Design Guide: TIDA-010960

One-Phase Shunt Power Meter Reference Design With Isolated ADC

Description

This reference design implements a single-phase energy meter using standalone isolated multichannel analog to-digital converters (ADC) to sample a shunt current sensor. The reference design achieves 0.5% accuracy across the input range (50mA–15A) with a 4kHz 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 and can be compiled with TI's Code Composer Studio™.

Resources

TIDA-010960	Design Folder
AMC130M02	Product Folder
MSPM0G1106	Product Folder
LMK6C, TLV761	Product Folder
Energy Metrology Library	Software

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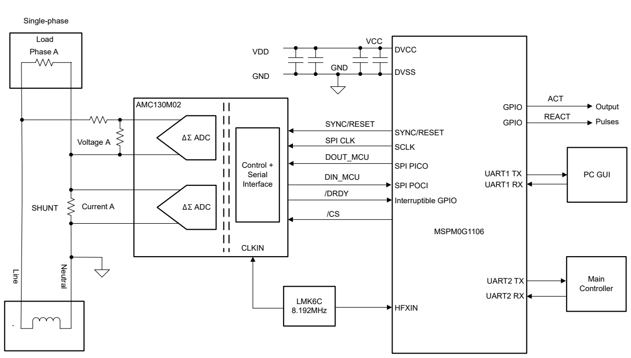
Features

- Single-phase 0.5% accuracy across the input range (50mA–15A) with 4kHz sampling rate
- Calculated parameters include active and reactive energy and power, RMS line current, RMS neutral current, RMS voltage, power factor, and line frequency
- Energy metrology software with pulsed outputs to a reference test system including results displaying on a Microsoft® Windows® PC GUI
- Flexibility in combining Metrology MCU and ADC for various performance points

Applications

- Electricity meter
- Major appliance
- Small home appliances
- Heat pump
- Lighting



1 System Description

The TIDA-010960 reference design has the properties described in Section 1.1 through Section 1.3.

1.1 Key System Specifications

FEATURES	DESCRIPTION
Number of phases	1 phase (current measured through a SHUNT), single voltage through a resistor divider
Accuracy class	< 0.5%
Dynamic range	50mA to 15A
Current Sensor	SHUNT
Tested current range	50mA to 15A
Tested voltage range	100V to 240V
AMC130M02 CLKIN frequency	8192000Hz (from LMK6C)
Oversampling ratio (OSR)	1024
Digital filter output sample rate	4000 samples per second (default) (adjustable per register setting)
Phase compensation implementation	Software
Selected central processing unit (CPU) clock frequency	79.87MHz
System nominal frequency	50Hz or 60Hz
Measured parameters	• Active, reactive, apparent power and energy • Root mean square (RMS) current and voltage • Power factor • Line frequency
Update rate for measured parameters	Approximately equal to 1 second
Communication options	PC graphical user interface (GUI) with a universal asynchronous receiver-transmitter (UART)
Utilized light emitting diodes (LED)	2 LEDs: Active energy and reactive energy
Board power supply	3.3V to 16V

1.2 End Equipment

As industries transition to clean, net-zero electricity systems, government is taking a important steps towards creating smart and flexible electricity systems, by helping unlock the potential for consumers to benefit from using smart technology to shift *when* electricity is used. The decisions help make sure consumers can use a wider range of services and devices in homes and small businesses to manage electricity consumption and reduce bills. For example, HVAC system heat pumps can be used or heated during the times when electricity is cheapest. An electricity meter can be used here for the following benefits:

- Use electricity detect to calculate the power consumption of the end equipment, show the data to the consumer, thus allowing the consumer to know the basic power information of the end equipment.
- Electricity with real-time clock (RTC) function: automatically heat or charge the end equipment when electricity is cheapest
- Electricity is also a power monitor, to inform the consumer if the end equipment is work normally

1.3 Electricity Meter

Different end equipment has different requirements for electricity meters; for example, multiphase or single-phase, accuracy, and isolated or non-isolated. This reference design is developed for an isolated single-phase design using isolated ADC AMC130M02, and integrates power and data isolation, with the following advantages:

- Meets the most stringent of accuracy requirements
- Meets minimum sample rate requirements (without compromising on accuracy) that is sometimes not obtainable with application-specific products or metrology systems on a chip (SoC)
- Enables flexibility in selecting the host MCU, based on the application requirements, such as the following:
  - Processing capability in million instructions per second (MIPS)
  - Minimum random access memory (RAM) and flash area
  - Number of communications modules:
    - Serial peripheral interface (SPI)
    - Universal asynchronous receiver - transmitter (UART)
    - Inter-integrated circuit (I2C)
    - Real-time clock (RTC)
    - Continuously transposed conductors (CRC) module

TIDA-010960 is a high-accuracy one-phase SHUNT electricity meter reference design, using two channels for standalone isolated AMC130M02 ADC and cost-effective MSPM0G1106 MCU. One channel is for SHUNT resistor current sensing and another channel is for voltage sensing.

The TIDA-010960 firmware specifically supports calculation of various metrology parameters for single-phase with Neural line energy measurement. These parameters can be viewed from the calibration GUI or through the ACT and REACT pulsed outputs, connected to a reference metrology test system.

- Phase active (kWh), reactive (kvarh), and apparent energy (kVAh) with pulse-generation outputs
- Phase active (kW), reactive (kvar), and apparent power (kVA)
- Phase voltage and current root mean square (RMS)
- Power factor
- Line frequency

2 System Overview

2.1 Block Diagram

Figure 2-1 shows that for voltage sensing, 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 AMC130M02 device. Since the AMC130M02 ADCs 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 ADCs are only a fraction of the full-scale voltage. By reducing the voltage fed to the AMC130M02 voltage ADC, voltage-to-current crosstalk, which actually affects metrology accuracy more than voltage ADC accuracy, is reduced at the cost of voltage accuracy. For current sensing, a SHUNT resistor is selected based on the current range required for energy measurements and also the minimization of the maximum power dissipation of the shunt.

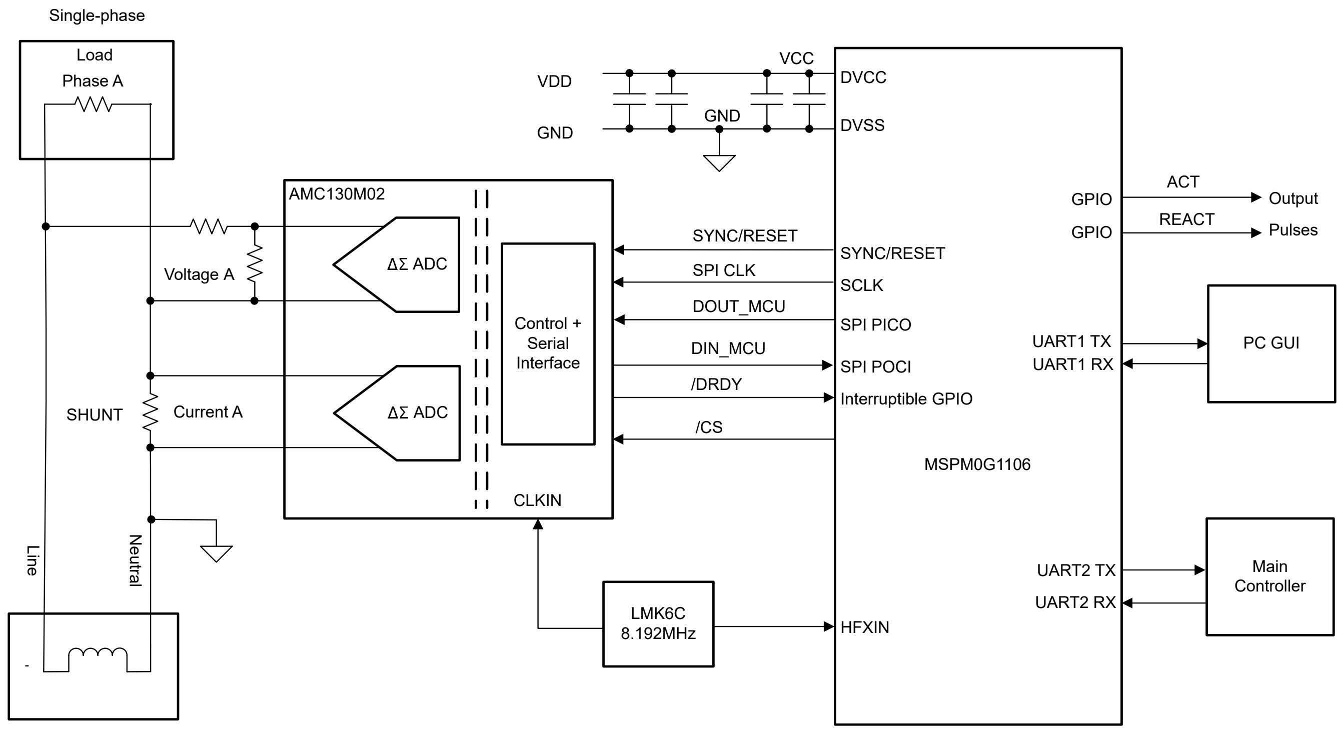


Figure 2-1. TIDA-010960 Block Diagram

In this design, the AMC130M02 device interacts with MSPM0 MCU in the following manner:

1. The clock for both MSPM0 and AMC130M02 are from LMK6C oscillator.
2. When new ADC samples are ready, the AMC130M02 device asserts the DRDY pin, which alerts the MSPM0 MCU that new samples are available.
3. After being alerted of new samples, the MSPM0 MCU uses one of the SPIs and the DMA to get the voltage and current samples from the AMC130M02 device
4. In addition, the MCU also communicates to a PC GUI through UART connection on J12.
5. ACT and REACT output signals from the MCU represent the active and reactive energy pulses used for accuracy measurement and calibration. Both are mandatory signals needed for calibrating the electricity meter against a reference meter.

2.2 Design Considerations

2.2.1 Voltage Measurement – Analog Front End

The nominal voltage from the mains in many regions of the world varies from 100V to 240V, so the voltage needs to be scaled down to be sensed by an ADC. Figure 2-2 shows the analog front end for the voltage scaling.

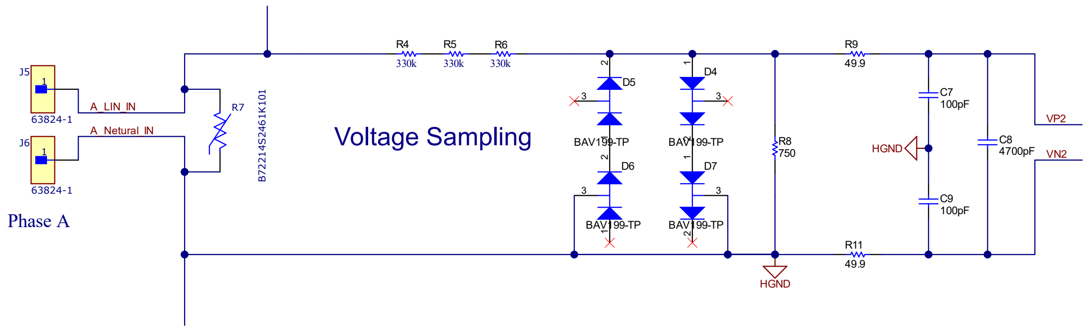


Figure 2-2. Analog Front End for Voltage Input

The analog front end for voltage input has a voltage divider network (R4, R5, R6, R8), and RC low-pass filter (R9, R11, C7, C9) and C8.

