TI Designs
Measurement Module for Branch Circuit Power Monitor/Sub Meter

TEXAS INSTRUMENTS

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Design Resources

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TIDA-00222	Tool Folder Containing Design Files
MSP430F6779	Product Folder
TPS7A6533-Q1	Product Folder
CSD17571Q2	Product Folder
OPA4314	Product Folder
LM4041B	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 High Accuracy
- Monitors up to Seven Current Channels and One Voltage Channel
- Current Measurement Accuracy <±2% From 10-200% of Rated Current
- Power Measurement Accuracy ±1% From 10-200% of Rated Current and Rated Voltage (110 V or 230 V AC)
- Sampling at 4096Hz
- Universal Asynchronous Receiver/Transmitter (UART) Interface (TTL Level) Connector for Communication
- Three LEDs for Indication

Featured Applications

- Data Centers
- Sub-metering
- Building automation
- Load Management
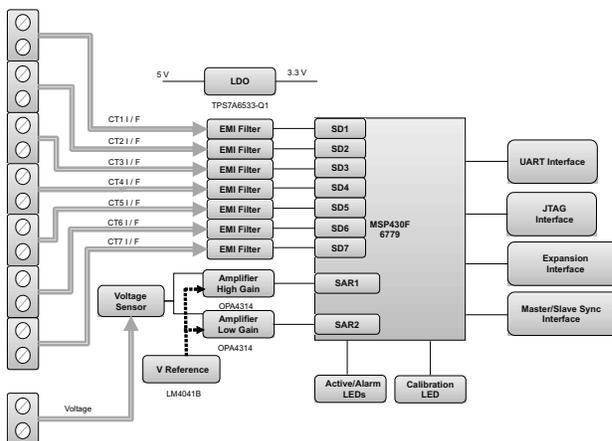
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1 System Description

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

The BCPM is a current sensing device that monitors multiples on a panel board within a power distribution unit. Designed for use in multiple-location data centers, the BCPM provides branch circuit amperage and power information, and initiates alarms. The BCPM enables the data center operator to manage power by anticipating overloaded circuit breakers.

The branch circuit power monitor system continuously measures the current on all breaker levels and warns of impending trouble, so that proactive steps can be taken. 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 BCPM consists of a signal acquisition board with current sensor and potential dividers for voltage measurement, RS485 for communication and visible and 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

1.2 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 sub-metering 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. Sub-metering 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.

1.3 Monitoring Electrical Usage

Sub-metering systems provide accurate and timely snapshots of a facility's energy use from a single circuit or device all the way up to an entire building and beyond sub-meters are installed on the facility side of the master utility meter to provide a number of energy monitoring functions including:

- Electrical usage analysis and identification of peak demand levels for load comparisons
- Fair and equitable cost allocation for tenant billing
- Measurement, verification and benchmarking of kW/kWh for energy and green building initiatives

1.4   Energy Analysis

The type of energy data needed by today's sophisticated facility manager is well beyond the capability of the master utility meter at the main service entrance. Master meters provide a broad indication of consumption and demand, but true load profiling requires specific interval usage data from key loads to isolate the causes of load peaks as a first step to eliminating them or moving them to off-peak hours when rates are lower.

As first-level data gathering tools in the facility load profiling process, sub-meters provide high-accuracy interval data snapshots of energy use and demand from enterprise level all the way down to a specific circuit or item of equipment. The use of meters and sub-metering systems provide energy information necessary for:

* Load profiling and benchmarking
* Measurement and verification
* BAS integration
* Power quality analysis
* Usage aggregation

1.5   Cost Allocation

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 are able to 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 will be inclined to take the necessary steps to ease the pressure on their budgets by reducing overall energy use.

1.6   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 are able to 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 sub-metering of actual energy usage in two ways.

First, 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. The second benefit is that they 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.

1.7   Commercial - Office and Retail

In today's commercial office, retail and mixed-use facility environments, you will find sub-meter-based energy monitoring solutions benefitting parties on both sides of the electric bill. At the enterprise level, sub-meters 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, sub-meters 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. Sub-meters 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.

1.8 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-ops and mixed-use buildings have been shown to use up to 25% less energy when sub-meters hold them accountable for the power they use. Wireless meters and accessories are the perfect cost-effective solution for tenant metering and common area allocation.

1.9 Industrial and 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.

In any type of industrial facility, whether process or discrete manufacturing, the Branch Circuit Power Monitor features include:

- The capability to monitor the following at the mains level:
  - RMS current (A)
  - RMS voltage (V)
  - Active power (W)
  - Apparent power (VA)
  - Power factor
  - Active energy (Wh)
  - Unbalanced load percentage
- The capability to monitor the following at the branch circuit level:
  - RMS current (A)
  - RMS voltage (V)
  - Active power (W)
  - Apparent power (VA)
  - Power factor
  - Active energy (Wh)
  - Unbalanced load percentage
- BCPM generic specifications:
  - Accuracy
    - ±1% for Power
    - ±2% for Currents and Voltages
  - Number of channels: Model dependent
  - Frequency: 50/60 Hz
  - Measurement resolution: > 1280 Hz
  - Serial communication - RS485 / RS232
  - Connection: 2-wire

1.10 Critical Requirements for BCPM/Sub-Meter

- Number of channels monitored for Voltages and Currents
- Measurement accuracy
- Communication capability

Table 1 provides a brief difference between Branch Current Monitor (BCM) and Branch Circuit Power Monitor (BCPM) for the current TI designs.

Table 1. Comparison BCM v/s BCPM

	BCM	BCPM
Current	7	7
Voltage	0	1
Power	NA	Yes
Communication	Yes	YEs

2 Design Features

This TI design demonstrates the Current Measurement, Voltage and Power measurement capabilities using Sigma-Delta ADC required for BCPM. With this design, customers will be able to measure the Current, Voltage and Power more accurately compared to many of the current solutions. All of the relevant design files like the schematics, bill of materials (BOM), layer plots, Altium files, Gerber, MSP430F6779 microcontroller (MCU) software and executable for easy-to-use graphical user interface (GUI) have also been provided.

Table 2. Design Specification

SL NUMBER	FEATURES	DESCRIPTION
1	Current Inputs and Range	7 ΔΣ ADC Current channel Range: 10 – 200% of Rated Current (50A)
2	Voltage Input and range	90 – 277 Vac
3	Input Frequency	50/60Hz
4	Current Accuracy	< ±2%
5	Voltage Accuracy	< ±2%
6	Power accuracy	As per IEC 62053-21 Class 1
7	Sampling Rate	4096Hz
8	MCU	MSP430F6779
9	Power supply	Input: 5 V Vdc Output: 3.3 Vdc
10	LED Indication	3 LEDs
11	Communication Interface	UART, serial peripheral interface (SPI), inter-integrated circuit (I2C)

3 Block Diagram

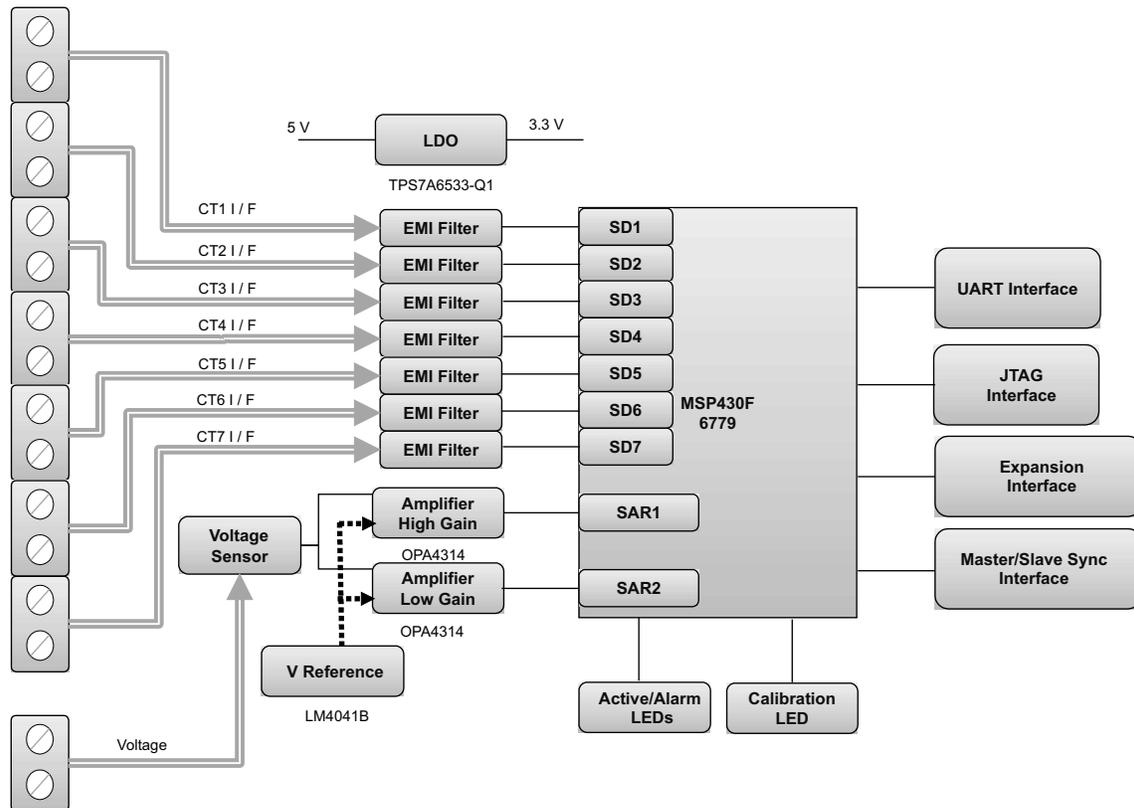The measurement module reference design includes the block shown in Figure 1.

Figure 1. Block Diagram of BCPM Module

3.1 MCU

MCU MSP430F6779 is used in the current design. This MCU has 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. AC input voltage is measured using internal 10-bit SAR ADC. The availability of Software Modules and integration of 24-bit ADC lead to the selection of the MSP430F6779 MCU.

3.2 Current Inputs, Voltage Inputs and EMI Filter

There is a 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 using 24-bit ΣΔ ADC. Distributed current is measured through CT. Interfacing of CT to the measurement module is through the 2-pin terminal block provided for each current channel. CT output 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.

AC input voltage is interfaced through 2-pin terminal block. Resistor divider is used to sense voltage. The choice of voltage divider resistors selected ensures the mains voltage is divided down to the normal input range, suitable to ADC. 10 bit SAR ADC is used to sense voltage signal. SAR ADC accepts only unipolar signal. AC input voltage is level shifted by AVCC/2 and given as input to ADC. The high gain ADC input is not being measured. This is for future expansion.

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 5 V 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 consumption, 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 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 BCPM.

AC input voltage is measured by internal SAR ADC of MCU. 10-bit SAR ADC is used to sense voltage. The ΣΔ24_B on the MSP430F6779 module has a trigger generator that triggers the ADC10 to ensure that the timing between the ADC10 and ΣΔ modules are grouped and synchronized. MSP430F6779 is used in this TI design.

4.2 Current Inputs, Voltage Inputs and EMI Filters

4.2.1 Current Inputs and 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.
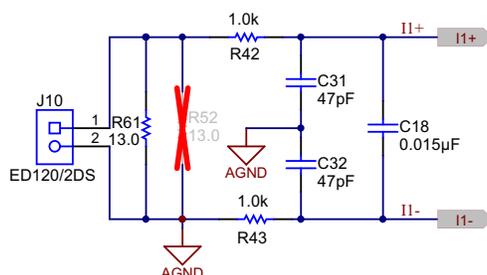

Figure 2. Current Input Schematic

The calculation shown below can be used to calculate burden resistor value:

Maximum Primary Sensing Current → Imax (pri)	= 100 Arms
Maximum Peak Primary Current → Imax_pk (pri)	= 100 Arms
	= 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) X Np/Ns
	= (141 X 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
	= <= 13.03 Ω

So, 13 Ω 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.

4.2.2 Voltage Inputs

The voltage divider resistors for the AC input voltage channel is selected to ensure the input to the MCU is less than the ADC input voltage for the entire range on input voltages; ferrite beads are used for filtering. 10-bit SAR ADC is used to sense the voltage signal. SAR ADC takes only unipolar signal. AC input voltage is bipolar. DC offset of AVCC / 2 (1.65 V) is provided to the op-amp circuit to level shift the AC input.

Resistor divider calculation:

Max sensing voltage → V_{max}	=	300 V_{rms} (taking design margin of ~20 V)
Peak Max sensing voltage → Vmax_pk	=	V_{max} X 1.414
	=	425 V

To make the bipolar signal unipolar, a DC offset of AVCC/2 = 1.65 V is added. So, the effective range for the Vmax_pk equivalent signal is 3.3 V − 1.65 V = 1.65 V = Vmax_pk_out.

