Design Guide: TIDA-010940
One-Phase Shunt Electricity Meter Reference Design

TEXAS INSTRUMENTS

Description

This reference design implements a single-phase energy meter using standalone multi-channel analog-to-digital converters (ADC) to sample a shunt current sensor. The combination of the shunt sensor and a ultra low-power Hall-effect sensor (DRV5032) minimizes the effect and enables the detection of magnetic tampering attacks. The reference design achieves class 0.5S accuracy across 4000:1 input range (25mA–100A) with 8kHz sampling rate and uses a TI Arm® Cortex®-M0+ host microcontroller for calculating the metrology parameters. The necessary software functionality is implemented in MSPM0-SDK Version: 2.02.00.05 and can be compiled with TI Code Composer Studio™.

Resources

TIDA-010940	Design Folder
ADS131M03	Product Folder
MSPM0L2228	Product Folder
THVD1400, ISO6731	Product Folder
Energy Metrology Library	Software

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Features

- Single-phase two-wire (1P1W) class 0.5S shunt electricity meter tested across 25mA to 100A input range
- Calculated parameters include active and reactive energy and power, RMS line current, RMS neutral current, RMS voltage, power factor, and line frequency
- Detects potential tamper attacks with DRV5032 digital-switch Hall-effect sensor
- RS-485 interface with $5kV_{RMS}$ isolation
- Energy metrology software with pulsed outputs to a reference test system including results displaying on a Microsoft® Windows® PC GUI.

Applications

- Electricity meter
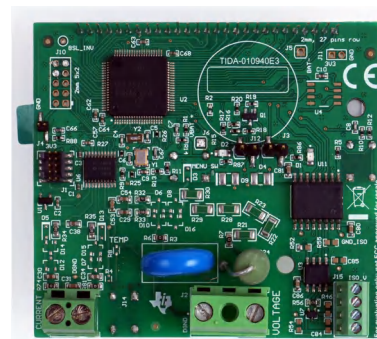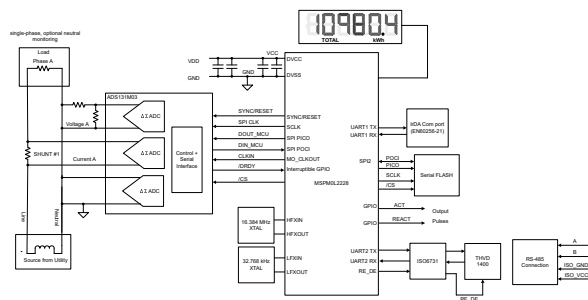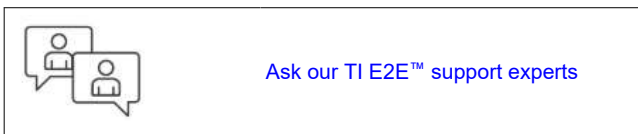
1 System Description

1.1 End Equipment

1.1.1 Electricity Meter

As the accuracy requirements and amount of processing expected from electricity meters rapidly increase, it becomes more and more difficult to solve these issues with a single metrology system-on-chip (SoC). A dual-chip approach with a standalone ADC and a host microcontroller (MCU) helps overcome the limitations of electricity meter SoCs and enables system designs, better tailored to the needs of specific markets or regions of the world. Combining a high-accuracy cost-optimized non-isolated standalone ADC, such as the ADS131M03, and a cost-optimized MSPM0L2228 MCU with LCD controller and a Backup (VBAT) power domain enables a new generation of cost-optimized electricity meters for single-phase with multiple advantages:

*   Achieving 0.5S accuracy requirements with a shunt current sensor at an attractive cost point with 3- (or only 2) channel simultaneous-sampling, delta-sigma ADC
*   MSPM0L2228 host MCU drives segmented LCD displays with up to 8×51 and 4×55 software definable COM and SEG lines for easier and more compact PCB
*   The VBAT island in MSPM0L2228 includes the low frequency clock system (LFOSC, LFXT), the real-time clock, the tamper detection and time-stamping logic, an independent watchdog timer, and a 32-byte backup memory
*   Support for external SPI FLASH memory and two UART interfaces: one for IrDA Optical port as per EN 62056-21 and second one for isolated RS-485 communication

The TIDA-010940 firmware specifically supports calculation of various metrology parameters for single-phase energy measurement by processing continuously the incoming ADS131M03 data samples. The most relevant parameters, that can be viewed from the calibration GUI or through the ACT and REACT pulsed outputs, connected to a reference metrology test system, are:

*   Active (kWh), reactive (kvarh), and apparent energy (kVAh) with pulse-generation outputs
*   RMS line current and RMS line voltage
*   Power factor
*   Line frequency

In addition, the MSPM0L2228 drives the liquid crystal display (LCD) of the board and communicates to a personal computer (PC) graphical user interface (GUI) through the isolated RS-485 circuitry on the board.

1.2 Key System Specifications

Table 1-1. Key System Specifications

FEATURES	DESCRIPTION
Number of phases	1
Electricity meter accuracy class	Class 0.5S
Current sensor	Shunt
Tested current range	0.025–100A
Tested voltage range	10 - 270V
ADS131M03 CLKIN frequency	8,192,000Hz
ADS131M03 delta-sigma modulation clock frequency	4,096,000Hz (= CLKIN / 2)
SPI Clock	8,000,000Hz
Oversampling ratio (OSR)	512
Digital filter output sample rate	8,000 samples per second
Phase compensation implementation	Software
Phase compensation resolution	0.0088° at 50Hz or 0.0105° at 60Hz
Selected CPU clock frequency	32MHz
System nominal frequency	50 or 60Hz

Table 1-1. Key System Specifications (continued)

FEATURES	DESCRIPTION
Measured parameters	• Active, reactive, apparent power and energy • Root mean square (RMS) line current, neutral current, and voltage • Power factor • Line frequency
Update rate for measured parameters	Approximately equal to 1 second
Communication options	• LCD • PC GUI through 5kV$_{RMS}$ isolated RS-485
Utilized LEDs	Active energy and reactive energy
Board power supply	External power: 3V3 and GND

2 System Overview

2.1 Block Diagram

Figure 2-1 depicts a high-level block diagram of this one-phase electricity meter application.
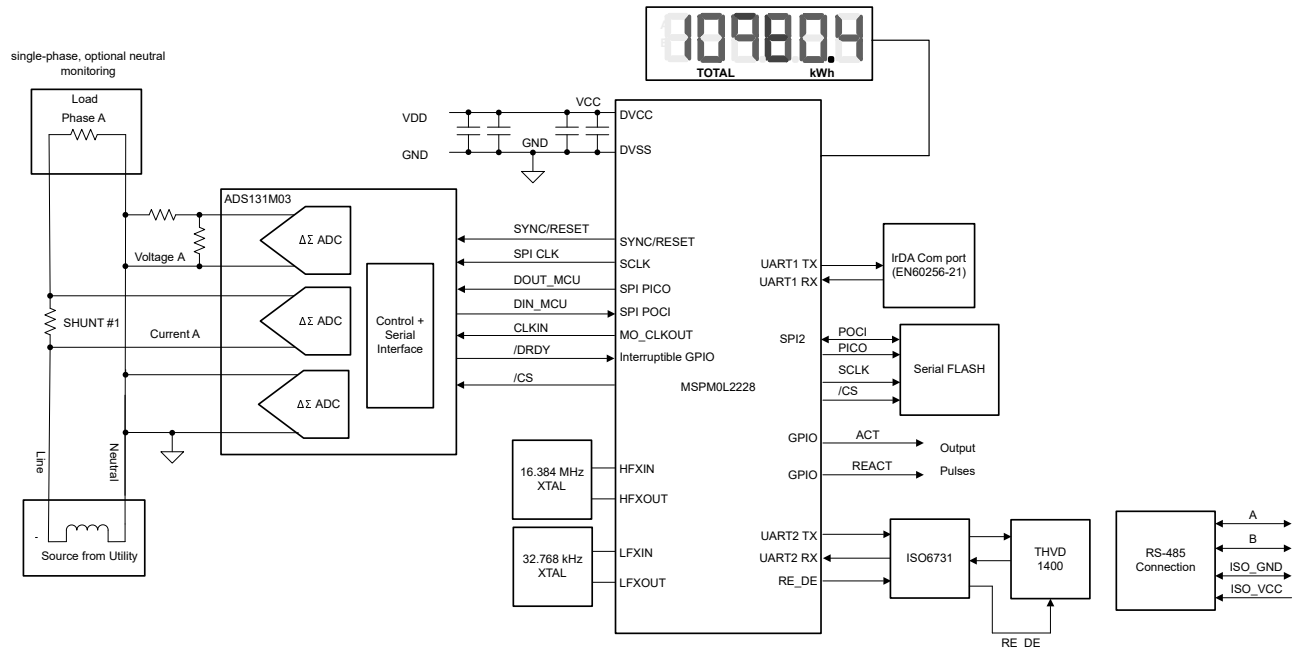

Figure 2-1. TIDA-010940 Block Diagram

The resistance of the shunt current sensor is selected based on the maximum current value required for energy measurements and needs to also minimize the power dissipation of the shunt.

