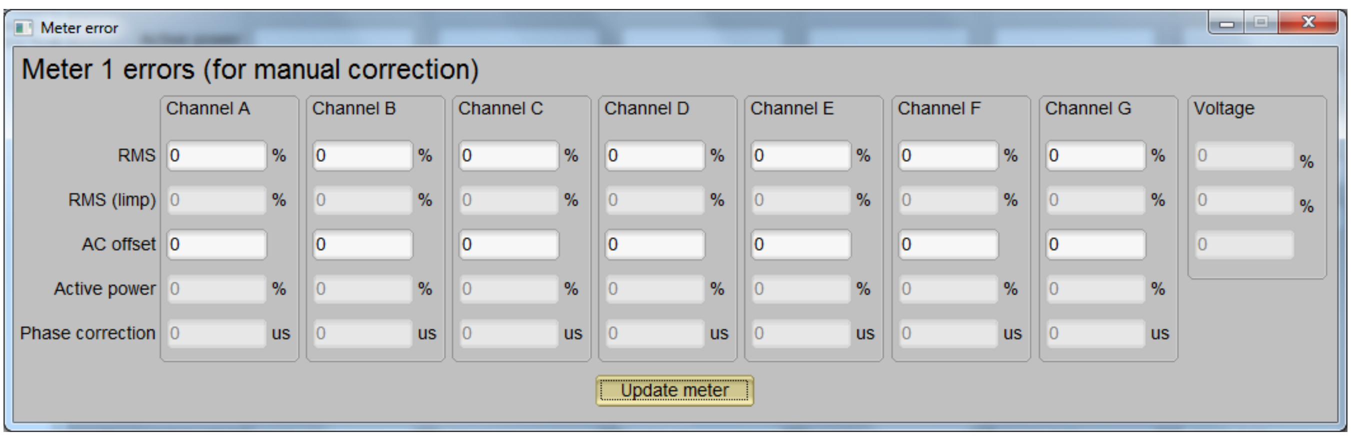


Figure 15. Manual Calibration Window (Snapshot of GUI Screen)

4. Calculate the correction values for each current. The correction values that need to be entered for the current fields are calculated by:

$$\text{Correction}(\%) = \left(\frac{\text{value}_{\text{observed}}}{\text{value}_{\text{desired}}} - 1\right) \cdot 100$$

   Where $\text{value}_{\text{observed}}$ is the value measured by the TI meter, and $\text{value}_{\text{desired}}$ is the calibration point configured in the AC test source.
5. After calculating Correction(%) for all currents, input these values as is (±) for the field “RMS” for the corresponding channels.
6. Click Update meter and the observed values for the currents on the GUI settle to the desired currents.

7 Test Results

7.1 Current Measurement Accuracy – Channel 1

Table 2. Test Results - Channel 1

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.499963	-0.01%
1	±1%	1.00008	0.01%
2.5	±1%	2.49995	0.00%
5	±1%	4.99943	-0.01%
10	±1%	10.0022	0.02%
15	±1%	15.0084	0.06%
25	±1%	25.004	0.02%
37.5	±1%	37.5029	0.01%
50	±1%	50.0011	0.00%
62.5	±1%	62.5045	0.01%
75	±1%	75.0189	0.03%
95	±1%	95.0579	0.06%

7.2 Current Measurement Accuracy – Channel 2

Table 3. Test Results - Channel 2

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.500044	0.01%
1	±1%	1.0002	0.02%
2.5	±1%	2.50036	0.01%
5	±1%	5.00036	0.01%
10	±1%	10.0032	0.03%
15	±1%	15.0105	0.07%
25	±1%	25.0072	0.03%
37.5	±1%	37.5039	0.01%
50	±1%	50.0063	0.01%
62.5	±1%	62.51	0.02%
75	±1%	75.0105	0.01%
95	±1%	95.0406	0.04%

7.3 Current Measurement Accuracy – Channel 3

Table 4. Test Results - Channel 3

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.500011	0.00%
1	±1%	1.00005	0.01%
2.5	±1%	2.49968	-0.01%
5	±1%	4.99986	0.00%
10	±1%	10.0008	0.01%
15	±1%	14.9981	-0.01%
25	±1%	24.9939	-0.02%
37.5	±1%	37.4922	-0.02%
50	±1%	49.9927	-0.01%
62.5	±1%	62.4936	-0.01%
75	±1%	74.9941	-0.01%
95	±1%	94.9936	-0.01%
100	±1%	100.018	0.02%

7.4 Current Measurement Accuracy – Channel 4

Table 5. Test Results - Channel 4

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.500023	0.00%
1	±1%	1.0001	0.01%
2.5	±1%	2.49985	-0.01%
5	±1%	5.0004	0.01%
10	±1%	10.0013	0.01%
15	±1%	15.0006	0.00%
25	±1%	24.9957	-0.02%
37.5	±1%	37.5009	0.00%
50	±1%	50.0009	0.00%
62.5	±1%	62.4976	0.00%
75	±1%	75.0042	0.01%
95	±1%	95.0056	0.01%
100	±1%	100.038	0.04%

7.5 Current Measurement Accuracy – Channel 5

Table 6. Test Results - Channel 5

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.49991	-0.02%
1	±1%	0.999975	0.00%
2.5	±1%	2.49944	-0.02%
5	±1%	4.99901	-0.02%
10	±1%	10	0.00%
15	±1%	14.9973	-0.02%
25	±1%	24.9922	-0.03%
37.5	±1%	37.491	-0.02%
50	±1%	49.9864	-0.03%
62.5	±1%	62.4894	-0.02%
75	±1%	74.996	-0.01%
95	±1%	94.9922	-0.01%
100	±1%	100.016	0.02%

7.6 Current Measurement Accuracy – Channel 6

Table 7. Test Results - Channel 6

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.499903	-0.02%
1	±1%	0.999998	0.00%
2.5	±1%	2.5003	0.01%
5	±1%	5.00028	0.01%
10	±1%	10.002	0.02%
15	±1%	15.0074	0.05%
25	±1%	25.0033	0.01%
37.5	±1%	37.5	0.00%
50	±1%	49.9962	-0.01%
62.5	±1%	62.4972	0.00%
75	±1%	74.9962	-0.01%
95	±1%	95.0319	0.03%

7.7 Current Measurement Accuracy – Channel 7

Table 8. Test Results - Channel 7

Current Input (A)	Expected Error	Reading Observed	Error
0.5	±1%	0.499952	-0.01%
1	±1%	1.00004	0.00%
2.5	±1%	2.50037	0.01%
5	±1%	5.00008	0.00%
10	±1%	10.0013	0.01%
15	±1%	15.0077	0.05%
25	±1%	25.0026	0.01%
37.5	±1%	37.4978	-0.01%
50	±1%	49.9955	-0.01%
62.5	±1%	62.4961	-0.01%
75	±1%	74.9928	-0.01%
95	±1%	95.0165	0.02%