Practically multiple parameters impact max range that can be measured by ADC. Parameters like ADC non-linearity, op-amp max output voltage. Here, the 100 mV margin is considered. So:

Effective Vmax_pk_out	=	1.65 V - 0.1 V
	=	1.55 V

Op-amp-based pre-amplifier circuit of gain 2 is used in the design. So, the resistor divider equivalent signal for effective Vmax_pk_o:

	=	1.55 V / 2
	=	775 mV

To limit power loss through resistor divider, total resistance across line and neutral should > 1 MΩ. So, 332 KΩ X 4 = 1.33 MΩ values are chosen.

Calculating R12 with Vmax_pk = 425 V, V_{out} = 775 mV
and Rupper = 1.33 MΩ.

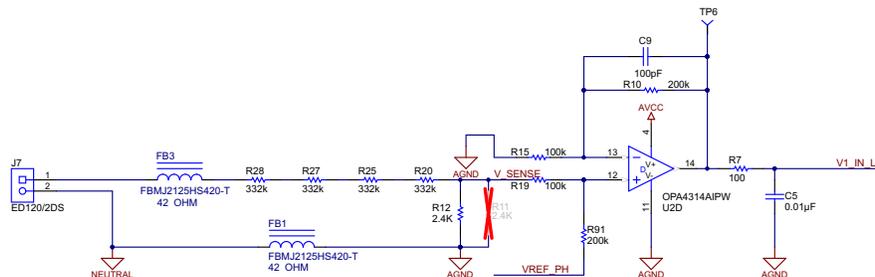|		
R12	=	V_{out} X Rupper / Vmax_pk
	=	2.42 KΩ

Figure 3. Voltage Input Schematic

4.2.3 OPA4314 Op-Amp

The OPA4314 family of single, dual and quad-channel operational amplifiers represents a new generation of low-power, general-purpose CMOS amplifiers. Rail-to-rail input and output swings, low quiescent current (150 µA typ at 5.0 VSS) combined with a wide bandwidth of 3 MHz, and very low noise (14 nV/√Hz at 1 kHz) make this family very attractive for a variety of battery-powered applications that require a good balance between cost and performance. The low input bias current supports applications with mega-Ω source impedances.

The robust design of the OPA314 devices provides ease-of-use to the circuit designer: unity-gain stability with capacitive loads of up to 300 pF, an integrated RF/EMI rejection filter, no phase reversal in overdrive conditions, and high electrostatic discharge (ESD) protection (4-kV HBM).

These devices are optimized for low-voltage operation as low as +1.8 V (±0.9 V) and up to +5.5 V (±2.75 V), and are specified over the full extended temperature range of –40°C to +125°C. The quad-channel OPA4314 used is TSSOP-14 package.

Table 3. OPA4314 Specifications

| Characteristics	OPA4314
Iq Total (Max) (mA)	0.720
Number of Channels	4
Rail-to-Rail	In/Out
Operating Temperature Range (°C) (Package dependent exception exist)	-40 to 125
Vos (Offset Voltage @ 25°C) (Max) (mV)	2.5
Offset Drift (Typ) (µV/C)	1
Vn at 1kHz (Typ) (nV/rtHz)	14
CMRR (Min) (dB)/PSRR	94/92
IBias (Max) (pA)	10
Total Supply Voltage (Max) (+5 V = 5, ± 5 V = 10)	5.5
Total Supply Voltage (Min) (+5 V = 5, ± 5 V = 10)	1.8
Slew Rate (Typ) (V/µs)	1.5
GBW (Typ) (MHz)	3
Pin/Package	14, TSSOP
ESD-Human model- KV	4
EMI Filter	Internal
Vo (Swing)	V_{CC}-60 mV
Vcm (input)	V-(-0.2 V) , V+ (+0.2 V)

4.2.4 LM4041 Adjustable Precision Shunt Voltage Reference

The LM4041 series of shunt voltage references are versatile, easy-to-use references suitable for a wide array of applications. The reference is used for level shifting the AC voltage input by AVDD/2. 1.65 V is a level by which the input voltage is shifted. This series requires no external capacitors for operation and is stable with all capacitive loads. Additionally, the reference offers low-dynamic impedance, low noise, and a low temperature coefficient to ensure a stable output voltage over a wide range of operating currents and temperatures. The LM4041 uses fuse and Zener-zap reverse breakdown voltage trim during wafer sort to offer four output voltage tolerances, ranging from 0.1% (max) for the A grade to 1% (max) for the D grade. Thus, a great deal of flexibility is offered to designers in choosing the best cost-to-performance ratio for their applications. The LM4041 is available in a fixed (1.225 V nominal) or an adjustable version (which requires an external resistor divider to set the output to a value between 1.225 V and 10 V).

4.2.5 Features

- Small packages: SOT23, SC70-5
- No output capacitor required
- Output voltage tolerance
- LM4041D: ±1% at 25°C
- Low output noise: 20 µVrms (10Hz to 10kHz)
- Wide operating current range: 60 µA to 12 mA
- Extended temperature range: -40°C to +125°C
- Low temperature coefficient : 100ppm/°C (max)

The reference output is buffered using Op-amp.
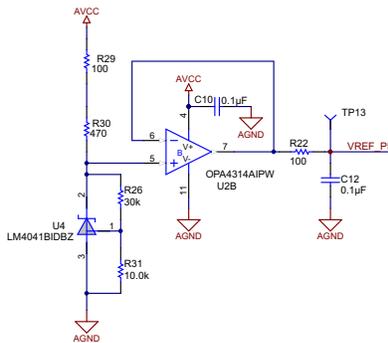
4.3 Power Supply

An external DC supply should be connected on 2-pin terminal block to power the measurement module. TPS7A6533-Q1 LDO is used in the design. A maximum of 12 V DC input must be applied. DVCC for the measurement module is 3.3 V. The power supply is protected for reverse polarity and over voltage. There is an LED to indicate the power supply healthiness.
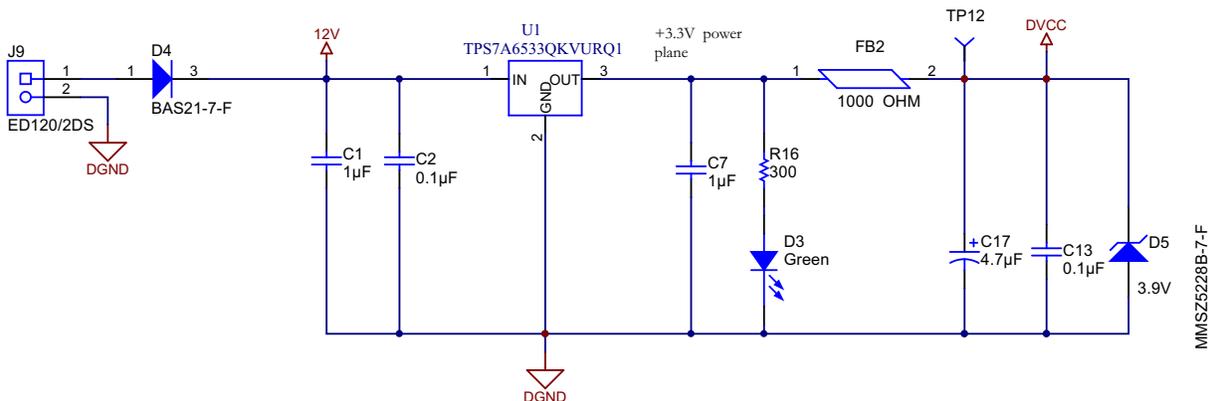

Figure 4. Power Supply

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.
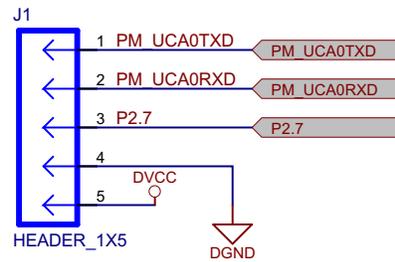
Figure 5. RS232 (TTL level) Communication Interface

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 the measurement module and can be programmed for some of the functions:

- Alive LED – This indicated that the measurement module functioning is normal
- Metrology LED – Metrology LED can magnitude of current flowing
- Alarm LED - Can be used to indicate any abnormal conditions of current during measurement

> **NOTE:** These features have not been implemented as part of this design.

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 input/output (GPIO). 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 the 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.

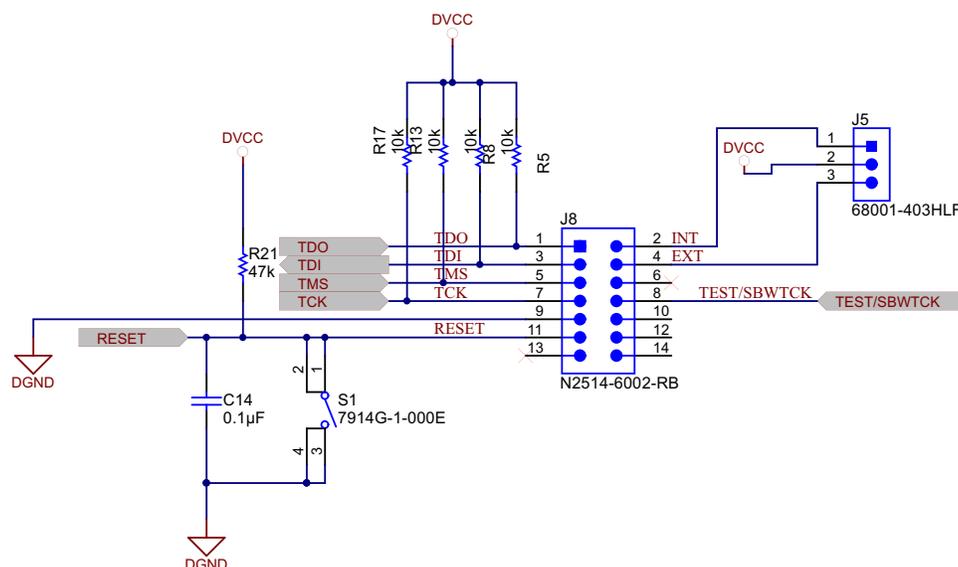**Figure 6. JTAG Programming Interface**

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.
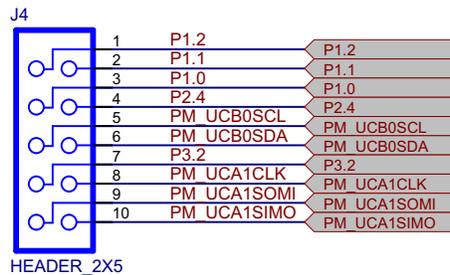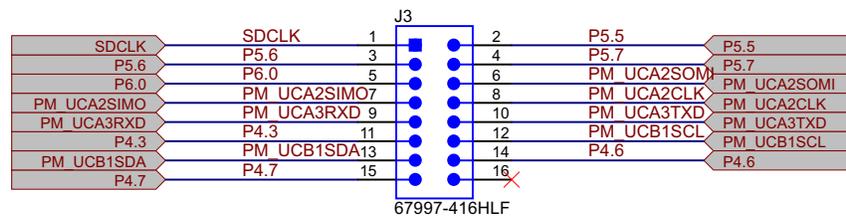

Figure 7. SPI, I2C, UART Expansion Interface

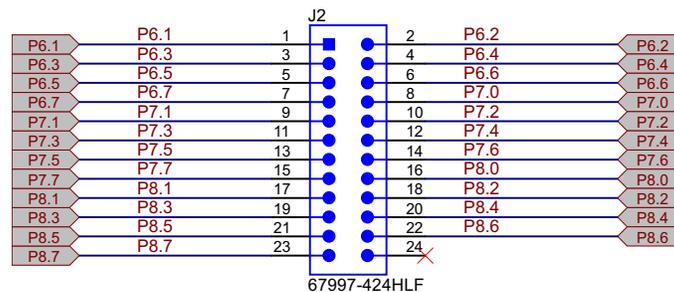- I/O interface connector – for future logic and communication expansion

Figure 8. I/O Expansion Interface

5 Software Description

The software has three projects in this design: one for mathematical routines, another primarily for metrology (current and voltage calculation), and an application wrapper that deals mainly with application-processor functionality (communication, and so forth). The software is described in the following subsections. 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 ΣΔ24s are 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
- A4.0+ and A4.0- → Current I5
- A6.0+ and A6.0- → Current I7

5.2 ADC10 Setup

The ADC10 is used to sample the Mains voltage and is triggered by the ΣΔ's trigger generator. When triggered by the ΣΔ, the ADC10 enters autoscan mode and samples all of its 16 ADC channels once. In the software, the clock to the ADC10 is set to 4 MHz. The sample and hold time for each converter is 8 cycles and the conversion time is 12 cycles, which results in a total of ≈ 20 cycles (≈5 μs) delay between conversion results of adjacent converters. In addition, the ADC10_A uses AVCC as the reference voltage and is configured to output 10-bit results that are scaled to 16-bit two's complement numbers (ADC10DF=1). This allows the ADC results from the ADC10 to be treated as a 16-bit signed number when performing mathematical operations.