The choice of voltage divider resistors for the voltage channel is selected to make sure the Mains voltage is divided down to adhere to the normal input ranges of the ADS131M03 device. Since the ADS131M03 ADC have a large dynamic range and a large dynamic range is not needed to measure voltage, the voltage front-end circuitry is purposely selected so that the maximum voltage seen at the inputs of the voltage channel ADC is only a fraction of the full-scale voltage. By reducing the input voltage range, voltage-to-current crosstalk, which actually affects metrology accuracy more than voltage ADC accuracy, is reduced at the cost of voltage accuracy. In Figure 2-1, a simple voltage divider is used for translating the Mains voltage to a voltage that can be sensed by the ADC, while current sensor is used for sensing the line current, whereas the neutral current is not monitored.

In this design, only two ADC channels are used, hence using the pin-compatible ADS131M02 can reduce the system design cost even further. The ADS131M03 device interacts with the MCU in the following manner:

1. The CLKIN clock used by the ADS131M03 device is provided from the M0_CLKOUT signal output of the MSPM0+ MCU.
2. The ADS131M03 device divides the clock at the CLKIN pin by two and uses this divided clock as the delta-sigma modulation clock.
3. When new ADC samples are ready the ADS131M03 device asserts the $\overline{\text{DRDY}}$ pin.
4. After being alerted of new samples, the MSPM0+ MCU uses one SPI interface in combination with the DMA controller to read the voltage and current samples from the ADS131M03 device.

Other signals of interest in Figure 2-1 are the active and reactive energy pulses used for accuracy measurement and calibration, named ACT and REACT. The design supports an isolated RS-485 interface through the use of the ISO6731 and THVD1400 devices on the board.

2.2 Highlighted Products

2.2.1 ADS131M03

The ADS131M03 is a three-channel, simultaneously sampling, 24-bit, delta-sigma (ΔΣ), analog-to-digital converter (ADC) that offers wide dynamic range, low power, and energy-measurement-specific features, making the device an excellent fit for energy metering, power metrology, and circuit breaker applications. The ADC inputs can be directly interfaced to a resistor divider network or a power transformer to measure voltage or to a current transformer, shunt, or a Rogowski coil to measure current.

The individual ADC channels can be independently configured depending on the sensor input. A low-noise, programmable gain amplifier (PGA) provides gains ranging from 1 to 128 to amplify low-level signals. Additionally, this device integrates channel-to- channel phase calibration and offset and gain calibration registers to help remove signal-chain errors.

A low-drift, 1.2V reference is integrated into the device reducing printed circuit board (PCB) area. Optional cyclic redundancy checks (CRC) on the data input, data output, and register map maintain communication integrity. The complete analog front-end (AFE) is offered in a 20-pin TSSOP package or a leadless 20-pin WQFN package and is specified over the industrial temperature range of –40°C to +125°C. Figure 2-2 shows a block diagram of this device.

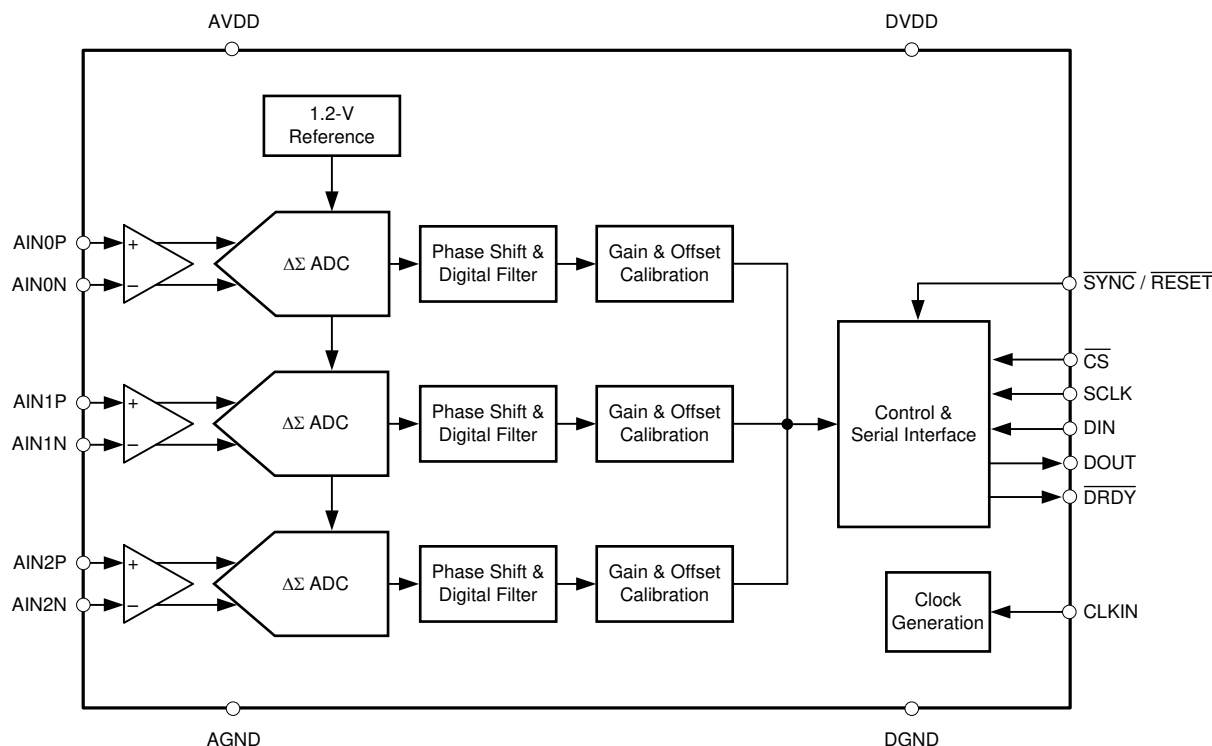**Figure 2-2. ADS131M03 Functional Block Diagram**

In Figure 2-2, 2.7V–3.6V must be fed between AVDD and AGND as well as between DVDD and GND. In addition, an external clock must be connected to CLKIN. The ADS131M03 device asserts $\overline{DRDY}$ pin to alert the host MCU that there are new ADC samples available and is configured for high-resolution mode. This mode utilizes the 8.192MHz frequency input, delivered thru the M0_CLKOUT pin of the MSPM0L2228 MCU.

2.2.2 MSPM0L2228

MSPM0Lx22x microcontrollers (MCU) are part of MSP highly integrated, ultra-low-power 32-bit MSPM0 MCU family based on the Arm® Cortex®-M0+ 32-bit core platform, operating at up to 32MHz frequency. These MCU offer a blend of cost optimization and design flexibility for applications requiring 128KB to 256KB of flash memory in small packages (down to 4mm x 4mm) or high pin count packages (up to 80 pins). These devices include a VBAT backup island, a segmented LCD controller on MSPM0L2228, cybersecurity enablers, and high

