

Implementation of a Low-Cost Three-Phase Electronic Watt-Hour Meter Using the MSP430F67641

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Metering Applications

ABSTRACT

This application report describes the implementation of a low-cost three-phase electronic electricity meter using the Texas Instruments MSP430F67641 metering processor. This application report includes the necessary information with regard to metrology software and hardware procedures for this single-chip implementation.

The MSP430F67641 source code that is described in this application report can be downloaded from <http://www.ti.com/lit/zip/slaa621>.

The MSP430F67641A source code can be downloaded from <http://www.ti.com/tool/TIDM-3PH-ENERGY5-ESD>.

The design files for the EVM can be downloaded with the Class 0.5 Three-Phase Smart Meter Reference Design ([TIDM-THREEPHASEMETER-F67641](#)).

WARNING

Failure to adhere to these steps and/or not heed the safety requirements at each step may lead to shock, injury, and damage to the hardware.

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1 Introduction

The MSP430F67641 device is the latest metering system-on-chip (SoC) that belongs to the MSP430F67xx family of devices. This family of devices belongs to the powerful 16-bit MSP430F6xx platform, which brings in many new features and provides flexibility to support robust poly-phase metrology solutions. These devices find their application in energy measurement and have the necessary architecture to support them.

The F67641 has a powerful 25-MHz CPU with MSP430CPUX architecture. The analog front-end consists of three 24-bit $\Sigma\Delta$ analog to digital converters (ADC) that are used for sensing current and a 10-bit SAR ADC for sensing phase voltages. The $\Sigma\Delta$ ADCs are based on a second-order sigma-delta architecture and they support differential inputs. The sigma-delta ADCs ($\Sigma\Delta24_B$) operate independently and are capable of 24-bit results. In addition, it also has an integrated gain stage to support gains up to 128 for amplification of low-output current sensors. In contrast, the 10-bit SAR supports single-ended inputs and performs sequential sampling of the three different phase voltages, the integrated temperature sensor, the voltage of the active supply powering the chip (VDSYS), and an additional optional auxiliary power supply (selected by the AUXADCSELx bits). The $\Sigma\Delta24_B$ on the F67641 module has a trigger generator that triggers the ADC10 to ensure that the timing between the ADC10 and $\Sigma\Delta$ modules are grouped and synchronized.

A 32-bit x 32-bit hardware multiplier on this chip can be used to further accelerate math intensive operations during energy computation. The software energy library supports calculation of various parameters for up to three-phase energy measurement. The key parameters calculated during energy measurements are: RMS current and voltage, active and reactive power and energies, power factor, and frequency. The library also provides the option to obtain raw samples of voltages and currents for advanced metering data such as harmonic analysis and total harmonic distortion (THD).

Complete metrology source code is provided. The MSP430F67641-based software can be downloaded from <http://www.ti.com/lit/zip/slaa621>. The MSP430F67641A-based software can be downloaded from <http://www.ti.com/tool/TIDM-3PH-ENERGY5-ESD>.

2 System Diagrams

Figure 1 shows a block diagram of the high level interface used for a three-phase energy meter application using the F67641. A three-phase four-wire star connection to the AC mains is shown in this case. Current sensors are connected to each of the current channels and a simple voltage divider is used for corresponding voltages. The CT has an associated burden resistor that must be connected at all times to protect the measuring device. The choice of the CT and the burden resistor is done based on the manufacturer and current range required for energy measurements. The CTs can be easily replaced by Rogowski coils with minimal changes to the front-end.

The trigger generator of the $\Sigma\Delta$ is used to trigger the ADC10 to perform conversions, thereby synchronizing it with the $\Sigma\Delta$ converter's timings. For the voltage sensor, a combination of a voltage divider and level shifter are used to ensure that the input voltage to the ADC fits within the single-ended voltage range of operation. The range of operation is determined by the chosen reference voltage source of the SAR ADCs. The choice of voltage divider resistors for the voltage channel is selected to ensure the mains voltage is divided down to the normal input ranges that are valid for the SAR ADC, based on the selected reference voltage. See the *MSP430x5xx and MSP430x6xx Family User's Guide* ([SLAU208](http://www.ti.com/lit/zip/slaa621)) and the device-specific data sheet for these values.

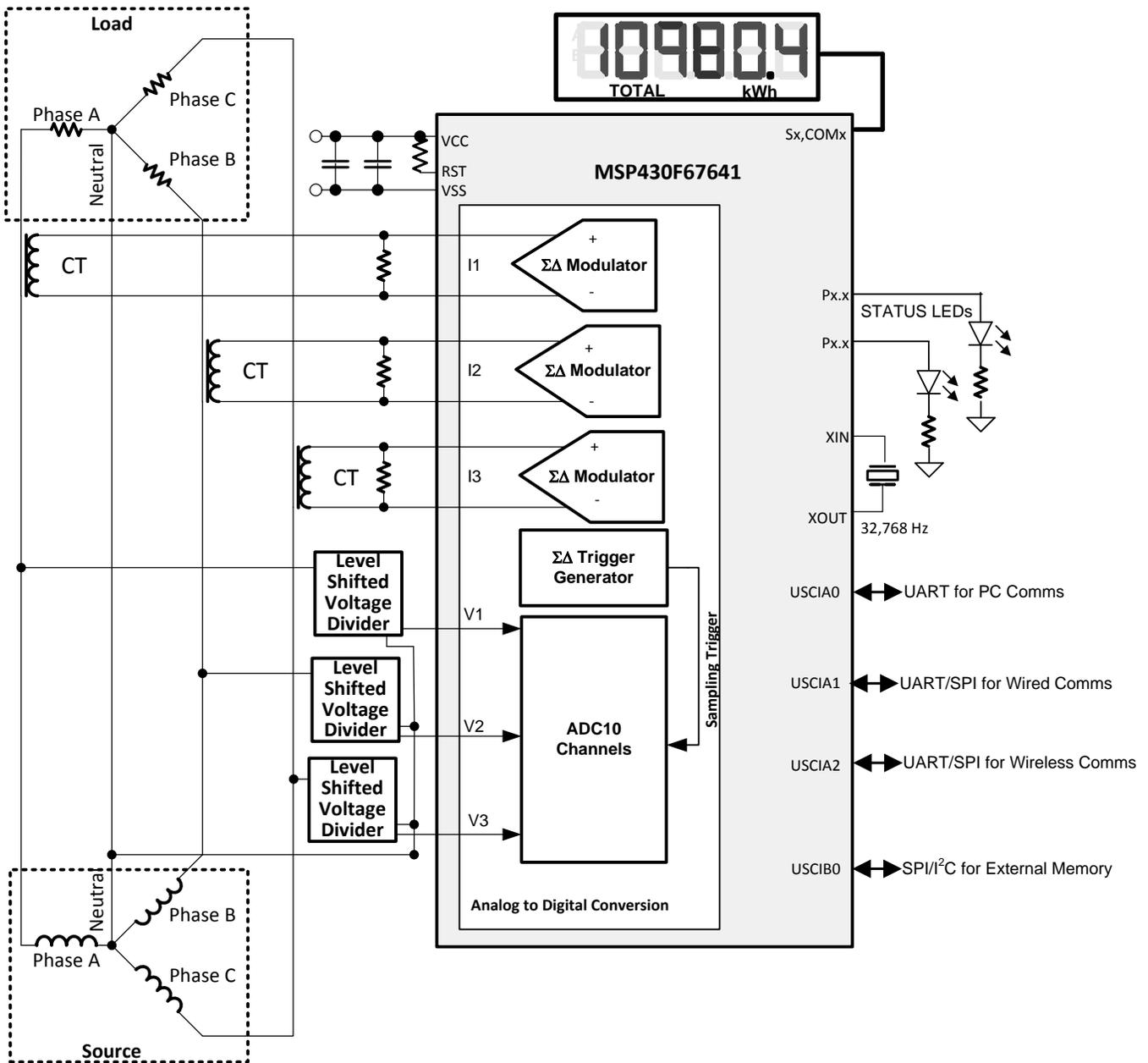


Figure 1. 3-Phase 4-Wire Star Connection Using MSP430F67641

3 Hardware Implementation

This section describes the hardware for the design of a working three-phase energy meter that uses the F67641.

3.1 Power Supply

The MSP430™ family of devices comprises ultra-low-power microcontrollers from Texas Instruments. These devices support a number of low-power modes and also have low-power consumption during active mode when the CPU and other peripherals are active. The low-power feature of this device family allows design of the power supply to be simple and inexpensive. The power supply allows the operation of the energy meter powered directly from the mains. The next sections describe the various power supply options that are available to users to support their design.

3.1.1 Resistor Capacitor (RC) Power Supply

Figure 2 shows a capacitor power supply that provides a single output voltage of 3.3 V directly from the mains of 120/230 V RMS AC at 50/60 Hz.

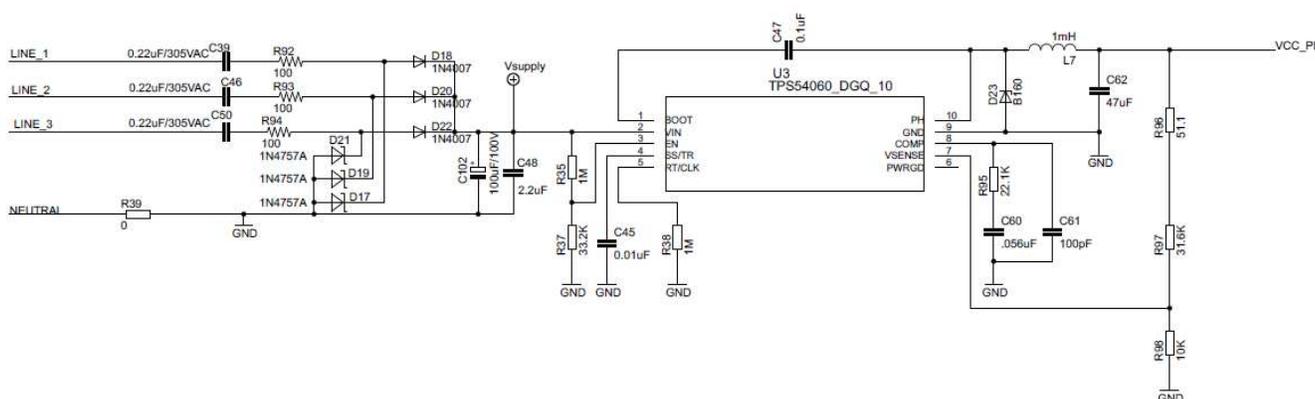


Figure 2. Simple Capacitive Power Supply for the MSP430 Energy Meter

Appropriate values of resistors (R92, R93, and R94) and capacitors (C39, C46, and C50) are chosen based on the required output current drive of the power supply. Voltage from mains is directly fed to a RC based circuit followed by a rectification circuit to provide a dc voltage for the operation of the MSP430. This dc voltage is regulated to 3.3 V for full-speed operation of the MSP430. The design equations for the power supply are given in the application report *Improved Load Current Capability for Cap-Drop Off-Line Power Supply for E-Meter* (SLVA491). The above configuration allows all three phases to contribute to the current drive, which is approximately three times the drive available from only one phase. If even higher output drive is required, the same circuitry can be used followed by an NPN output buffer. Another option would be to replace the above circuitry with a transformer-based or switching-based power supply.

3.1.2 Switching Power Supply

Figure 3 shows a switching-based power supply that provides a single output voltage of 3.3 V directly from the AC mains at 100 V to 230 V RMS. In the configuration shown, the meter is powered as long as there is AC voltage on Phase C, corresponding to LINE 3 on the schematic and board. The internal circuitry of a switching power supply is omitted from this application report. For the drive of the power supply, refer to the documentation of the power supply module.