The following is the relevant ADC10 channel associations:

A4 → Voltage

5.3 Foreground Process

The foreground process includes the initial setup of the MSP430 hardware and software immediately after a device RESET. Figure 9 shows the flowchart for this process.
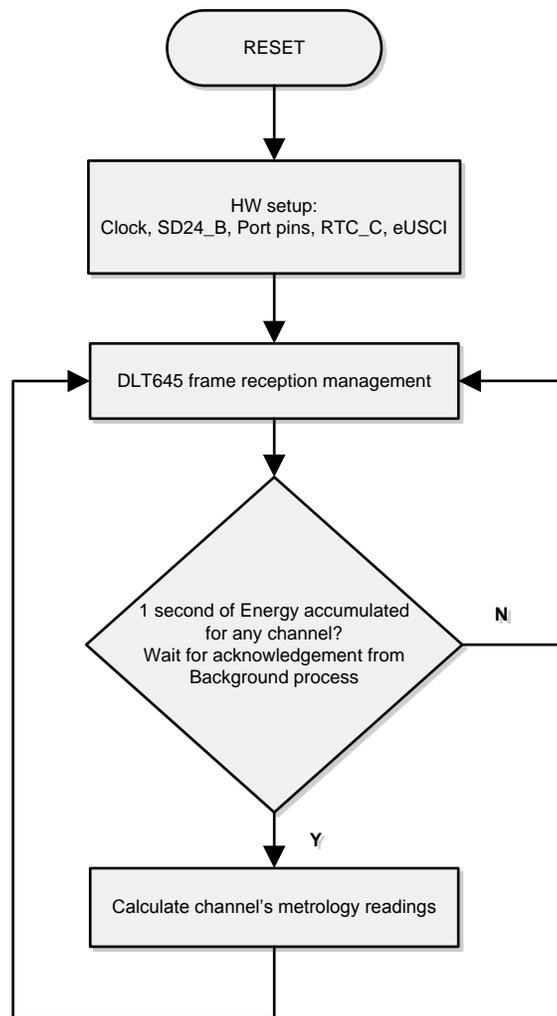

Figure 9. Foreground Process

The initialization routines involve the setup of the ADC, clock system, GPIO (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. The data frame consists of the processed dot products that were accumulated for one second in the background process. This is equivalent to accumulation of 50 or 60 cycles of data synchronized to the incoming voltage signal. In addition, a sample counter keeps track of how many samples have been accumulated over this frame period. This count can vary as the software synchronizes with the incoming mains frequency.

The processed dot products include the V_{RMS}, I_{RMS}, active power, and reactive power. These dot products are used by the foreground process to calculate the corresponding metrology readings in real-world units. Processed voltage dot products are accumulated in 48-bit registers. In contrast, processed current dot products, active energy dot products, and reactive energy dot products are accumulated in separate 64-bit registers to further process and obtain the RMS and mean values. Using the foreground's calculated values of active and reactive power, the apparent power is calculated. The frequency (in Hertz) and power factor are also calculated using parameters calculated by the background process using the formulas in Section 4.2.1.

The formula used to calculate RMS current is shown in Equation 1.

5.3.1 Computation Formulas

This section briefly describes the formulas used for the voltage, current, energy, and temperature calculations.

5.3.1.1 *RMS Voltage and Current*

As described in the previous sections, voltage and current samples are obtained from the ΣΔ converters at a sampling rate of 4096 Hz. All of the samples that are taken in 1 second are kept and used to obtain the RMS values for voltage and current for each channel. The RMS values are obtained in Equation 1.

$$V_{RMS,ch} = K_{v,ch} * \sqrt{\frac{\sum_{n=1}^{Sample\ count} v_{ch}(n) * v_{ch}(n)}{Sample\ count}} - v_{offset,ch} \qquad I_{RMS,ch} = K_{i,ch} * \sqrt{\frac{\sum_{n=1}^{Sample\ count} i_{ch}(n) * i_{ch}(n)}{Sample\ count}} - i_{offset,ch}$$

(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)]
- $V_{ch}(n)$ = Voltage sample at a sample instant *n*
- $V_{offset,\ ch}$ = Offset used to subtract effects of the additive white Gaussian noise from the voltage converter
- Sample count = Number of samples in one second
- $K_{i,ch}$ = Scaling factor for each current

5.3.1.2 *Power and Energy*

Power and energy are calculated for one frame's worth of active and reactive energy samples. These samples are phase corrected and passed on to the foreground process, which uses the number of samples (sample count) to calculate channel active and reactive powers by the formulas in Equation 2.

$$P_{ACT,ch} = K_{ACT,ch} \frac{\sum_{n=1}^{Sample\ count} v(n) \times i_{ch}(n)}{Sample\ count} \qquad P_{REACT,ch} = K_{REACT,ch} \frac{\sum_{n=1}^{Sample\ count} v_{90}(n) \times i_{ch}(n)}{Sample\ count}$$

(2)

Where,

- v_{90},ch (n) = Voltage sample at a sample instant *n* shifted by 90°
- $K_{ACT,ch}$ = Scaling factor for active power
- $K_{REACT,ch}$ = Scaling factor for reactive power
- For reactive power, the 90° phase shift approach is used for two reasons:
- It allows accurate measurement of the reactive power for very small currents.
- It conforms to the international specified measurement method.

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Because the frequency of the mains varies, it is important to first measure the mains frequency accurately to phase shift the voltage samples accordingly (see Section 5.4.2).

To get an exact 90° phase shift, interpolation is used between two samples. For these two samples, a voltage sample slightly more than 90° before the current sample and a voltage sample slightly less than 90° before the current sample are used. The application's phase shift implementation consists of an integer part and a fractional part. The integer part is realized by providing an N samples delay. The fractional part is realized by a one-tap FIR filter. In the software, a lookup table provides the filter coefficients that are used to create the fractional delays.

After calculating the active and reactive power, each phase's apparent power is calculated in Equation 3.

$$P_{APP,ch} = \sqrt{P_{ACT,ch}^2 + P_{REACT,ch}^2} \tag{3}$$

The calculated powers for each phase are then converted to energy by Equation 4.

$$E_{ACT,ch} = P_{ACT,ch} \times Samplecount$$

$$E_{REACT,ch} = P_{REACT,ch} \times Samplecount$$

$$E_{APP\ ch} = P_{APP\ ch} \times Samplecount \tag{4}$$

The calculated energies are then accumulated into buffers that store the total amount of energy consumed since meter reset. There are seven sets of buffers that are available: one for each channel. Within each set of buffers, the following energies are accumulated:

- Active import energy (active energy when active energy >= 0)
- Active export energy (active energy when active energy < 0)
- Reactive Quad I energy (reactive energy when reactive energy >=0 and active power >=0; inductive load)
- Reactive Quad II energy (reactive energy when reactive energy >=0 and active power <0; capacitive generator)
- Reactive Quad III energy (reactive energy when reactive energy <0 and active power <0; inductive generator)
- Reactive Quad IV energy (reactive energy when reactive energy <0 and active power >=0; capacitive load)
- Approximate import energy (apparent energy when active energy >=0)
- Approximate export energy (apparent energy when active energy <0)

5.3.1.3   Frequency (Hz)

The background process calculates the frequency in terms of samples per mains cycle. The foreground process then converts this to Hertz by Equation 5.

$$Frequency\ (\textbf{Hz}) = \frac{Sampling\ Rate\ (samples\ /\ second)}{Frequency\ (samples\ /\ cycle)} \tag{5}$$

5.3.1.4   Power Factor

After the active power and apparent power have been calculated, the absolute value of the power factor is calculated. In the meter's internal representation of power factor, a positive power factor corresponds to a capacitive load and generator and a negative power factor corresponds to an inductive load and generator. The sign of the internal representation of power factor is determined based on the sign of the active and reactive power. Therefore, the internal representation of power factor is calculated in Equation 6.

$$Internal\ Representation\ of\ Power\ Factor = \begin{cases} \dfrac{|P_{Act}|}{P_{Apparent}}, if\ capacitive\ load\ /\ generator \\[3mm] -\dfrac{|P_{Act}|}{P_{Apparent}}, if\ inducitive\ load\ /\ generator \end{cases} \tag{6}$$

5.4   Background Process

The background function deals mainly with timing critical events in software. It uses the ΣΔ interrupt as a trigger to collect voltage and current samples. The ΣΔ interrupt is generated when the trigger generator of the ΣΔ triggers the ADC10. Once the trigger to the ADC is generated, sample processing is done on the previously obtained voltage and current samples. This sample processing is done by the *per_sample_dsp()* function. The flowchart for the *per_sample_dsp()* function is shown in Figure 10.

The *per_sample_dsp()* function is used to calculate intermediate dot product results that are fed into the foreground process for the calculation of metrology readings. The ADC10 is configured to represent the 10-bit voltage results as a 16-bit signed result. Because 16-bit voltage samples are used, the voltage samples are further processed and accumulated in dedicated 48-bit registers. In contrast, since 24-bit current samples are used, the current samples are processed and accumulated in dedicated 64-bit registers. Per-channel active power and reactive power are also accumulated in 64-bit registers.

After sufficient samples (approximately one second's worth) have been accumulated, then the foreground function is triggered to calculate the final values of V_{RMS}, I_{RMS}, active, reactive, and apparent powers, active, reactive, and apparent energy, and power factor. 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.

Whenever there is a leading-edge zero-crossing (- to + voltage transition) on a voltage channel, the *per_sample_dsp()* function is also responsible for updating the corresponding phase's frequency (in samples/cycle) and voltage sag or swell conditions. For the sag conditions, whenever the RMS voltage is below a certain user-defined threshold percentage, the number of Mains cycles where this condition persists is logged as the sag duration. The number of periods in time where there was a sag condition is logged as the sag events count. Note that the sag duration corresponds to the total number of cycles in a sag condition since reset, and is not cleared for every sag event. Also, when the RMS voltage is above a certain threshold percentage, swell events and duration are logged in a similar way.
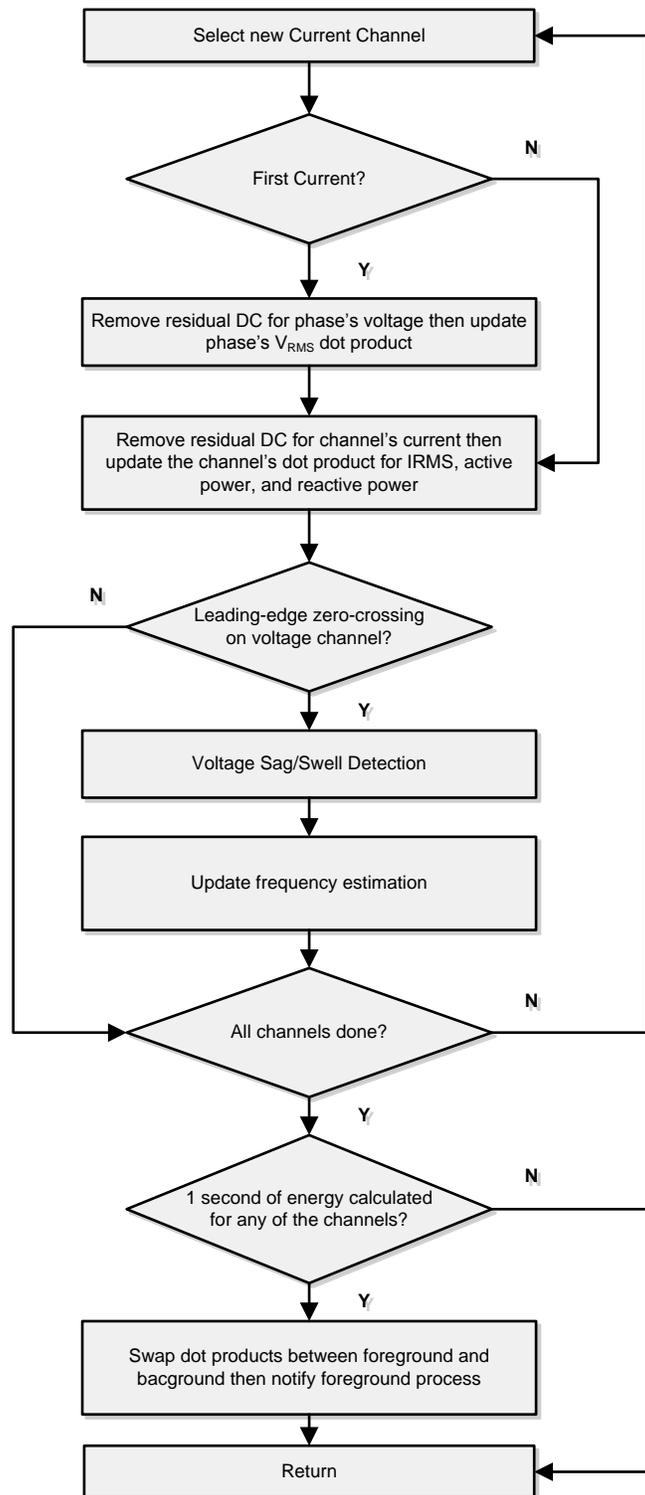
Figure 10. per_sample_dsp() Function

The following sections describe the various elements of electricity measurement in the *per_sample_dsp()* function.