performance integrated analog, and provide excellent low power performance across the operating temperature range. Figure 2-3 shows a block diagram of this device.
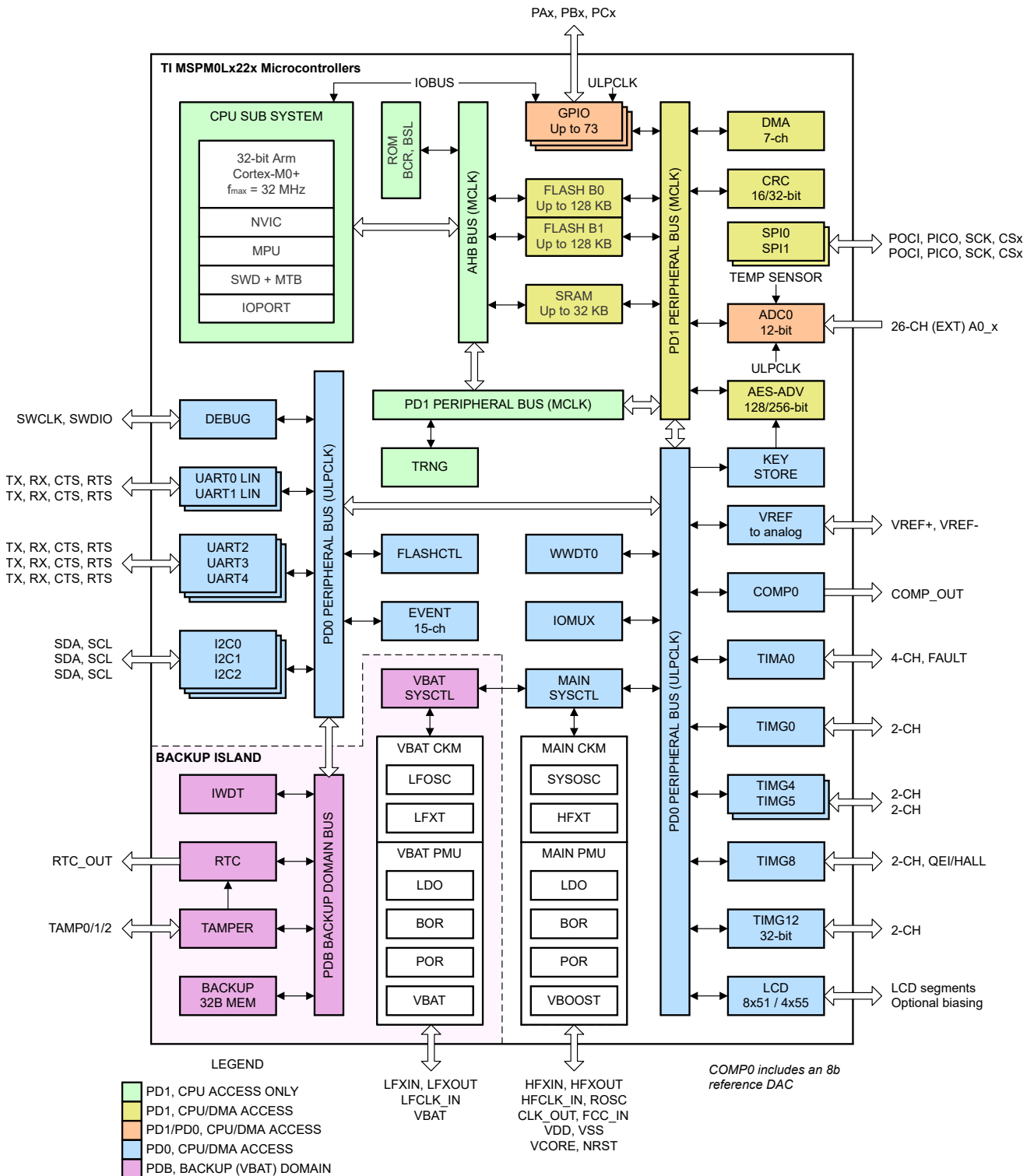

Figure 2-3. MSPM0L2228 Functional Block Diagram

Up to 256KB of embedded flash program memory with built-in error correction code (ECC) and up to 32KB SRAM with ECC and parity protection is provided. The flash memory is organized into two main banks to support field firmware updates, with address swap support provided between the two main banks. An additional 32-byte

backup memory is provided in the VBAT island, supplied by the VBAT pin and retained even when the main supply (VDD) is lost.

The VBAT island provides a fully independent auxiliary power domain (separate from the main supply) which supplies low frequency modules from an alternate supply such as a battery, supercapacitor, or alternate voltage level (1.62 to 3.6V). The VBAT island includes the low frequency clock system (LFOSC, LFXT), the real-time clock, the tamper detection and time-stamping logic, an independent watchdog timer, and a 32-byte backup memory. Up to five digital IOs are powered from the VBAT supply. A charging mode is provided to optionally trickle charge a supercapacitor on the VBAT pin from the primary (VDD) supply when VDD is greater than VBAT.

An ultra-low power segmented LCD controller supports driving LCD glass with up to 59 pins in a variety of mux and bias configurations, enabling use of low cost displays.

Flexible cybersecurity enablers can be used to support secure boot, secure in-field firmware updates, IP protection (execute-only memory), key storage, and more. Hardware acceleration is provided for a variety of AES symmetric cipher modes, as well as a TRNG entropy source. The cybersecurity architecture is Arm® PSA Level 1 certified.

The MSPM0L2228 MCU in this design retrieves voltage and current samples from the ADS131M03 device and calculates metrology parameters. In addition, the device also keeps track of time with the RTC module, drives the LCD on the board with the internal LCD driver module, and uses one of the UART interfaces to communicate to a PC GUI using the isolated RS-485 circuit of the board. The CRC module of the MSPM0+ MCU is used to accelerate the CRC16 calculations that are done to verify the integrity of the ADC data packet sent by the ADS131M03 device.

2.2.3 THVD1400

The THVD1400 device is a robust half-duplex RS-485 transceiver for industrial applications. The bus pins are immune to high levels of IEC Contact Discharge ESD events eliminating the need of additional system-level protection components. The device operates from a single 3 to 5.5V supply. The wide common-mode voltage range and low input leakage on bus pins make the THVD1400 device designed for multi-point applications over long cable runs.

The THVD1400 device is available in an industry standard 8-pin SOIC package for drop-in compatibility as well as in the industry-leading, small SOT package and is characterized from –40°C to 125°C. This device converts the data from UART to RS-485 signals.

2.2.4 ISO6731

The isolated RS-485 portion of this reference design uses capacitive galvanic isolation, which has an inherent life span advantage over an opto-isolator. In particular, industrial devices are usually pressed into service for much longer periods of time than consumer electronics; therefore, the maintenance of effective isolation over a period of 15 years or longer is important.

The variant of the ISO6731 device used in the RS-485 circuitry of this reference design provides galvanic isolation up to $5kV_{RMS}$ for one minute per UL. This digital isolator has three isolated channels where two channels are forward channels and the other is a reverse channel. In this design, two isolation channels are used for the TX and RX. If RS-485 is selected for communication, the third isolation channel is used for the control signal to enable the receiver or driver. Each isolation channel has a logic input and output buffer separated by a double capacitive silicon dioxide (SiO_2) insulation barrier. This chip supports a signaling rate of 50 Mbps and operates from a 2.5V, 3.3V, and 5V supply and logic levels and is characterized from –40°C to 125°C.

2.2.5 DRV5032

The DRV5032 device is an ultra-low-power digital switch Hall effect sensor, designed for the most compact and battery-sensitive systems. The device is offered in multiple magnetic thresholds, sampling rates, output drivers, and packages to accommodate various applications.

When the applied magnetic flux density exceeds the BOP threshold, the device outputs a low voltage. The output stays low until the flux density decreases to less than BRP, and then the output either drives a high voltage or becomes high impedance, depending on the device version. By incorporating an internal oscillator, the

device samples the magnetic field and updates the output at a rate of 80Hz, 20Hz or 5Hz for the lowest current consumption. Omnipolar and unipolar magnetic responses are available.

The device operates from a VCC range of 1.65V to 5.5V, and is packaged in a standard SOT-23, TO-92 and small X2SON, the recommended operating ambient temperature is from –40°C to 85°C.

2.3 Design Considerations

2.3.1 Design Hardware Implementation

2.3.1.1 Analog Inputs

The analog front end in this design consists of the ADS131M03 delta-sigma standalone ADC. Each of the three internal converter channels is differential and requires that the input voltages at the pins does not exceed ±1.2V (gain = 1). To meet this input voltage specification, the current and voltage inputs must be divided down. In addition, the ADS131M03 device can sense voltages down to −1.2V; therefore, AC signals from mains can be directly interfaced without the need for level shifters. This subsection describes the analog front end used for voltage and current channels.

2.3.1.1.1 Voltage Measurement Analog Front End

The nominal voltage from the mains is from 100V–240V and has to be scaled down to be sensed by the ADC. Figure 2-4 shows the analog front end used for this voltage scaling after J2, where the Line voltage and Neutral are applied.

$$V_{ADC\_Swing, Voltage} = \pm V_{RMS} \times \sqrt{2}\left(\frac{R_{32}}{R_{21} + R_{22} + R_{23} + R_{28} + R_{29} + R_{30} + R_{32}}\right) \tag{1}$$
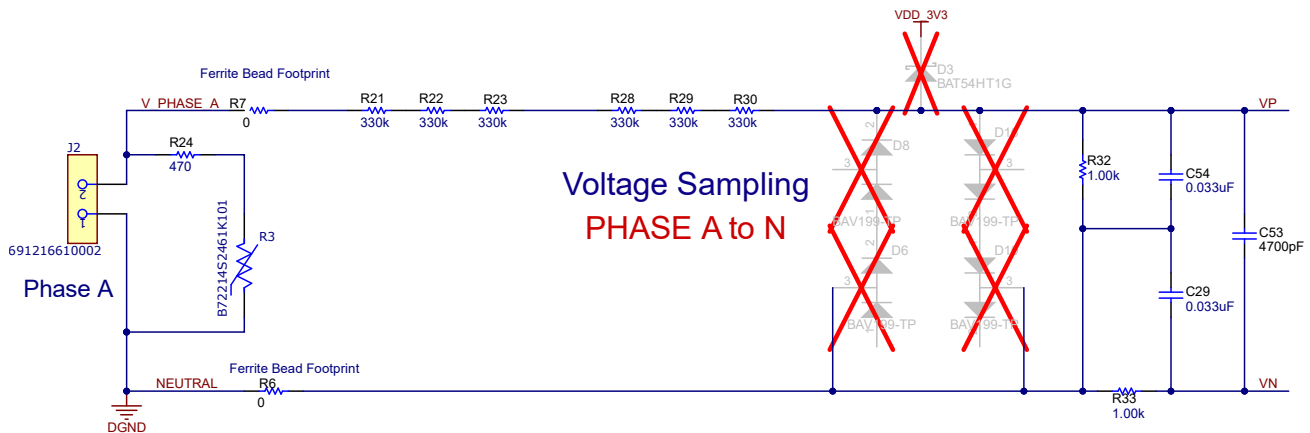

Figure 2-4. Analog Front End for Voltage Inputs

In the analog front end for voltage, there consists a spike protection varistor (R3), a protection resistor R24, footprints for electromagnetic interference filter beads (resistors R6 and R7), a voltage divider network (R21, R22, R23, R28, R29, R30 and R32), and an RC low-pass filter (R33, C29, C54 and C53).