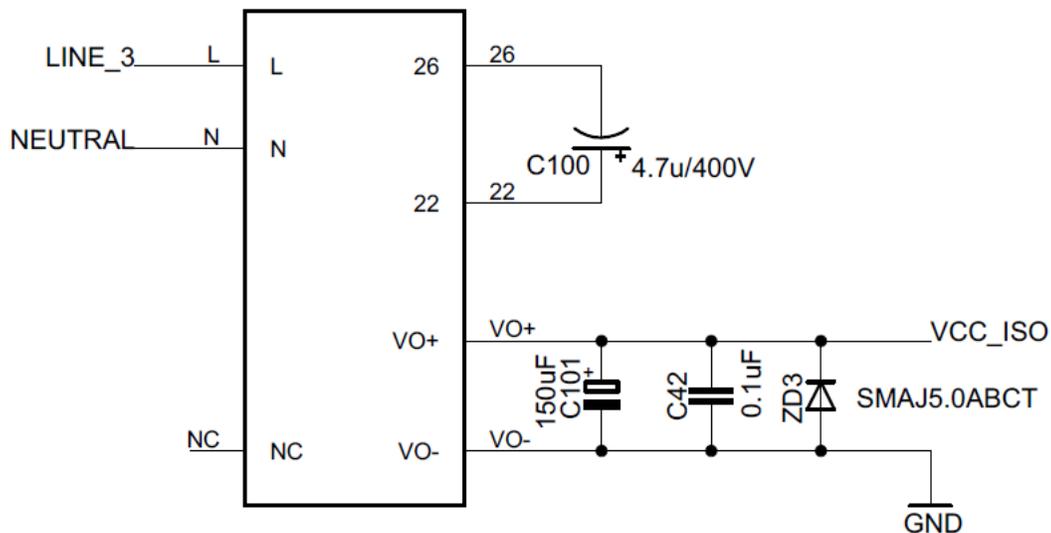


Figure 3. Switching-Based Power Supply for the MSP430 Energy Meter

3.2 Analog Inputs

The MSP430F6741 has a 10-bit SAR ADC (ADC10_A), three $\Sigma\Delta$ ADCs, and a mechanism to synchronize these two types of converters. Since the magnitude of the current waveform varies more than the magnitude of the voltage waveform, the higher accuracy ADCs should always be used to sense current. As a result, the three $\Sigma\Delta$ ADCs should be used for measuring the phase currents. For measuring phase voltages, the SAR ADC could be used.

The $\Sigma\Delta$ ADC is differential and requires that the input voltages at the pins do not exceed ± 920 mV (gain = 1). To meet this specification, the current inputs must be divided down. In addition, the $\Sigma\Delta 24$ allows a maximum negative voltage of -1 V. Therefore, the AC current signal from mains can be directly interfaced without the need for level shifters.

In contrast, the ADC10_A module has single-ended inputs. Therefore the ADC10_A requires that the sensed voltage is between 0-VREF Volts, with the VREF source/voltage being selectable in software. As a result, after Mains voltage is divided down for sensing, the voltage front-end circuitry requires a level shifter to properly interface to the ADC10_A module.

The following sections describe the analog front end used for voltage and current channels.

3.2.1 Voltage Inputs

The voltage from the mains is usually 230 V or 120 V and must be brought down to within VREF volts. The analog front end for voltage consists of spike protection varistors followed by a voltage divider/shifter network, and a RC low-pass filter that acts like an anti-alias filter.

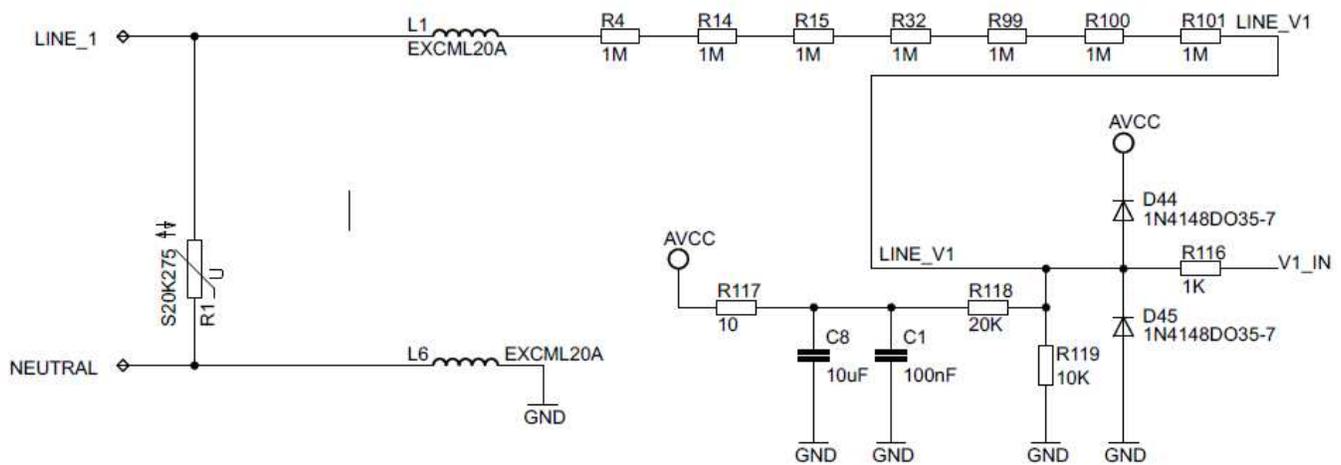


Figure 4. Analog Front End for Voltage Inputs

Figure 4 shows the analog front end for the voltage inputs for a mains voltage of 230 V. The voltage is brought down to a range within VREF volts, where VREF is selected to be the 2.0 V reference produced by the chip's reference module. The maximum voltage that is fed to the ADC is usually a certain margin below the maximum VREF voltage. As an example, when the 2.0 V reference is selected, the front-end may be built to produce a maximum voltage of 1.4-1.6 V when the maximum Mains voltage is applied. This margin helps prevent ADC clipping when the meter is exposed to harmonics or an over-voltage condition.

3.2.2 Current Inputs

The analog front-end for current inputs is different from the analog front end for the voltage inputs. Figure 5 shows the analog front end used for a current channel.

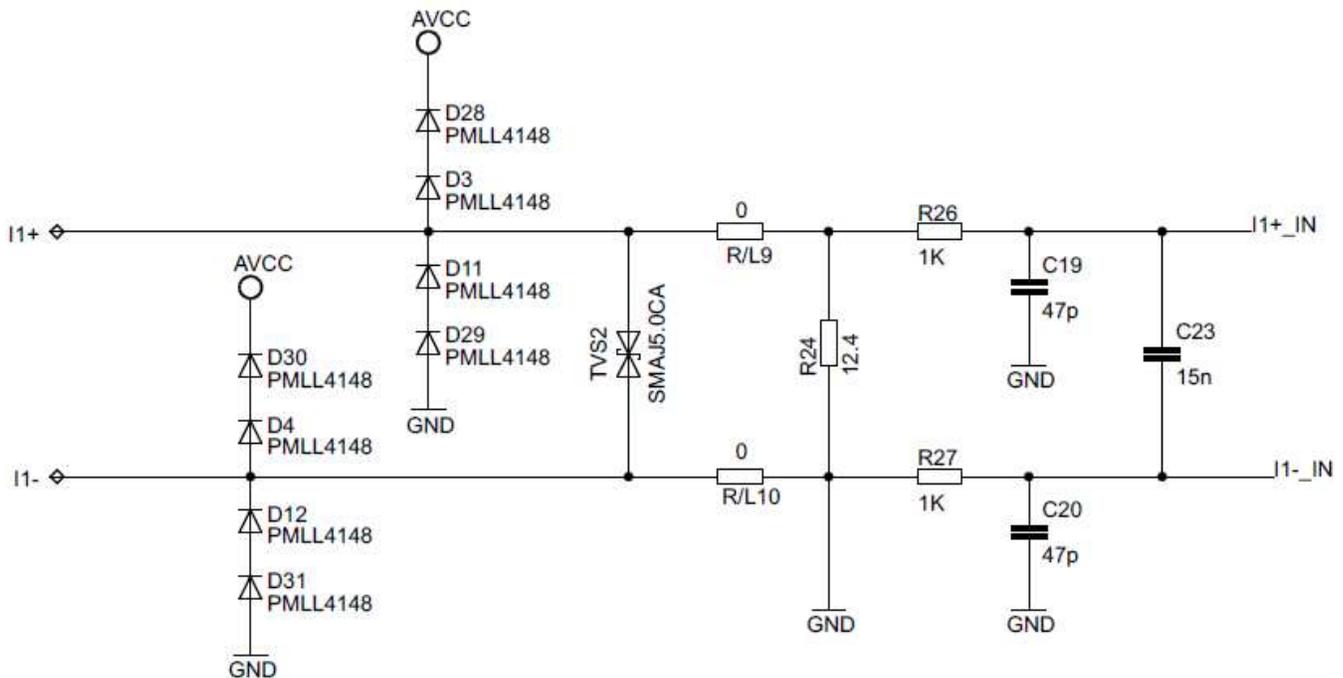


Figure 5. Analog Front End for Current Inputs

Resistor R24 is the burden resistor that is selected based on the current range used and the turns ratio specification of the CT. The value of the burden resistor for this design is 12.4 Ω . The antialiasing circuitry, consisting of resistors and capacitors, follows the burden resistor. The input signal to the converter is a fully differential input with a voltage swing of ± 877 mV maximum when the maximum current rating of the meter (100 A) is applied.

4 Software Implementation

The software has three projects: one for mathematical routines, another primarily for metrology (including calculation of voltage, current, and power), and an application wrapper that deals mainly with application-processor functionality (such as communication, RTC, and LCD display). The separation of the metrology and application processor enables easy porting from TI's EVM to a customer's board with minimal changes to the metrology code. Also, if it is desired to get the readings of the metrology parameters to make any further additions to the code, the "metrology-readings.h" file could be used to view the different functions that could be called from the application project to retrieve the newest set of metrology parameters. Refer to "metrology-types.h" to see the associated units of these returned metrology parameters.

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

4.1 Peripherals Setup

The major peripherals are the 24-bit sigma delta ($\Sigma\Delta 24_B$) ADC, the 10-bit SAR ADC (ADC10_A), auxiliary power supply module (AUX), clock system, real-time clock (RTC), and LCD.

4.1.1 $\Sigma\Delta 24$ Setup

The F67641 has three sigma delta data converters, which are used to measure the three currents in a three-phase system. In addition, it has a trigger generator module that is used to trigger the ADC10, which is used to sense the corresponding three voltages of the three-phase system. The code that accompanies this application report is designed for the metrology of a three-phase system with limited anti-tampering features. The clock to the $\Sigma\Delta 24$ ADCs and trigger generator (f_M) is derived from system clock, which is configured to run at 25 MHz. The sampling frequency is defined as $f_s = f_M/OSR$, where the OSR is chosen to be 256 and the modulation frequency f_M is chosen as 1.048576 MHz. This results in a sampling frequency of 4.096 ksp/s for the converters and a triggering frequency of 4096 Hz for the trigger generator. At every sampling instance, the $\Sigma\Delta 24$ s are configured to generate regular interrupts.

The following are the $\Sigma\Delta$ channels associations:

- A0.0+ and A0.0- \rightarrow Current I1
- A1.0+ and A1.0- \rightarrow Current I2
- A2.0+ and A2.0- \rightarrow Current I3

4.1.2 ADC10_A Setup

The ADC10 is used to sample the three Mains voltages and is triggered by the $\Sigma\Delta$'s trigger generator. When triggered by the $\Sigma\Delta$, the ADC10 enters autoscan mode and samples all of its 16 ADC channels once. In the software, the clock to the ADC10 is set to 4MHz. The sample and hold time for each converter is 8 cycles and the conversion time is 12 cycles, which results in a total of approximately 20 cycles (approximately 5 μ s) delay between conversion results of adjacent converters. In addition, the ADC10_A uses the 2.0 V reference from the REF module and is configured to output 10-bit results that are scaled to 16-bit two's complement numbers (ADC10DF = 1). This allows the ADC results from the ADC10 to be treated as a 16-bit signed number when performing mathematical operations.