If offset calibration is not performed, the voltage-to-current crosstalk affects active energy accuracy much more than voltage accuracy when the current is low. To maximize the accuracy at lower currents, in this design the entire ADC range is not used for the voltage channel. The reduced ADC range for the voltage channels in this design still provide 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.

$$V_{ADC_{Swing},\,Voltage} = \pm V_{RMS} \times \sqrt{2}\left(\frac{R_8}{R_4 + R_5 + R_6 + R_8}\right) \tag{1}$$

Based on this formula and selected resistor values in Figure 2-2, for a main voltage of 230V, the input signal to the voltage ADC has a voltage swing of ±246mV (174mV_{RMS}). The ±246mV voltage ranges are both well within the –1.3V to 2.7V range, that can be sensed by AMC130M02.

2.2.2 Current Measurement Analog Front End

Figure 2-3 shows how the current input analog front end is different from voltage analog front end.

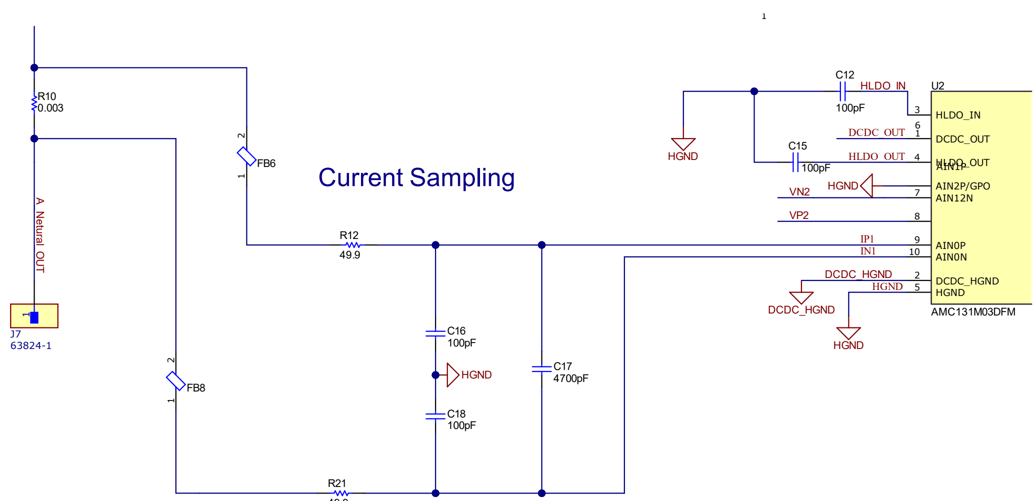


Figure 2-3. Analog Front End for Current Input

The analog front end for current consists of footprints for electromagnetic interference filter beads (FB6 and FB8), and a RC low-pass filter (R12, R21, C16, C18).

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

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

A SHUNT value of 3mΩ is used, the input signal to the current ADC has a voltage swing of ±63.6mV, 63.6mV when the current rating of the meter (15A) is applied. This relatively low voltage, when using GAIN = 16 is well within the required Full-Scale Range of ±75mV. See also the *full-scale range table* in the *AMC130M02 2-Channel, 64kSPS, Simultaneous-Sampling, 16-Bit, Reinforced Isolated Delta-Sigma ADC With Integrated DC/DC Converter* data sheet.

Table 2-1. Full-Scale Range

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

2.2.3 Input Voltage

Figure 2-4 shows the input power supply To meet a wider input power rail from the main controller, this design uses a linear voltage regulator TLV76133, which supports 2.5V to 16V input voltage and provides a stable 3.3V output to MSPM0 and AMC130M02.

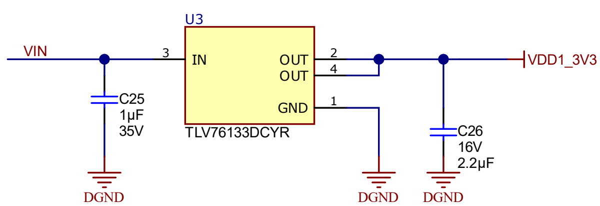


Figure 2-4. Input Power Supply

2.2.4 Clock

This design uses an ultra-low jitter, fixed frequency (8.192MHz) oscillator LMK6CE008192CDLFR. This oscillator provides clocks for both AMC130M02 and MSPM0. Jumper J11 was used to connect LMK6C output to AMC130M02, providing flexibility for connection to another clock from crystal or the MCU.

2.3 Highlighted Products

2.3.1 AMC130M02

The AMC130M02 is a precision, two-channel, data and power-isolated, simultaneous-sampling, 16-bit, delta-sigma (ΔΣ), analog-to-digital converter (ADC). The AMC130M02 offers wide dynamic range, low power, and energy-measurement-specific features designed for energy metering and power metrology applications. The ADC inputs can be directly interfaced to a resistor-divider network or a shunt current sensor because of the device high input impedance.

The AMC130M02 features a fully integrated isolated DC/DC converter that allows single-supply operation from the low-side of the device. The reinforced capacitive isolation barrier is certified according to VDE 0884-17 and

UL1577. This isolation barrier separates parts of the system that operate on different common-mode voltage levels and protects lower-voltage parts from damage, making the AMC130M02 an excellent choice for polyphase energy metering applications using shunt current sensors.

An integrated negative charge pump allows absolute input voltages as low as 1.3V below HGND, which enables measurements of input signals varying around ground with a single-ended power supply. The device features a programmable gain amplifier (PGA) with gains up to 128. An integrated input precharge buffer enabled at gains greater than 4 provides high input impedance at high PGA gain settings. The ADC receives the reference voltage from an integrated 1.2V reference. The device allows differential input voltages as large as the reference. Two power-scaling modes allow designers to trade power consumption for ADC dynamic range. Each ADC channel on the AMC130M02 contains a digital decimation filter that demodulates the output of the ΔΣ modulators. The filter enables data rates as high as 64kSPS per channel in high-resolution mode. The relative phase of the samples can be configured between channels, thus enabling an accurate compensation for the sensor phase response. Offset and gain calibration registers can be programmed to automatically adjust output samples for measured offset and gain errors. Figure 2-5 provides a detailed diagram of the AMC130M02

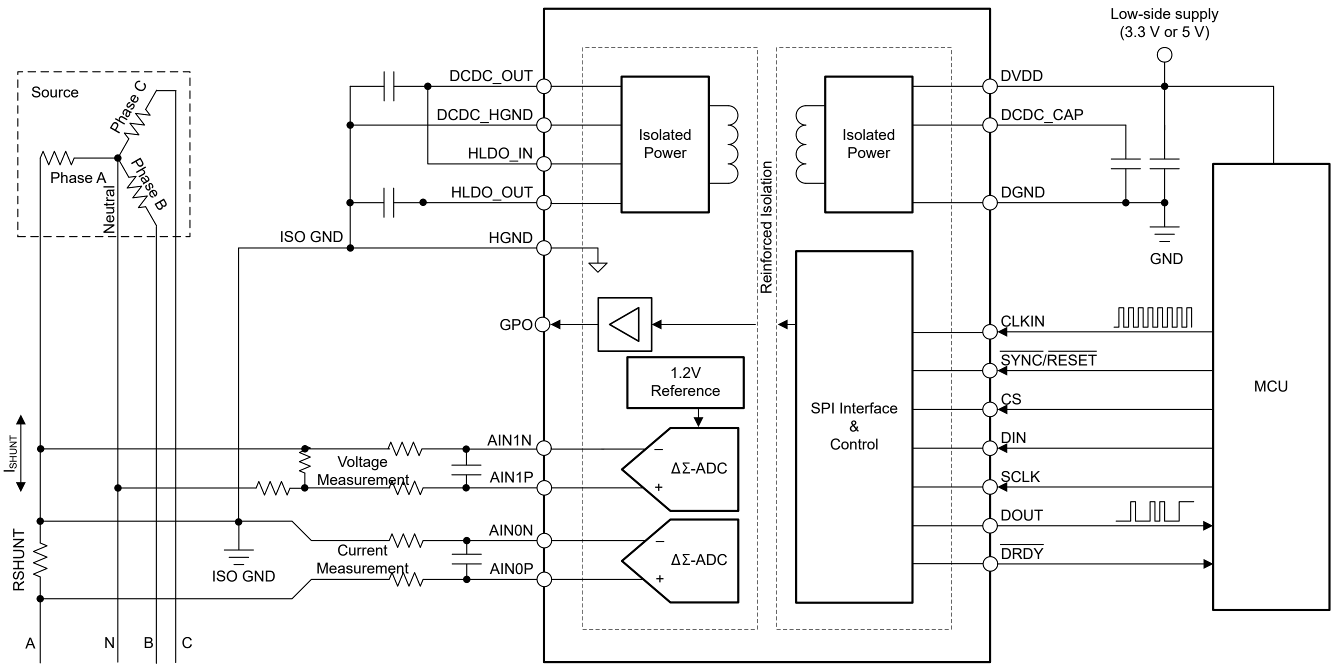


Figure 2-5. AMC130M02 Functional Block Diagram

2.3.2 MSPM0G1106

MSPM0G110x microcontrollers (MCUs) are part of the MSP highly-integrated, ultra-low-power 32-bit MCU family based on the enhanced Arm® Cortex®-M0+ 32-bit core platform operating at up to 80MHz frequency. These cost-optimized MCUs offer high-performance analog peripheral integration.

The MSPM0+ MCU in this design retrieves voltage and current samples from the ADC devices and calculates the metrology parameters. In addition, the device also keeps track of time with the RTC module, and uses one of the UART interfaces to communicate to a PC GUI. The CRC16 hardware module of the MSPM0+ MCU is used to accelerate the CRC calculations needed to verify the integrity of the ADC sampling data packets sent by the main features of the MSPM0G1106 ADC are the extended temperature range: –40°C up to 105°C; the wide supply voltage range: 1.62V to 3.6V; and the integrated 64KB of flash memory with built-in error correction code (ECC) and 32KB of ECC protected SRAM with hardware parity.