At lower currents, voltage-to-current crosstalk affects active energy accuracy much more than voltage accuracy. Since the ADCs of the ADS131M03 device are high-accuracy ADCs, using the reduced ADC range for the voltage channels in this design still provides more than enough accuracy for measuring voltage.

Equation 1 shows how to calculate the range of differential voltages fed to the voltage ADC channel for a given Mains voltage and selected voltage divider resistor values. Based on this equation for a mains voltage of 230V, the input signal to the voltage ADC has a voltage swing of ±164 mV (116 mV$_{RMS}$). The ±164-mV voltage range is well within the ±1.2V input voltage that can be sensed by the ADS131M03 device with selected PGA gain value of 1 for the voltage channel.

2.3.1.1.2 Current Measurement Analog Front End

Analog Front End for Shunt Current Input shows the analog front end for the current input, where the positive and negative leads from the external current SHUNT sensor (not shown) are connected to pins 1 and 2 of header J14.
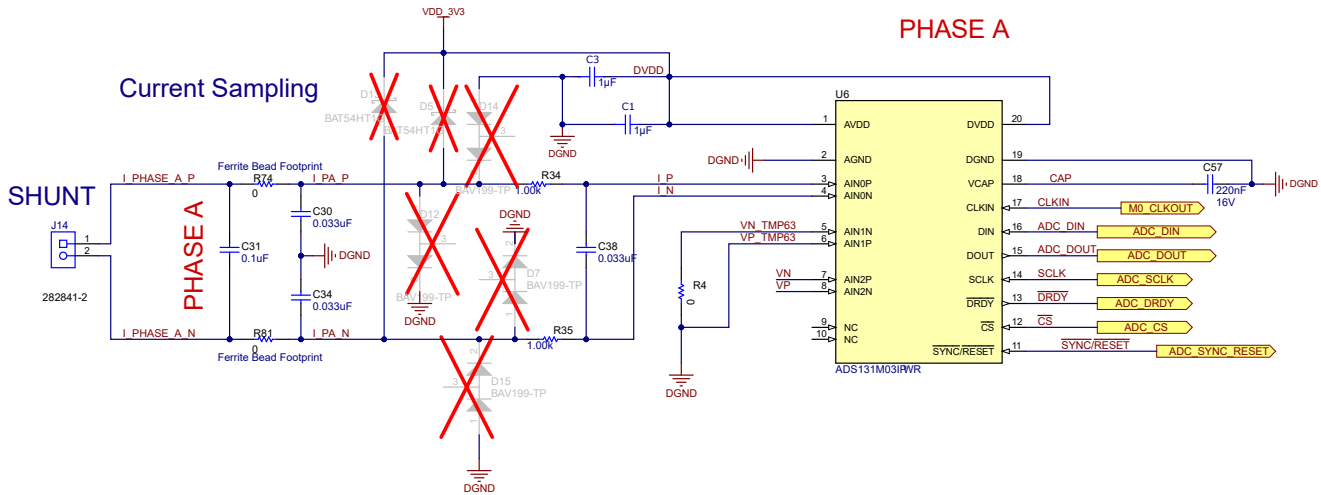

Figure 2-5. Analog Front End for Shunt Current Input

The analog front end for current input consists of footprints for electromagnetic interference filter beads (R74 and R81), and an RC low-pass filter (C30, C34, R34, R35, and C38) that functions as an anti-alias filter.

Equation 2 shows how to calculate the range of differential voltages fed to the current ADC channel for a given maximum current and shunt value.

$$V_{ADC_{Swing},Current,Shunt} = \pm\sqrt{2}\left(R_{shunt}\right)I_{RMS,max}$$

(2)

The shunt sensor value for an electricity meter is selected based on the tradeoff between accuracy and shunt power dissipation. If the shunt value is decreased, less power is dissipated through the shunt; however, the decreased shunt value means a smaller output voltage from the shunt, which leads to worse accuracies at lower currents, even if a higher PGA gain is used to boost the shunt output.

Based on the $V_{ADC, Current,Shunt}$ range, select the proper PGA gain by looking at the full-scale range table in Table 2-1 to find the two gain ranges that $V_{ADC, Current,Shunt}$ fits between. From these two gain values, select the lower one as the PGA gain setting as this maximizes the utilized ADC range without saturation occurring at higher currents. As an example, suppose a 100A maximum RMS current and a 200µΩ shunt is used. Based on these values, $V_{ADC,shunt}$ RMS varies between ±28.3mV and this voltage range lies between the maximum ±37.5mV voltage at a gain of 32 and ±18.75mV at a PGA gain of 64; so the PGA gain setting of the shunt channel is set for 32 (the lower gain value).

Table 2-1. Full-Scale Range of ADS131M03

GAIN SETTING	FSR
1	±1.2V
2	±600mV
4	±300mV
8	±150mV
16	±75mV
32	±37.5mV
64	±18.75mV
128	±9.375mV

2.3.2 Energy Metrology Software

The metrology software used for testing TIDA-010940 is delivered as a middleware example in the latest MSPM0 SDK, Version 2.02.00.05 or later. There are other middleware examples for MSPM0G3507, supporting both *Cost-Effective, 3-Phase CT Electricity Meter Reference Design Using Standalone ADC* and *Single-Phase and Split-Phase Shunt Energy Metrology Reference Design* energy metrology designs.

The MSPM0 Energy Metrology middleware software packages contains hardware abstraction layers which enable communication between an ADC and an ARM® Cortex®-M0+ microprocessor (MCU) and a library of metrology calculations for energy measurements. Also included in the software is a Windows® PC GUI to display the metrology parameters from the TIDA-010940 reference design. This PC GUI can be found in the *tools* directory under C:\ti\mspm0_sdk_2_02_00_05\tools\metrology_gui.

The resource utilization of TIDA-010940 middleware code example, using TI CCS compiler optimization setting of 2 are:

- 38,008 Bytes FLASH for Application code
- 256 Bytes FLASH for calibration data
- 2,787 Bytes RAM memory

The test data included in this reference design was collected using the MSPM0-SDK middleware code example for the single-phase electricity meter, found at:
C:\ti\mspm0_sdk_2_02_00_05\examples\nortos\LP_MSPM0L2228\energy_metrology\single_phase_TIDA_010940_SW

2.3.2.1 Software Architecture

For a detailed description of the software partitioning and the related formulas for energy calculations please refer to Chapters 3.1.5 thru 3.1.13 in *Single-Phase and Split-Phase Shunt Energy Metrology Reference Design*.

Additional documentation about the metrology calculations and a detailed Energy Metrology software overview are found in the latest *MSPM0-SDK Version*:

file:///C:/ti/mspm0_sdk_2_02_00_05/docs/english/middleware/energy_metrology/doc_guide/doc_guide-srcs/index.html

2.3.2.2 Setup

2.3.2.2.1 Clocking Scheme

An external 16.384MHz crystal is connected to the HFXIN and HFXOUT pins of MSPM0L2228 device and provides accurate and low-jitter clock signal, which is then divided by two and output on M0_CLKOUT pin of the MSPM0+ MCU. The ADS131M03 further divides this clock by two and uses the resulting 4,096MHz clock for the delta-sigma modulator clock. Another external 32.768kHz crystal is used as the clock source for the auxiliary clock (ACLK) of the MSPM0L2228.

2.3.2.2.2 SPI

The MSPM0L2228 has two SPI bus, one is connected to an external Serial FLASH device for logging data, while the other one is used to communicate with the ADS131M03 device.

- SPI0 Port → Pins P58, P59, P60, and P76 to ADS131M03
- SPI0 Port → Pins P25, P26, P27, and P30 to serial FLASH

The clock frequency for both is set to 8MHz in the TIDA_010940.syscfg file.

2.3.2.2.3 UART Setup for GUI Communication

The MSPM0L2228 MCU is configured to communicate to the PC GUI through the RS-485 connection J15 on this reference design using a UART module configured for 8N1 at 9600 baud. The PC GUI polls data from the MSPM0L2228 using a UART protocol for formatting the data, named DLT-645, and uses two DMA Channels: Channel 2 for data receive and Channel 3 for data transmit. See also the *MSP430AFE253 Test Report for China State Grid Specification* and *Single Phase and DC Embedded Metering (Power Monitor) Using MSP430I2040* application notes.