7.8 Current Measurement Accuracy Graph

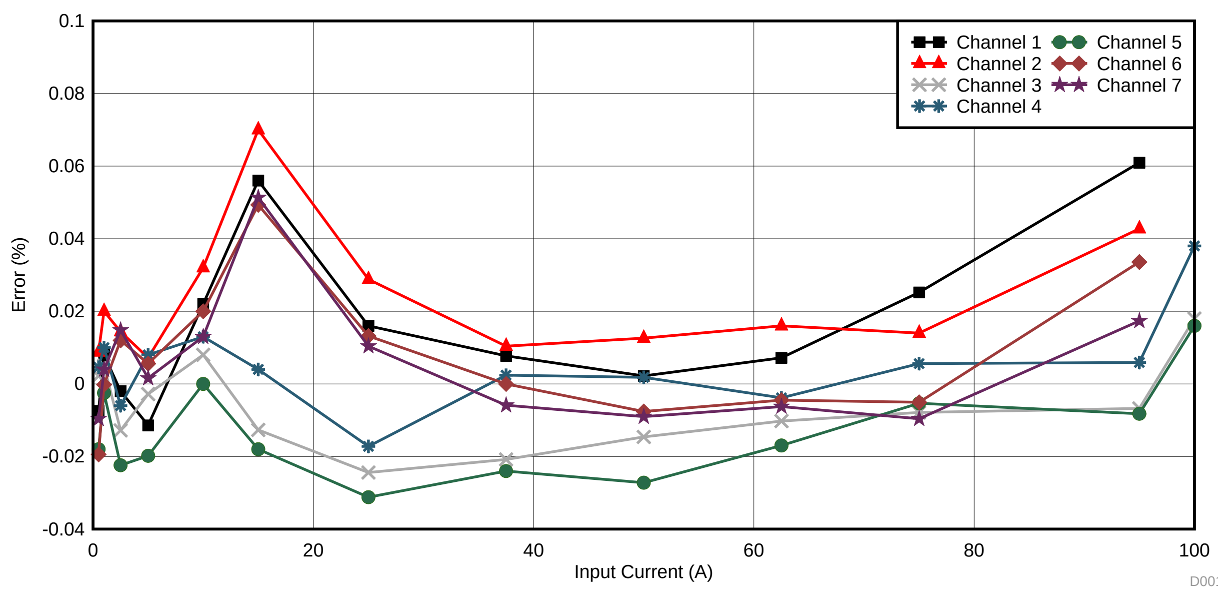


Figure 16. Current Measurement Accuracy for Channel 1 to Channel 7

NOTE: Accuracy of Current source is <0.1%.

8 Schematic

To download the schematics, see the design files at TIDA-00222.

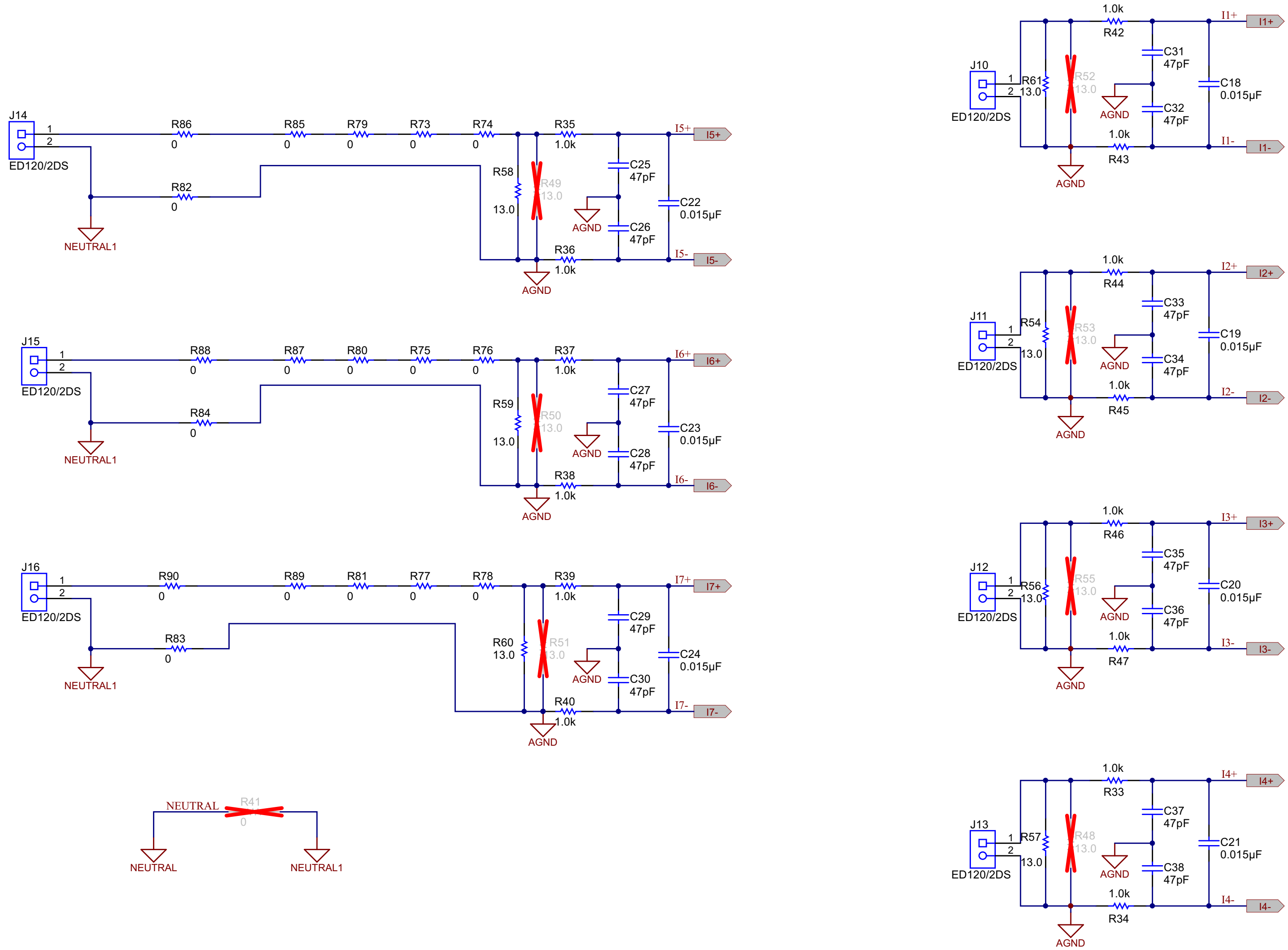


Figure 17. Schematic - Analog Front End (Current)