5.4.1 Voltage and Current Signals

The output of each ΣΔ and ADC10 converter is a signed integer and any stray dc or offset value on these converters are removed using a dc tracking filter. Separate dc estimates for all voltages and currents are obtained using the filter and voltage and current samples, respectively. These estimates are then subtracted from each voltage and current sample.

The resulting instantaneous voltage and current samples are used to generate the following intermediate dot product results:

- Accumulated squared values of voltages and currents, which is used for V_{RMS} and I_{RMS} calculations, respectively.
- Accumulated energy samples to calculate active energies
- Accumulated energy samples using current and 90° phase shifted voltage to calculate reactive energies

5.4.2 Frequency Measurement and Cycle Tracking

The instantaneous voltage of each phase is accumulated in 48-bit registers. In contrast, the instantaneous current, active power, and reactive power are accumulated in 64-bit registers. A cycle tracking counter and sample counter keep track of the number of samples accumulated. When approximately one second's worth of samples have been accumulated, the background process switches the foreground and background then notifies the foreground process to produce the average results such as RMS and power values. Cycle boundaries are used to trigger the foreground averaging process since it produces very stable results.

For frequency measurements, a straight line interpolation is used between the zero crossing voltage samples. Figure 11 shows the samples near a zero cross and the process of linear interpolation.
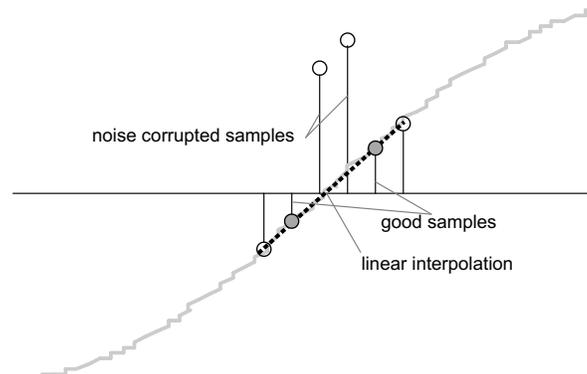

Figure 11. Frequency Measurement

Because noise spikes can also cause errors, the application uses a rate of change check to filter out the possible erroneous signals and make sure that the two points are interpolated from are genuine zero crossing points. For example, with two negative samples, a noise spike can make one of them positive and, therefore, make the negative and positive pair looks as if there is a zero crossing.

The resultant cycle-to-cycle timing goes through a weak low-pass filter to further smooth out cycle-to-cycle variations. This results in a stable and accurate frequency measurement that is tolerant of noise.

5.4.3 Phase Compensation

When a current transformer (CT) is used as a sensor, it introduces additional phase shift on the current signals. Also, the voltage and current input circuit's passive components may introduce additional phase shift. Another source of phase shift is the sequential sampling on the voltage channel. The relative phase shift between voltage and current samples must be compensated to ensure accurate measurements. The ΣΔ converters have programmable delay registers (ΣΔ24PREx) that can be applied to any current. This built-in feature (PRELOAD) is used to provide the phase compensation required.

The fractional delay resolution of the preload register is a function of input frequency (f_{IN}), OSR, and the sampling frequency (f_S).

$$Delay\ resolution_{Deg} = \frac{360° \times f_{IN}}{OSR \times f_S} = \frac{360° \times f_{IN}}{f_M}$$

(7)

In this application, for input frequency of 60 Hz, OSR of 256, and sampling frequency of 4096, the resolution for every bit in the preload register is approximately 0.02° with a maximum of 5.25° (maximum of 255 steps). When using CTs that provide a larger phase shift than this maximum, sample delays along with fractional delay must be provided. This phase compensation can also be modified while the application is running to accommodate temperature drifts in CTs, but conversions on the ΣΔ must be stopped while changes are made to the phase compensation.

5.5 Configuring for BCPM

The code base for BCM and BCPM are part of the below named exe files:

- EnergyLibraryBCM-3.0-windows-installer.exe
- EnergyLibraryBCPM-3.0-windows-installer.exe

Although each executable produces a different package, the code base for the two packages are the same. The only difference is the definition of either the "CONFIGURATION_BCM" or "CONFIGURATION_BCPM" macros, which is used to choose between the BCM and BCPM software. These macros are in "metrology-template.h", so it requires the metrology project being compiled first then the application project if the setting is changed.

5.6 Future Enhancements

Sufficient processing and memory is available to implement the following:

- Alarms for voltages
- Alarms for currents
- Alarms for power
- Average voltages and currents
- Frequency
- Demand computation
- Modbus protocol for communication

6   Test Data

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 the one below:

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-6602"/>
      <log requests= "on" responses="on"/>
      <scaling voltage="1.0" current="1.0"/>
  </reference-meter>
```

4. Run calibrator.exe in the 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 will open.

   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.

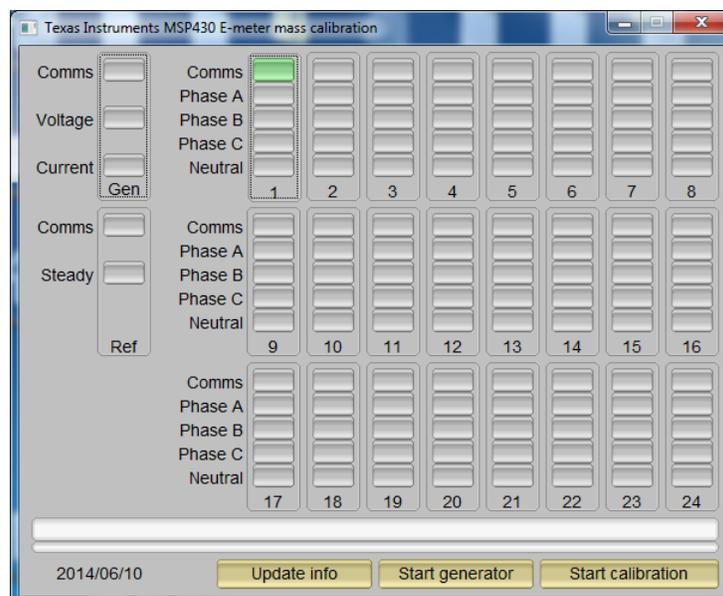5. Click on the green button to open the results window (see Figure 12).

Figure 12. GUI Startup Window

6. From the results window, the total-energy consumption readings and sag/swell logs could be viewed by pressing the "Meter Consumption" button. Once this is pressed, the meter events and consumption window pops up as shown in Figure 14.
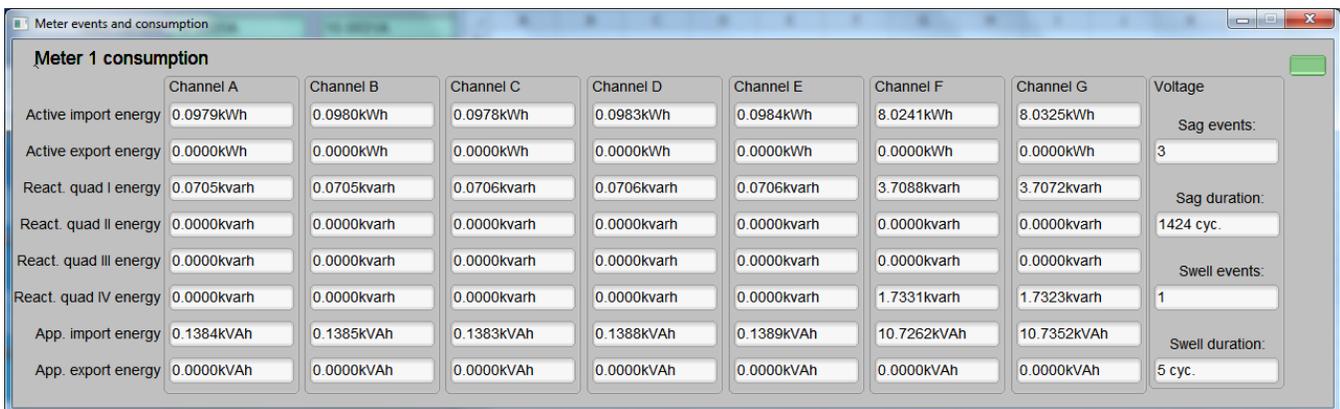

Figure 13. Results Window

Figure 14. Meter Events and Consumption

7. The configuration of the meter can also be viewed by clicking Meter features to open the screen shown in Figure 15.
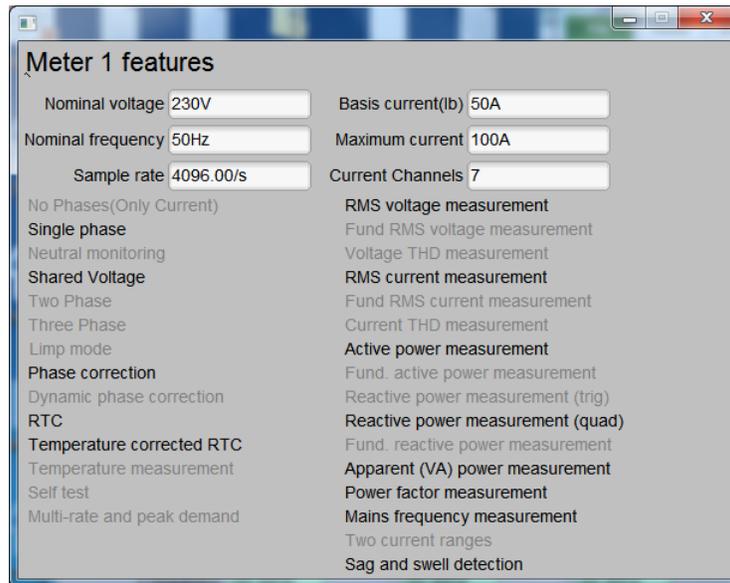

Figure 15. Meter Features Window

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 calibration to be performed accurately, an accurate AC test source and a reference meter must be available. The source should be able to generate any desired voltage, current, and phase shift (between V and I). To calculate errors in measurement, the reference meter acts as an interface between the source and the meter that is being calibrated. This section describes a simple and effective method of calibration of 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 meter, there are four main calibration factors for each channel: current scaling factor, current AC offset, power scaling factor, and the phase compensation factor. In addition, there is also the voltage scaling factor and voltage AC offset for the voltage converter. The voltage, current, and power scaling factors translate measured quantities in metrology software to real-world values represented in volts, amps, and watts, respectively. The voltage AC offset and current AC offset are used to eliminate the effect of additive white Gaussian noise associated with each channel. This noise is orthogonal to everything except itself. As a result, it is present only when calculating RMS voltages and currents. The last calibration factor is the phase compensation factor, which is used to compensate any phase shifts introduced by the current sensors and other passives.

When the meter software is flashed with the code (available in the zip file, which is provided with the installer in the software design files), 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 16. 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. For phase correction, a conversion must be made from microseconds to register units since the software's phase correction parameters are in units of modulation clock cycles instead of microseconds. To convert the value displayed by the GUI into a value that can be used by the associated macro in emeter-template, multiply the "Phase correction" variable on the GUI by 8.338608, round the resulting number to the nearest integer, and then right-shift by 3.
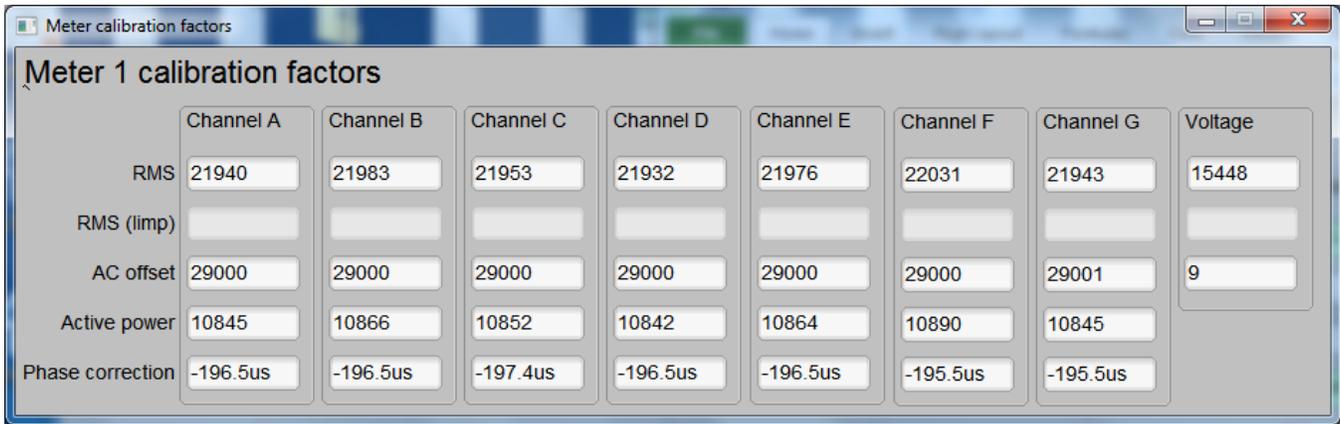
Figure 16. Calibration Factors Window

6.2.1 Voltage, Current and Power Gain Calibration

To perform gain calibration:

1. Connect the GUI to view result for voltage, current, active power, and the other metering parameters.

2. Configure the test source to supply the desired voltage and current for all phases. Make sure that these are the voltage and current calibration points with a zero-degree phase shift between each phase's voltage and current. For example, 230 V, 10A, 0° (PF = 1). Typically, these values are the same for every channel.

3. Click the Manual calibrate button in the Results window (see Figure 17) to open the window shown in Figure 17.
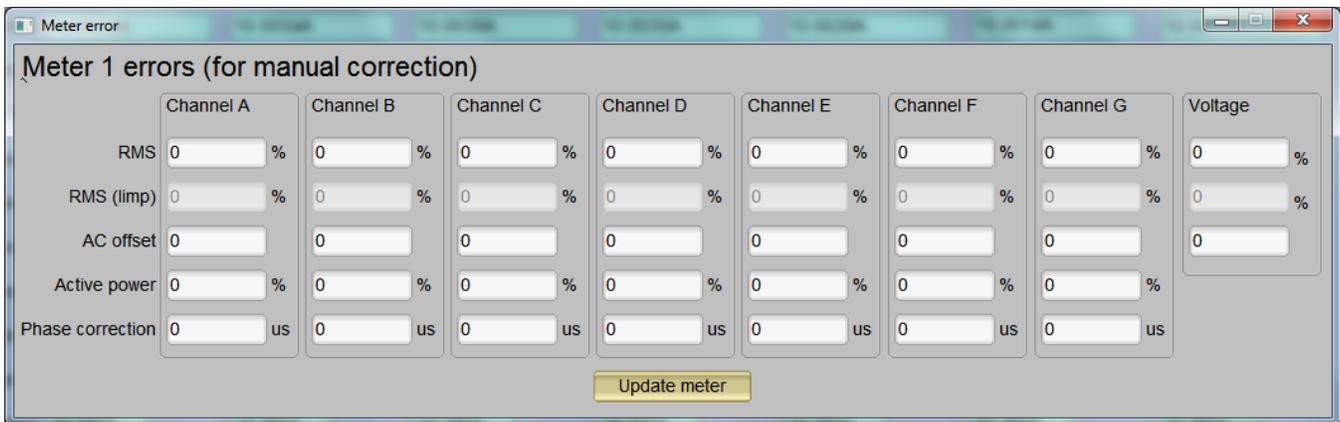
Figure 17. Manual Calibration Window

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

$$Correction\ (\%) = \left(\frac{value_{observed}}{value_{desired}} - 1 \right) * 100$$

(8)

Where, value$_{observed}$ is the value measured by the TI meter, and value$_{desired}$ 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. After calculating Correction(%) for the voltage, input these values as is (±) for the field "RMS" for voltage.

7. After calculating Correction(%) for all active powers, input these values as is (±) for the field "Active Power" for the corresponding channels.

8. Click Update meter and the observed values for the currents on the GUI settle to the desired currents.

6.2.2 Phase Compensation

Note that this example is for a given channel. Repeat these steps for other channels.

After performing power gain correction, phase calibration must be performed. Use the following steps to perform phase correction calibration:

1. If the AC test source has been turned OFF or reconfigured, perform steps 1- 3 from the gain calibration section using the identical voltages and currents used in that section.