The following are the relevant ADC10 channel associations:

- A12 (internal channel) → (AUXADC Voltage)/3, where AUXADC is selected to be DVCC
- A11 (internal channel) → (VDSYS Voltage)/2
- A10 (internal channel) → Temperature Sensor
- A5 → Voltage V1
- A4 → Voltage V2
- A3 → Voltage V3

4.1.3 AUX Module

To ensure that the 32-kHz oscillator is powered, AUXVCC3 must be powered. This is done in software by powering it internally from DVCC using AUXVCC3's internal charger. Also, the ability to use the ADC10 to measure the primary or an auxiliary supply is enabled. In this software, the ADC10 is set to measure DVCC.

The AUX module is set so that hardware switching is enabled for DVCC, AUXVCC1, and AUXVCC2. In the software, the SVSMH voltage is set to level 4 (see data sheet for the range of exact voltages that corresponds to a particular level). When VDSYS, the supply selected to power the chip, falls below this SVSMH level it would trigger for VDSYS to switch to another supply as long as the supply to switch to is above a user-defined threshold. The OK-voltage threshold for AUXVCC1 (AUX1LVL) and AUXVCC2(AUX2LVL) is level 5. The OK-voltage level for DVCC (AUX0LVL) is level 6. Note that if DVCC was previously not declared OK, but is later declared OK, the AUX module switches to DVCC even if VDSYS is not below the SVSMH level. This auto-switch behavior is only true for DVCC and is not applicable for AUXVCC1 or AUXVCC2. For more information about the AUX module, see the *MSP430x5xx and MSP430x6xx Family User's Guide* ([SLAU208](#)).

4.1.4 Real-Time Clock (RTC_C)

The RTC_C is a real-time clock module that is configured to give precise 1 second interrupts. Based on these 1-second interrupts, the time and date are updated in software, as necessary. RTC temperature and offset compensation are also implemented. In the software, a base offset of 118 ppm is applied, which is based on RTC errors observed on samples of this EVM. For temperature compensation, a temperature error of -34 ppm/(°C²) is used. This temperature error coefficient is taken from the data sheet of the crystal used on this EVM.

4.1.5 LCD Controller

The LCD controller on the MSP430F67641 can support up to 8-mux displays and 320 segments. It is also equipped with an internal charge pump that can be used for good contrast. In the current design, the LCD controller is configured to work in 4-mux mode using 160 segments with a refresh rate set to 512 Hz. For information, about the parameters that are displayed on the LCD, see [Section 6.1](#).

4.2 Foreground Process

The foreground process includes the initial setup of the MSP430 hardware and software immediately after a device RESET. [Figure 6](#) shows the flowchart for this process.

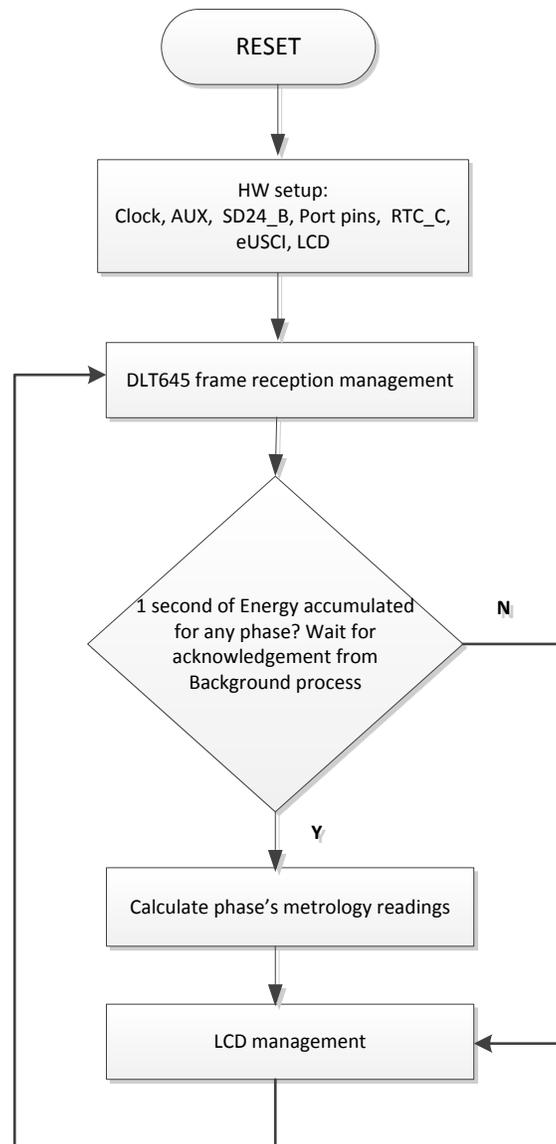


Figure 6. Foreground Process

The initialization routines involve the setup of the analog to digital converter, clock system, auxiliary supply system, general purpose input/output (port) pins, RTC module for clock functionality, LCD, and the USCI_A0 for UART functionality. In addition, if ZigBee™ communication is enabled, USCI_A2 is configured.

After the hardware is setup, any received frames from the GUI are processed. Subsequently, the foreground process checks whether the background process has notified it to calculate new metering parameters. This notification is done through the assertion of 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 one second in the background process. This is equivalent to accumulation of 50 or 60 cycles of data synchronized to the incoming voltage signal. In addition, a sample counter keeps track of how many samples have been accumulated over this frame period. This count can vary as the software synchronizes with the incoming mains frequency.

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

The foreground process also takes care of updating the LCD. The LCD display item is changed every two seconds. For more information, about the different items displayed on the LCD, see [Section 6.1](#).

4.2.1 Computation Formulas

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

4.2.1.1 RMS Voltage and Current

As described in the previous sections, voltage and current samples are obtained from the ADC10 and $\Sigma\Delta$ converters at a sampling rate of 4096 Hz. All of the samples that are taken in one second are kept and used to obtain the RMS values for voltage and current for each phase. The RMS values are obtained by the following formulas:

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

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

where

- ph = Phase whose parameters are being calculated [that is, Phase A(=1), B(=2), or C(=3)]
- 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 in one second
- K_{v,ph} = Scaling factor for voltage
- K_{i,ph} = Scaling factor for each current

(1)

4.2.1.2 Power and Energy

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

$$P_{ACT,ph} = K_{ACT,ph} \frac{\sum_{n=1}^{Sample\ count} v(n) \times i_{ph}(n)}{Sample\ count}$$

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

where

- $v_{90,ph}(n)$ = Voltage sample at a sample instant n shifted by 90 degrees
 - $K_{ACT,ph}$ = Scaling factor for active power
 - $K_{REACT,ph}$ = Scaling factor for reactive power
- (2)

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

- It allows accurate measurement of the reactive power for very small currents.
- It conforms to the international specified measurement method.

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Because the frequency of the mains varies, it is important to first measure the mains frequency accurately to phase shift the voltage samples accordingly (see [Section 4.2.1.3](#)).

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

After calculating the active and reactive power, each phase's apparent power is calculated by the following formula:

$$P_{APP,ph} = \sqrt{P_{ACT,ph}^2 + P_{REACT,ph}^2}$$
(3)

In addition to calculating the per-phase active, reactive and apparent powers, the cumulative sum of these parameters are calculated by the below equations:

$$P_{ACT,Cumulative} = \sum_{ph=1}^3 P_{ACT,ph}$$

$$P_{REACT,Cumulative} = \sum_{ph=1}^3 P_{REACT,ph}$$

$$P_{APP,Cumulative} = \sum_{ph=1}^3 P_{APP,ph}$$
(4)

The calculated powers for each phase are then converted to energy by the following equations:

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

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

$$E_{APP,ph} = P_{APP,ph} \times Samplecount$$
(5)

From there, they are also accumulated to calculate the cumulative energies, as shown by the below equations:

$$E_{ACT, Cumulative} = \sum_{ph=1}^3 E_{ACT, ph}$$

$$E_{REACT, Cumulative} = \sum_{ph=1}^3 E_{REACT, ph}$$

$$E_{APP, Cumulative} = \sum_{ph=1}^3 E_{APP, ph} \quad (6)$$

The calculated energies are then accumulated into buffers that store the total amount of energy consumed since meter reset. Note that these energy are different from the working variables used to accumulate energy for outputting energy pulses. There are four sets of buffers that are available: one for each phase and one for the cumulative of the phases. Within each set of buffers, the following energies are accumulated:

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

4.2.1.3 Frequency (Hz)

The background process calculates the frequency in terms of samples per mains cycle. The foreground process then converts this to Hertz by [Equation 7](#).

$$\text{Frequency (Hz)} = \frac{\text{Sampling Rate (samples/second)}}{\text{Frequency (samples/cycle)}} \quad (7)$$

4.2.1.4 Power Factor

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

$$\text{Internal Representation of Power Factor} = \begin{cases} \frac{|P_{Act}|}{P_{Apparent}}, & \text{if capacitive load/generator} \\ -\frac{|P_{Act}|}{P_{Apparent}}, & \text{if inductive load/generator} \end{cases} \quad (8)$$

4.2.1.5 Temperature

Temperature is calculated using the TLV entries on the F67641. The measured values for 30°C ±3°C and 85°C ±3°C for the 2.0 V reference are used for calculating temperature. The exact formula that is used to calculate temperature is shown below:

$$Temp = (ADC(raw) - CAL_ADC_20T30) \times \left(\frac{85 - 30}{CAL_ADC_20T85 - CAL_ADC_20T30} \right) + 30 \quad (9)$$

The temperature is measured in units of Celsius. More information on this method of calculating temperature could be found in the User's Guide.

4.3 Background Process

The background function deals mainly with timing critical events in software. It uses the ΣΔ interrupt as a trigger to collect voltage and current samples. The ΣΔ interrupt is generated either when a new current sample is ready or when the trigger generator of the ΣΔ triggers the ADC10. Once the trigger to the ADC is generated, sample processing is done on the previously obtained voltage and current samples. This sample processing is done by the "per_sample_dsp()" function. After sample processing, the background process uses the "per_sample_energy_pulse_processing()" for the calculation and output of energy-proportional pulses. Figure 7 shows the flowchart for this process.