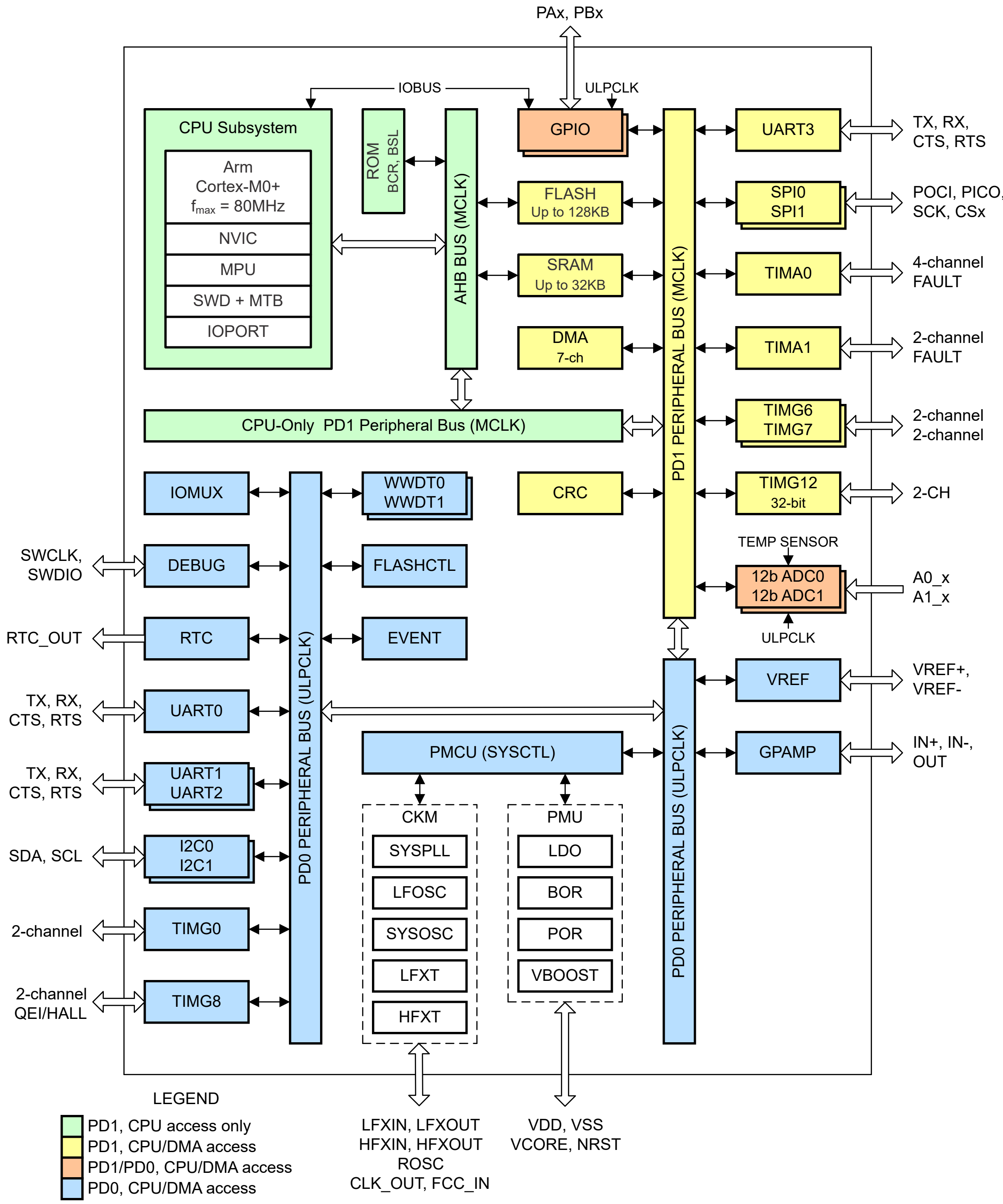


Figure 2-6. MSPM0G110x Functional Block Diagram

2.3.3 LMK6C

Texas Instruments' Bulk-Acoustic Wave (BAW) is a micro-resonator technology that enables integration of high-precision BAW resonator directly into packages with ultra-low jitter clock circuitry. BAW is fully designed and manufactured at TI factories like other silicon-based fabrication processes.

The LMK6x device is an ultra-low jitter, fixed frequency oscillator which incorporates the BAW as the resonator source. The device is factory programmed per specific operation mode, including frequency, voltage, output type, and function pin. With a high-performance fractional frequency divider, the LMK6x is capable of producing any frequency within the specified range providing a single device family for all frequency needs.

The high-performance clocking, mechanical stability, flexibility, and small package options for this device are designed for reference and core clocks in high speed SERDES used in telecommunications, data and enterprise network, and industrial applications.

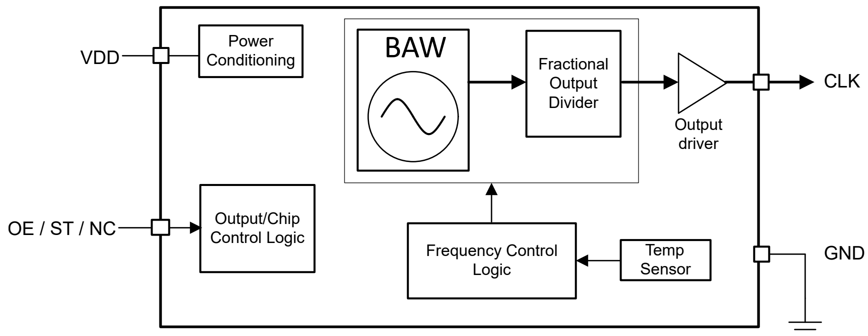


Figure 2-7. LMK6C Functional Block Diagram

2.3.4 TLV76133

The TLV761 is a linear voltage regulator that improves the functionality of a traditional x1117 regulator (TLV1117 or LM1117) with tighter output accuracy and low quiescent current (I_Q) to lower the standby power consumption. The TLV761 is pin-to-pin compatible with other fixed SOT-223, TO-252 regulators.

The TLV761 input voltage range is from 2.5V to 16V and provides an output voltage range from 0.8V to 13V to support a wide variety of applications. The wide bandwidth PSRR performance of the TLV761 is typically greater than 60dB at 1kHz and 40dB at 1MHz, which helps attenuate the switching frequency of an upstream DC/DC converter and minimizes post regulator filtering.

Additionally, the TLV761 has an internal soft start feature to reduce inrush current during start-up, which can help save space and cost in a design by minimizing input capacitance. The TLV761 features a foldback current limit that limits the power dissipation of the device during high-load current faults or shorting events.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Hardware Requirements

This reference design can be powered by J1(up to 16V) and then through an LDO (TLV76133) to output the voltage to 3.3V, for MCU and ADC power supplies.

The MSPM0G1106 device provides the minimum resources for running the metrology library and has the required peripherals to interface to the standalone ADCs and the PC GUI.

The required MCU peripheral modules include:

- HF Clocking subsystem using external oscillator
- SPI with DMA (data transfer between stand-alone ADCs and MSPM0 MCU)
- UART with DMA (data transfer between external PC GUI and MSPM0 MCU for calibration and metrology values read out)
- GPIOs (inputs with interrupts or outputs for LEDs and ADCs control)
- RTC (calendar mode based off 32.768kHz from internal LFOSC)

All the previously-listed peripherals or MCU modules are configured through the TIDA-010960.syscfg file in the MSPM0-SDK middleware, utilizing the graphical SysConfig tool, which enables intuitive MCU configuration changes over a GUI interface.

1. The M0+ clocking scheme is derived from the external 8.192MHz oscillator, which is feeding the PLL module and is being multiplied and divided with specific factors to generate the MCLK frequency (the CPU clock speed) of 79.87MHz.
2. The SPI bus runs at 8MHz data rate with DMA support using two channels, one for transmit and one for receive.
3. The MSPM0G1106 is configured to communicate to the PC GUI through a non-isolated UART connection at maximum 115,200 baud with 8N1. The UART driver supports a bidirectional transfer (two DMA channels are used, one for transmit and one for receive) with a minimum MCU interrupt load.
4. The DRDY lines are wired to GPIO inputs of MSPM0+ MCU with interrupt enabled on the falling edge. Three MCU GPIO outputs are needed: the SYNC_RESET line to trigger ADCs, and ACT and REACT outputs. These pulsed outputs are for the Active and Reactive energy, being calculated by the metrology middleware and are used to measure the TIDA-010960 accuracy using an external test system, which reads the pulses.
5. The RTC module supports calendar mode, which is a common requirement for an electricity meter. The M0+ MCU internal 32.768kHz LFOSC is used as the clock source for the auxiliary clock (RTCCLK) of the device.

3.2 Software Requirements

This section discusses the features of the test software and provides insight on how the calculation of many metrology parameters are implemented. The metrology software used for testing TIDA-010960 is delivered as a middleware example in the latest MSPM0 SDK, *Version 2.01.00.03 or later*.

The middleware contains hardware abstraction layers which enable communication between the standalone ADCs and an Arm Cortex-M0+ MCU and a library of metrology calculations for energy measurements. A Microsoft Windows PC GUI software is used to display metrology parameters from the TIDA-010960 reference design and can be found in MSPM0-SDK, see the `/tools` directory under `C:\ti\mspm0_sdk_2_01_00_03\tools\metrology_gui`.

The resource utilization of the TIDA-010960 middleware code example, using optimization setting of 2 are:

- 33232 Bytes FLASH for Application code
- 256 Bytes FLASH for calibration data
- 9090 Bytes RAM memory

3.2.1 Formulas

This section briefly describes the formulas used for the voltage, current, power, and energy calculations. As previously described, voltage and current samples are obtained at a sampling rate of 4kHz. All of the samples that are taken in approximately one second frames are kept and used to obtain the RMS values for voltage and current. The RMS values are obtained with the following formulas.

$$V_{RMS,\,ph} = K_{v,\,ph} \times \sqrt{\frac{\sum_{n=1}^{\text{Sample count}} V_{ph}(n) \times V_{ph}(n)}{\text{Sample Count}} - V_{offset,\,ph}} \quad (3)$$

$$I_{RMS,\,ph} = K_{i,\,ph} \times \sqrt{\frac{\sum_{n=1}^{\text{Sample count}} I_{ph}(n) \times I_{ph}(n)}{\text{Sample Count}} - I_{offset,\,ph}} \quad (4)$$

where

- $V_{ph}(n)$ = Voltage sample at a sample instant *n*
- $V_{offset,ph}$ = Offset used to subtract effects of the additive white Gaussian noise from the voltage converter
- $I_{ph}(n)$ = Each current sample at a sample instant *n*
- $I_{offset,ph}$ = Offset used to subtract effects of the additive white Gaussian noise from the current converter
- Sample count = Number of samples within the present frame
- $K_{v,ph}$ = Scaling factor for voltage
- $K_{i,ph}$ = Scaling factor for current

Power and energy are calculated for active and reactive energy samples of one frame. These samples are phase-corrected and passed on to the foreground process, which uses the number of samples (sample count) to calculate phase active and reactive powers through the following formulas:

$$P_{ACT,\,ph} = K_{ACT,\,ph} \frac{\sum_{n=1}^{\text{Sample count}} V_{ph}(n) \times I_{ph}(n)}{\text{Sample Count}} - P_{ACT_{Offset},\,ph} \quad (5)$$

$$P_{REACT,\,ph} = K_{REACT,\,ph} \frac{\sum_{n=1}^{\text{Sample count}} V_{90,\,ph}(n) \times I_{ph}(n)}{\text{Sample Count}} - P_{REACT_{Offset},\,ph} \quad (6)$$

$$P_{APP,\,ph} = \sqrt{P_{ACT,\,ph}^{2} + P_{REACT,\,ph}^{2}} \quad (7)$$

where

- $V_{90}(n)$ = Voltage sample at a sample instant *n* shifted by 90°
- $K_{ACT,ph}$ = Scaling factor for active power
- $K_{REACT,ph}$ = Scaling factor for reactive power
- $P_{ACT\_offset,ph}$ = Offset used to subtract effects of crosstalk on the active power measurements
- $P_{REACT\_offset,ph}$ = Offset used to subtract effects of crosstalk on the reactive power measurements

Note

For reactive energy, the 90° phase shift approach is used for two reasons:

1. This approach allows accurate measurement of the reactive power for very small currents
2. This approach conforms to the measurement method specified by IEC and ANSI standards

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Because the frequency of the mains varies, the mains frequency is first measured accurately to phase shift the voltage samples accordingly.