2. Modify only the phase-shift of the calibrated phase to a non-zero value; typically, +60° is chosen. The reference meter will now display a different % error for active power measurement. Note that this value may be negative.

3. Using the % error readings provided by your reference meter (denoted as $\%_{error}$), the phase shift supplied by your source meter (denoted as $\varphi_{desired}$), and the line frequency fed into the meter (denoted as f_{Mains}), calculate the correction factor (in units of microseconds) by using Equation 9. For Equation 9, note that $\varphi_{desired}$ and φ_{error} must be in units of degrees while f_{Mains} must be in units of Hertz.

$$\phi_{error} = \arccos\left(\left(\frac{\%_{error}}{100}+1\right)*cos(\phi_{desired})\right)-\phi_{desired}$$

$$correction = \frac{-\phi_{error}\times 10^6}{f_{Mains}\times 360}$$

(9)

4. Enter the calculated correction into the "Phase Correction" field for the phase that is being calibrated.

5. Click Update meter.

6. If this error is not close to zero, or is unacceptable, fine-tune the phase correction by following these steps:

   (a) Enter a small value as an update for the "Phase Correction" field for the channel that is being calibrated. Usually, a small positive or negative integer should be entered to bring the error close to zero. Additionally, for a phase shift greater than 0 (for example, +60°), a positive (negative) error would require a positive (negative) number as correction.

   (b) Click Update meter and monitor the error values on the reference meter.

   (c) If this measurement error (%) is not accurate enough, fine tune by incrementing or decrementing by a value of 1 based on Step 6a and 6b.

   > **NOTE:** When the error is very close to zero, changing the fine-tuning value by 1 can result in the error oscillating on either side of zero. Select the value that has the smallest absolute error.

   (d) Change the phase to -60° and check if this error is still acceptable. Ideally, errors should be symmetric for same phase shift on lag and lead conditions.

After performing phase correction, calibration is complete for one channel.

7   Test Results

7.1   *Current Measurement Accuracy – Channel 1*

Table 4. Current Measurement Accuracy 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 5. Current Measurement Accuracy 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 6. Current Measurement Accuracy 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 7. Current Measurement Accuracy 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 8. Current Measurement Accuracy 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 9. Current Measurement Accuracy 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 10. Current Measurement Accuracy 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 - for Channel 1 to Channel 7
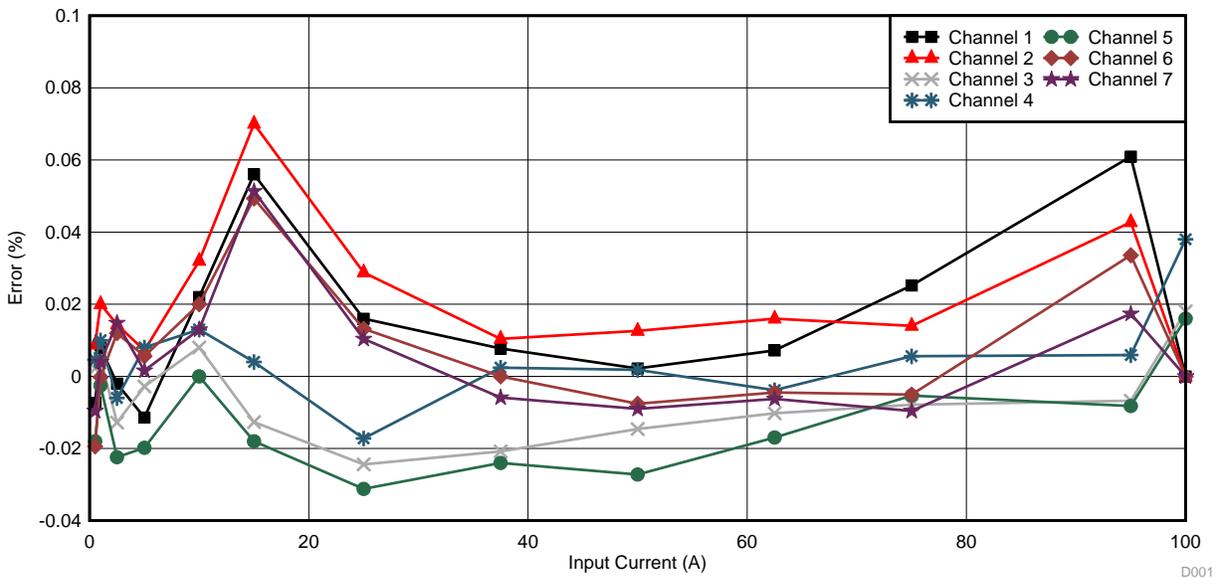

Figure 18. Current Measurement Accuracy Graph

7.9 Voltage Measurement Accuracy

Table 11. Voltage Measurement Test Results

INPUT VOLTAGE	MEASURED VOLTAGE	ERROR
92	92.029	0.03%
138	138.059	0.04%
184	184.007	0.00%
230	229.986	-0.01%

7.10 Power Measurement Accuracy – Channel 1

Table 12. Power Measurement Accuracy Test Results – Channel 1

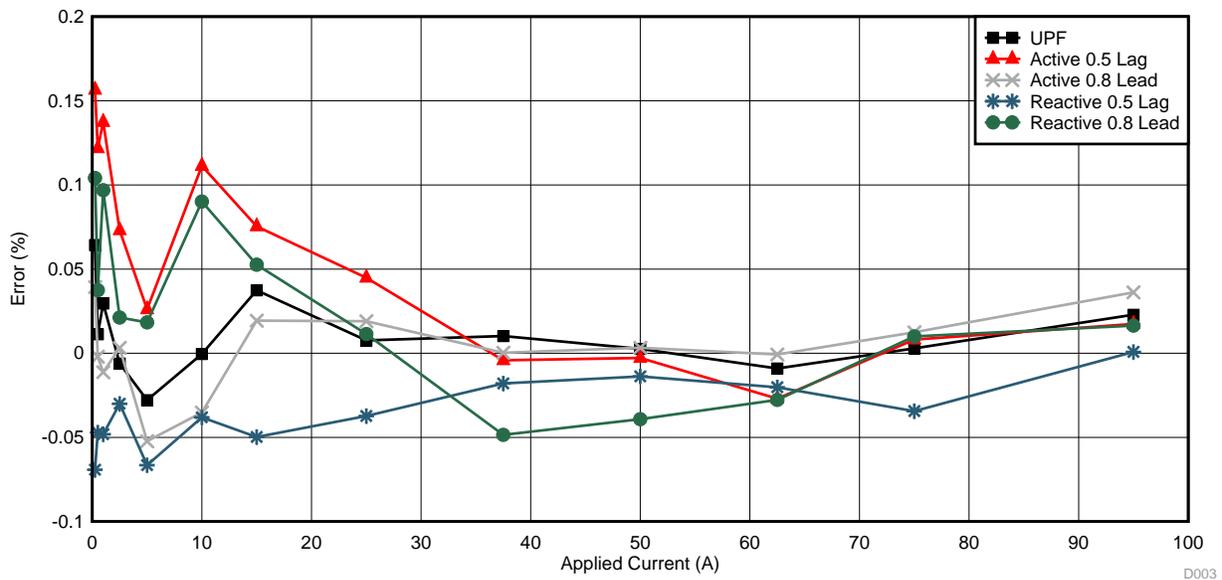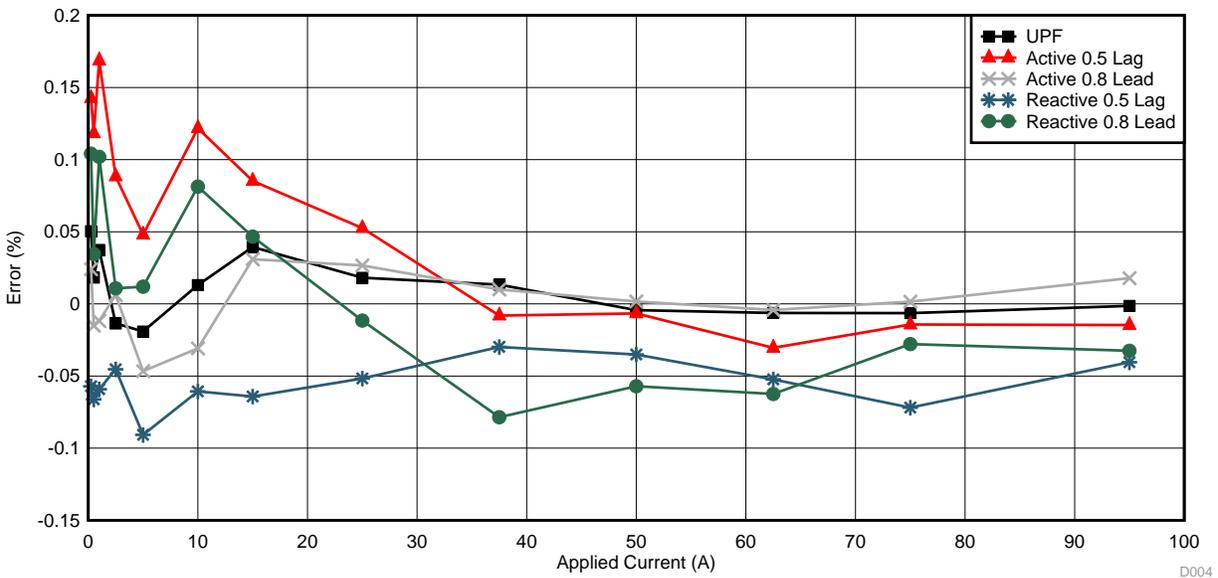| CHANNEL 1		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.06%	0.16%	0.04%	-0.07%	0.10%
0.50%	0.01%	0.12%	0.00%	-0.05%	0.04%
1.00%	0.03%	0.14%	-0.01%	-0.05%	0.10%
2.50%	-0.01%	0.07%	0.00%	-0.03%	0.02%
5.00%	-0.03%	0.03%	-0.05%	-0.07%	0.02%
10.00%	0.00%	0.11%	-0.04%	-0.04%	0.09%
15.00%	0.04%	0.08%	0.02%	-0.05%	0.05%
25.00%	0.01%	0.04%	0.02%	-0.04%	0.01%
37.50%	0.01%	0.00%	0.00%	-0.02%	-0.05%
50.00%	0.00%	0.00%	0.00%	-0.01%	-0.04%
62.50%	-0.01%	-0.03%	0.00%	-0.02%	-0.03%
75.00%	0.00%	0.01%	0.01%	-0.03%	0.01%
95.00%	0.02%	0.02%	0.04%	0.00%	0.02%

Figure 19. Power Measurement Accuracy – Channel 1 Graph

7.11   Power Measurement Accuracy – Channel 2

Table 13. Power Measurement Accuracy Test Results – Channel 2

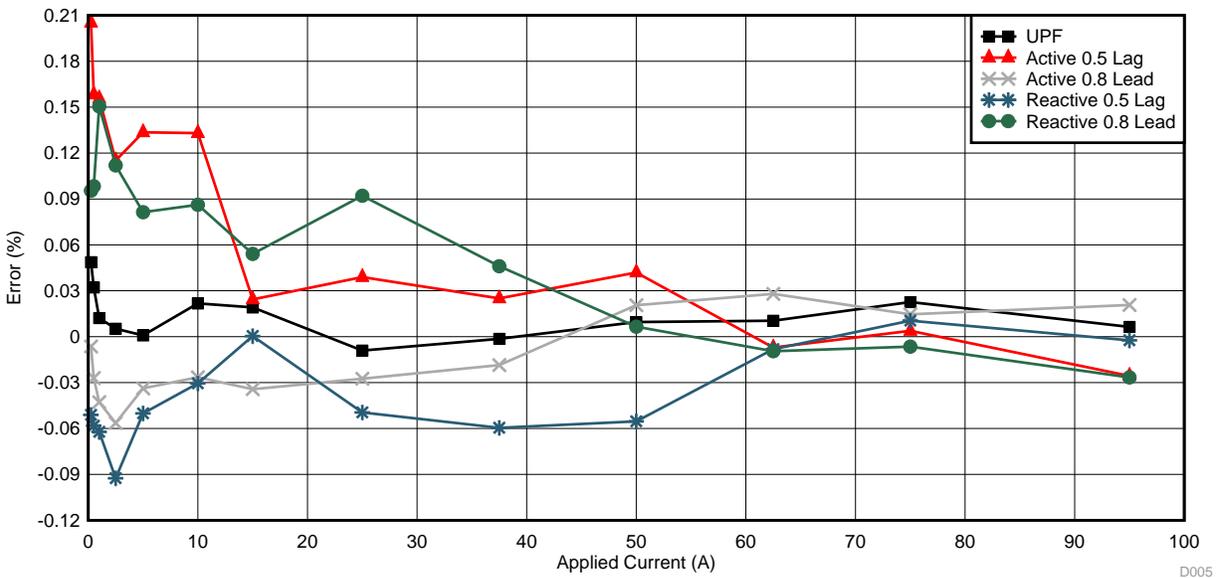| CHANNEL 2		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.05%	0.14%	0.02%	-0.06%	0.10%
0.50%	0.02%	0.12%	-0.02%	-0.07%	0.03%
1.00%	0.04%	0.17%	-0.01%	-0.06%	0.10%
2.50%	-0.01%	0.09%	0.01%	-0.05%	0.01%
5.00%	-0.02%	0.05%	-0.05%	-0.09%	0.01%
10.00%	0.01%	0.12%	-0.03%	-0.06%	0.08%
15.00%	0.04%	0.09%	0.03%	-0.06%	0.05%
25.00%	0.02%	0.05%	0.03%	-0.05%	-0.01%
37.50%	0.01%	-0.01%	0.01%	-0.03%	-0.08%
50.00%	0.00%	-0.01%	0.00%	-0.04%	-0.06%
62.50%	-0.01%	-0.03%	0.00%	-0.05%	-0.06%
75.00%	-0.01%	-0.01%	0.00%	-0.07%	-0.03%
95.00%	0.00%	-0.01%	0.02%	-0.04%	-0.03%

Figure 20. Power Measurement Accuracy – Channel 2 Graph

7.12 Power Measurement Accuracy – Channel 3

Table 14. Power Measurement Accuracy Test Results – Channel 3

CHANNEL 3		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.05%	0.21%	-0.01%	-0.05%	0.10%
0.50%	0.03%	0.16%	-0.03%	-0.06%	0.10%
1.00%	0.01%	0.16%	-0.04%	-0.06%	0.15%
2.50%	0.01%	0.12%	-0.06%	-0.09%	0.11%
5.00%	0.00%	0.13%	-0.03%	-0.05%	0.08%
10.00%	0.02%	0.13%	-0.03%	-0.03%	0.09%