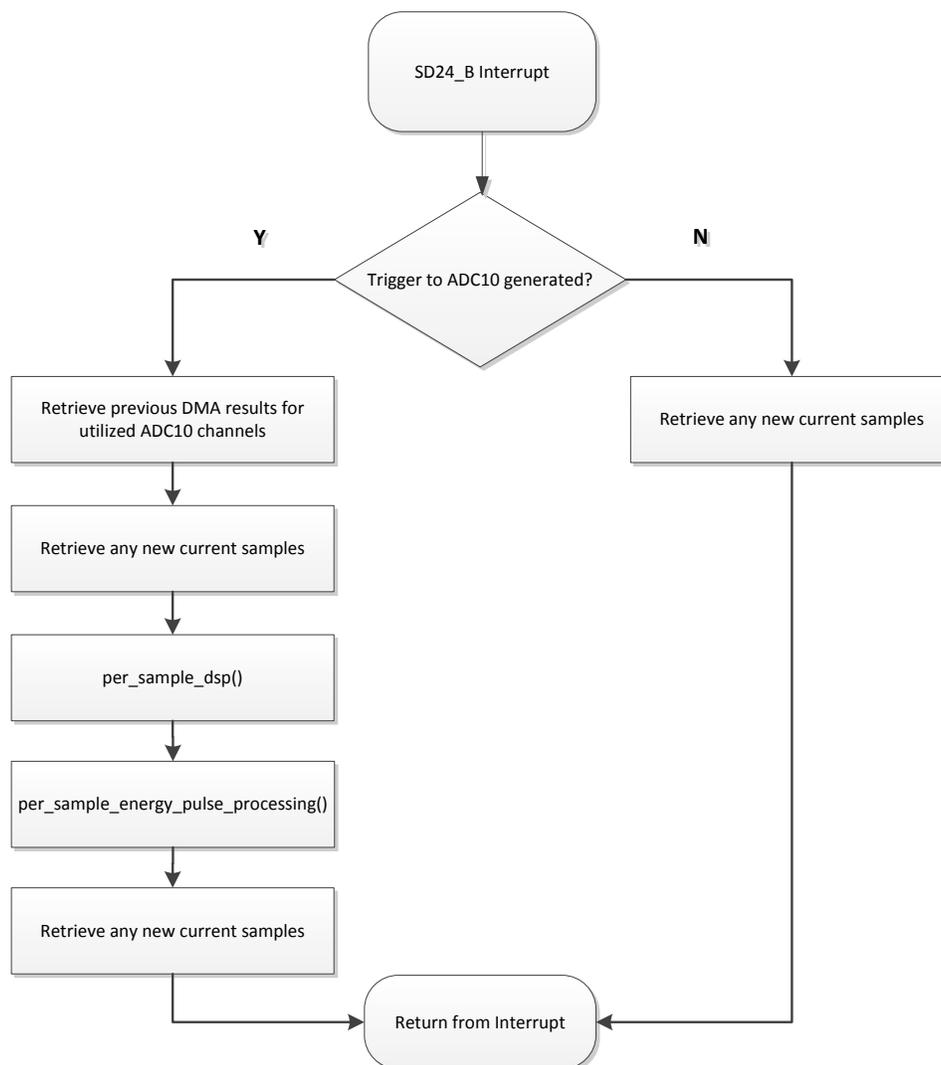


Figure 7. Background Process

When a trigger is generated, the next set of ADC10 conversions occur in parallel to the activity in the background process. This parallel activity is shown in [Figure 8](#), where the green items represent items that are done automatically by the configuration of the ADC10, DMA, and $\Sigma\Delta$ modules. For these green items, CPU intervention is not required.

As is represented in the [Figure 8](#), whenever the ADC10 is triggered, the ADC10 enters autoscan mode and samples all of its 16 ADC channels once. After each channel has a conversion result, the DMA automatically places these results in memory and the next channel's conversion is automatically started. For each converter, there is a memory location that stores the conversion results for that particular converter. The procedure of sampling a converter and storing the results in memory is repeated until the last converter (ADC10INCH=0) is sampled. Since the clock to the ADC10 is set to 4MHz, the sample and hold time for each converter is 8 cycles, and the conversion time is 12 cycles, there is a total of approximately 20 cycles (approximately 5 μ s) delay between conversion results of adjacent converters.

To sense the internal temperature sensor using the ADC10, a recommended sample period of at least 30 μ s must be used. As a result, the temperature reading measured in the autoscan mode may be invalid since the sample time used is not sufficient. To mitigate this, a single conversion of the ADC10 temperature channel is triggered. This is triggered in the DMA ISR when all of the autoscan ADC results have been placed in the proper memory locations. After a temperature reading has been received, the ADC10 ISR is triggered. In this ISR, the temperature reading is stored and the ADC10 settings are then reset to support autoscan mode. The ADC10 enters autoscan mode again at the next trigger from the $\Sigma\Delta$'s trigger generator.

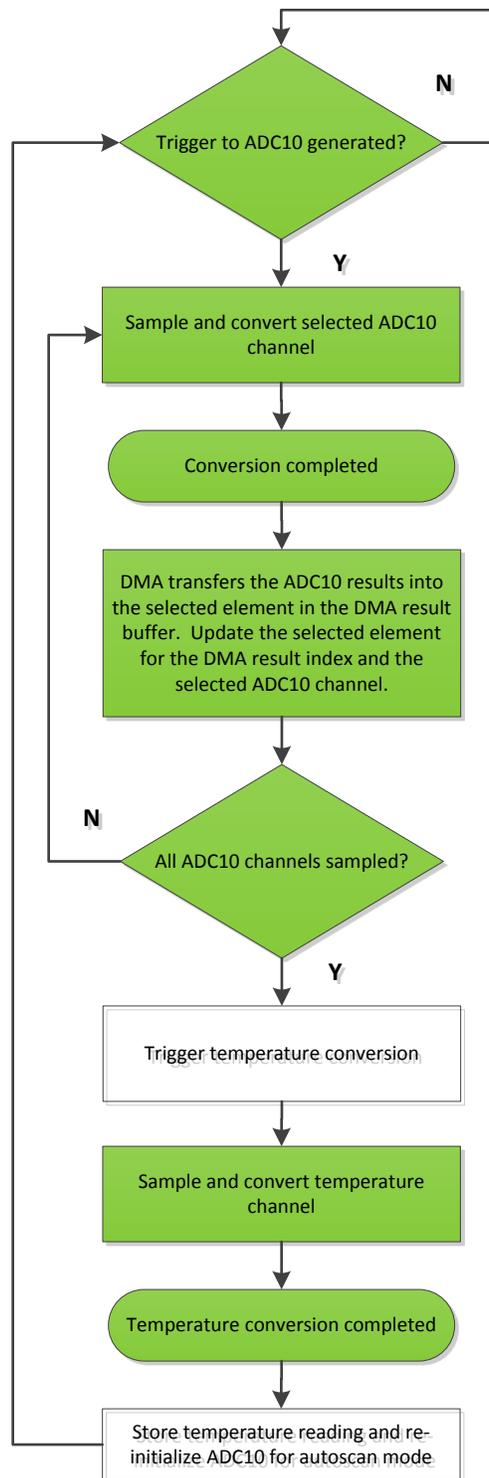


Figure 8. ADC10 Triggering Process

4.3.1 per_sample_dsp()

The flowchart for the `per_sample_dsp` function is shown in [Figure 9](#). In this function, the `per_sample_dsp` function is used to calculate intermediate dot product results that are fed into the foreground process for the calculation of metrology readings. The ADC10 is configured to represent the 10-bit voltage results as a 16-bit signed result. Because 16-bit voltage samples are used, the voltage samples are further processed and accumulated in dedicated 48-bit registers. In contrast, since 24-bit current samples are used, the current samples are processed and accumulated in dedicated 64-bit registers. Per-phase active power and reactive power are also accumulated in 64-bit registers.

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

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

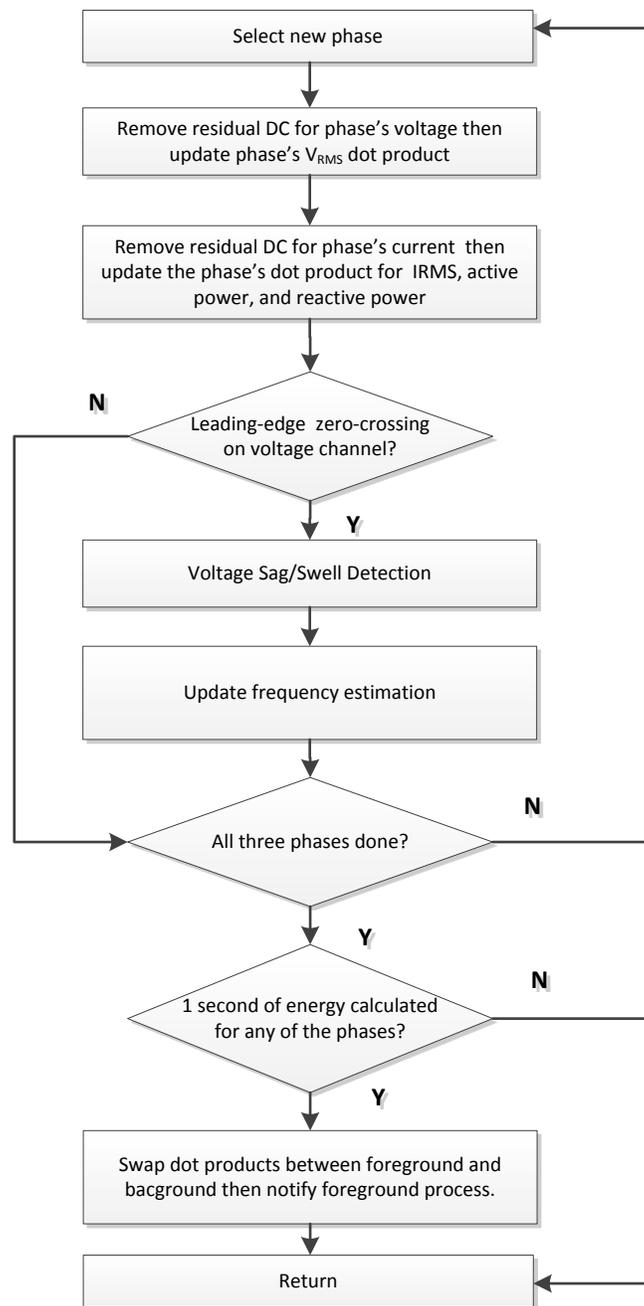


Figure 9. per_sample_dsp()

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

4.3.1.1 Voltage and Current Signals

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

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

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

These accumulated values are processed by the foreground process.

4.3.1.2 Frequency Measurement and Cycle Tracking

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

For frequency measurements, a straight line interpolation is used between the zero crossing voltage samples. Figure 10 shows the samples near a zero cross and the process of linear interpolation.

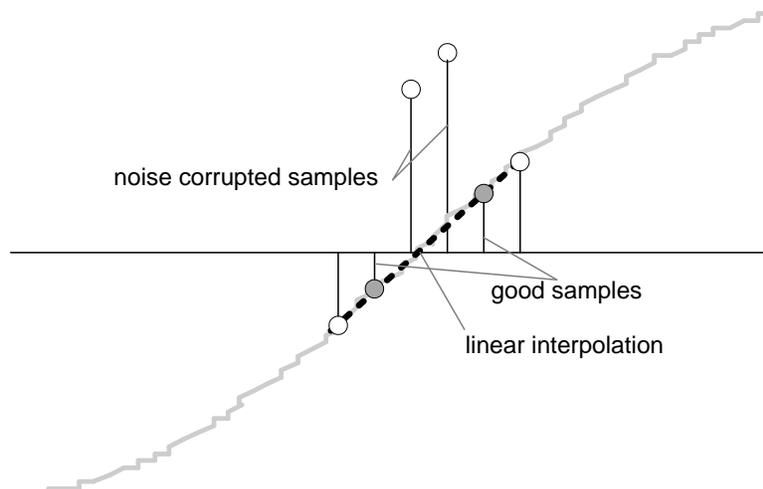


Figure 10. Frequency Measurement

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

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

4.3.2 LED Pulse Generation (per_sample_energy_pulse_processing)

In electricity meters, the active energy consumed is normally measured in fraction of kilowatt-hour (kWh) pulses. This information can be used to calibrate any meter for accurate measurement. Typically, the measuring element (the MSP430 microcontroller) is responsible to generate pulses proportional to the energy consumed. To serve both these tasks efficiently, pulse generation must be accurate with relatively little jitter. Although, time jitters are not an indication of bad accuracy, they give a negative indication on the overall accuracy of the meter. Hence the jitter must be averaged out.

This application uses average power to generate these energy pulses. The average power (calculated by the foreground process) is accumulated every $\Sigma\Delta$ interrupt, thereby spreading the accumulated energy from the previous 1 second time frame evenly for each interrupt in the current 1 second time frame. This is equivalent to converting it to energy. When the accumulated energy crosses a threshold, a pulse is generated. The amount of energy above this threshold is kept and new energy value is added on top of it in the next interrupt cycle. Because the average power tends to be a stable value, this way of generating energy pulses are very steady and free of jitter.