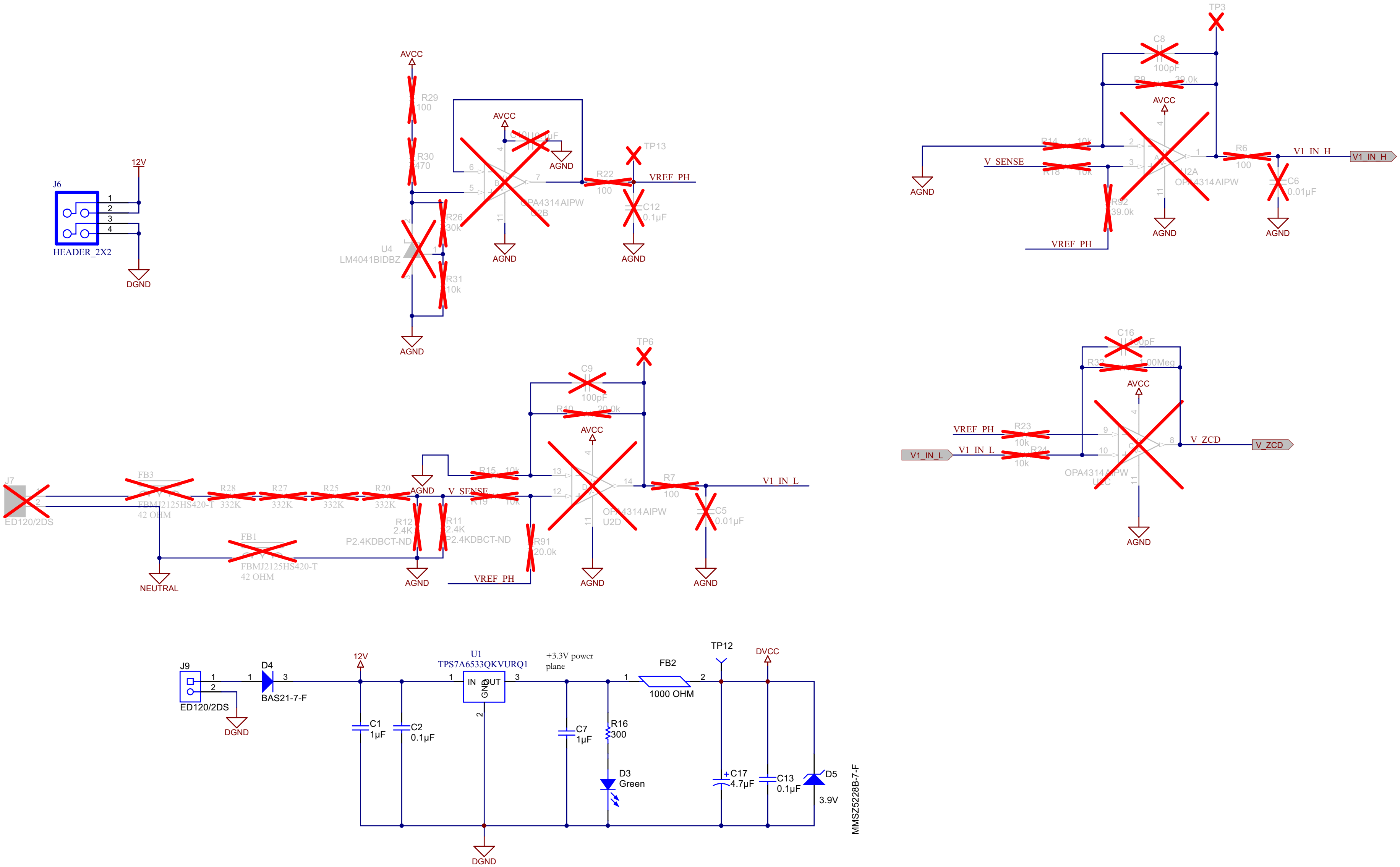


Figure 18. Schematic - LDO + ZCD

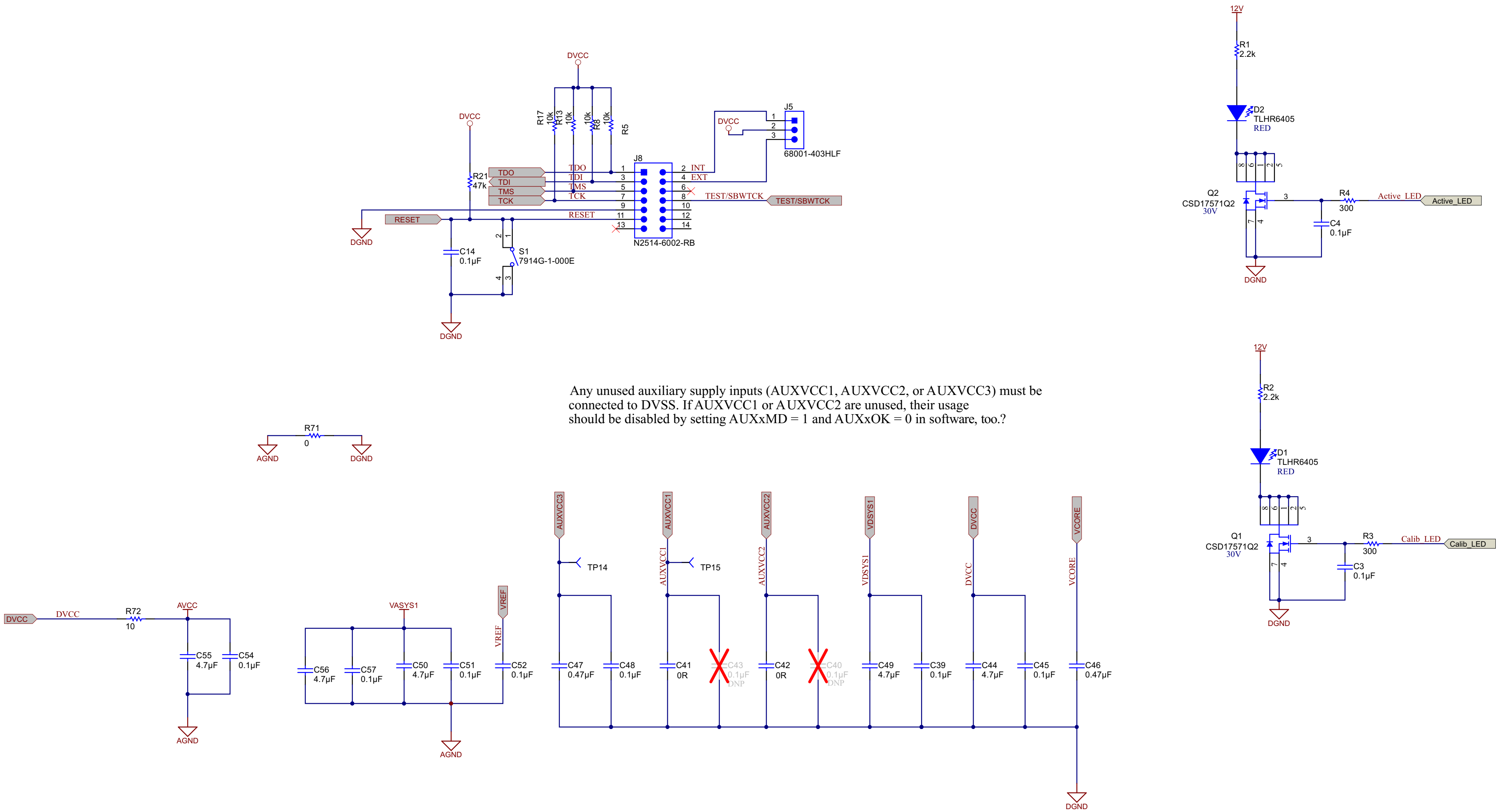


Figure 19. Schematic - JTAG Interface + LEDs + Decoupling Capacitors

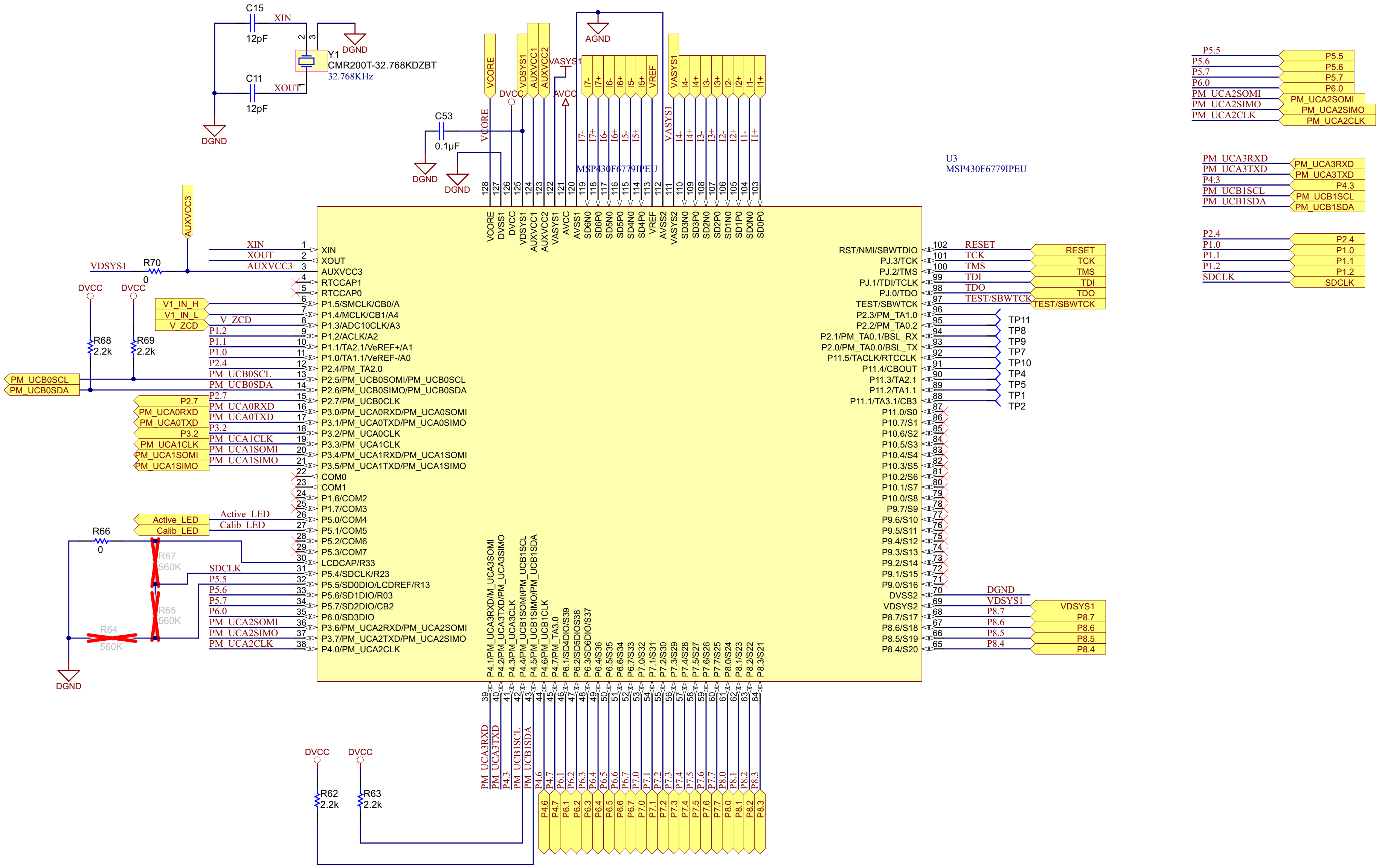


Figure 20. Schematic - MSP430F6779 + Crystal

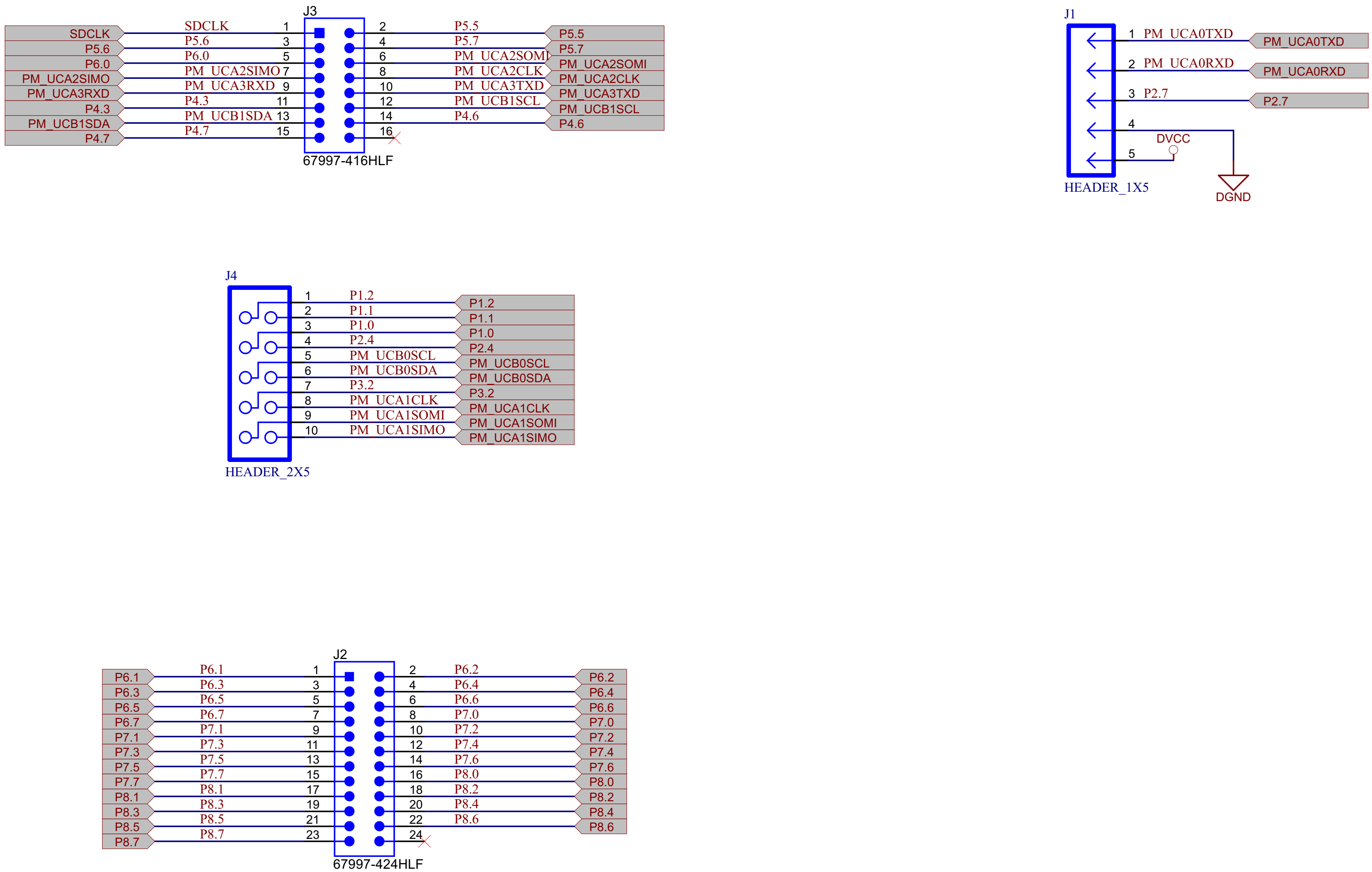


Figure 21. Schematic - Interface Connectors

9 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00222.

Table 9. Bill of Materials

Qty	Reference	Part Description	Manufacturer	Manufacturer PartNumber	PCB Footprint	Note
1	!PCB1	Printed Circuit Board	Any	TIDA-00221		
2	C1, C7	CAP, CERM, 1 µF, 16 V, ±10%, X7R, 0603	TDK	C1608X7R1C105K	0603	
2	C2, C13	CAP, CERM, 0.1 µF, 50 V, ±10%, X7R, 0603	Kemet	C0603C104K5RACTU	0603	
11	C3, C4, C14, C39, C45, C48, C51, C52, C53, C54, C57	CAP, CERM, 0.1 µF, 25 V, ±5%, X7R, 0603	AVX	06033C104JAT2A	0603	