UART data is processed in the HAL_startUARTDMAReceive() function, by setting a trigger at 14 bytes, as this is the byte which codes the packet length (which can change dynamically from packet to packet).

2.3.2.2.4 Real-Time Clock

The real-time clock (RTC) module of the MSPM0+ MCU can configured to give precise one-second interrupts and update the calendar time and date, as necessary.

2.3.2.2.5 LCD Controller

The LCD controller on the MSPM0L2228 can support up to 8-MUX displays with 408 segments or 4-MUX displays with 220 segments and is configured to work in 4-MUX mode using 23 segments and 4 COM lines. The configuration of MCU pins for the LCD display is handled in the SysConfig file and can be easily modified to support customer displays with any configuration of SEG and COM pins, due to the software controlled pin functionality.

2.3.2.2.6 Direct Memory Access

The direct memory access (DMA) module supports communication over UART and SPI bus and enables packet transfers from and to MSPM0L2228 with minimal CPU bandwidth load.

Two DMA channels are used for communicating to the ADS131M03 over SPI Bus: DMA Channel 0 is used to send data to the ADS131M03 and DMA Channel 1 is used to simultaneously receive data from the ADS131M03. Once a complete packet has been received from the ADS131M03, a *DMA done interrupt* is generated and triggers the necessary post-transfer processing, such as CRC verification and data packet disassembly into voltage and current raw ADC values.

DMA Channel 2 is used for UART data reception from the PC GUI, the 14th byte of each DLT-645 packet contains the total packet length sent by the PC GUI (as packet length can change dynamically from packet to packet). The UART data is handled by HAL_startUARTDMAReceive() function, by setting the initial expected DMA length at 14 bytes. After decoding the byte 14, the UART DMA transfer length value gets updated, and now equals the rest of the DLT-645 protocol packet (total length - 14) in bytes. Thus the PC GUI packet can be received with two interrupts in total, as the DMA triggers again at the end of the UART packet.

2.4 Hardware, Software, Testing Requirements, and Test Results

2.4.1 Required Hardware and Software

2.4.1.1 Cautions and Warnings

At high currents, the terminal block can get warm. In addition, note that the line voltage is fed to the board so take the proper precautions, especially if the system is referenced with respect to line.

WARNING

⚠ Hot Surface! Contact can cause burns. Do not touch. Take the proper precautions when operating.

CAUTION

⚠ High Voltage! Electric shocks are possible when connecting the board to live wires. The board must be handled with care by a professional. For safety, use of isolated test equipment with overvoltage or overcurrent protection is highly recommended.

2.4.1.2 Hardware

Figure 2-6 shows the location of various components of the reference design on the top layer of the PCB. The bottom layer (not shown) accommodates the LCD display with the Menu switch and two mechanical tamper switches to detect a case opening event.
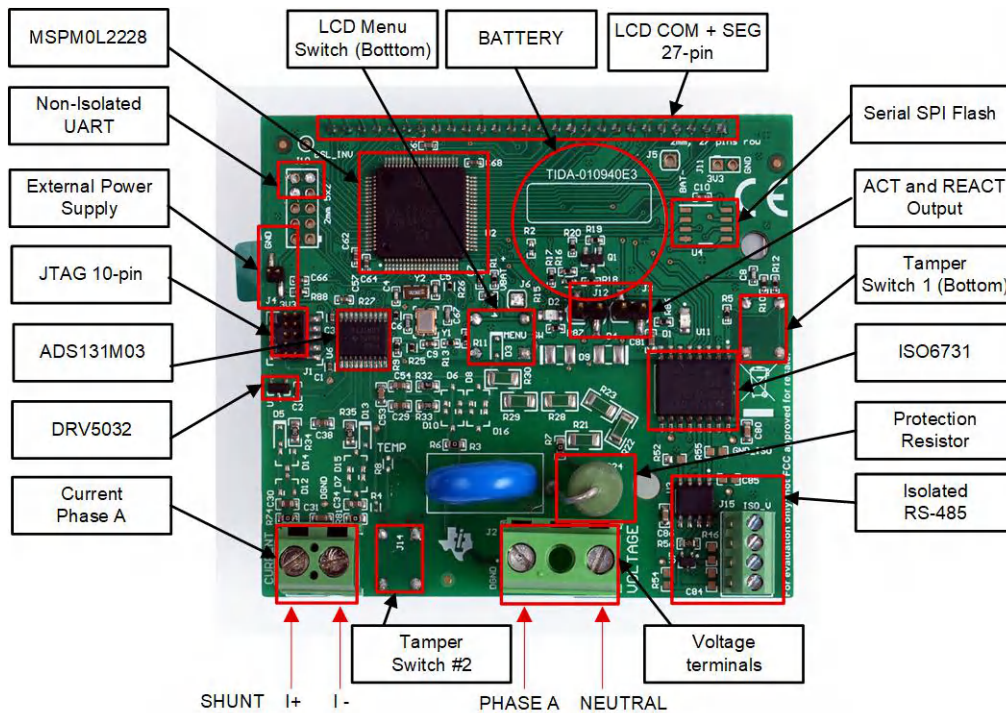

Figure 2-6. Top Layer of TIDA-010940 PCB With Components Highlighted

2.4.1.2.1 Connections to the Test Setup

AC voltages and currents can be applied to the board for testing purposes at these points:

- Terminal block J2 is a two-position terminal block for the line and neutral voltage connections of ±270V
- Terminal block J14 is connected to the output terminals of the shunt. This terminal block is also a two-position terminal block. For the gain of 32 used in this design, the differential voltage across the two J14 terminals need to be less than ±37.5mV.

Note

Phase A voltage has to be supplied to J2, Pin 1, which is marked with DGND on the silkscreen, while Neutral is connected to J2, Pin 2.

2.4.1.2.2 Power Supply Options and Jumper Settings

The MSPM0L228 and ADS131M043 are powered from an external power supply by connecting the 3.3V and GND to header J4.

Note

The headers with **(WARNING)** text in the *MAIN FUNCTIONALITY* column are not isolated, so do not use measuring equipment there (especially if the system is referenced with respect to the line) when running off the Mains. This applies, unless either isolators external to the board of the design are used to connect at the headers, if the equipment is battery powered and does not connect to Mains, or if AC mains is isolated.

Table 2-2. Header Names and Jumper Settings

Header or Header Option Name	Type	Main Functionality	Valid Use-Case	Comments
J1	10-pin header	Programming of MSPM0L2228**(WARNING)**	Apply 10-pin cable from XDS110 Debugger on a TI Launch Pad to flash MSPM0+ MCU.	TI MSPM0G3507 or MSPM0L1306 LaunchPads provide XDS110 debug functionality for external targets / TI MCU devices. Since this header and the XDS110 are not isolated, do not connect to this header when running off Mains and Mains is not isolated.
J2	2-pin Terminal block	Line and Neutral connections **(WARNING)**	Connect Line and Neutral	Connect High Voltage for Line and Neutral from Test equipment here
J4	2-pin jumper header	External power supply**(WARNING)**	Header with GND and 3V3 pins, marked with text.	Used for testing, non-isolated 3V3 and GND can be also provided from TI LaunchPad.
J5, J6	1-pin headers	Connections for CR2032 battery backup **(WARNING)**	VBAT and GND.	These are two pins: GND and VBAT, so a battery can be soldered to the PCB.
J11	10-pin 2-row connector	JTAG: MSPM0+ programming header **(WARNING)**	Connect an external XDS110 debugger to this connector to program the MSPM0L2228 MCU.	
J3	2-pin header	Active energy pulses **(WARNING)**	Probe here for active energy pulses based on the shunt active power readings. This header has two pins: GND and ACT, which is where the active energy pulses are actually output.	This header is not isolated from AC mains, so do not connect measuring equipment here (especially when referencing the system from line).
J12	2-pin header	Reactive energy pulses **(WARNING)**	Probe here for active energy pulses based on the shunt active power reading. This header has two pins: GND and REACT, which is where the reactive energy pulses are actually output.	This header is not isolated from AC mains, so do not connect measuring equipment here (especially when referencing the system from line).
J15	4-pin terminal block	RS-485 connection	Connection point for RS-485	To view the GUI using RS-485, connect the USB to RS-485 adapter here. 3V3 must be provided externally on pin 4 of this header. Pin 2 of this header is the RS-485 ground, pin 3 is the B bus I/O line, and pin 4 is the A bus I/O line.

2.4.1.3 Calibration

The GUI used for viewing results can easily be used to calibrate the design. During calibration, parameters called calibration factors are modified in the test software to give the least error in measurement. For this meter, there are six main calibration factors for each phase: voltage scaling factor, active power offset (erroneously called voltage AC offset in the GUI), current scaling factor, reactive power offset (erroneously called current AC offset in the GUI), power scaling factor, and the phase compensation factor. 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 power offset is used to subtract voltage to current crosstalk, which appears as a constant power offset and causes greater inaccuracies at lower currents. Note that offset calibration was only used for the shunt channel and not the CT channel. 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. Note that the voltage, current, and power calibration factors are independent of each other. Therefore, calibrating voltage does not affect the readings for RMS current or power.