The threshold determines the energy "tick" specified by meter manufacturers and is a constant. It is usually defined in pulses per kWh or just in kWh. One pulse is generated for every energy "tick". For example, in this application, the number of pulses generated per kWh is set to 1600 for active and reactive energies. The energy "tick" in this case is 1 kWh/1600. Energy pulses are generated and available on a header and also via LEDs on the board. General-purpose I/O (port) pins are used to produce the pulses.

In the EVM, the LEDs that are labeled "Phase 1", "Phase 2", "Phase 3", and "Active" correspond to the active energy consumption for phase A, phase B, phase C, and the cumulative three-phase sum, respectively. "Reactive" corresponds to the cumulative three-phase reactive energy sum. The number of pulses per kWh and each pulse duration can be configured in software. [Figure 11](#) shows the flow diagram for pulse generation. This flow diagram is valid for pulse generation of individual or accumulative phase active, reactive, and apparent energy.

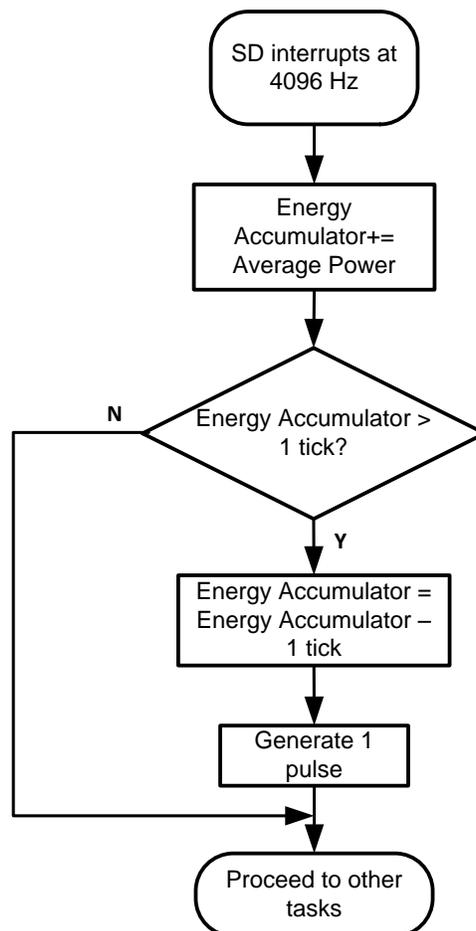


Figure 11. Pulse Generation for Energy Indication

The average power is in units of 0.001 W and the 1 kWh threshold is defined as:

$$1 \text{ kWh threshold} = (1 / 0.001) \times 1 \text{ kW} \times (\text{number of interrupts per second}) \times (\text{number of seconds in one hour}) = 1000000 \times 4096 \times 3600 = 0xD693A400000$$

4.3.3 Phase Compensation

When a current transformer (CT) is used as a sensor, it introduces additional phase shift on the current signals. Also, the voltage and current input circuit's passive components may introduce additional phase shift. Another source of phase shift is the sequential sampling on the voltage channel. The relative phase shift between voltage and current samples must be compensated to ensure accurate measurements. The $\Sigma\Delta$ converters have programmable delay registers (SD24PREx) that can be applied to any current. This built-in feature (PRELOAD) is used to provide the phase compensation required.

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

$$\text{Delay resolution}_{\text{Deg}} = \frac{360^\circ \times f_{IN}}{\text{OSR} \times f_s} = \frac{360^\circ \times f_{IN}}{f_M} \quad (10)$$

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

4.4 Energy Meter Configuration

Include files are used to initialize and configure the energy meter to perform several metrology functions. This section describes the user-configurable options. The main user-configurable options are within the following three files: metrology-calibration-template.h, metrology-template.h, and emter-template.h. Note that some options are dependent on other options. Therefore, some options may automatically be enabled if a particular option is selected. Many of the option associations are listed in the metrology-interactions.h file.

4.4.1 metrology-calibration-template.h

The metrology-calibration-template file contains the default calibration values that are first programmed into a meter before calibration. This file is located within the "emeter-metrology\emeter-metrology-67641" directory.

In the project settings, the calibration factors are set so that they are automatically deleted and set to the default calibration values whenever the meter firmware is reflashed. If it is desired to reflash the meter and maintain the same calibration values, the project settings could be changed so that only main memory is erased and information memory is retained. Alternatively, the default calibration values could be replaced with the meter's current calibration values. The relevant calibration factor macros are described below:

1. CALADC10_20V_30C: This macro references the TLV structure to obtain the necessary information to calculate temperature. This particularly refers to the temperature calibration data when the ADC10 uses a reference voltage of 2.0 V and the temperature is $30^\circ\text{C} \pm 3^\circ\text{C}$. For higher precision measurements, an external temperature sensor could be used instead.
2. CALADC10_20V_85C: This macro references the TLV structure to obtain the necessary information to calculate temperature. This particularly refers to the temperature calibration data when the ADC10 uses a reference voltage of 2.0 V and the temperature is $85^\circ\text{C} \pm 3^\circ\text{C}$. For higher precision measurements, an external temperature sensor could be used instead.
3. DEFAULT_V_RMS_SCALE_FACTOR_A: This macro holds the scaling factor for voltage at phase A. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
4. DEFAULT_V_DC_ESTIMATE_A: This macro holds an estimate for the dc level of the voltage channel of phase A. Using this estimate helps reduce the initial settling time of the dc voltage filter for phase A.
5. DEFAULT_V_AC_OFFSET_A: This macro removes the effect of the Additive White Gaussian Noise from the voltage ADC of phase A. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS voltage. When performing calculations for RMS voltage, this macro is subtracted out from the mean-squared voltage before its square root is taken to produce RMS voltage. Set this factor to an approximately correct value, and it will be fine tuned during calibration.

6. `DEFAULT_V_RMS_SCALE_FACTOR_B`: This macro holds the scaling factor for voltage at phase B. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
7. `DEFAULT_V_DC_ESTIMATE_B`: This macro holds an estimate for the dc level of the voltage channel of phase B. Using this estimate helps reduce the initial settling time of the dc voltage filter for phase B.
8. `DEFAULT_V_AC_OFFSET_B`: This macro removes the effect of the Additive White Gaussian Noise from the voltage ADC of phase B. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS voltage. When performing calculations for RMS voltage, this macro is subtracted out from the mean-squared voltage before its square root is taken to produce RMS voltage. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
9. `DEFAULT_V_RMS_SCALE_FACTOR_C`: This macro holds the scaling factor for voltage at phase C. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
10. `DEFAULT_V_DC_ESTIMATE_C`: This macro holds an estimate for the dc level of the voltage channel of phase C. Using this estimate helps reduce the initial settling time of the dc voltage filter for phase C.
11. `DEFAULT_V_AC_OFFSET_C`: This macro removes the effect of the Additive White Gaussian Noise from the voltage ADC of phase C. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS voltage. When performing calculations for RMS voltage, this macro is subtracted out from the mean-squared voltage before its square root is taken to produce RMS voltage. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
12. `DEFAULT_I_RMS_SCALE_FACTOR_A`: This macro holds the scaling factor for current at phase A. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
13. `DEFAULT_I_DC_ESTIMATE_A`: This macro holds an estimate for the dc level of the current channel of phase A. Using this estimate helps reduce the initial settling time of the dc current filter for phase A.
14. `DEFAULT_I_AC_OFFSET_A`: This macro removes the effect of the Additive White Gaussian Noise from the current ADC of phase A. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS current. When performing calculations for RMS current, this macro is subtracted out from the mean-squared current before its square root is taken to produce RMS current. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
15. `DEFAULT_I_RMS_SCALE_FACTOR_B`: This macro holds the scaling factor for current at phase B. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
16. `DEFAULT_I_DC_ESTIMATE_B`: This macro holds an estimate for the dc level of the current channel of phase B. Using this estimate helps reduce the initial settling time of the dc current filter for phase B.
17. `DEFAULT_I_AC_OFFSET_B`: This macro removes the effect of the Additive White Gaussian Noise from the current ADC of phase B. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS current. When performing calculations for RMS current, this macro is subtracted out from the mean-squared current before its square root is taken to produce RMS current. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
18. `DEFAULT_I_RMS_SCALE_FACTOR_C`: This macro holds the scaling factor for current at phase C. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
19. `DEFAULT_I_DC_ESTIMATE_C`: This macro holds an estimate for the dc level of the current channel of phase C. Using this estimate helps reduce the initial settling time of the dc current filter for phase C.
20. `DEFAULT_I_AC_OFFSET_C`: This macro removes the effect of the Additive White Gaussian Noise from the current ADC of phase C. Additive White Gaussian Noise is orthogonal to everything except itself. This results in the noise squaring when performing calculations for RMS current. When performing calculations for RMS current, this macro is subtracted out from the mean-squared current before its square root is taken to produce RMS current. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
21. `DEFAULT_P_SCALE_FACTOR_A`: This macro holds the scaling factor for active power at phase A. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
22. `DEFAULT_P_SCALE_FACTOR_B`: This macro holds the scaling factor for active power at phase B. Set this factor to an approximately correct value, and it will be fine tuned during calibration.

23. **DEFAULT_P_SCALE_FACTOR_C**: This macro holds the scaling factor for active power at phase C. Set this factor to an approximately correct value, and it will be fine tuned during calibration
24. **DEFAULT_BASE_PHASE_A_CORRECTION**: This macro holds the value for phase correction to compensate for delay due to the current transformer/front-end circuitry at phase A. This can be set to a value that is in fairly acceptable range, and it will be fine tuned under phase correction during calibration.
25. **DEFAULT_BASE_PHASE_B_CORRECTION**: This macro holds the value for phase correction to compensate for delay due to the current transformer/front-end circuitry at phase B. This can be set to a value that is in fairly acceptable range, and it will be fine tuned under phase correction during calibration.
26. **DEFAULT_BASE_PHASE_C_CORRECTION**: This macro holds the value for phase correction to compensate for delay due to the current transformer/front-end circuitry at phase C. This can be set to a value that is in fairly acceptable range, and it will be fine tuned under phase correction during calibration.

4.4.2 metrology-template.h

The metrology-template file contains the different user-configurable metrology-related options. This file is located within the "emeter-metrology\emeter-metrology-67641" directory. The relevant user-configurable options are below:

1. **NUM_PHASES**: This selects the maximum number of phases that the EVM supports. This value should be left at the default value of 3. It should not be changed.
2. **TWENTYFOUR_BIT**: This selects the resolution of the current channels. If it is defined, 24-bit samples are used for current. If it is not defined, 16-bits are used for voltage. Since there is no benefit in using a smaller resolution, this macro should be left defined and not be disabled.
3. **PHASE_1_CURRENT_ADC_CHANNEL**: This defines the Sigma Delta converter number that corresponds to Phase 1 (phase A).
4. **PHASE_1_VOLTAGE_ADC_CHANNEL**: This defines the ADC10 channel that is associated with phase 1 (phase A).
5. **PHASE_2_CURRENT_ADC_CHANNEL**: This defines the Sigma Delta converter number that corresponds to Phase 2(phase B).
6. **PHASE_2_VOLTAGE_ADC_CHANNEL**: This defines the ADC10 channel that is associated with phase 2 (phase B).
7. **PHASE_3_CURRENT_ADC_CHANNEL** : This defines the Sigma Delta converter number that corresponds to Phase 3 (phase C).
8. **PHASE_3_VOLTAGE_ADC_CHANNEL**: This defines the ADC10 channel that is associated with phase 3 (phase C).
9. **SD_LIVE_CURRENT_GAIN**: This macro defines the gain of the $\Sigma\Delta 24_B$'s internal programmable gain amplifier (PGA) for all the three currents. In this application it is set to 1.
10. **SD_CLOCK_DIVISION**: This defines the ratio of the ADC clock source's frequency and the ADC clock frequency. Since a 25 MHz clock is used to produce a modulation clock of approximately 1 MHz, the division factor is 24. This macro could only have a value of 8, 16, 20, or 24 and it should not be changed if the software's default clock frequency is used.
11. **MAINS_NOMINAL_FREQUENCY**: The nominal mains frequency, in Hz that is used to prime the mains frequency filter to make it settle more quickly.
12. **MAINS_NOMINAL_VOLTAGE**: This selects the nominal voltage used for sag/swell detection.
13. **VCC_MEASURE_SUPPORT**: Defining this macro supports the storing of the VDSYS/2 reading into the "vcc" variable.
14. **MAINS_BASIS_CURRENT**: This selects the basis current.
15. **MAINS_MAXIMUM_CURRENT**: This selects the maximum operating current.
16. **IEC_THD_SUPPORT**: This selects support for IEC style THD readings. If this is not defined, IEEE style readings will be produced for any THD readings.
17. **MAINS_FREQUENCY_SUPPORT**: The macro configures the meter to measure the frequency of the AC mains.