To get an exact 90° phase shift, interpolation is used between two samples. For these two samples, a voltage sample slightly more than 90 degrees before the most recent voltage sample and a voltage sample slightly less than 90 degrees before the most recent voltage sample are used. The phase shift implementation of the application 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 test software, a lookup table provides the filter coefficients that are used to create the fractional delays.

Using the calculated powers, energies are calculated with the following formulas:

$$E_{ACT,\,ph} = P_{ACT,\,ph} \times \text{Sample Count} \quad (8)$$

$$E_{REACT,\,ph} = P_{REACT,\,ph} \times \text{Sample Count} \quad (9)$$

$$E_{APP,\,ph} = P_{APP,\,ph} \times \text{Sample Count} \quad (10)$$

The calculated energies are then accumulated into buffers that store the total amount of energy consumed since system reset. These energies are different from the working variables used to accumulate energy for outputting energy pulses. There are three sets of buffers that are available: one for each V-I mapping. Within each set of buffers, the following energies are accumulated:

1. Active import energy (active energy when active power ≥ 0)
2. Active export energy (active energy when active power < 0)
3. Fundamental active import energy (fundamental active energy when fundamental active power ≥ 0)
4. Fundamental active export energy (fundamental active energy when fundamental active power < 0)
5. React. Quad I energy (reactive energy when reactive power ≥ 0 and active power ≥ 0; inductive load)
6. React. Quad II energy (reactive energy when reactive power ≥ 0 and active power < 0; capacitive generator)
7. React. Quad III energy (reactive energy when reactive power < 0 and active power < 0; inductive generator)
8. React. Quad IV energy (reactive energy when reactive power < 0 and active power ≥ 0; capacitive load)
9. Apparent import energy (apparent energy when active power ≥ 0)
10. Apparent export energy (apparent energy when active power < 0)

The background process also calculates the frequency in terms of samples-per-mains cycle. The foreground process then converts this samples-per-mains cycle to Hertz with Equation 11:

$$\text{Frequency (Hz)} = \frac{\text{Sample Rate (samples/second)}}{\text{Frequecy (sample/cycle)}} \quad (11)$$

After the active power and apparent power have been calculated, the absolute value of the power factor is calculated. In the internal representation of power factor of the system, a positive power factor corresponds to a capacitive load; a negative power factor corresponds to an inductive load. The sign of the internal representation of power factor is determined by whether the current leads or lags voltage, which is determined in the background process. Therefore, the internal representation of power factor is calculated with Equation 12:

$$\text{Internal Representation of Power Factor} = \begin{cases} \frac{P_{ACT}}{P_{App}}, \textit{if capacitive load} \\ -\frac{P_{ACT}}{P_{APP}}, \textit{if inductive load} \end{cases} \quad (12)$$

3.2.2 Metrology Software Process

Section 3.2.2.1 through Section 3.2.2.8 introduce the basic setup of MSPM0 MCU, metrology software process, and functions.

3.2.2.1 UART for PC GUI Communication

The MSPM0+ MCU is configured to communicate to the PC GUI through an UART interface on J12 in this reference design. The PC GUI polls data from the MSPM0G1106 using a UART module configured for 9600 baud with 8N1. The UART protocol for formatting the UART data is named DLT-645 and the UART module utilizes two DMA Channels: Channel 2 for data receive and Channel 3 for data transmit. See also the *Single Phase and DC Embedded Metering (Power Monitor) Using MSP430I2040* application note.

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). After decoding the byte 14, the UART DMA transfer length value gets updated to a new length, which equals the rest of the DLT-645 protocol packet, transmitted by the PC GUI.

3.2.2.2 Direct Memory Access (DMA)

The MCU DMA module transfers data packets between the MSPM0G1106 MCU and AMC130M03 devices with minimal hardware resources and timing overhead over the SPI bus. Two DMA channels are utilized for the SPI data transfer: DMA Channel 0 sends SPI data (0x00) to the ADC and DMA Channel 1 receives the measurements data from ADC over the SPI bus. AMC130M02 transfers 12 bytes packet due to 2 analog input, once a complete SPI data packet has been received from the ADC, an DMA Ready interrupt is generated and the CRC16 verification of the data packet starts. After the CRC16 check was successful, the data packet is disassembled into voltage and current values for Phase A.

3.2.2.3 ADC Setup

The AMC130M02 device register must be initialized to deliver proper measurement data on all relevant analog input channels. Figure 3-1 is followed at every start of the metrology application.

The SPI module of the MSPM0+ MCU is configured as a controller device that uses 4-wire mode. After the SPI is set up, all interrupts are disabled and a reset pulse on the SYNC_RESET line is sent from the MSPM0+ MCU. Interrupts are then re-enabled and the MSPM0+ MCU sends SPI write commands to AMC130M02:

- MODE register settings: 16-bit CCITT CRC used, 24-bit length for each word in the AMC131M03 data packet, the DRDY signal is asserted on the most lagging enabled channel, DRDY is asserted high when the conversion value is not available, DRDY is asserted low when the conversion values are ready.
- GAIN1 register settings for Voltage and Current: PGA gain = 1 used for the voltage channel, measuring the line-to-neutral, PGA gain = 16 for the current channels on Phase A and Neutral.
- CHx_CFG register settings (where x is the channel number: 0, 1): two ADC channel inputs connected to external ADC pins and the channel phase delay set to 0 for each channel (the software phase compensation in the SDK middleware is used instead of hardware phase compensation)
- CLOCK register settings: 1024 OSR, all channels enabled, and high-resolution modulator power mode

The MSPM0+ MCU is configured at start-up to generate a port interrupt whenever a falling edge occurs on the DRDY pins, which indicate that new measurement samples are available.

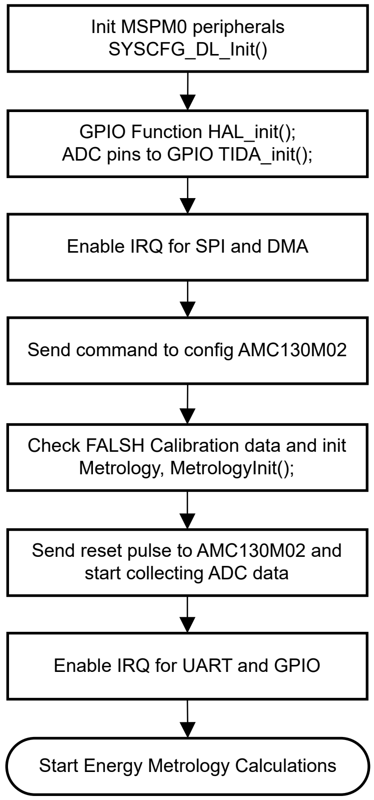


Figure 3-1. ADC Initialization Procedure

The ADC modulator clock is derived from the clock fed to the CLKIN pin which gets internally divided by two, to generate the ADC modulator clock. Equation 13 shows the definition of the sampling frequency of the ADC.

$$f_S = \frac{f_M}{OSR} = \frac{f_{CLKIN}}{2 \times OSR} \tag{13}$$

where

- f_S is the sampling rate
- f_M is the modulator clock frequency
- f_{CLKIN} is the clock fed to the AMC130M02 CLKIN pin
- OSR is the selected oversampling ratio

In this design, the CLKIN pin gets Clock from an external oscillator at a fixed frequency of 8.192MHz. The oversampling ratio is selected to be 1024 with the appropriate register setting. The sample rate is set to 4000 samples per second.

This design uses the following AMC130M02 channel mappings:

- AIN0P and AIN0N AMC130M02 ADC channel pins → Voltage
- AIN1N and AIN1P AMC130M02 ADC channel pins → Shunt Current (this can measure either the neutral or line current)

3.2.2.4 Foreground Process

The foreground process includes the initial setup of the MSPM0+ MCU hardware and software and AMC130M02 registers immediately after a device RESET. Figure 3-2 shows the flow chart for this process

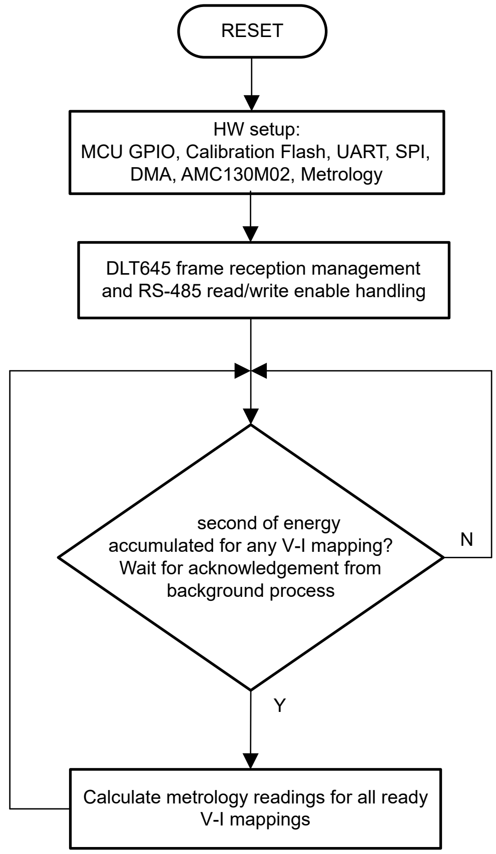


Figure 3-2. Foreground Process

The initialization routines involve the setup of the MSPM0G1106:

- General purpose input/output (GPIO) port pins
- Clock system (MCLK or CPU clock, RTC clock, SPI clock, CLK_OUT pin)
- 2 UART port
- 4 DMA channels, one each per SPI receive and transmit and one each per UART receive and transmit
- AMC130M02 registers
- Metrology variables

After the hardware is set up, any received frames from the GUI are processed. Next, the foreground process checks whether the background process has notified the foreground process to calculate new metrology parameters for any voltage-current mappings. This notification is accomplished through the assertion of the PHASE_STATUS_NEW_LOG status flag whenever a frame of data is available for processing. The data frame consists of the processed dot products that were accumulated for CYCLES_PER_COMPUTATION number of cycles of data. The value for CYCLES_PER_COMPUTATION is 10 cycles when the nominal frequency setting in the software is 50Hz and 12 cycles when the nominal frequency setting in the software is set to 60Hz. When the measured line frequency is equal to the nominal frequency of the design, this is equivalent to 200 milliseconds of accumulated data.