0	C5, C6	CAP, CERM, 0.01 µF, 25 V, ±5%, C0G/NP0, 0603	TDK	C1608C0G1E103J	0603	DNI
0	C8, C9, C16	CAP, CERM, 100 pF, 50 V, ±1%, C0G/NP0, 0603	AVX	06035A101FAT2A	0603	DNI
0	C10, C12	CAP, CERM, 0.1 µF, 25 V, ±5%, X7R, 0603	AVX	06033C104JAT2A	0603	DNI
2	C11, C15	CAP, CERM, 12 pF, 50 V, ±5%, C0G/NP0, 0603	AVX	06035A120JAT2A	0603	
1	C17	CAP, TA, 4.7 µF, 35 V, ±10%, 1.9 ohm, SMD	Vishay-Sprague	293D475X9035C2TE3	6032-28	
7	C18, C19, C20, C21, C22, C23, C24	CAP, CERM, 0.015 µF, 50 V, ±10%, X7R, 0805	AVX	08055C153KAT2A	0805_HV	
14	C25, C26, C27, C28, C29, C30, C31, C32, C33, C34, C35, C36, C37, C38	CAP, CERM, 47 pF, 500 V, ±5%, C0G/NP0, 0805	MuRata	GRM21A5C2E470JW01D	0805_HV	
0	C40, C43	CAP, CERM, 0.1 µF, 25 V, ±5%, X7R, 0603	AVX	06033C104JAT2A	0603	DNI
3	C41, C42, R66	RES 0.0 Ω, 1/10 W JUMP 0603 SMD	Vishay-Dale	CRCW06030000Z0EA	0603	