18. VRMS_SUPPORT: This macro is used to configure the meter to calculate VRMS from the voltage samples.
19. SAG_SWELL_SUPPORT: This selects support for sag and swell detection.
20. SAG_SWELL_WINDOW_LEN: This selects the number of mains cycles over which sag and swell detection works.
21. SAG_THRESHOLD: This selects the percentage fall from the nominal voltage for sag detection.
22. SWELL_THRESHOLD: This selects the percentage rise above the nominal voltage for swell detection.
23. FUNDAMENTAL_VRMS_SUPPORT: This selects support for fundamental RMS voltage measurement.
24. VOLTAGE_THD_SUPPORT: This selects support for measuring the THD in the voltage waveform.
25. IRMS_SUPPORT: This macro is used to configure the meter to calculate IRMS from the current samples.
26. FUNDAMENTAL_IRMS_SUPPORT: This selects support for fundamental RMS current measurement.
27. CURRENT_THD_SUPPORT: This selects support for measuring the THD in the current waveform.
28. FUNDAMENTAL_ACTIVE_POWER_SUPPORT: This selects support for fundamental active power measurement.
29. REACTIVE_POWER_SUPPORT: This selects support for reactive power measurement.
30. REACTIVE_POWER_BY_QUADRATURE_SUPPORT: This selects support for reactive power measurement through quadrature processing. This is only effective when REACTIVE_POWER_SUPPORT is enabled.
31. FUNDAMENTAL_REACTIVE_POWER_SUPPORT: This selects support for fundamental reactive power measurement.
32. APPARENT_POWER_SUPPORT: The selects support for apparent or VA power measurement.
33. POWER_FACTOR_SUPPORT: This macro is used to configure the meter to calculate the power factor for both lead and lag. A frequency independent method, based on the ratio of scalar dot products, is used.
34. RESIDUAL_POWER_CUTOFF: Tiny power levels should not record energy at all, as they may just be rounding errors, noise, or the consumption of the meter itself. This value is the cutoff level in milliwatts (this is the cutoff per phase).
35. TOTAL_RESIDUAL_POWER_CUTOFF: Tiny power levels should not record at all, as they may just be rounding errors, noise, or the consumption of the meter itself. This value is the cutoff level, in 0.01W increments (this is the cutoff for the aggregate power).
36. ACTIVE_ENERGY_SUPPORT: This switch selects support for measuring the active energy consumption on a phase by phase basis. This will allow the GUI to display each phase's active energy consumption in kWh.
37. ACTIVE_ENERGY_PULSES_PER_KW_HOUR: This macro defined the total number of pulses per 1 kWh of active energy at each phase. In this application it is defined to 1600 if pulses generation for each individual phase has been enabled. If the value of this macro is increased, it may be necessary to decrease the pulse duration.
38. REACTIVE_ENERGY_SUPPORT: This switch selects support for measuring the reactive energy consumption on a phase by phase basis. This will allow the GUI to display each phase's reactive energy consumption in kvarh.
39. APPARENT_ENERGY_SUPPORT: This switch selects support for measuring the apparent energy consumption on a phase by phase basis. This will allow the GUI to display each phase's apparent energy consumption in kVA.
40. TOTAL_ACTIVE_ENERGY_SUPPORT: This switch selects support for measuring the total active energy consumption. This will allow the GUI to display the cumulative phase's active energy consumption in kWh.
41. TOTAL_REACTIVE_ENERGY_SUPPORT: This switch selects support for measuring the total reactive energy consumption. This will allow the GUI to display the cumulative phase's reactive energy consumption in kvarh.

42. **TOTAL_APPARENT_ENERGY_SUPPORT**: This switch selects support for measuring the total apparent energy consumption. This will allow the GUI to display the cumulative phase's apparent energy consumption in kVA.
43. **TOTAL_ACTIVE_ENERGY_PULSES_PER_KW_HOUR**: This sets the number of pulses per kilo-watt hour the meter will produce at its total active energy pulse. It does not affect the energy accumulation process. The default setting for this macro is 1600.
44. **TOTAL_REACTIVE_ENERGY_PULSES_PER_KVAR_HOUR**: This sets the number of pulses per kilo-var hour the meter will produce at its total reactive energy pulse. It does not affect the energy accumulation process. The default setting for this macro is 1600.
45. **ENERGY_PULSE_DURATION**: The duration of the LED on time for an energy pulse. This is measured in ADC samples (that is, increments 1/4096s). The maximum allowed is 255, giving a pulse of about 62ms. The default value for this macro is 80. For higher pulses/kwh constants, the value for this macro may need to be reduced.
46. **TEMPERATURE_SUPPORT**: This switch enables use of the MSP430's internal temperature diode to measure the meter's temperature.
47. **PRECALCULATED_PARAMETER_SUPPORT**: Normally the meter software only calculates the properly scaled values for voltage, current, etc. as these values are needed. This define enables additional global parameters, which are regularly updated with all the metrics gathered by the meter. This is generally less efficient, as it means calculating things more often than necessary. However, some may find this easier to use, so it is offered as a choice for the meter designer.
48. **custom_adc_interrupt()**: This is called every ADC interrupt, after the main DSP work has finished. It can be used for things like custom keypad operations. It is important this is a very short routine, as it is called from the main ADC interrupt.

4.4.3 emeter-template.h

The emeter-template file contains the different user-configurable application-related options. This file is located within the "emeter-app\emeter-app-67641" directory. The relevant user-configurable options are below

1. **SERIAL_CALIBRATION_SUPPORT**: This switch, in combination with the calibrator switch, enables calibration with the meter cooperating with an external reference, through a UART port.
2. **SERIAL_CALIBRATION_REF_SUPPORT**: This switch enables the sending of the current readings, through a UART port, for use in cooperative calibration with other meters.
3. **RTC_SUPPORT**: This selects real time clock support.
4. **IHD430_SUPPORT**: This macro allows ZigBee communication to an IHD430 in-home display. A CC2530 transmitter must be placed in the EVM's RF connector to enable this. For more information, see [Section 6.2](#).
5. **DLT645_SUPPORT**: This macro enables DLT645 communication.
6. **custom_active_energy_pulse_start**: This macro defines the command used to turn on the active energy LED for a pulse.
7. **custom_active_energy_pulse_end**: This macro defines the command used to turn off the active energy LED for a pulse.
8. **custom_reactive_energy_pulse_start**: This macro defines the command used to turn on the reactive energy LED for a pulse.
9. **custom_reactive_energy_pulse_end**: This macro defines the command used to turn off the reactive energy LED for a pulse.
10. **OUTPUT_RTCCLK**: If this macro is defined, the active pulse capability is disabled and the RTCCLK, which is used for calibration, is output on the header normally used for active power pulses.

In addition to the above macros, there are also various macros for defining the display properties of the EVM's LCD and the values of the LCD display registers. Also there are macros that are used to initialize the values of the DIR, SEL, OUT, and REN registers of each port. In the software, these values are set to values to correspond to the hardware of this EVM.

5 Energy Meter Demo

The energy meter evaluation module (EVM) associated with this application report has the MSP430F67641 and demonstrates energy measurements. The complete demonstration platform consists of the EVM that can be easily hooked to any test system, metrology software and a PC GUI, which is used to view results and perform calibration.

5.1 EVM Overview

The following figures of the EVM show the hardware. [Figure 12](#) is the top view of the energy meter. [Figure 13](#) shows the location of various pieces of the EVM based on functionality.