The processed dot products include the V_{RMS}, I_{RMS}, active power, reactive power, fundamental voltage, fundamental active power, and fundamental reactive power. These dot products are used by the foreground process to calculate the corresponding metrology readings in real-world units. All the processed dot products are accumulated in separate 64-bit registers to further process and obtain the RMS and mean values. The apparent power is calculated using the calculated values of active and reactive power of the foreground process,.

Similarly – using the calculated values of the foreground for the fundamental voltage, fundamental reactive power, and fundamental active power, the fundamental current, fundamental apparent power – voltage THD, and current THD are calculated. Additionally, voltage underdeviation and voltage overdeviation are calculated using the value of the calculated RMS voltage and the defined nominal voltage of the design. The frequency (in Hz) and power factor are also calculated using parameters calculated by the background process using the formulas in Section 3.2.1.

3.2.2.5 Background Process

Figure 3-3 shows the different events that occur when sampling voltage and current, where the items in green are done by the MSPM0G1106 hardware modules.

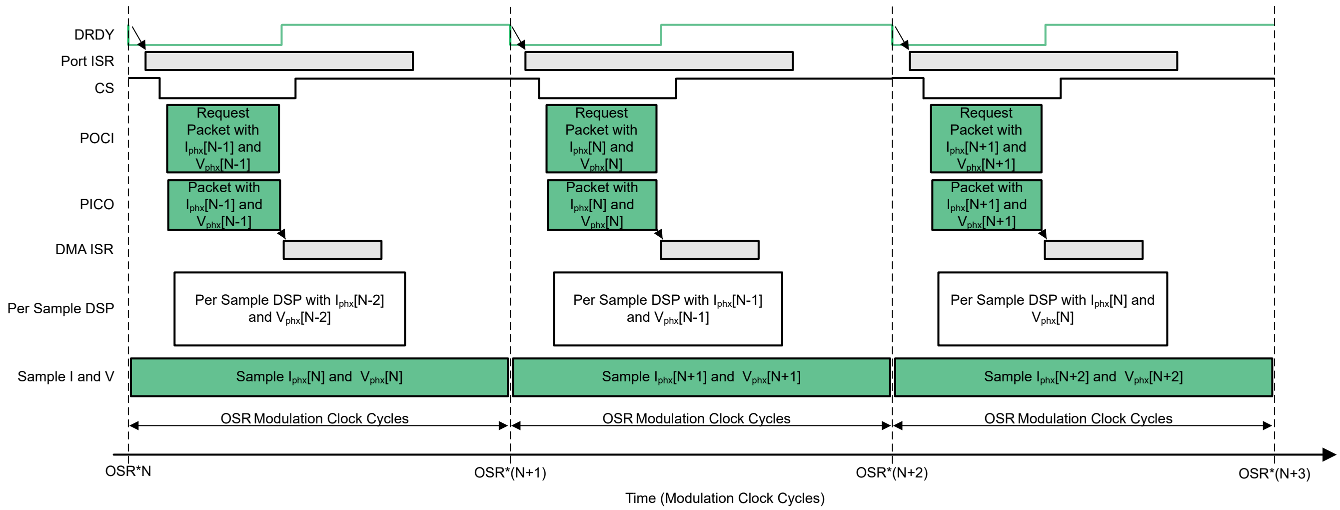


Figure 3-3. Voltage and Current Sampling Events

New current samples for each phase are ready every OSR, or 1024 modulation clock cycles for this design, thus resulting in 4000 samples per second over the SPI bus to MSPM0+ MCU. Once new samples are ready, the DRDY pin causes a GPIO interrupt on the MSPM0+ MCU, which triggers the Port ISR, and the background process is run within the Port ISR.

Figure 3-4 shows the background process, which mainly deals with timing-critical events in the test software.

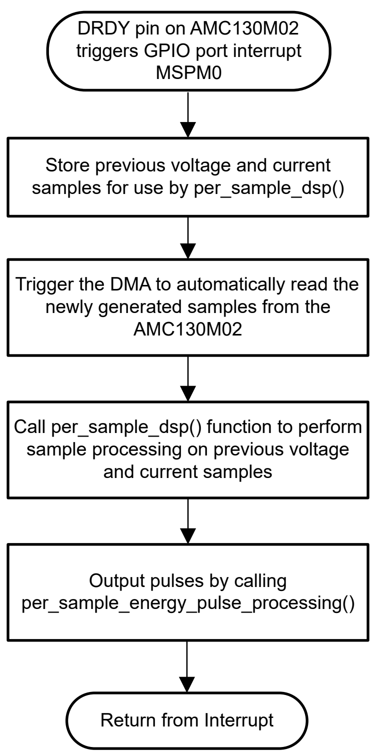


Figure 3-4. Background Process

3.2.2.6 Software Function `per_sample_dsp ()`

Figure 3-5 shows the flowchart for the per_sample_dsp() function. 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. Both voltage and current samples are processed and accumulated in dedicated 64-bit registers. Per-phase active power and reactive power are also accumulated in 64-bit registers.

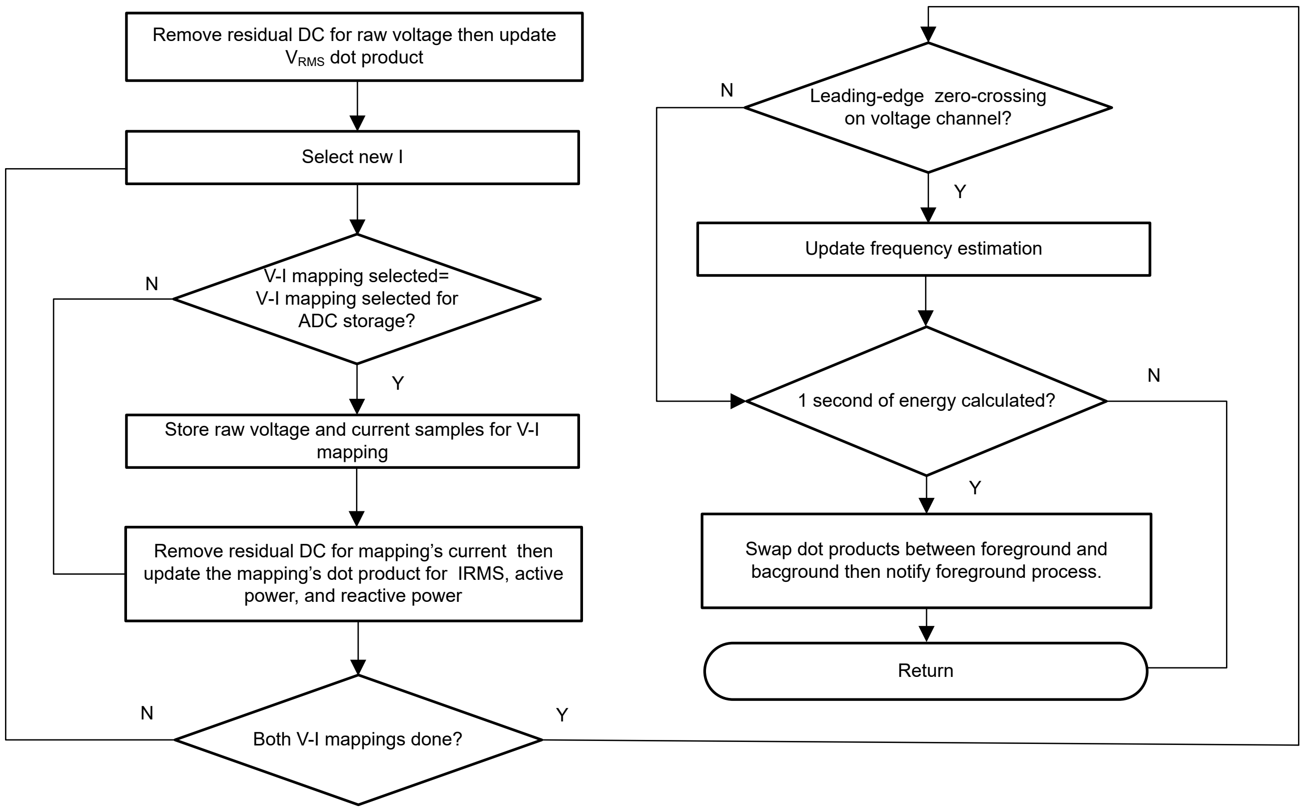


Figure 3-5. `per_sample_dsp ()` Function

3.2.2.7 Frequency Measurement and Cycle Tracking

The instantaneous voltage, currents, active powers, and reactive powers are accumulated in 64-bit registers. A cycle tracking counter keeps track of the number of cycles accumulated. When CYCLES_PER_COMPUTATION number of cycles have been accumulated, the background process stores these accumulation registers and 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 because this process produces very stable results.

For frequency measurements, a straight line interpolation is used between the zero crossing voltage samples. 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 genuine zero crossing points. For example, with two negative samples, a noise spike can make one of the samples positive, thereby making the negative and positive pair appear as if there is a zero crossing.

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

3.2.2.8 LED Pulse Generation

In electricity meters, the energy consumption of the load is normally measured in a fraction of kilowatt-hour (kWh) pulses. This information can be used to accurately calibrate any meter for accuracy measurement. Typically, the measuring element (the MSPM0+ MCU) is responsible for generating pulses proportional to the energy consumed.

This application uses average power to generate these energy pulses. The average power accumulates at every DRDY port ISR interrupt, thereby spreading the accumulated energy from the previous one-second time frame evenly for each interrupt in the current one-second time frame. This accumulation process is equivalent to converting power to energy. When the accumulated energy crosses a threshold, a pulse is generated. The amount of energy above this threshold is kept and a new energy value is added on top of the threshold in the next interrupt cycle. Because the average power tends to be a stable value, this way of generating energy pulses is very steady and free of jitter.