15.00%	0.02%	0.02%	-0.03%	0.00%	0.05%
25.00%	-0.01%	0.04%	-0.03%	-0.05%	0.09%
37.50%	0.00%	0.03%	-0.02%	-0.06%	0.05%
50.00%	0.01%	0.04%	0.02%	-0.06%	0.01%
62.50%	0.01%	-0.01%	0.03%	-0.01%	-0.01%
75.00%	0.02%	0.00%	0.01%	0.01%	-0.01%
95.00%	0.01%	-0.03%	0.02%	0.00%	-0.03%

Figure 21. Power Measurement Accuracy – Channel 3 Graph

Measurement Module for Branch Circuit Power Monitor/Sub Meter 33

7.13 *Power Measurement Accuracy – Channel 4*

Table 15. Power Measurement Accuracy Test Results – Channel 4

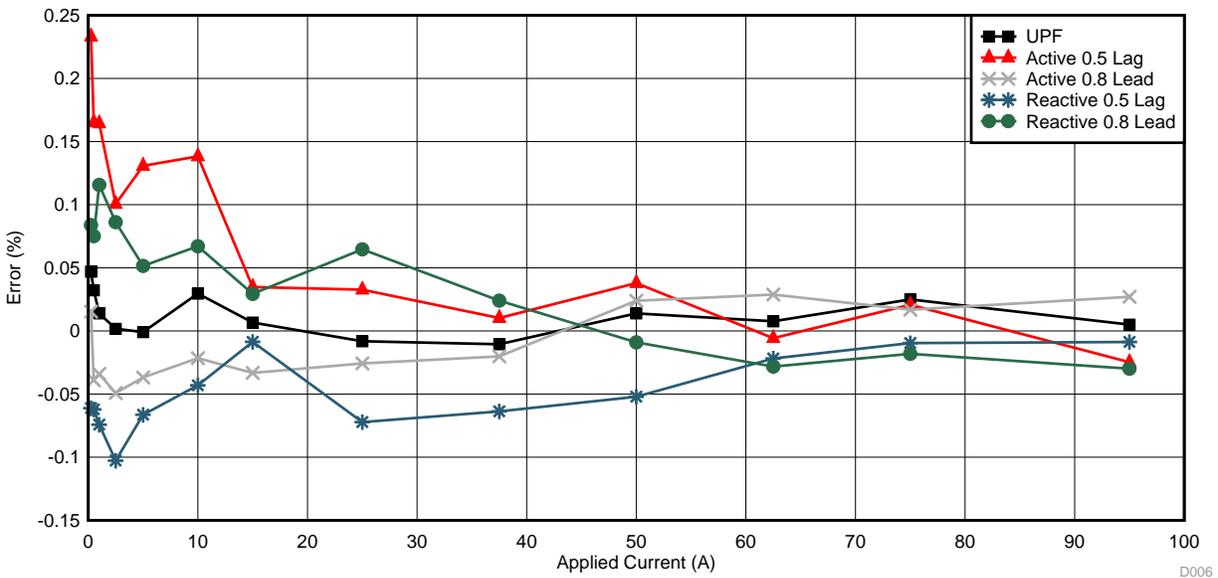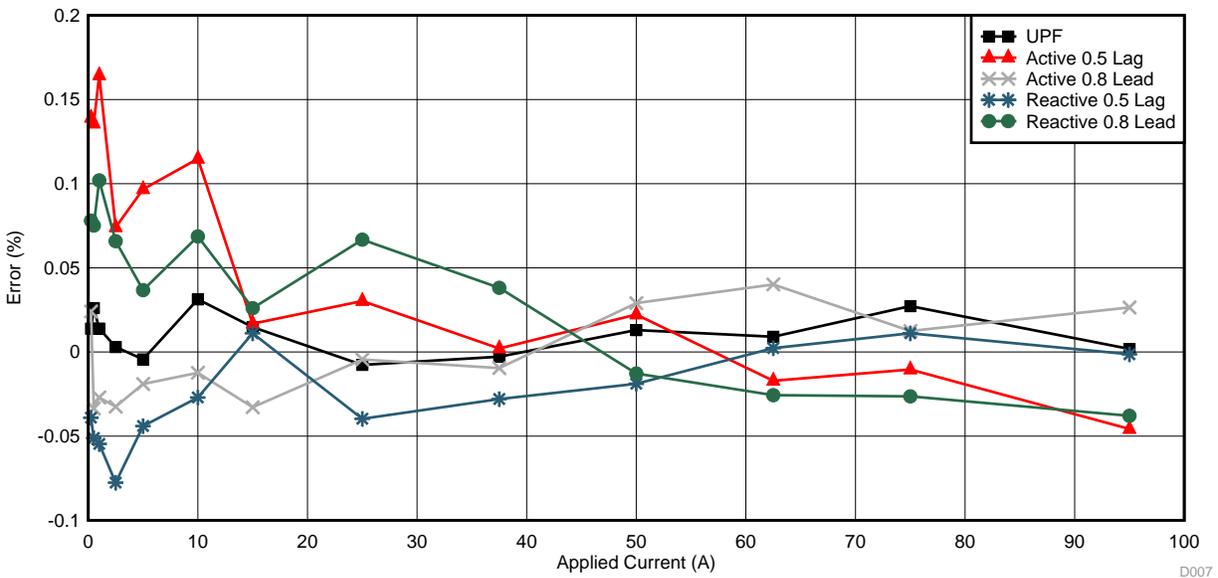| CHANNEL 4		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.05%	0.23%	0.02%	-0.06%	0.08%
0.50%	0.03%	0.17%	-0.04%	-0.06%	0.08%
1.00%	0.01%	0.16%	-0.03%	-0.07%	0.12%
2.50%	0.00%	0.10%	-0.05%	-0.10%	0.09%
5.00%	0.00%	0.13%	-0.04%	-0.07%	0.05%
10.00%	0.03%	0.14%	-0.02%	-0.04%	0.07%
15.00%	0.01%	0.03%	-0.03%	-0.01%	0.03%
25.00%	-0.01%	0.03%	-0.03%	-0.07%	0.06%
37.50%	-0.01%	0.01%	-0.02%	-0.06%	0.02%
50.00%	0.01%	0.04%	0.02%	-0.05%	-0.01%
62.50%	0.01%	-0.01%	0.03%	-0.02%	-0.03%
75.00%	0.02%	0.02%	0.02%	-0.01%	-0.02%
95.00%	0.01%	-0.02%	0.03%	-0.01%	-0.03%

Figure 22. Power Measurement Accuracy – Channel 4 Graph

7.14 *Power Measurement Accuracy – Channel 5*

Table 16. Power Measurement Accuracy Test Results – Channel 5

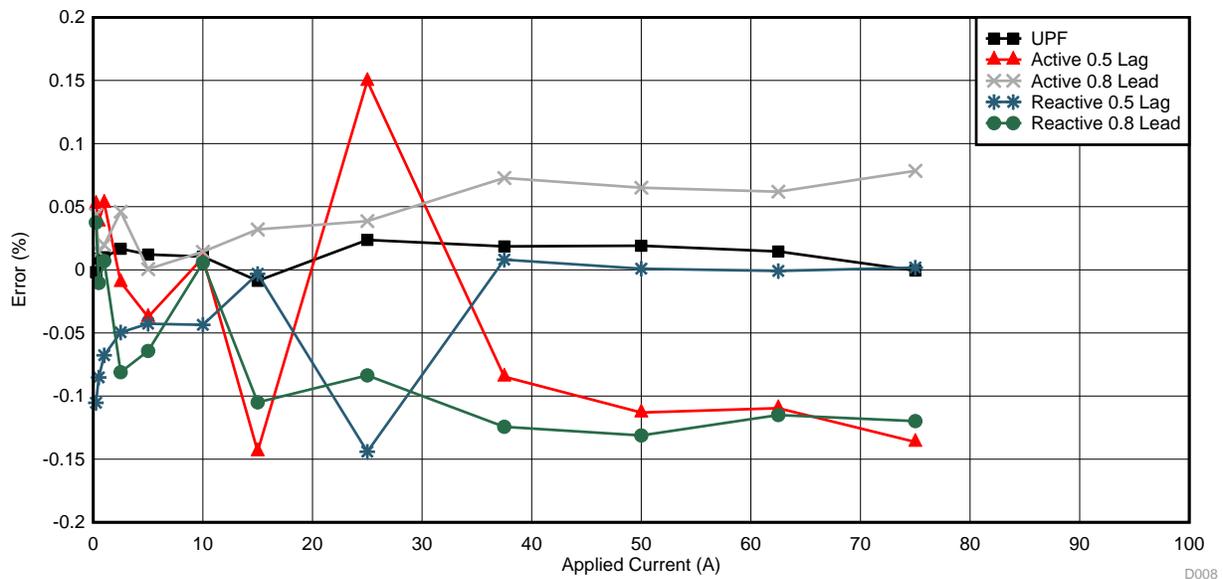| CHANNEL 5		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.01%	0.14%	0.02%	-0.04%	0.08%
0.50%	0.03%	0.14%	-0.03%	-0.05%	0.08%
1.00%	0.01%	0.16%	-0.03%	-0.05%	0.10%
2.50%	0.00%	0.07%	-0.03%	-0.08%	0.07%
5.00%	0.00%	0.10%	-0.02%	-0.04%	0.04%
10.00%	0.03%	0.11%	-0.01%	-0.03%	0.07%
15.00%	0.01%	0.02%	-0.03%	0.01%	0.03%
25.00%	-0.01%	0.03%	0.00%	-0.04%	0.07%
37.50%	0.00%	0.00%	-0.01%	-0.03%	0.04%
50.00%	0.01%	0.02%	0.03%	-0.02%	-0.01%
62.50%	0.01%	-0.02%	0.04%	0.00%	-0.03%
75.00%	0.03%	-0.01%	0.01%	0.01%	-0.03%
95.00%	0.00%	-0.05%	0.03%	0.00%	-0.04%

Figure 23. Power Measurement Accuracy – Channel 5 Graph

7.15 Power Measurement Accuracy – Channel 6

Table 17. Power Measurement Accuracy Test Results – Channel 6

CHANNEL 5		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	0.00%	0.05%	0.04%	-0.11%	0.04%
0.50%	0.01%	0.04%	0.01%	-0.09%	-0.01%
1.00%	0.01%	0.05%	0.02%	-0.07%	0.01%
2.50%	0.02%	-0.01%	0.05%	-0.05%	-0.08%
5.00%	0.01%	-0.04%	0.00%	-0.04%	-0.06%
10.00%	0.01%	0.01%	0.01%	-0.04%	0.01%
15.00%	-0.01%	-0.14%	0.03%	0.00%	-0.10%
25.00%	0.02%	0.15%	0.04%	-0.14%	-0.08%
37.50%	0.02%	-0.08%	0.07%	0.01%	-0.12%
50.00%	0.02%	-0.11%	0.07%	0.00%	-0.13%
62.50%	0.01%	-0.11%	0.06%	0.00%	-0.12%
75.00%	0.00%	-0.14%	0.08%	0.00%	-0.12%

Figure 24. Power Measurement Accuracy – Channel 6 Graph

7.16 *Power Measurement Accuracy – Channel 7*

Table 18. Power Measurement Accuracy Test Results – Channel 7

CHANNEL 5		ERROR - ACTIVE POWER		ERROR - REACTIVE POWER	
APPLIED CURRENT	UPF	0.5Lag	0.8Lead	0.5Lag	0.8Lead
0.25%	-0.03%	0.06%	-0.04%	0.00%	-0.06%
0.50%	-0.02%	0.08%	-0.05%	-0.06%	-0.02%
1.00%	-0.01%	0.12%	-0.05%	-0.06%	0.05%
2.50%	0.00%	0.07%	-0.01%	-0.07%	-0.02%
5.00%	-0.01%	0.04%	-0.05%	-0.04%	0.00%
10.00%	-0.01%	0.08%	-0.04%	-0.06%	0.06%
15.00%	-0.02%	-0.08%	-0.02%	-0.03%	-0.04%
25.00%	0.02%	0.17%	-0.01%	-0.13%	-0.03%
37.50%	0.00%	-0.01%	0.03%	-0.01%	-0.07%
50.00%	0.00%	-0.07%	0.02%	-0.01%	-0.06%
62.50%	0.00%	-0.06%	0.02%	-0.02%	-0.08%
75.00%	0.00%	-0.10%	0.04%	-0.01%	-0.06%
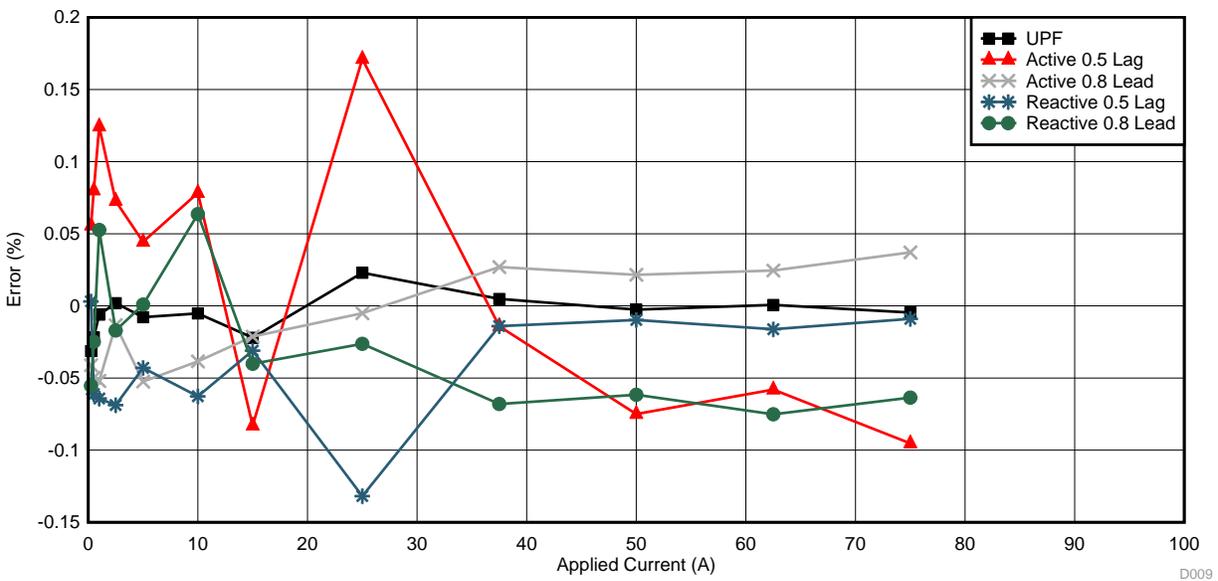
Figure 25. Power Measurement Accuracy – Channel 7 Graph

8 Design Files

8.1 Schematics
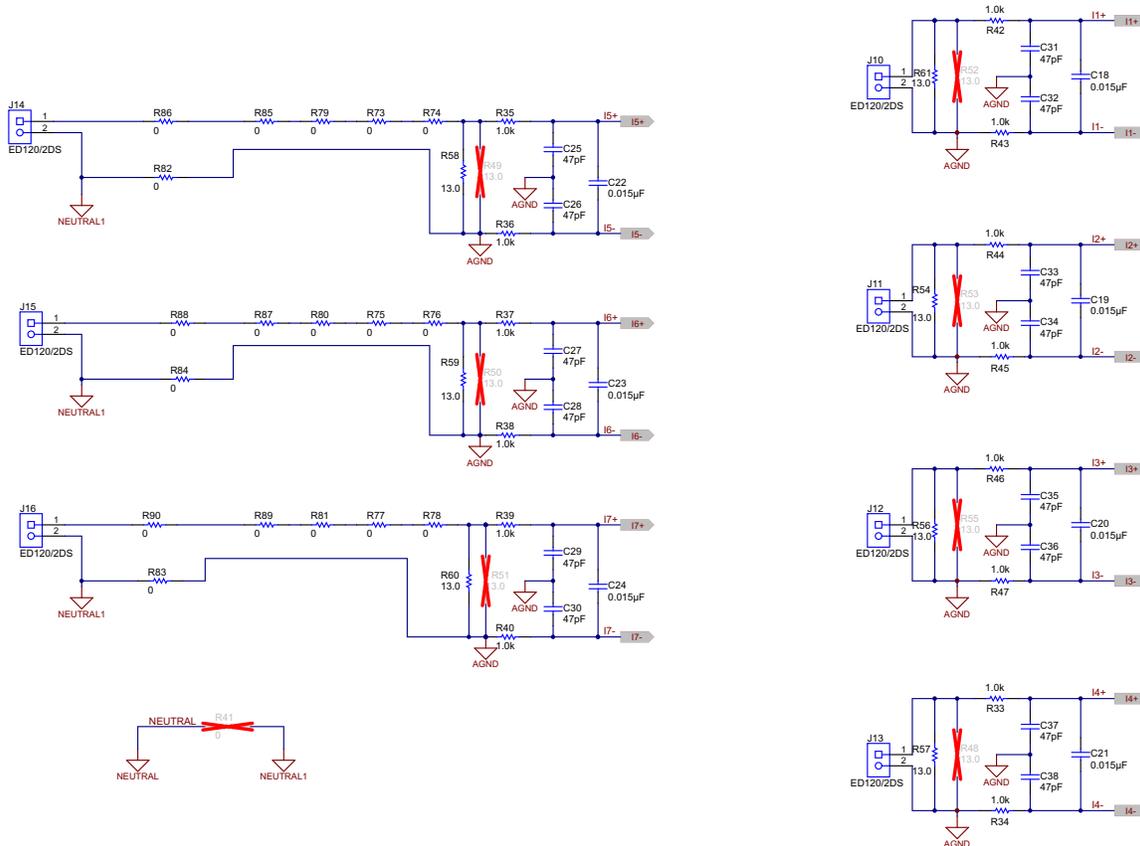
The schematics are presented in the following order:

Figure 26. Analog Front End (Current)

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Figure 27. Analog Front End Opamp (Voltage) + LDO + ZCD

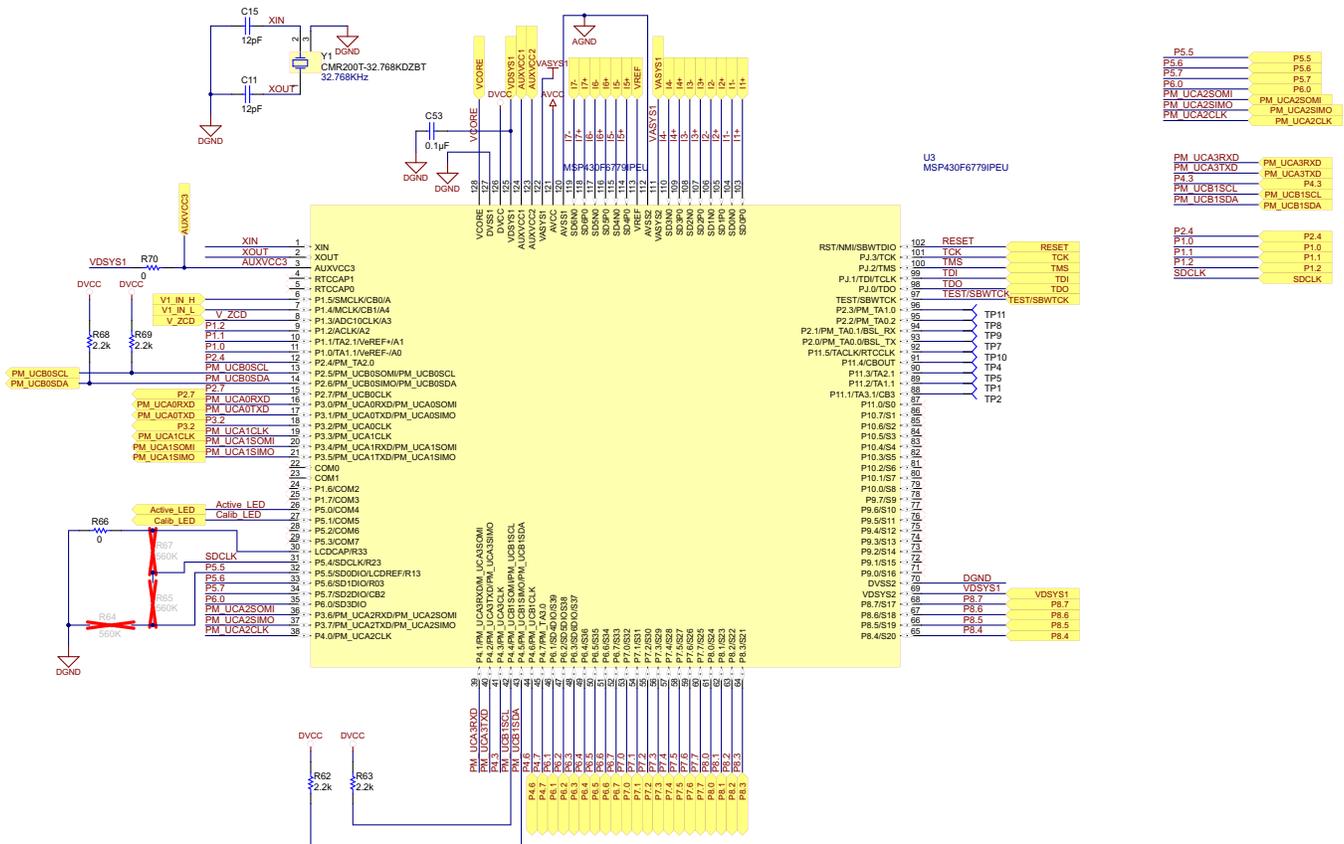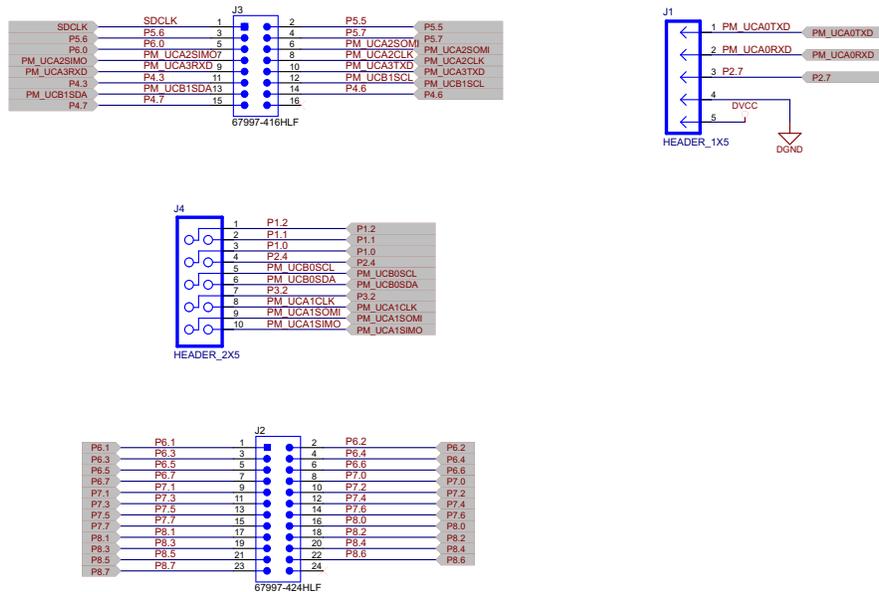**Figure 28. JTAG Interface + LEDs + Decoupling Capacitors**

Figure 29. MSP430F6779 + Crystal

Figure 30. Interfaces

8.2 Bill of Materials (BOM)

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

Table 19. Bill of Materials (BOM)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PART NUMBER	PCB FOOTPRINT	DNIe
1	!PCB1	Printed Circuit Board	Any	TIDA-00222		
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	
13	C3, C4, C10, C12, C14, C39, C45, C48, C51, C52, C53, C54, C57	CAP, CERM, 0.1 µF, 25V, ±5%, X7R, 0603	AVX	06033C104JAT2A	0603	
2	C5, C6	CAP, CERM, 0.01 µF, 25V, ±5%, C0G/NP0, 0603	TDK	C1608C0G1E103J	0603	
3	C8, C9, C16	CAP, CERM, 100 pF, 50V, v1%, C0G/NP0, 0603	AVX	06035A101FAT2A	0603	
2	C11, C15	CAP, CERM, 12 pF, 50V, ±5%, C0G/NP0, 0603	AVX	06035A120JAT2A	0603	
1	C17	CAP, TA, 4.7 µF, 35 V, ±10%, 1.9 Ω, 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 1/10W 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, 25V, ±10%, X7R, 0603	MuRata	GRM188R71E474KA12J	0603	
2	D1, D2	LED, 5MM, RED, TH	VISHAY	TLHR6405	LED_5MM	
1	D3	LED SmartLED Green 570NM	OSRAM	LG L29K-G2J1-24-Z	LED0603AA	
1	D4	Diode, Switching, 200 V, 0.2A, 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	