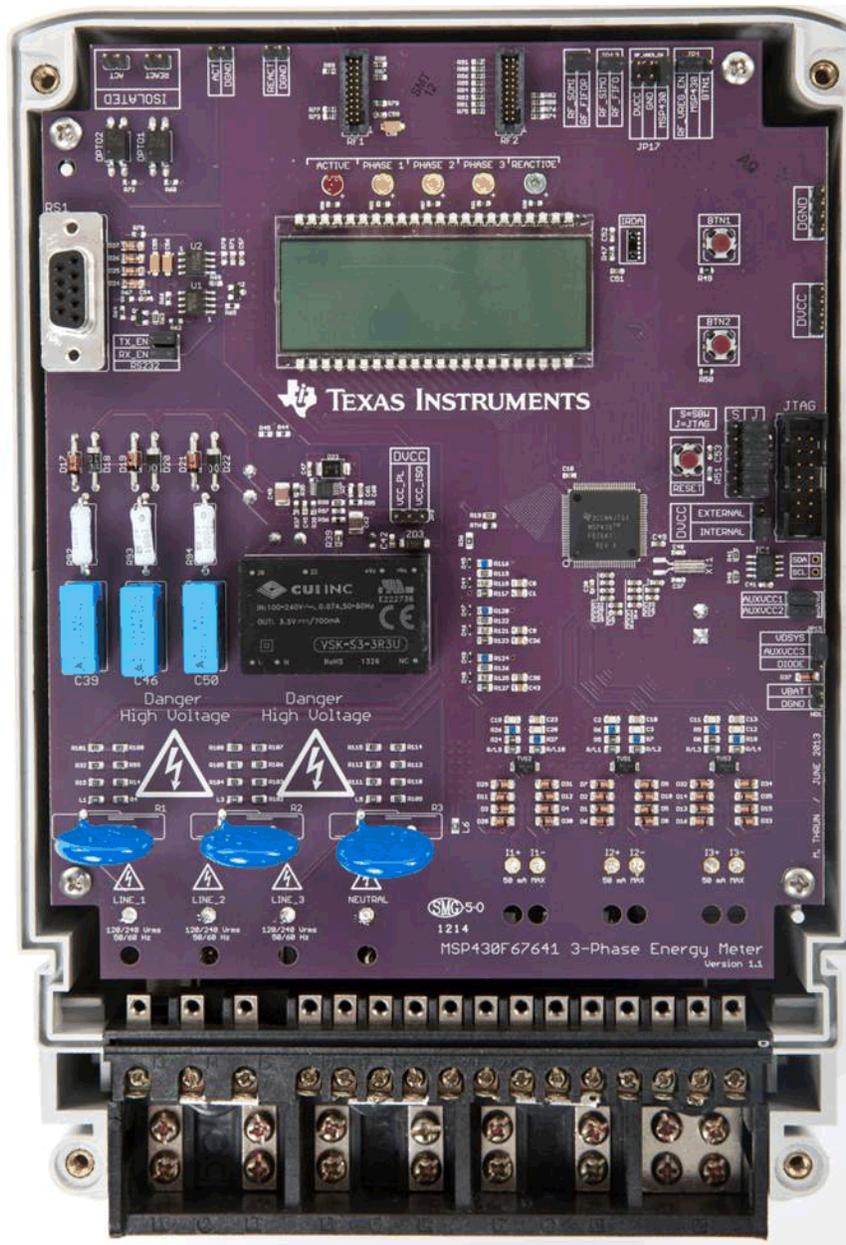


Figure 12. Top View of the Three Phase Energy Meter EVM

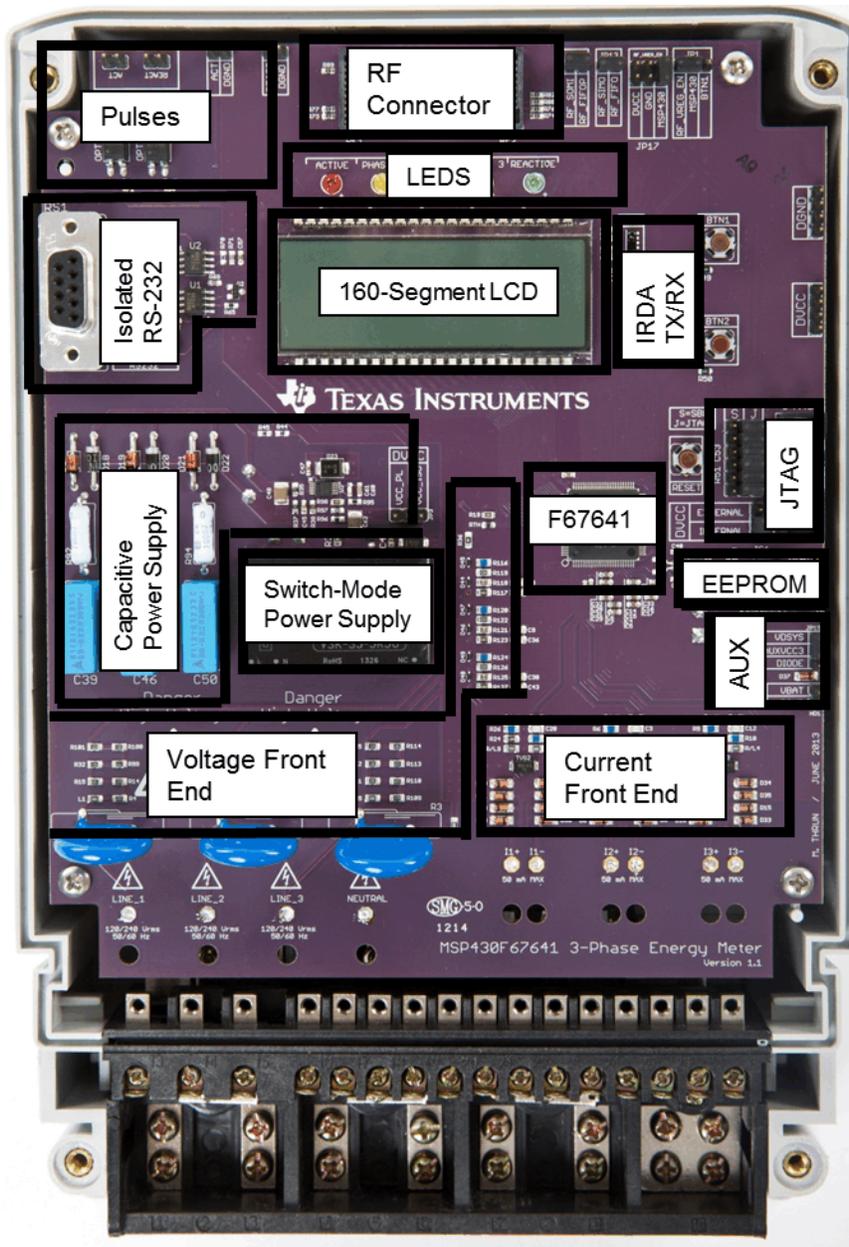


Figure 13. Top View of the EVM With Components Highlighted

	<p>Danger High Voltage</p>	<p>Electric shock possible when connecting board to live wires. Board should be handed with care by a professional. For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended.</p>
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5.1.1 Connections to the Test Setup or AC Voltages

CAUTION

Do not leave EVM powered when unattended.

AC voltage or currents can be applied to the board for testing purposes at these points:

- Pad LINE_1 corresponds to the line connection for phase A.
- Pad LINE_2 corresponds to the line connection for phase B.
- Pad LINE_3 corresponds to the line connection for phase C.
- Pad NEUTRAL corresponds to the Neutral voltage.

The voltage between any of the three line connections to the neutral connection can be up to 230 V AC at 50/60 Hz.

- I1+ and I1- are the current inputs after the sensors for phase A. When a current sensor is used, make sure that the voltage across I1+ and I1- does not exceed 920 mV. THIS IS CURRENTLY CONNECTED TO A CT ON THE EVM.
- I2+ and I2- are the current inputs after the sensors for phase B. When a current sensor is used, make sure that the voltage across I2+ and I2- does not exceed 920 mV. THIS IS CURRENTLY CONNECTED TO A CT ON THE EVM.
- I3+ and I3- are the current inputs after the sensors for phase C. When a current sensor is used, make sure that the voltage across I3+ and I3- does not exceed 920 mV. THIS IS CURRENTLY CONNECTED TO A CT ON THE EVM.

Figure 14 and Figure 15 show the various connections that need to be made to the test setup for proper functionality of the EVM.

When a test AC source needs to be connected, the connections must be made according to the EVM design. Figure 14 shows the connections from the top view. VA+ , VB+, and VC+ corresponds to the line voltage for phases A, B, and C, respectively. VN corresponds to the neutral voltage from the test AC source.

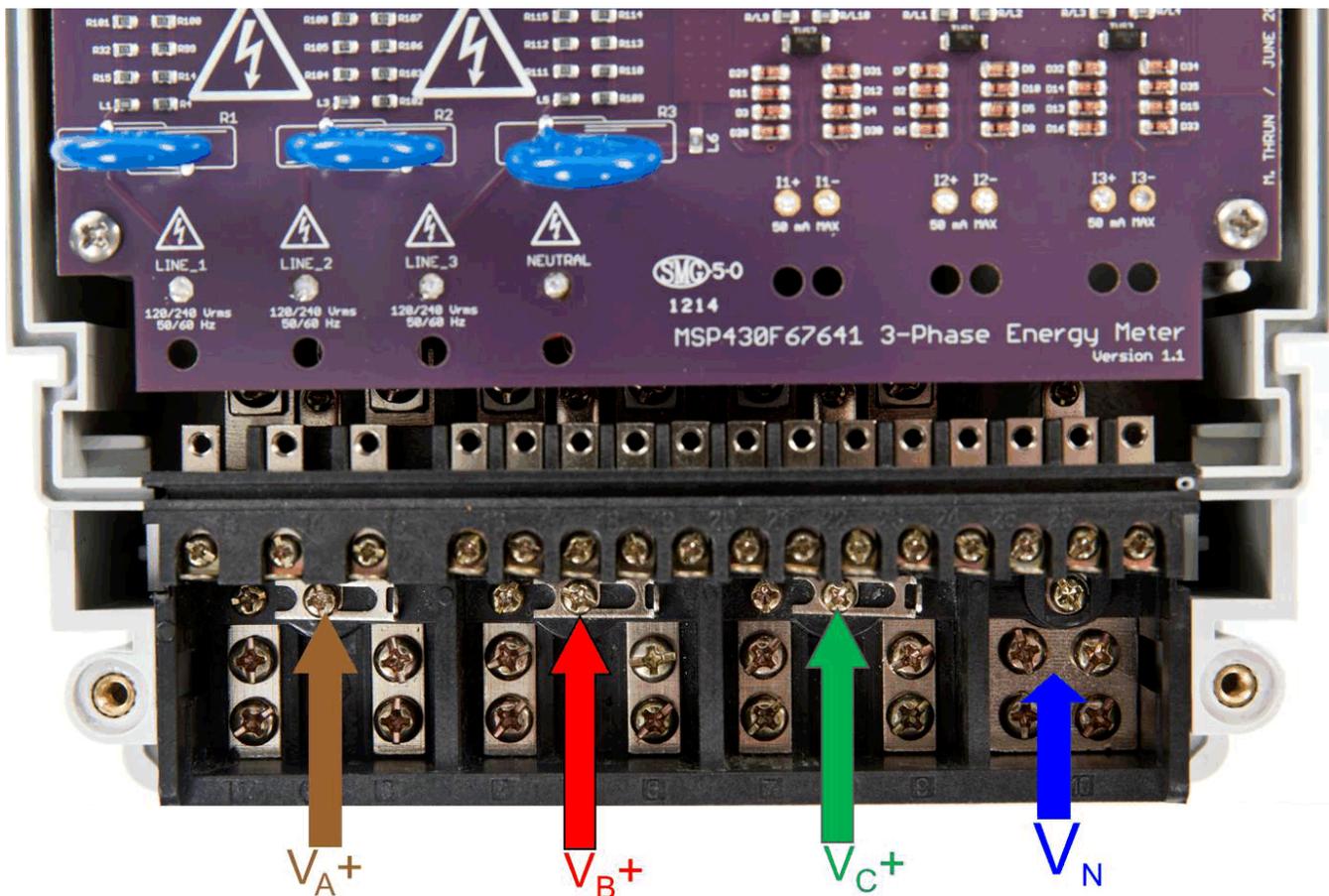


Figure 14. Top View of the EVM With Test Setup Connections

Figure 15 shows the connections from the front view. IA+ and IA- correspond to the current inputs for phase A, IB+ and IB- correspond to the current inputs for phase B, and IC+ and IC- correspond to the current inputs for phase C. VN corresponds to the neutral voltage from the test setup.

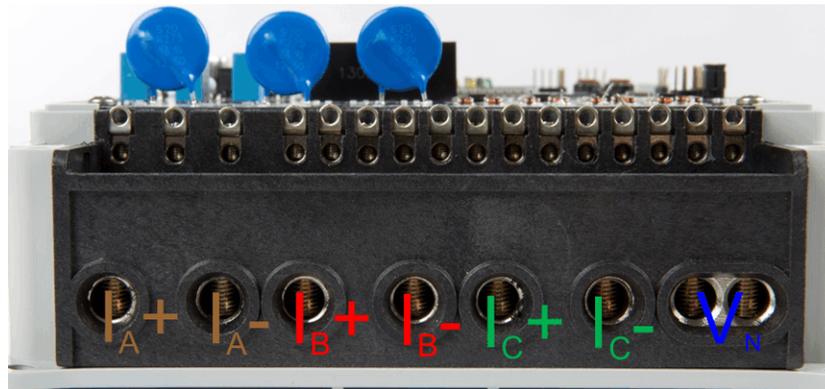


Figure 15. Front View of the EVM With Test Setup Connections

5.1.2 Power Supply Options and Jumper Settings

The EVM can be configured to operate with different sources of power. The entire board can be powered by a single dc voltage rail (DVCC), which can be derived either via JTAG, external power, or AC mains through either the capacitive or switching power supplies. Various jumper headers and jumper settings are present to add to the flexibility to the board. Some of these headers require that jumpers be placed appropriately for the board to correctly function. Table 1 describes the functionality of each jumper on the board and the associated functionality.