The threshold determines the energy tick specified by meter manufacturers and is a constant. The tick is usually defined in pulses-per-kWh or just in kWh. One pulse must be generated for every energy tick. For example, in this application, the number of pulses generated per kWh is set to 6400 for active and reactive energies. The energy tick in this case is 1kWh / 6400. Energy pulses are generated and available on the ACT and REACT pin headers and also through light-emitting diodes (LEDs) on the board. GPIO pins are used to produce the ACT and REACT energy pulses.

Figure 3-6 shows the flow diagram for pulse generation with a pulse constant of 6400, though TI recommends reducing this value to 3600 or even lower if the energy meter supports currents beyond 80A.

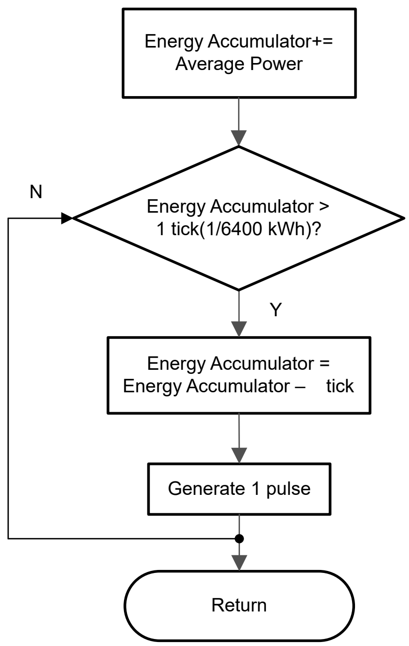


Figure 3-6. Pulse Generation for Energy Indication

The average power is in units of 0.001W and a 1kWh threshold is defined in Equation 14.

$$\text{1kWh threshold} = \frac{1}{0.001} \times \text{1kW} \times \left(\text{Number of interrupts per second}\right) \times \left(\text{Number of seconds in one hour} = 1000000 \times 8000 \times 3600 = \text{0x1A3185C50000}\right. \quad (14)$$

3.3 Test Setup

3.3.1 Power Supply and Jumper Settings

Figure 3-7 shows the location of various components of the reference design on the top layer of the PCB. The bottom layer has no soldered components.

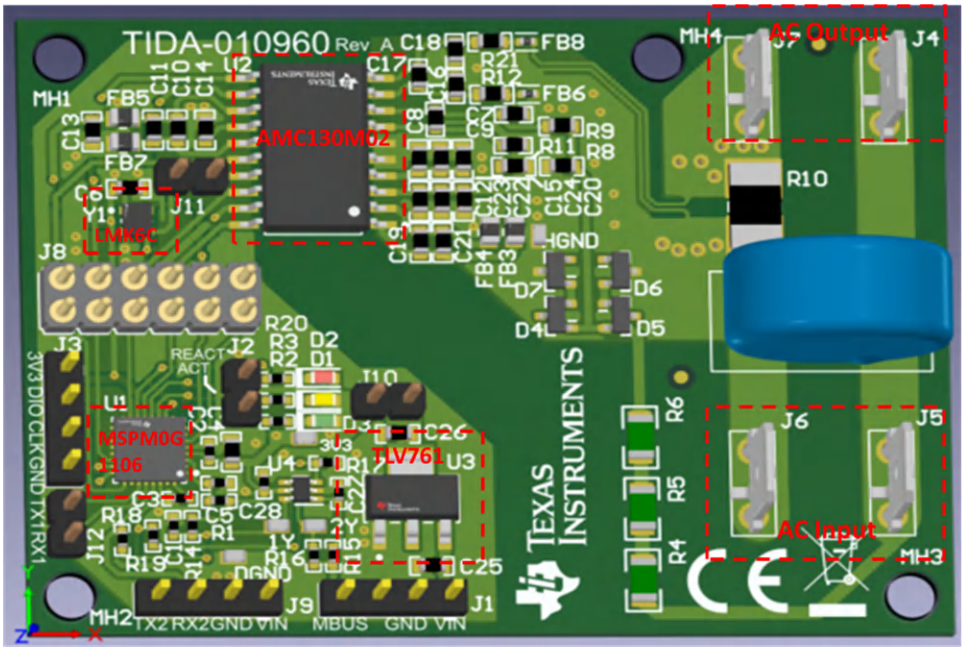


Figure 3-7. TIDA-010960 Hardware 3D View

Table 3-1 lists the jumper settings.

Table 3-1. Hardware Jumper Settings

HEADER NAME	TYPE	MAIN FUNCTIONALITY	COMMENTS
J1	4 pin	External power supply	Additional pin for M_BUS communication
J2	2 pin	Active and Reactive energy pulses	Those two pins are isolated from AC mains, but do not contain GND
J3	4 pin	JTAG: MSPM0 programming header	
J4, J7	1 pin	Positive and negative AC output header	Connect load the J4 J7
J5, J6	1 pin	Positive and negative AC input header	Connect AC Line and Neutral to J5 J6
J8	12 pin	Jumper to connect MSPM0 and AMC130M02	Flexible setting for MCU
J9	4 pin	UART output to connect to main controller	
J10	2 pin	Jumper to connect 3.3V from external input power	
J11	2 pin	Jumper to connect clock from LMK6C to AMC1310M02	Flexible setting for clock, LMK6C also connect to MSPM0
J12	2 pin	UART to connect with PC GUI	

3.3.2 Viewing Metrology Readings and Calibration

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

1. Select UART connection for communication to the PC GUI. Connect J12 to PC USB and a COM port is created on the PC. The testing was done using UART with 9600, 8N1 setting.
2. Open the 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 system. As Figure 3-8 shows, this field is changed to COM7.

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

Figure 3-8. GUI Configuration File Changed to Communicate With Energy Measurement System

4. 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 3-9). 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.

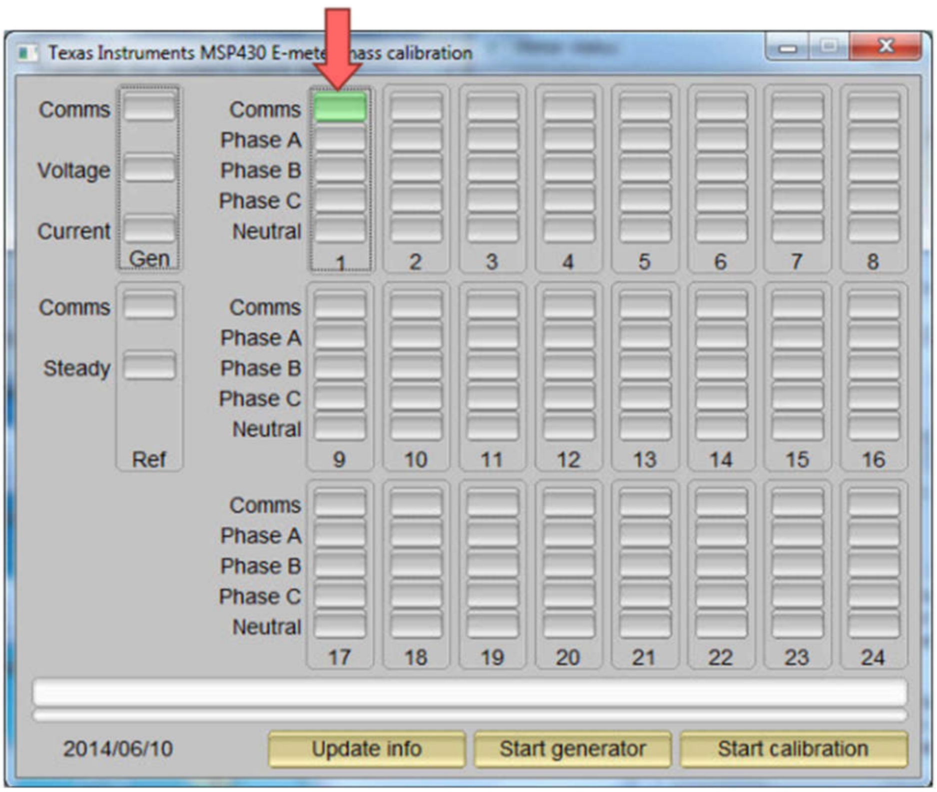


Figure 3-9. GUI Start-Up Window

The results window opens after clicking on the green button (see Figure 3-10).

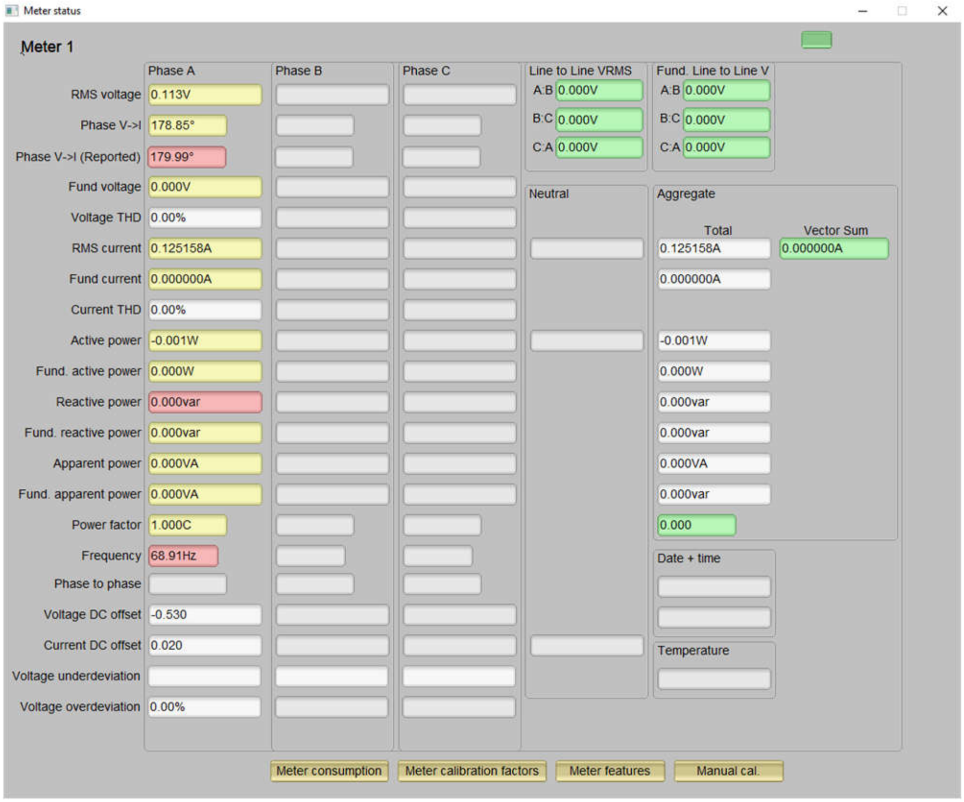


Figure 3-10. GUI Results Window

3.3.3 Calibration

3.3.3.1 Voltage and Current Offset Calibration

To calibrate the voltage and current offset, perform the following steps:

1. Connect the GUI to view results for voltage and current.
2. Configure the test source to supply the desired voltage and current.
   - Using a low but non-zero value is recommended; for example, 120V and 0.5A.
3. Click on the *Manual cal.* button.
4. Input the difference from the expected input versus what the GUI is reading into the appropriate fields.