5	C44, C49, C50, C55, C56	CAP, CERM, 4.7 µF, 10 V, ±10%, X5R, 0603	AVX	0603ZD475KAT2A	0603	
2	C46, C47	CAP, CERM, 0.47 µF, 25 V, ±10%, X7R, 0603	MuRata	GRM188R71E474KA12J	0603	
2	D1, D2	LED, 5 MM, RED, TH	VISHAY	TLHR6405	LED_5MM	
1	D3	LED SmartLED Green 570 NM	OSRAM	LG L29K-G2J1-24-Z	LED0603AA	
1	D4	Diode, Switching, 200 V, 0.2 A, SOT-23	Diodes Inc.	BAS21-7-F	SOT-23	
1	D5	Diode Zener 3.9 V, 500 MW, SOD123	Diodes Incorporated	MMSZ5228B-7-F	sod-123	
0	FB1, FB3	Ferrite Bead, 42 Ω, 4 A, DCR0.008 Ω, SMT-0805	TAIYO YUDEN	FBMJ2125HS420-T	0805_hv	DNI
1	FB2	Ferrite Chip 1000 Ω, 300 mA, 0603	TDK Corporation	MMZ1608B102C	0603	
1	J1	Header, Male 5-pin, 100-mil spacing	TE Connectivity	826926-5	HEADER_5P	
1	J2	Header, TH, 100-mil, 12×2, Gold plated, 230 mil above insulator	FCI	67997-424HLF	TSW-112-07-G-D	