When the Energy Metrology middleware is flashed on the MSPM0+ MCU for the first time, default calibration factors are loaded into these calibration factors. These values are modified through the GUI during calibration. The calibration factors are stored into a FLASH sector, and therefore, remain the same if the hardware is restarted.

Calibrating any of the scaling factors is referred to as gain correction. Calibrating the phase compensation factors is referred to as phase correction. For the entire calibration process, the AC test source must be ON, meter connections consistent with Section 2.4.1.2.1, and the energy pulses connected to the reference meter.

2.4.2 Testing and Results

2.4.2.1 Test Setup

To test for metrology accuracy, a source generator is used to provide the voltage (J2) and current (J14) to the system. Additionally, a nominal voltage of 120V, calibration current of 10A with phase calibration at 60° and nominal frequency of 60Hz are used. During all of the tests, the board is powered directly thru J4 using 3V3 and GND from a bench power supply.

When the voltage and current are applied to the system, the system outputs the active energy pulses and reactive energy pulses at a rate of 6400 pulses/kWh. The pulse output is fed into a reference meter, which is test equipment which integrates a reader for the pulse output and a voltage and current source generator. This reference meter determines the energy % error based on the actual energy provided to the system and the measured energy as determined by the active and reactive energy output pulses of TIDA-010940 reference design. Note that active energy error testing and reactive energy error testing are performed after running energy gain calibration, phase calibration, and energy offset calibration.

All active and reactive energy testing is performed using a 200µΩ shunt and the current is varied from 50mA to 100A while voltage is held at 120V. In addition, the system is referenced with respect to the neutral for all tests.

For the following test results, gain, phase, and offset calibration are applied to the meter. At higher currents, the % error shown is dominated by shunt resistance drift caused by the increased heat generated at high currents.

2.4.2.1.1 Viewing Metrology Readings and Calibration

Calibration is key to any meter 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, every meter must be calibrated. To perform calibration accurately, there must be an accurate AC test source and a reference meter available. The source must be able to generate any desired voltage, current, and phase shifts (between V and I) per phase. To calculate errors in measurement, the reference meter acts as an interface between the source and the meter being calibrated.

The exact calibration procedure is described in Chapter 3.2.3 Viewing Metrology Readings and Calibration of *Single-Phase and Split-Phase Shunt Energy Metrology Reference Design* and applies here also.

2.4.2.1.1.1 Viewing Results From LCD

The LCD is used to display various parameters being calculated by the energy metrology library.

2.4.2.1.1.2 Viewing Results From PC GUI

To view the metrology parameter values from the GUI, perform the following steps:

1. Select whether to use the RS-485 or UART connection for communication to the PC GUI. The testing was done using UART with 9600, 8N1 setting on pins XY.
2. Connect the reference design to a PC
   - UART option: Connect the reference design to a PC using a UART cable, wired to Pins X and Y on header J?.
   - RS-485 option: Use a USB to RS-485 adapter to communicate between the PC GUI and the RS-485 port on this design. The USB to RS-485 adapter need to create a COM port on the PC when it is plugged in. The other end of the adapter needs to have wires for the RS-485 Data A and Data B connections as well as a GND connection and a 3.3V power connection.
3. Open the GUI folder and open *calibration-config.xml* in a text editor.
4. Change the *port name* field within the *meter* tag to the COM port connected to the system. As Figure 2-7 shows, this field is changed to *COM7*.

```
260          </correction>
261        </phase>
262        <temperature/>
263        <rtc/>
264      </cal-defaults>
265      <meter position="1">
266          <port name="com7" speed="9600"/>
267      </meter>
268      <reference-meter>
269          <port name="USB0::0x0A69::0x0835::A66200101281::INSTR"/>
270          <type id="chroma-66202"/>
271          <log requests="on" responses="on"/>
272          <scaling voltage="1.0" current="1.0"/>
273      </reference-meter>
```

Figure 2-7. GUI Configuration File Changed to Communicate With Energy Measurement System

5. Run the *calibrator.exe* file, which is located in the GUI folder. If the COM port in the *calibration-config.xml* was changed in the previous step to the COM port connected to the reference design, the GUI opens (see Figure 2-8). If the GUI connects to the design properly, 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.
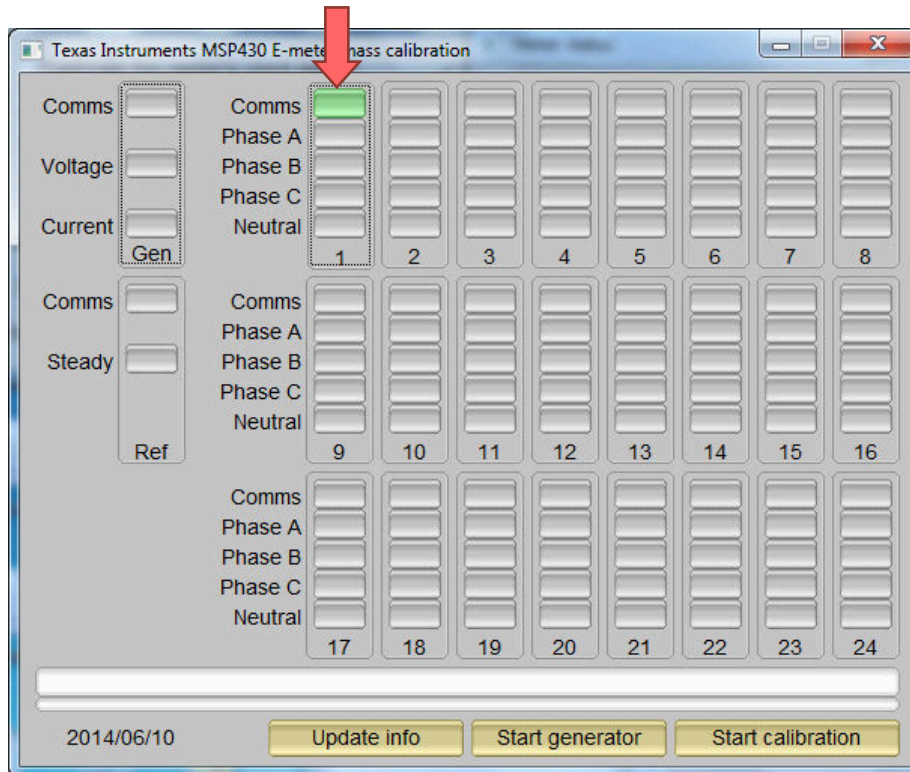
Figure 2-8. GUI Startup Window

When clicking the green button, the results window opens (see Figure 2-9). In the figure, there is a trailing "L" or "C" on the *Power factor* values to indicate an inductive or capacitive load, respectively. Note that by default, the column in the GUI labeled "Phase A" is actually the shunt channel and the column labeled "Neutral" is actually the CT channel. If the system and shunt is referenced with respect to the neutral, the shunt can actually measure the neutral current and the CT can measure the line current, unlike how the GUI is labeled.
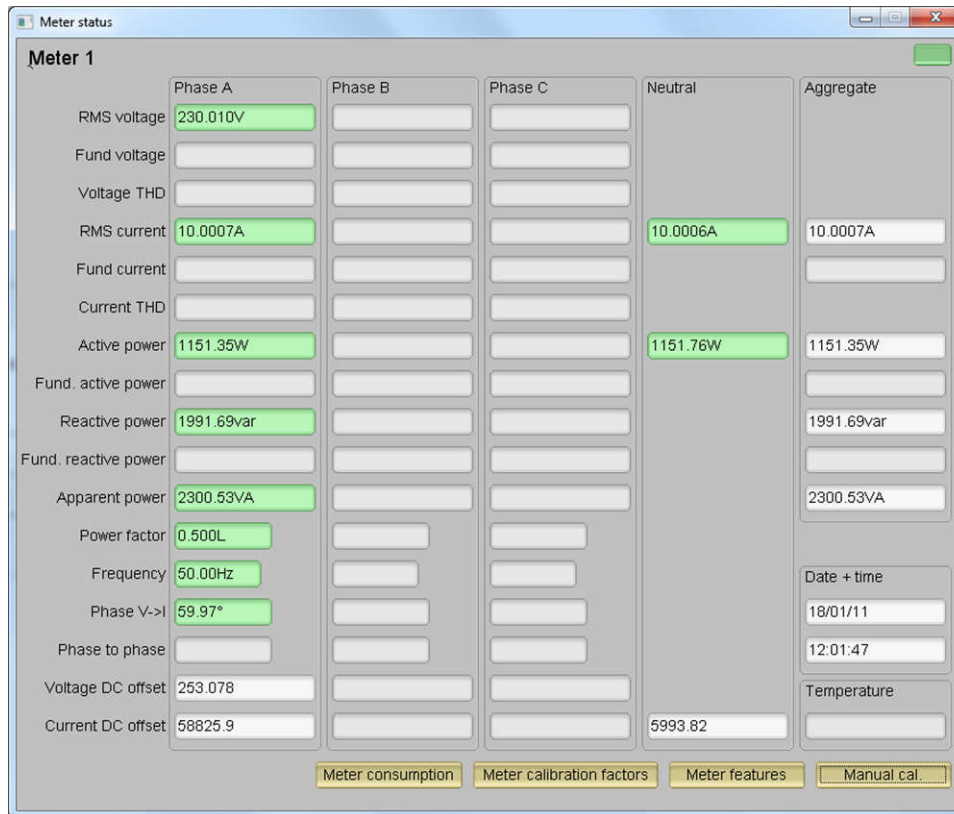
Figure 2-9. GUI Results Window