Note

AC current offset is in microamps and AC voltage offset is in millivolts.

3.3.3.2 Voltage and Current Gain Calibration

To calibrate the voltage and current readings, perform the following steps:

1. Connect the GUI to view results 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 voltage and current. For example, for 120V, 10A, 0° (PF = 1). Typically, these values are the same for every phase.
3. Click on the *Manual cal.* button as illustrated in Figure 3-10.

   The screen in Figure 3-11 pops up:

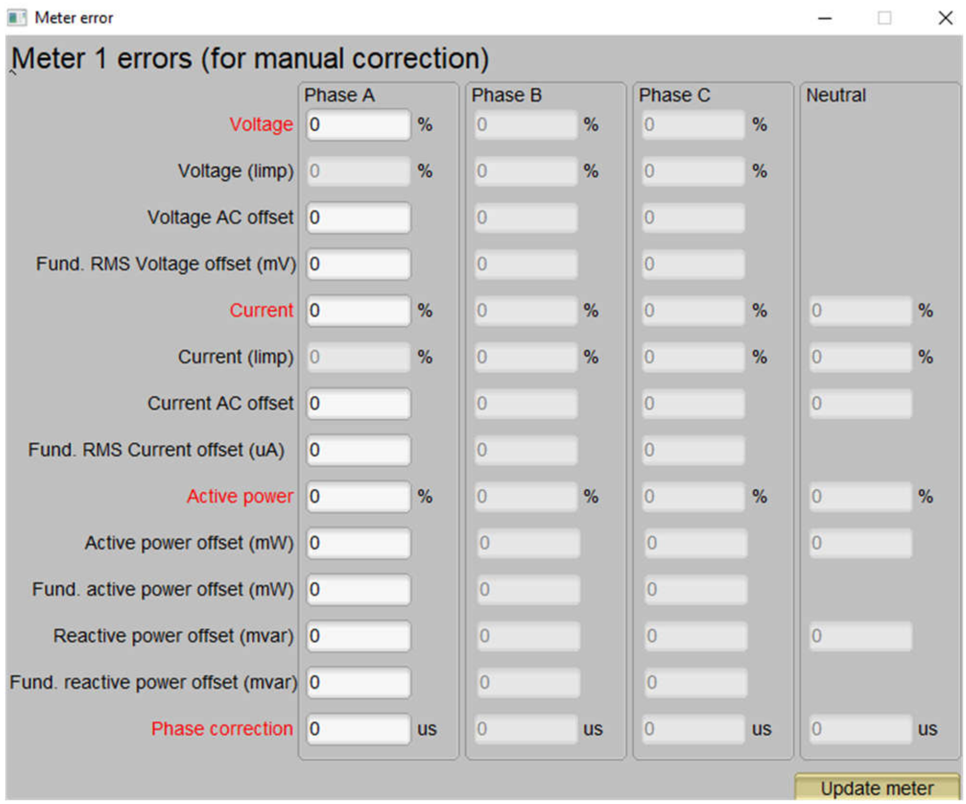


Figure 3-11. Manual Calibration Window

4. Calculate the correction values for each voltage and current. The correction values that must be entered for the voltage and current fields are calculated using Equation 15.

$$\text{Correction (\%)} = \left(\frac{\text{value}_{\text{observed}}}{\text{value}_{\text{desired}}} - 1\right) \times 100 \tag{15}$$

where

- $\text{value}_{\text{observed}}$ is the value measured by the TI meter
- $\text{value}_{\text{desired}}$ is the calibration point configured in the AC test source

3.3.3.3 Active Power Gain Calibration

After performing gain correction for voltage and current, gain correction for active power must be completed. Gain correction for active power is done differently in comparison to voltage and current. Although, conceptually, calculating the active energy % error as is done with voltage and power can be done, this method is not the most accurate.

The best option to get the Correction (%) is directly from the reference meters measurement error of the active power. This error is obtained by feeding energy pulses to the reference meter. To perform active power calibration, complete the following steps:

1. Turn off the system and connect the energy pulse output of the system to the reference meter. Configure the reference meter to measure the active power error based on these pulse inputs.
2. Turn on the AC test source.
3. Repeat Step 1 to Step 3 from Section 3.3.3.2 with the identical voltages, currents, and 0° phase shift that were used in the same section.
4. Obtain the % error in measurement from the reference meter.

Note

The error can be negative.

---

5. Enter the error obtained in Step 4 into the *Active power* field under the corresponding phase in the GUI window. This error is already the value and does not require calculation.

6. Click the *Update meter* button and the error values on the reference meter immediately settle to a value close to zero.

3.3.3.4 Offset Calibration

After performing gain calibration, if the accuracy at low currents is not acceptable, offset calibration can be done. Offset calibration removes any crosstalk, such as the crosstalk to the current channels of a phase from the line voltages.

To perform active power offset calibration for a phase, add the offset to be subtracted from the active power reading (in units of mW) to the current value of the active power offset (labeled *Voltage AC offset* in the meter calibration factors window) and then enter this new value in the Voltage AC offset field in the Manual Calibration window. As an example, if the *Voltage AC offset* has a value of 200 (0.2W) in the meter calibration window, and subtracting an additional 0.300mW is desired, then enter a value of 500 in the *Voltage AC* offset field in the *Manual Calibration* window. After entering the value in the *Voltage AC offset* field in the *Manual Calibration* window, press the *Update meter* button.

To perform reactive power offset calibration for a phase, a similar process is followed as the process used to perform active power offset calibration.

3.3.3.5 Phase Calibration

After performing power gain correction, do the phase calibration. To perform phase correction calibration, complete the following steps:

1. If the AC test source has been turned OFF or reconfigured, perform Step 1 through Step 3 from Section 3.3.3.2 using the identical voltages and currents used in that section.
2. Modify only the phase-shift to a non-zero value; typically, +60° is chosen. The reference meter now displays a different % error for active power measurement.

   Note

   This value can be negative.

3. If the error from Step 3 is not close to zero, or is unacceptable, perform phase correction by following these steps:
   a. Enter a value as an update for the *Phase correction* field for the phase that is being calibrated. Usually, a small ± integer must be entered to bring the error closer to zero. Additionally, for a phase shift greater than 0 (for example: +60°), a positive (negative) error requires a positive (negative) number as correction.
   b. Click on the *Update meter* button 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 4. After a certain point, the fine-tuning only results in the error oscillating on either side of zero. The value that has the smallest absolute error must be selected.
   d. Change the phase now to –60° and check if this error is still acceptable. In best practice, errors must be symmetric for the same phase shift on lag and lead conditions.

After performing phase calibration, calibration is complete. Figure 3-12 shows the new calibration factors.

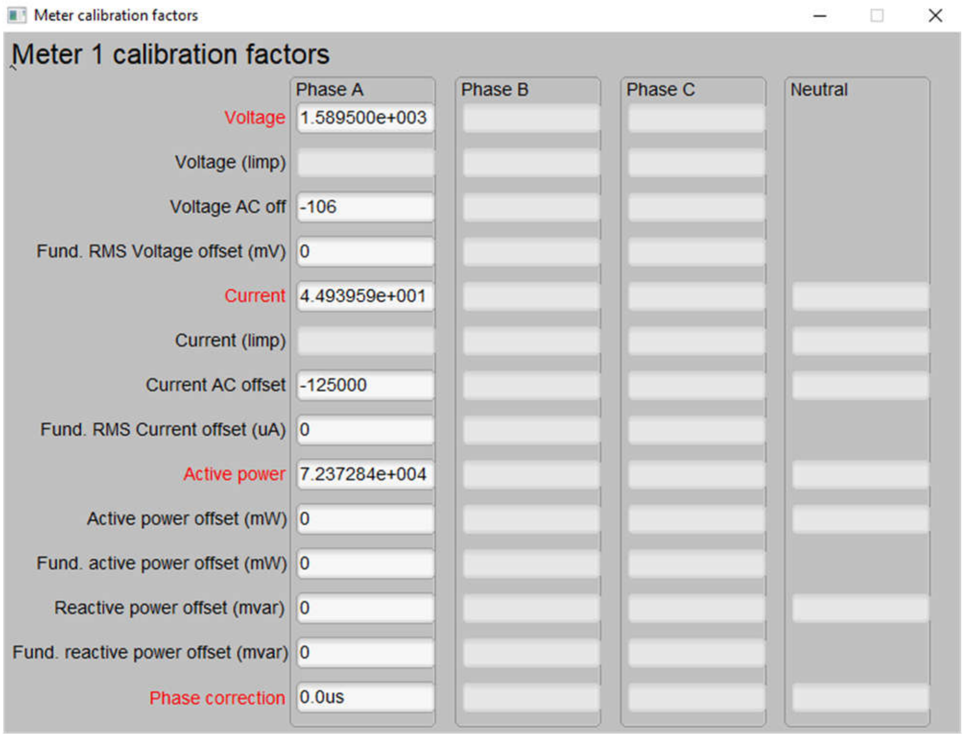


Figure 3-12. Calibration Factors Window

3.4 Test Results

For cumulative active energy and individual phase error testing, current is varied from 50mA to 15A, 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.

For the V_{RMS} accuracy test, the voltage was varied from 100V to 240V while current was held steady at 1A. For the I_{RMS} accuracy test, the voltage was kept steady at 230V, while current was varied from 50mA to 15A.

3.4.1 Electricity Meter Metrology Accuracy Results

After gain, phase, and offset calibration, the test results are shown in the following tables. Table 3-2 and Figure 3-13 show the active energy test results.