2	FB1, FB3	FERRITE BEAD, 42 Ω, 4 A, DCR0.008 Ω, SMT-0805	TAIYO YUDEN	FBMJ2125HS420-T	0805_hv	
1	FB2	FERRITE CHIP 1000 Ω 300MA 0603	TDK Corporation	MMZ1608B102C	0603	
1	J1	Header, Male 5-pin, 100mil spacing,	TE Connectivity	826926-5	HEADER_5P	
1	J2	Header, TH, 100mil, 12x2, Gold plated, 230 mil above insulator	FCI	67997-424HLF	TSW-112-07-G-D	
1	J3	Header, 8x2, 100mil, TH	FCI	67997-416HLF	TSW-108-07-G-D	
1	J4	Header, Male 2x5-pin, 100 mil spacing	FCI	67997-410HLF	HDR2X5	
1	J5	3 pin berger	FCI	68001-403HLF	HDR1X3	

Table 19. Bill of Materials (BOM) (continued)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PART NUMBER	PCB FOOTPRINT	DNIe
1	J6	Header, 2x2-pin, 100 mil spacing	FCI	67997-404HLF	HDR_2X2	
9	J7, J9, J10, J11, J12, J13, J14, J15, J16	TERMINAL BLOCK 5.08MM VERT 2POS, TH	On-Shore Technology	ED120/2DS	CONN_ED120-2DS	
1	J8	Header, 7x2, 100 mil, SMT	Molex	N2514-6002-RB	3M_N2514-6002-RB	
2	Q1, Q2	MOSFET, N-CH, 30 V, 22A, SON 2X2 MM	TEXAS INSTRUMENTS	CSD17571Q2	SON_CSD17571Q2	
6	R1, R2, R62, R63, R68, R69	RES, 2.2k Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW06032K20JNEA	0603	
3	R3, R4, R16	RES, 300 Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW0603300RJNEA	0603	
6	R5, R8, R13, R17, R23, R24	RES 10K Ω 1/10W 5% 0603 SMD	Vishay-Dale	CRCW060310K0JNEA	0603	
4	R6, R7, R22, R29	RES, 100 Ω, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603100RFKEA	0603	
2	R9, R92	RES 390K Ω 1/10W 1% 0603 SMD	Vishay Dale	CRCW0603390KFKEA	0603	
2	R10, R91	RES, 200k Ω, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603200KFKEA	0603	
0	R11	RES 2.40K Ω 1/8W 1% 0805 SMD	Vishay-Dale	CRCW08052K40FKEA	0805_hv	DNI
1	R12	RES 2.40K Ω 1/8W 1% 0805 SMD	Vishay-Dale	CRCW08052K40FKEA	0805_hv	
4	R14, R15, R18, R19	RES, 100k Ω, 1%, 0.1W, 0603	Vishay-Dale	CRCW0603100KFKEA	0603	
4	R20, R25, R27, R28	RES, 332k Ω, 1%, 0.125W, 0805	Vishay-Dale	CRCW0805332KFKEA	0805_HV	
1	R21	RES, 47k Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW060347K0JNEA	0603	
1	R26	RES, 30k Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW060330K0JNEA	0603	
1	R30	RES, 470 Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW0603470RJNEA	0603	
1	R31	RES, 10.0k Ω, 1%, 0.1W, 0603	Vishay-Dale	CRCW060310K0FKEA	0603	
1	R32	RES 1.00M Ω 1/10W 1% 0603 SMD	Vishay-Dale	CRCW06031M00FKEA	0603	
14	R33, R34, R35, R36, R37, R38, R39, R40, R42, R43, R44, R45, R46, R47	RES, 1.0k Ω, 5%, 0.1W, 0603	Vishay-Dale	CRCW06031K00JNEA	0603	
0	R41	RES, 0 Ω, 5%, 0.125W, 0805	Vishay-Dale	CRCW08050000Z0EA	0805_HV	DNI
0	R48, R49, R50, R51, R52, R53, R55	RES, 13.0 Ω, 1%, 0.125W, 0805	Vishay-Dale	CRCW080513R0FKEA	0805_HV	DNI
7	R54, R56, R57, R58, R59, R60, R61	RES, 13.0 Ω, 1%, 0.125W, 0805	Vishay-Dale	CRCW080513R0FKEA	0805_HV	
0	R64, R65, R67	RES 560K Ω 1/10W 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%, 0.125W, 0805	Vishay-Dale	CRCW08050000Z0EA	0805_HV	
1	R72	RES, 10 Ω, 5%, 0.125W, 0805	Vishay-Dale	CRCW080510R0JNEA	0805_HV	

Table 19. Bill of Materials (BOM) (continued)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PART NUMBER	PCB FOOTPRINT	DNIe
1	S1	Switch, Tactile, SPST-NO, 0.1A, 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	TI	TPS7A6533QKVURQ1	KVU_1	
1	U2	Low-voltage rail-to-rail output operational amplifiers, PW0014A	Texas Instruments	OPA4314AIPW	PW0014A_N	
1	U3	IC, MCU 16-BIT 512KB Flash, LQFP-128	TEXAS INSTRUMENTS	MSP430F6779IPEU	QFP50P1600X2200X160-128N	
1	U4	IC, Micropower Shunt Voltage Reference 100 ppm/°C, 45 µA-12 mA, Adjustable	TI	LM4041BIDBZ	SOT-23	

8.3 Layer Plots

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

Figure 31. Top Overlay

Figure 32. Top Solder Mask

Figure 33. Top Layer

Figure 34. Bottom Layer

Figure 35. Bottom Solder Mask

Figure 36. Bottom Overlay

8.4 Altium Project

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

Figure 37. Fab Drawing

Figure 38. Combined Plot Diagram

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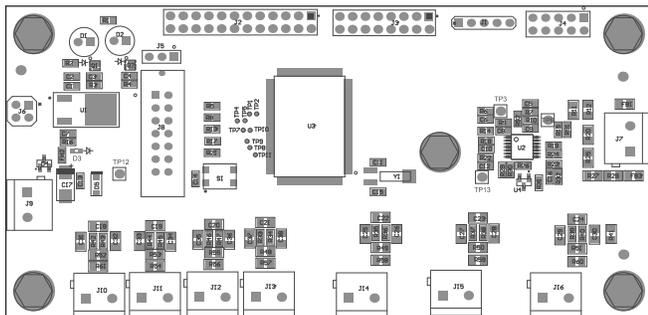
8.5 Assembly Drawings
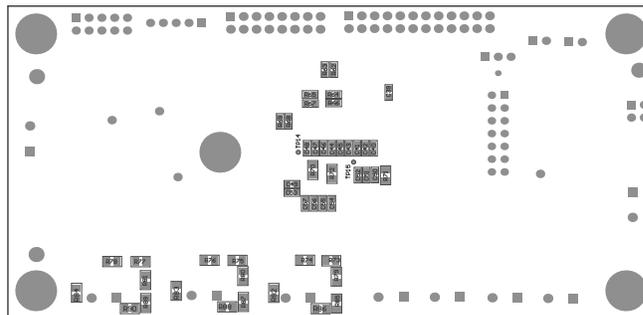

Figure 39. Top Assembly

Figure 40. Bottom Assemly

8.6 Software Files

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

9 References

- *MSP430 Hardware Tools User's Guide* (SLAU278)
- *MSP430 Programming Via the JTAG Interface User's Guide* (SLAU320)

10 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.

BART BASILE is asystems and applications engineer in the Texas Instruments Smart Grid Solutions Team, focusing on the e-metering and grid infrastructure industries. Bart works across multiple product families and technologies to leverage the best solutions possible for system level application design. Bart received his Bachelors of Science in Electronic Engineering from Texas A&M University.

MEKRE MESGANAW is a System Applications Engineer in the Smart Grid and Energy group at Texas Instruments, where he primarily works on electricity metering customer support and reference design development. Mekre received his Bachelor of Science and Master of Science in Computer Engineering from the Georgia Institute of Technology.

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