From the results window, the total-energy consumption readings can be viewed by clicking the *Meter Consumption* button. After the user clicks this button, the *Meter events and consumption* window pops up, as Figure 2-10 shows.
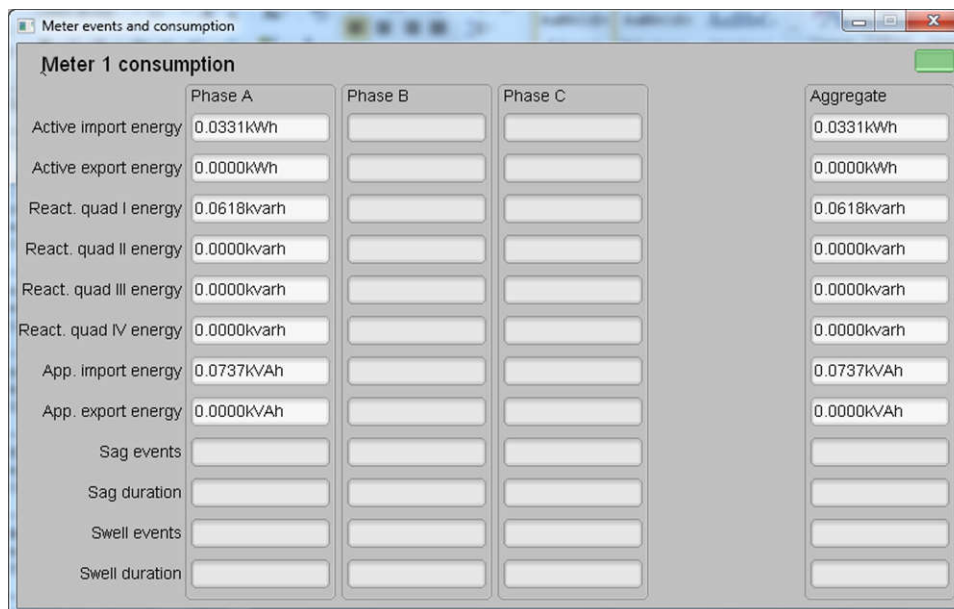

Figure 2-10. Meter Events and Consumption Window

From the results window, the meter settings can be viewed by clicking the *Meter features* button, view the system calibration factors by clicking the *Meter calibration factors* button, or open the window used for calibrating the system by clicking the *Manual cal.* button.

2.4.2.2 Electricity Meter Metrology Accuracy Testing

For cumulative active energy error, cumulative reactive energy error testing, and individual phase active energy testing, current is varied from 50mA to 100A. For cumulative active energy and individual phase error testing, a phase shift of 0° (PF = 1), PF = 0.5i (inductive) and PF = 0.8c (capacitive) is applied between the voltage and current waveforms fed to the reference design. Based on the error from the active energy output pulse, a plot of active energy % error versus current is created for the three PF values.

For cumulative reactive energy error testing, a similar process is followed except that a phase shift of 90° (sin φ = 1i), sin φ = 0.5i (inductive) and sin φ = 0.8c (capacitive) are used, and cumulative reactive energy error is plotted instead of cumulative active energy error.

All these tests were run using the 8000 samples per second rate setting of the ADS131M03 device.

For the VRMS accuracy test on Phase A, the voltage was varied from 10V to 270V while current was held steady at 10A. Testing beyond 270V can also be done; however, this requires the 275V varistors to be removed from the design and replaced with varistors that are rated for a higher voltage.

For the IRMS accuracy test on Phase A, the voltage was kept steady at 120V, while current was varied from 0.1A to 100A.

The following two plots for Active and Reactive Power are per IEC 62053-22 limits for class 0.5S accuracy, assuming Inominal = 15A, hence the 5% point of Inominal is at 750mA.

The average error for each measurement is calculated from five test series, taken sequentially for each current value, and the maximum deviation from these five measurements is calculated (not shown in the following plots) to confirm the stability of this metrology subsystem being below 10% of the maximum error allowed.

2.4.2.3 Electricity Meter Metrology Accuracy Results

For the following test results, gain, phase, and offset calibration are applied to the meter. At higher currents, the % error shown is dominated by shunt resistance drift caused by the increased heat generated at high currents.

Table 2-3. Active Energy % Error Versus Current, 200µΩ Shunts

CURRENT (A)	AVG ERROR % PF = 1, cos PHI = 0°	LIMIT (%) [CLASS 0.5] IEC 62053-22 (PF = 1)	AVG ERROR % PF = 0.5i, cos cos PHI = 60°	LIMIT (%) [CLASS 0.5] IEC 62053-22 (PF 0.5i/ 0.8c)	AVG ERROR % PF = 1, cos PHI = −36.87°
0.10	0.322	1.0	0.571	1.0	0.563
0.50	0.105	1.0	-0.017	1.0	0.227
0.75	0.089	1.0	-0.073	1.0	0.212
1.5	0.058	0.5	-0.101	0.6	0.165
3	0.063	0.5	-0.123	0.6	0.150
7.5	0.053	0.5	-0.156	0.6	0.144
15	0.041	0.5	-0.161	0.6	0.124
30	0.005	0.5	-0.187	0.6	0.110
60	−0.002	0.5	-0.265	0.6	0.077
75	-0.061	0.5	-0.304	0.6	0.008
100	-0.181	0.5	-0.502	0.6	−0.129
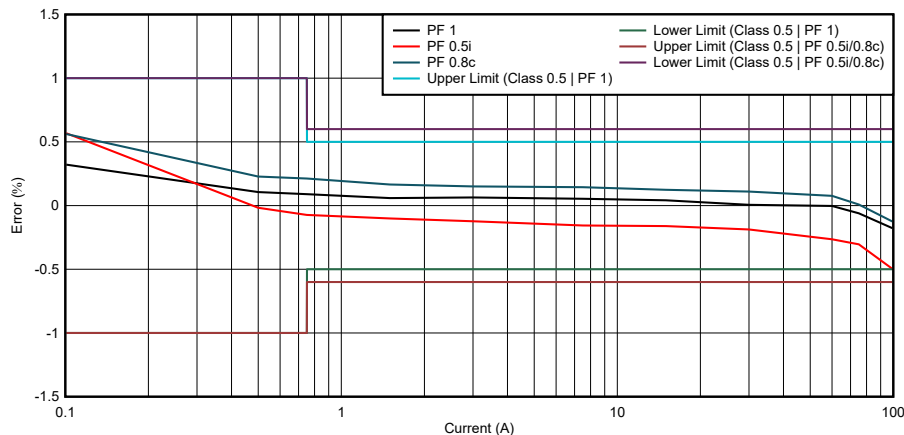
Figure 2-11. Active Energy % Error Versus Current, 200-µΩ Shunts

Table 2-4. Reactive Energy % Error Versus Current, 200-µΩ Shunts

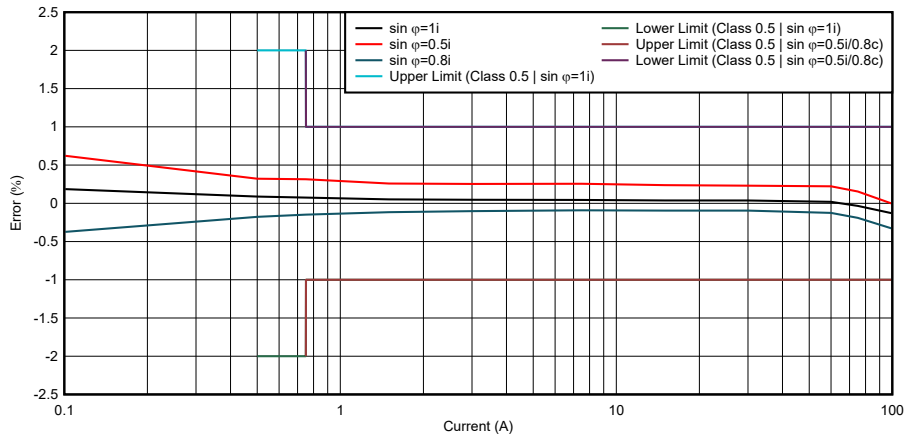| CURRENT (A)	AVG ERROR % sin PHI = 1i (90°)	LIMIT (%) [CLASS 0.5] IEC 62053-22 (sin PHI = 1, 90°)	AVG ERROR % sin PHI = 0.5i (30°)	LIMIT (%) [CLASS 0.5] IEC 62053-22 (sin PHI = 0.5i/0.8c, 30°/-53.13°)	AVG ERROR % sin PHI = 0.8c (-53.13°)
0.10	0.186		0.623		-0.374
0.50	0.088	2.0	0.322		−0.177
0.75	0.074	2.0	0.314		−0.148
1.5	0.051	1.0	0.258	2.0	−0.116
3	0.046	1.0	0.252	1.0	−0.102
7.5	0.043	1.0	0.255	1.0	−0.092
15	0.037	1.0	0.2	1.0	−0.095
30	0.037	1.0	0.230	1.0	−0.095
60	0.019	1.0	0.222	1.0	−0.126
75	-0.033	1.0	0.154	1.0	−0.190
100	-0.131	1.0	-0.006	1.0	−0.332