Table 3-2. Active Energy % Error Versus Current, 3mΩ Shunts, 230V

CURRENT (A)	AVG ERROR% PF=1 Cos PHI = 1 (0°)	AVG ERROR% PF=0.5i Cos PHI = 0.5i (60°)	AVG ERROR% PF=0.8c Cos PHI = 0.8c (–36.87°)
0.1	–0.3943	–0.5190	–0.3493
0.25	–0.3770	–0.5150	–0.3113
0.5	–0.3707	–0.5147	–0.2917
1	–0.3437	–0.4487	–0.2627
2	–0.2897	–0.3633	–0.2510
5	–0.2527	–0.1237	–0.1720
10	–0.1090	0.0700	–0.0063
15	0.3040	0.3717	0.2200

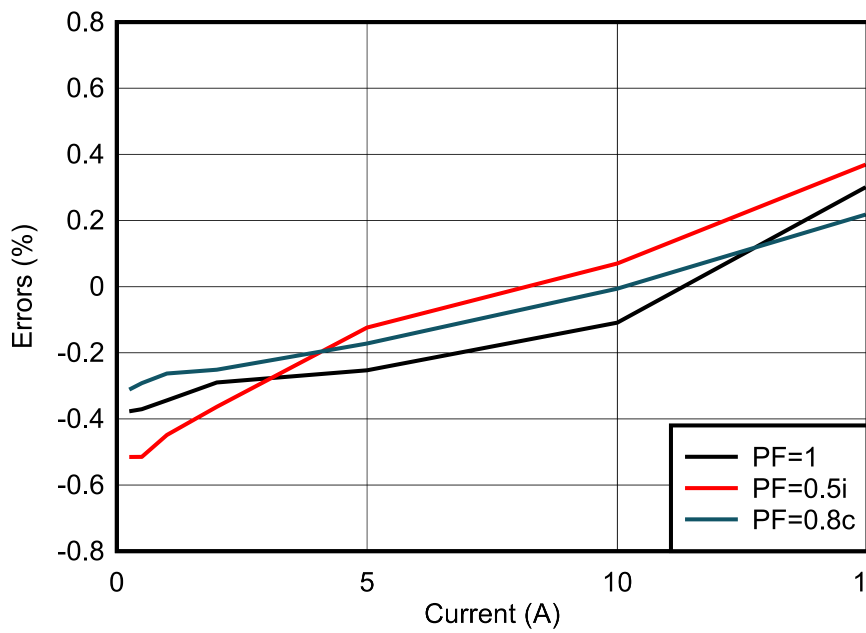


Figure 3-13. Active Energy % Error Versus Current, 3mΩ Shunts, 230V

Table 3-3 and Figure 3-14 show the reactive energy test results.

Table 3-3. Reactive Energy % Error Versus Current, 3mΩ Shunts

CURRENT (A)	AVG ERROR% Sin PHI = 1i (90°)	AVG ERROR% Sin PHI = 0.5i (30°)	AVG ERROR% Sin PHI = 0.8c (–53.13°)
0.1	–0.1147	0.2880	–0.7110
0.25	–0.3323	–0.1407	–0.4090
0.5	–0.3070	–0.1383	–0.3867
1	–0.2980	–0.1457	–0.3527
2	–0.2603	–0.1917	–0.2880
5	–0.0947	–0.2067	–0.1530
10	0.1030	–0.0213	0.0220
15	0.3437	0.3747	0.2523

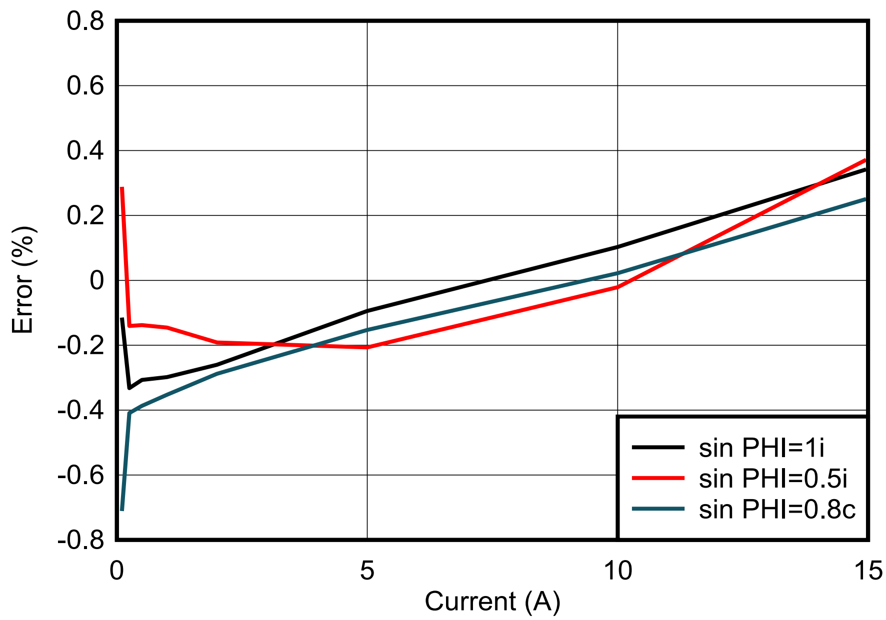


Figure 3-14. Reactive Energy % Error Versus Current, 3mΩ Shunts

Table 3-4 and Figure 3-15 show the current RMS percentage error test results.

Table 3-4. Current RMS % Error at 230V, 3mΩ Shunts

CURRENT (A)	%ERROR
0.05	–0.243
0.1	0.511
0.25	–0.0331
0.5	–0.257
1	–0.316
2	–0.378
5	–0.352
10	–0.215
15	0.0519

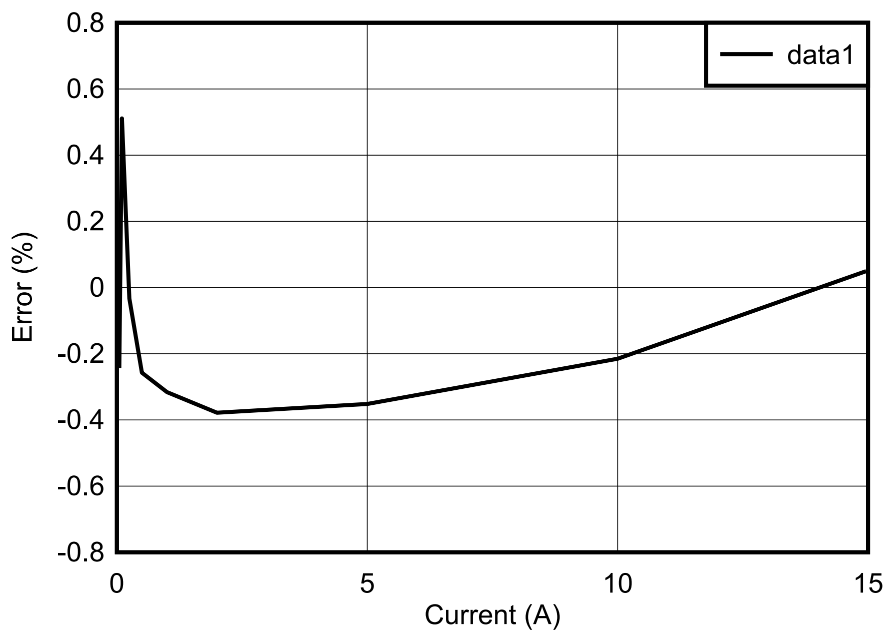


Figure 3-15. Current RMS % Error at 230V, 3mΩ Shunts

Table 3-5 and Figure 3-16 show the voltage RMS percentage error test results.

Table 3-5. Voltage RMS % Error at 1A, 3mΩ Shunts

VOLTAGE	%ERROR
10	0.004
20	–0.0125
50	–0.0004
75	0.000267
100	0.002
120	0.00583
140	–0.00643
160	0.0025
180	0.00555
200	0.0095
220	–0.00136
230	0.0130
240	0.0121

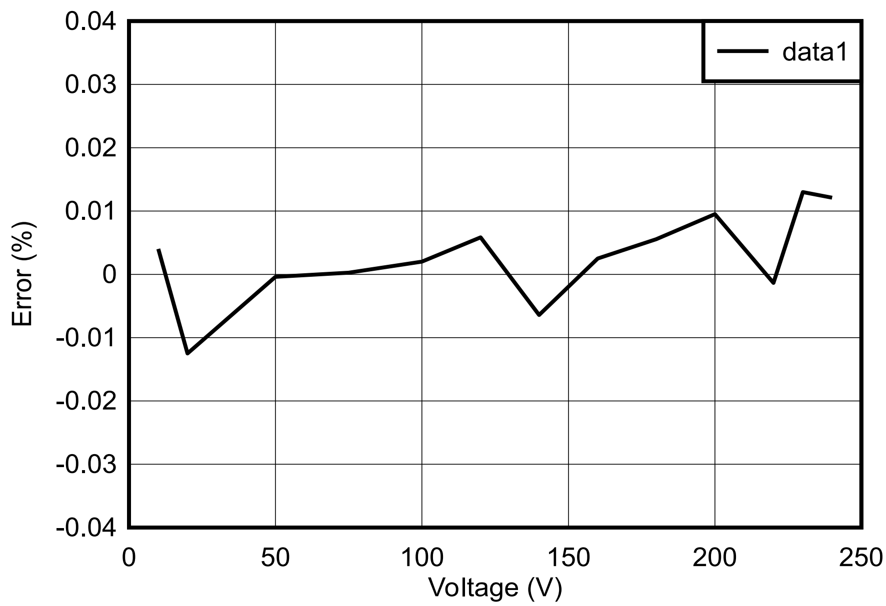


Figure 3-16. Voltage RMS % Error at 1A, 3mΩ Shunts

4 Design and Documentation Support

4.1 Design Files

4.1.1 Schematics

To download the schematics, see the design files at TIDA-010960.

4.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010960.

4.1.3 PCB Layout Recommendations

For this design, follow these general guidelines:

- 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 AMC130M02. In this design, there is a ground plane on both the top and bottom layer for the HGND (high-voltage side). Make sure that there is good stitching between the planes through the liberal use of vias.
- Keep the two traces to the inputs of each ADC channel symmetrical and as close as possible to each other.
- Crosstalk from the voltage to current channels can reduce accuracy at lower currents if power offset is not performed.
- For AMC130M02 devices, place the 0.1µF capacitor closer to the AVDD pin than the 1µF capacitor. Do the same thing for the 0.1µF and 1µF capacitors connected to DVDD.
- For the oscillator, there must be clean ground underneath and avoid placing any traces. Also, keep high-frequency signals away from the crystal.
- Use wide traces for power-supply connections.
- Make sure of the clearance and creepage spacing

4.1.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010960.

4.1.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010960.

4.1.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010960.

4.1.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010960.

4.2 Tools and Software

Tools

CCSTUDIO	Code Composer Studio™ integrated development environment (IDE)
SYSCONFIG	System configuration tool with an intuitive graphical user interface for configuring pins, peripherals, radios, software stacks, RTOS, clock tree, and other components.

Software

TIDA-010960	Source code of Energy Library for TIDA-010960 in latest MSPM0 SDK with default install path.

4.3 Documentation Support

1. Texas Instruments, *AMC130M02 2-Channel, 64-kSPS, Simultaneous-Sampling, 16-Bit, Reinforced Isolated Delta-Sigma ADC With Integrated DC/DC Converter Data Sheet*
2. Texas Instruments, *MSPM0G110x Mixed-Signal Microcontrollers Data Sheet*
3. Texas Instruments, *LMK6x Low Jitter, High-Performance BAW Oscillator Data Sheet*
4. Texas Instruments, *One-Phase Shunt Electricity Meter Reference Design*
5. Texas Instruments, *Single-Phase and Split-Phase Shunt Energy Metrology Reference Design*
6. Texas Instruments, *One-Phase Shunt Electricity Meter Reference Design Using Standalone ADCs Design Guide*

4.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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