Table 9. Bill of Materials (continued)

Qty	Reference	Part Description	Manufacturer	Manufacturer PartNumber	PCB Footprint	Note
1	J3	Header, 8×2, 100 mil, TH	FCI	67997-416HLF	TSW-108-07-G-D	
1	J4	Header, Male 2×5-pin, 100-mil spacing	FCI	67997-410HLF	HDR2X5	
1	J5	3-pin berger	FCI	68001-403HLF	HDR1X3	
1	J6	Header, 2×2-pin, 100-mil spacing	FCI	67997-404HLF	HDR_2X2	
0	J7	Terminal Block 5.08 MM Vert 2POS, TH	On-Shore Technology	ED120/2DS	CONN_ED120-2DS	DNI
1	J8	Header, 7×2, 100 mil, SMT	Molex	N2514-6002-RB	3M_N2514-6002-RB	
8	J9, J10, J11, J12, J13, J14, J15, J16	Terminal Block 5.08 MM Vert 2POS, TH	On-Shore Technology	ED120/2DS	CONN_ED120-2DS	
2	Q1, Q2	MOSFET, N-CH, 30 V, 22 A, SON 2×2 MM	Texas Instruments	CSD17571Q2	SON_CSD17571Q2	
6	R1, R2, R62, R63, R68, R69	RES, 2.2 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06032K20JNEA	0603	
3	R3, R4, R16	RES, 300 Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW0603300RJNEA	0603	
4	R5, R8, R13, R17	RES 10 KΩ, 1/10 W, 5% 0603 SMD	Vishay-Dale	CRCW060310K0JNEA	0603	
0	R6, R7, R22, R29	RES, 100 Ω, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603100RFKEA	0603	DNI
0	R9, R92	RES 390 KΩ, 1/10 W, 1% 0603 SMD	Vishay Dale	CRCW0603390KFKEA	0603	DNI
0	R10, R91	RES, 200 kΩ, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603200KFKEA	0603	DNI
0	R11, R12	RES 2.40 KΩ, 1/8 W, 1% 0805 SMD	Vishay-Dale	CRCW08052K40FKEA	0805_hv	DNI
0	R14, R15, R18, R19	RES, 100 kΩ, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603100KFKEA	0603	DNI
0	R20, R25, R27, R28	RES, 332 kΩ, 1%, 0.125 W, 0805	Vishay-Dale	CRCW0805332KFKEA	0805_HV	DNI
1	R21	RES, 47 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW060347K0JNEA	0603	
0	R23, R24	RES 10 KΩ, 1/10 W, 5% 0603 SMD	Vishay-Dale	CRCW060310K0JNEA	0603	DNI
0	R26	RES, 30 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW060330K0JNEA	0603	DNI
0	R30	RES, 470 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW0603470RJNEA	0603	DNI
0	R31	RES, 10.0 kΩ, 1%, 0.1 W, 0603	Vishay-Dale	CRCW060310K0FKEA	0603	DNI
0	R32	RES 1.00 MΩ, 1/10 W, 1% 0603 SMD	Vishay-Dale	CRCW06031M00FKEA	0603	DNI
14	R33, R34, R35, R36, R37, R38, R39, R40, R42, R43, R44, R45, R46, R47	RES, 1.0 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00JNEA	0603	
0	R41	RES, 0 Ω, 5%, 0.125 W, 0805	Vishay-Dale	CRCW08050000Z0EA	0805_HV	DNI
0	R48, R49, R50, R51, R52, R53, R55	RES, 13.0 Ω, 1%, 0.125 W, 0805	Vishay-Dale	CRCW080513R0FKEA	0805_HV	DNI
7	R54, R56, R57, R58, R59, R60, R61	RES, 13.0 Ω, 1%, 0.125 W, 0805	Vishay-Dale	CRCW080513R0FKEA	0805_HV	
0	R64, R65, R67	RES 560 KΩ, 1/10 W, 1% 0603 SMD	Vishay-Dale	CRCW0603560KFKEA	0603	DNI
20	R70, R71, R73, R74, R75, R76, R77, R78, R79, R80, R81, R82, R83, R84, R85, R86, R87, R88, R89, R90	RES, 0 Ω, 5%, 0.125 W, 0805	Vishay-Dale	CRCW08050000Z0EA	0805_HV	

Table 9. Bill of Materials (continued)

Qty	Reference	Part Description	Manufacturer	Manufacturer PartNumber	PCB Footprint	Note
1	R72	RES, 10 Ω, 5%, 0.125 W, 0805	Vishay-Dale	CRCW080510R0JNEA	0805_HV	
1	S1	Switch, Tactile, SPST-NO, 0.1 A, 16 V, SMT	Bourns	7914G-1-000E	SW_7914G-1-000E	
1	U1	IC, 300-mA 40-V Low-Dropout Regulator with 25-µA Quiescent Current	Texas Instruments	TPS7A6533QKVURQ1	KVU_1	
0	U2	Low-Voltage Rail-to-Rail Output Operational Amplifiers, PW0014A	Texas Instruments	OPA4314AIPW	PW0014A_N	DNI
1	U3	IC, MCU 16BIT, 512KB FLASH, LQFP-128	Texas Instruments	MSP430F6779IPEU	QFP50P1600X2200X160-128N	
0	U4	IC, Micropower Shunt Voltage Reference 100 ppm/°C, 45 µA to 12 mA, Adjustable	Texas Instruments	LM4041BIDBZ	SOT-23	DNI
1	Y1	Crystal, 32.768 KHz, 6 pF, ±20 PPM, SMD-3P	CITIZEN	CMR200T-32.768KDZBT	XTAL_CMR200T	

10 PCB Layer Plots

To download the layer plots, see the design files at TIDA-00222.