Figure 2-12. Reactive Energy % Error Versus Current, 200-μΩ Shunts

Table 2-5. Current RMS % Error at 120V, 200-μΩ Shunts

CURRENT (A)	%ERROR
0.025	−23.562
0.05	−8.155
0.1	−2.049
0.25	−0.492
0.5	−0.203
1	−0.100
2	−0.050
5	−0.049
10	-0.021
20	-0.037
30	-0.023
40	-0.027
50	-0.015
60	0.002
70	0.011
80	0.021
90	0.034
100	0.064
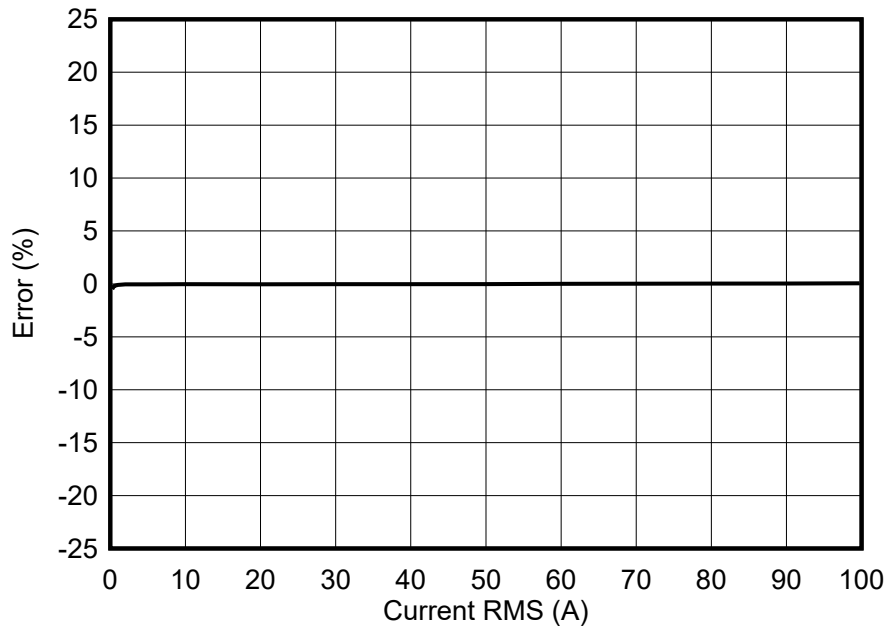
Figure 2-13. Current RMS %Error Versus Voltage, 9V to 270V, 200-µΩ Shunts

Table 2-6. Voltage RMS % Error at 10A, 200-µΩ Shunts

VOLTAGE (V)	%ERROR
9	0.021
10	0.037
30	0.027
50	0.009
70	0.004
90	−0.006
100	0.008
120	−0.004
140	-0.006
160	0.001
180	0.018
200	-0.002
220	0.011
230	0.023
240	0.009
260	0.027
270	0.025
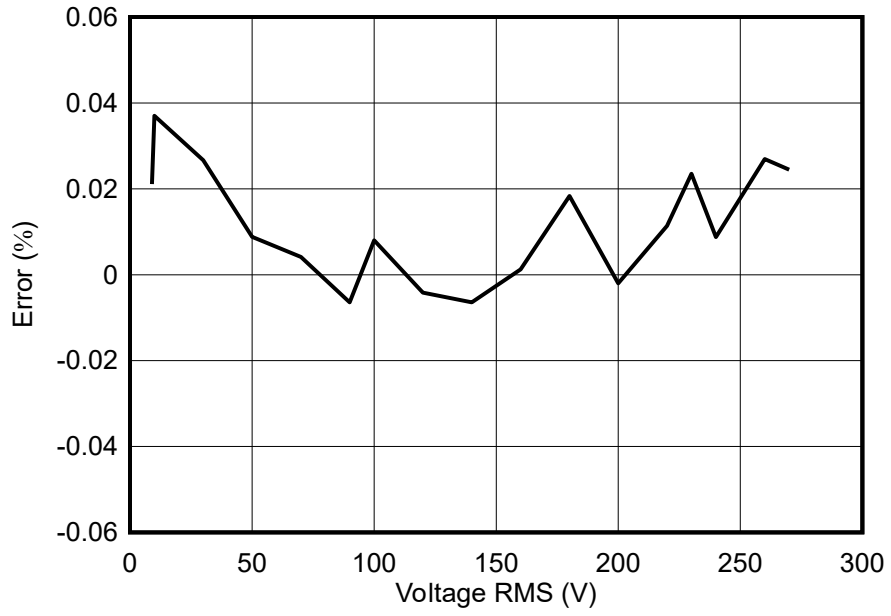
Figure 2-14. Voltage RMS %Error at 10A, 200µΩ Shunts

3 Design Files

3.1 Schematics

To download the schematics, see the design files at TIDA-010940.

3.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010940.

3.3 PCB Layout Recommendations

For this design, the following general guidelines need to be followed:

- Place decoupling capacitors close to the associated pins.
- Use ground planes instead of ground traces and minimize the cuts in the ground plane, especially near the ADS131M03 device. In this design, there is a ground plane on both the top and bottom layer; for this situation, make sure that there is good stitching between the planes through the liberal use of vias.
- Keep the two traces to the inputs of an ADC channel symmetrical and as close as possible to each other.
- For the ADS131M03 device, place the 0.1µF capacitor closer to the AVDD pin than the 1µF capacitor. Do the same thing also for the 0.1-µF and 1-µF capacitors connected to DVDD.
- Minimize the length of the traces used to connect the crystal to the MCU. Place guard rings around the leads of the crystal and ground the crystal housing. In addition, there must be clean ground underneath the crystal and avoid placing any traces underneath the crystal. Also, keep high-frequency signals away from the two MCU crystals.
- Use wide traces for power-supply connections.
- Use a different ground plane for the isolated RS-485. This other ground plane is at the potential of the RS-485 ground and not the GND used elsewhere in the board.
- Make sure that the recommended clearance and creepage spacing are met for the ISO6731.

3.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010940.

3.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010940.

3.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010940.

3.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010940.

4 Related Documentation

1. Texas Instruments, *ADS131M03 3-Channel, Simultaneously-Sampling, 24-Bit, Delta-Sigma ADC*, data sheet.
2. Texas Instruments, *ADS131M04 Evaluation board*.
3. Texas Instruments, *MSPM0L222x, MSPM0L122x Mixed-Signal Microcontrollers*, data sheet.
4. Texas Instruments, *LP-MSPM0L2228 Evaluation board*
5. Texas Instruments, *THVD1400, THVD1420 3.3-V to 5-V RS-485 Transceivers in Small Package with ±12-kV IEC ESD Protection*, data sheet.
6. Texas Instruments, *ISO6731 General-Purpose Triple-Channel Digital Isolator with Robust EMC*, data sheet.
7. Texas Instruments, *DRV5032 Ultra-Low-Power Digital-Switch Hall Effect Sensor*, data sheet.
8. Texas Instruments, *Split-Phase Shunt e-Meter Reference Design*, design guide.
9. Texas Instruments, *One-Phase Shunt Electricity Meter Reference Design Using Standalone ADC*, design guide.
10. Texas Instruments, *Compact Multichannel Current Sensing*, application note.

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GAVIN LOERA (B.S BME) is a system engineer at TI, working in the Energy Infrastructure field and focusing on Current Sense technologies and metering applications. After graduating, Gavin spent some time as a Test Technician for Abbott Laboratories, before accepting a position at TI in the Applications Rotation program in 2022. Gavin joined the Energy Infrastructure SEM team, with focus on metering and current sensing and spent six months with Precision Analog-Digital Converters (PADC) Applications team, where Gavin learned more about precision ADC, the key analog component for electricity meters.

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