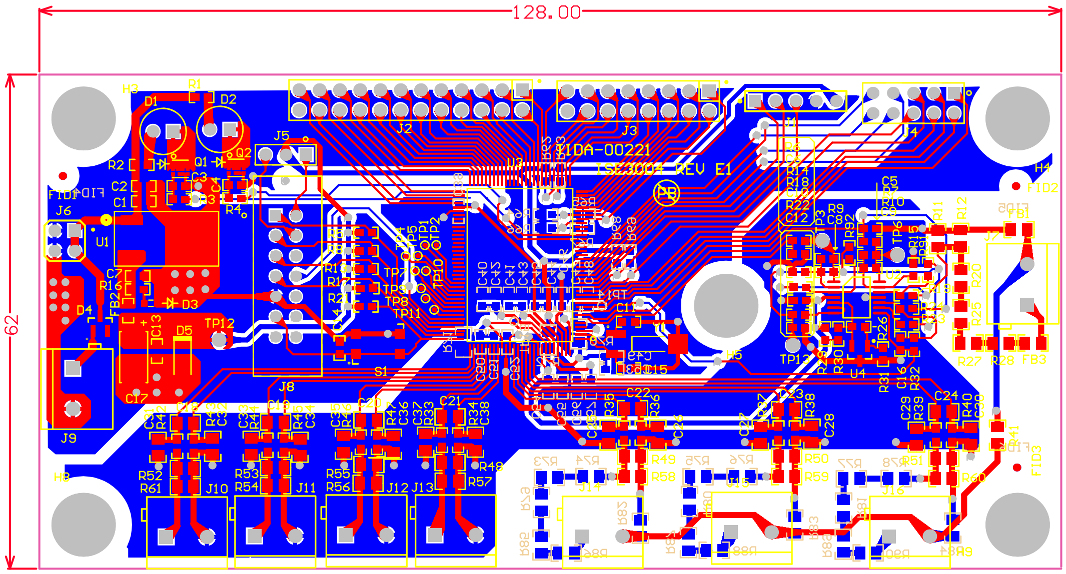


Figure 22. Multilayer Composite Print

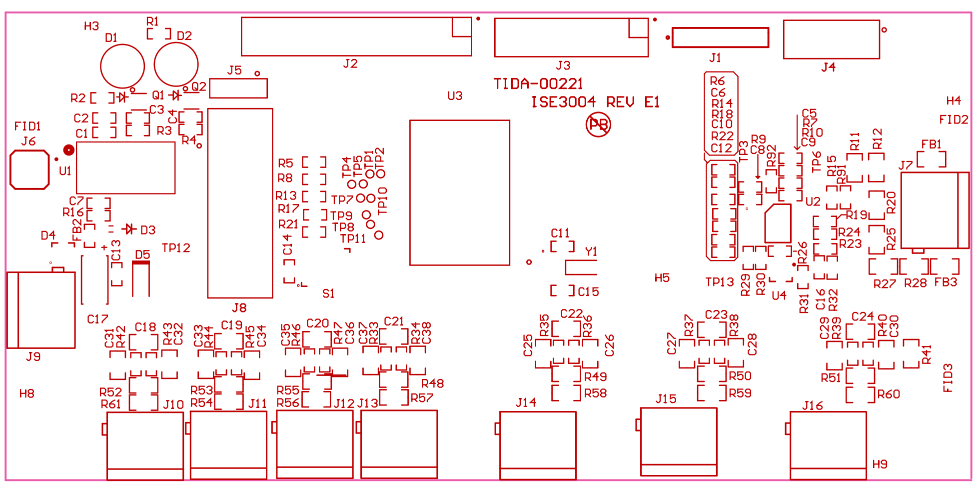


Figure 23. Top Overlay

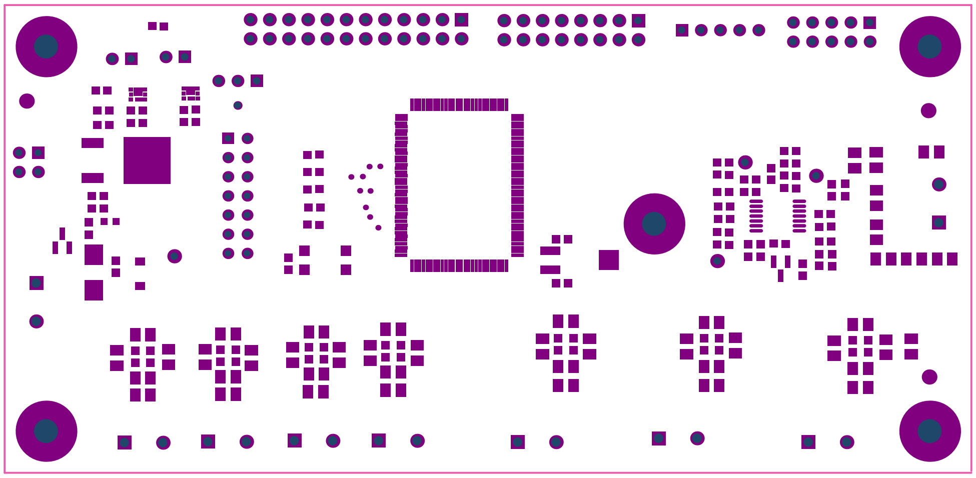


Figure 24. Top Solder

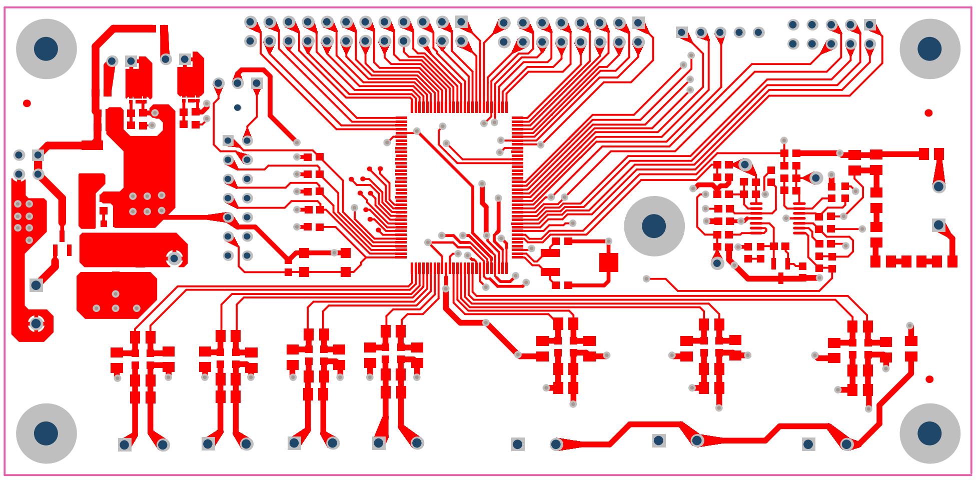


Figure 25. Top Layer

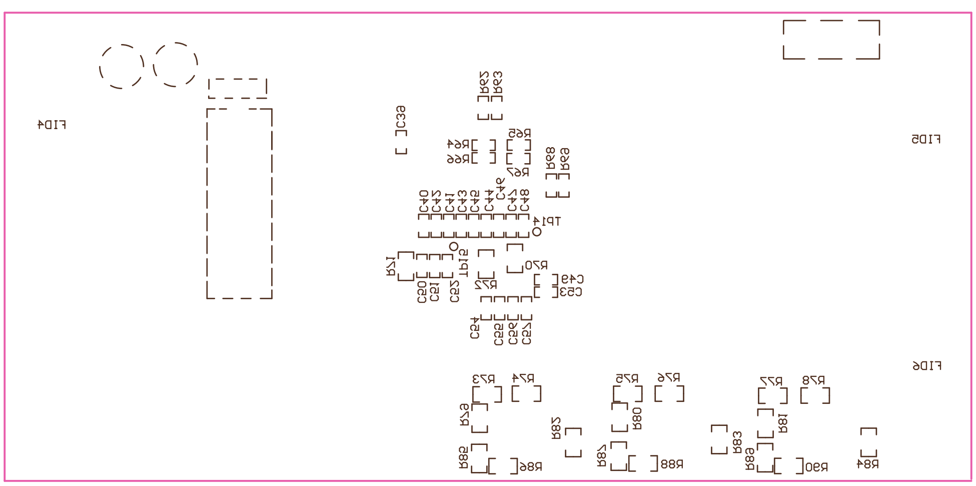


Figure 26. Bottom Overlay

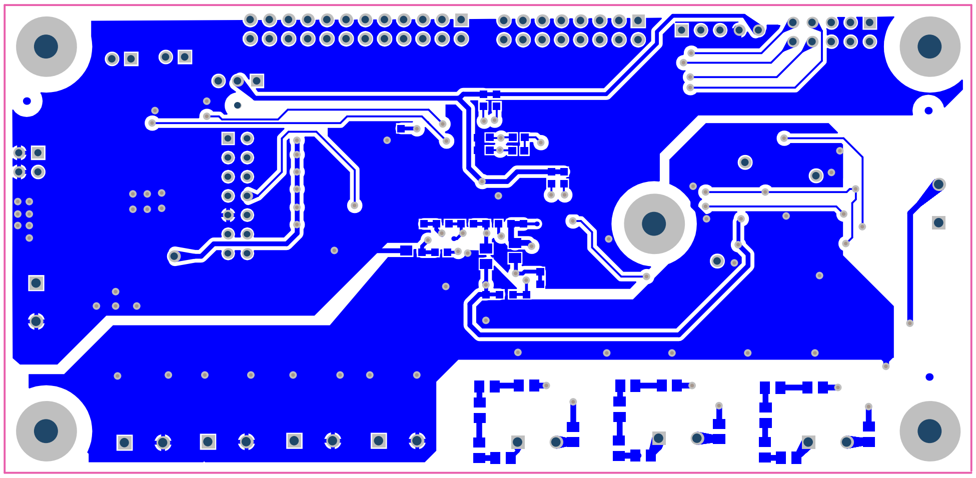


Figure 27. Bottom Layer

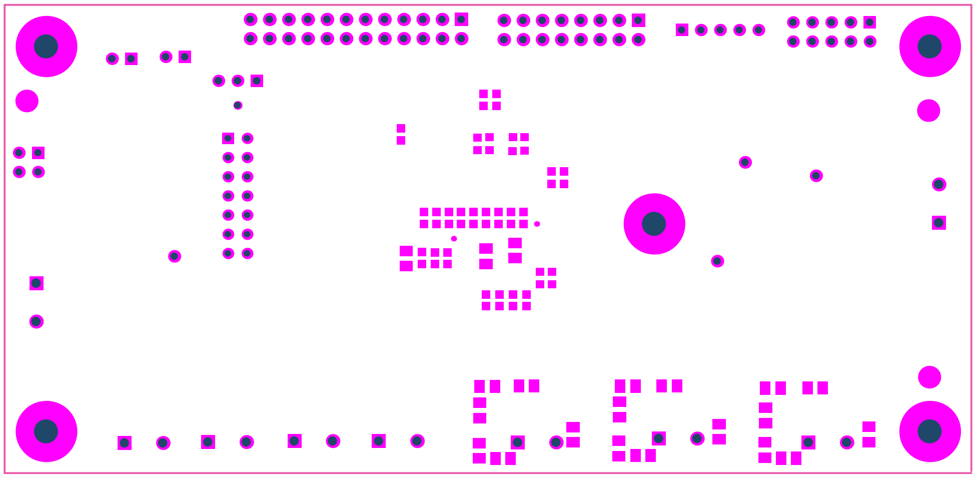
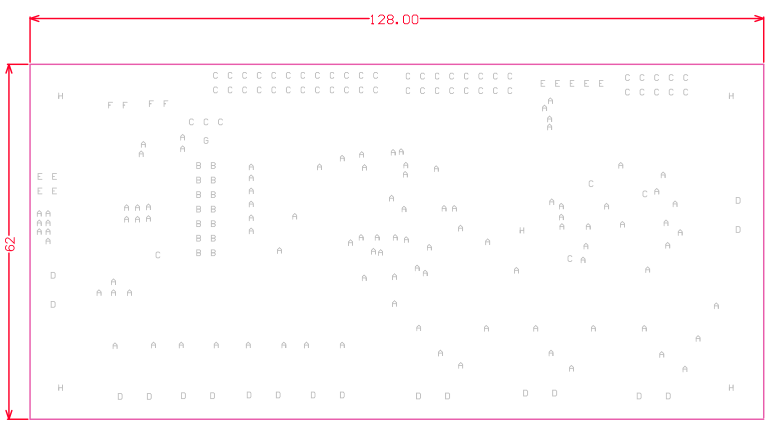


Figure 28. Bottom Solder



Symbol	Hit Count	Tool Size	Plated	Hole Type
A	100	20mil (0.508mm)	PTH	Round
G	1	35mil (0.889mm)	NPTH	Round
B	14	35mil (0.889mm)	PTH	Round
E	9	38mil (0.965mm)	PTH	Round
C	57	40mil (1.016mm)	PTH	Round
F	4	40.945mil (1.04mm)	PTH	Round
D	18	49.213mil (1.25mm)	PTH	Round
H	5	125.984mil (3.2mm)	PTH	Round
	208 Total			

Drill Table

Figure 29. Drill Drawing

11 Altium Project

To download the Altium project files, see the design files at TIDA-00222.

12 About the Author

PRAHLAD SUPEDA is a Systems Engineer at Texas Instruments India where he is responsible for developing reference design solutions for the Smart Grid within Industrial Systems. Prahlad Supeda brings to this role his extensive experience in power electronics, EMC, Analog, and Mixed Signal Designs. He has system-level product design experience in Switchgears, Circuit Breakers & Energy Meters. Prahlad Supeda earned his Bachelor of Instrumentation and Control Engineering from Nirma University, India. He can be reached at prahlad@ti.com

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TIDA-00221 Revision History

Changes from Original (October 2014) to A Revision **Page**

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

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