Table 1. Header Names and Jumper Settings on the EVM430-F67641

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
ACT/RTCCLK (Not isolated, do not probe)	2-pin Header	Active Energy Pulses/RTC Calibration (WARNING)	Probe between here and ground for cumulative three-phase active energy pulses. Alternatively, enable port mapping to connect this pin instead to RTCCLK. When connected to RTCCLK, probe here to measure the frequency of RTCCLK, which is used for calibrating the RTC.	This header is not isolated from AC voltage, so do not connect measuring equipments unless isolators external to the EVM are available. See the ISOLATED ACT header, instead. Note that by default this pin is configured for outputting active pulses. The software must be modified to output RTCCLK.
AUXVCC1 (Not isolated, do not probe)	2-pin Header	AUXVCC1 Selection and External Power (WARNING)	Place a jumper here to connect AUXVCC1 to GND. This jumper must be present if AUXVCC1 is not used as a backup power supply. Alternatively, it can be used to provide a backup power supply to the MSP430. To do so, connect the alternative power supply to this header. In addition, on the bottom of the board, an optional super capacitor has been added. If this super capacitor is not desired for the user's selected AUX configuration, it should be removed.	
AUXVCC2 (Not isolated, do not probe)	2-pin Jumper Header	AUXVCC2 selection; AUXVCC2 External Power (WARNING)	Place a jumper here to connect AUXVCC2 to GND. This jumper must be present if AUXVCC2 is not used as a backup power supply. Alternatively, it can be used to provide a backup power supply to the MSP430. To do so, simply connect the alternative power supply to this header.	
AUXVCC3 (Not isolated, do not probe)/JP15	3-pin Jumper Header Option	AUXVCC3 Selection and External Power (WARNING)	To power the RTC externally regardless of whether or not DVCC is available, provide external voltage at AUXVCC3, disable the internal AUXVCC3 charger in software, and do not connect a jumper at this header. Alternatively, place a jumper at the "VDSYS" option to connect AUXVCC3 to VDSYS so that it is powered from whichever supply (DVCC, AUXVCC1, or AUXVCC2) is powering the chip. If this jumper is placed, disable the internal charger in software. To power the RTC externally only when DVCC is not available, enable the internal charger, place a jumper at the "Diode" option, and apply external voltage at the VBAT header.	

Table 1. Header Names and Jumper Settings on the EVM430-F67641 (continued)

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
DGND (Not isolated, do not probe)	Header	Ground Voltage Header (WARNING)	Not a jumper header, probe here for GND voltage. Connect negative terminal of bench or external power supply when powering the board externally.	Do not probe if board is powered from AC mains, unless the AC mains are isolated. This voltage can be hot or neutral if AC wall plug is connected to the meter
DVCC (Not isolated, do not probe)	Header	VCC Voltage Header (WARNING)	Not a jumper header, probe here for VCC voltage. Connect positive terminal of bench or external power supply when powering the board externally.	Do not probe if board is powered from AC mains, unless the AC mains are isolated.
DVCC EXTERNAL (Do not connect JTAG if AC mains is the power source Isolated JTAG or supply is fine)	Jumper Header Option	JTAG External Power Selection Option (WARNING)	Place a jumper at this header option to select external voltage for JTAG programming.	This jumper option and the DVCC INTERNAL jumper option comprise one three-pin header used to select the voltage source for JTAG programming.
DVCC INTERNAL (Do not connect JTAG if AC mains is the power source).	Jumper Header Option	JTAG Internal Power Selection Option (WARNING)	Place a jumper at this header option to power the board using JTAG and to select the voltage from the USB FET for JTAG programming.	This Jumper option and the DVCC EXTERNAL jumper option comprise one three-pin header used to select the voltage source for JTAG programming.
DVCC VCC_ISO (Not isolated, do not probe)	Jumper Header Option	Switching-Mode Supply Select	Place a jumper at this header position to power the board via AC mains using the switching power supply	Place a jumper only if AC mains voltage is needed to power the DVCC rail. This header option and the DVCC VCC_PL header option comprise one three-pin header that selects a capacitive power supply, a switching-mode power supply, or neither.
DVCC VCC_PL (Not isolated, do not probe)	Jumper Header Option	Capacitor Power Supply Select (WARNING)	Place a jumper at this header position to power the board via AC mains using the capacitor power supply	Place a jumper only if AC mains voltage is needed to power the DVCC rail. Do not debug using JTAG unless AC source is isolated or JTAG is isolated. This header option and the DVCC VCC_ISO header option comprise one three-pin header that selects a capacitive power supply, a switching-mode power supply, or neither.
ISOLATED ACT	1-pin Header	Isolated Active Energy Pulses	Not a jumper header, probe between here and ground for cumulative three-phase active energy pulses	This header is isolated from AC voltage so it is safe to connect to scope or other measuring equipment since isolators are already present.
ISOLATED REACT	1-pin Header	Isolate Reactive Energy Pulses	Not a jumper header, probe between here and ground for cumulative three-phase reactive energy pulses	This header is isolated from AC voltage so it is safe to connect to scope or other measuring equipment since isolators are already present.
J (Do not connect JTAG if AC mains is the power source)	Jumper Header Option	4-wire JTAG Programming Option (WARNING)	Place jumpers at the J header options of all of the six JTAG communication headers to select 4-wire JTAG.	There are six headers that jumpers must be placed at to select a JTAG communication option. Each of these six headers have a J option and an S option to select either 4-wire JTAG or SBW. To enable 4-wire JTAG, configure all of these headers for the J option. To enable SBW, configure all of the headers for the S option.

Table 1. Header Names and Jumper Settings on the EVM430-F67641 (continued)

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
JP1	Jumper Header Option	MSP430 P1.7 Connection Selection	Place a jumper at the "BTN1" option to connect P1.7 of the MSP430 to the EVM's "BTN1" button. Place a jumper at the "RF_VREG_EN" option, to connect P1.7 of the MSP430 to the "MSP430" option of JP17(RF_VREG_EN section).	When the BTN1 option is selected, pressing BTN1 makes P1.7 LOW. When the button is not pressed, P1.7 is HIGH. When the "RF_VREG_EN" is selected, the "MSP430" option must be selected from JP17 to connect P1.7 to the "RF_VREG_EN" of the radio module connected to the board's RF connectors.
JP13	Jumper Header	RF Connector Transmit Enable	Place a jumper here to enable transmission to the radio module connected to the EVM's RF connectors.	
JP14	Jumper Header	RF Connector Receiver Enable	Place a jumper here to enable receiving from the radio connected to the EVM's RF connectors	
JP17	Jumper Header Option (Connect only one option to RF_VREG_EN)	RF Connector's RF_VREG_EN Connection Selection (WARNING)	Place a jumper between DVCC and RF_VREG_EN to connect the RF connector's RF_VREG_EN connection to DVCC. Place a jumper between GND and RF_VREG_EN to connect the RF connector's RF_VREG_EN connection to Ground. Place a jumper between DVCC and RF_VREG_EN to connect the RF connector's RF_VREG_EN connection to the "RF_VREG_EN" option of the JP1 header.	When the "MSP430" option is selected, the "RF_VREG_EN" option must be selected from JP1 to connect P1.7 to the "RF_VREG_EN" of the radio module connected to the board's RF connectors.
REACT (Not isolated, do not probe)	1-pin Header	Reactive Energy Pulses (WARNING)	Not a jumper header, probe between here and ground for cumulative three-phase reactive energy pulses	This header is not isolated from AC voltage so do not connect measuring equipments unless isolators external to the EVM are available. See the ISOLATED REACT header, instead.
RX_EN	Jumper Header	RS-232 Receive enable	Place a jumper here to enable receiving characters using RS-232.	
S (Do not connect JTAG if AC mains is the power source)	Jumper Header Option	SBW JTAG Programming Option (WARNING)	Place jumpers at the S header options of all of the six JTAG communication headers to select SBW	There are six headers where jumpers must be placed at to select a JTAG communication mode. Each of these six headers that have a J option and an S option to select either 4-wire JTAG or SBW. To enable 4-wire JTAG, all of these headers must be configured for the J option. To enable SBW, all of the headers must be configured for the S option.
SCL (Not isolated, do not probe)	1-pin Jumper Header	I2C/EEPROM SCL probe point (WARNING)	Probe here to probe I2C SCL line	Probe only when AC mains is isolated.
SDA (Not isolated, do not probe)	1-pin Jumper Header	I2C/EEPROM SDA probe point (WARNING)	Probe here to probe I2C SDA line	Probe only when AC mains is isolated.
TX_EN	Jumper Header	RS-232 Transmit Enable	Place a jumper here to enable RS-232 transmissions.	
	2-pin Jumper Header	AUXVCC3 External Power For AUXVCC3 "Diode" Option (WARNING)	When the "Diode" option is selected for AUXVCC3, apply voltage at this header so that the RTC can still be powered when the voltage at DVCC is removed.	

5.2 Loading the Example Code

The source code is developed in the IAR Embedded Workbench™ environment using IAR version 5.60.7 for the MSP430 IDE and version 6.6.4.2867 for the IAR Embedded Workbench common components. The current version of IAR can be viewed from the "Product Info" option in the Help menu.

There are four main parts to the energy metrology software:

- The toolkit that contains a library of mostly mathematics routines
- The metrology code that is used for calculating metrology parameters
- The application code that is used for the host-processor functionality of the meter (for example, communication, LCD display, and RTC setup)
- The GUI that is used for calibration

5.2.1 Opening the Project

Figure 16 shows the contents of the Source folder.

Source

Name	Date modified	Type	Size
 GUI	2/16/2014 2:26 PM	File folder	
 emeter-metrology	2/16/2014 2:24 PM	File folder	
 emeter-toolkit	2/16/2014 2:23 PM	File folder	
 settings	2/16/2014 2:22 PM	File folder	
 emeter-app	2/16/2014 2:21 PM	File folder	
 F67641.eww	2/12/2014 9:20 AM	IAR IDE Workspace	1 KB

Figure 16. Source Folder Structure

Within the emeter-app-67641 folder in the emeter-app folder, the emeter-app-67641.ewp project corresponds to the application code. Similarly, within the emeter-metrology-67641 folder in the emeter-metrology folder, the emeter-metrology-67641.ewp project corresponds to the portion of the code for metrology. Additionally, the folder emeter-toolkit-67641 within emeter-toolkit has the corresponding toolkit project file emeter-toolkit-67641.ewp. For first time use, it is recommended that all three projects be completely rebuilt by performing the following steps:

1. Open the IAR IDE.
2. Open the F67641 workspace, which is located in the "Source" folder.
3. Within IAR's workspace window, click the "Overview" tab to have a list view of all the projects.
4. Right-click the "emeter-toolkit-67641" option in the workspace window and select Rebuild All, as shown in Figure 17.
5. Right-click the "emeter-metrology-67641" option in the workspace window and select Rebuild All, as shown in Figure 18.
6. Within IAR's workspace window, click the "emeter-app-67641" tab.
7. Within the workspace window, select "emeter-app-67641", click Rebuild All as shown in Figure 19, and then download this project onto the MSP430F67641.

NOTE: If any changes are made to any of the files in the toolkit project and the project is compiled, the metrology project must be recompiled. After recompiling the metrology project, the application project must then be recompiled. Similarly, if any changes are made to any of the files in the metrology project and the project is compiled, the application project must then be recompiled.

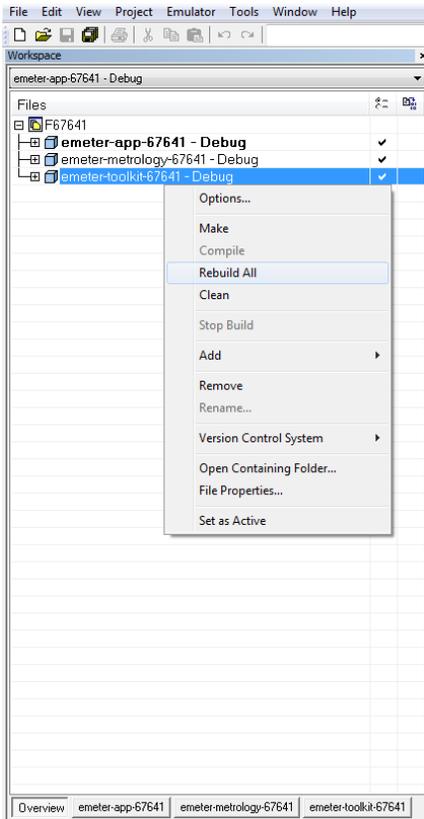


Figure 17. Toolkit Project Compilation

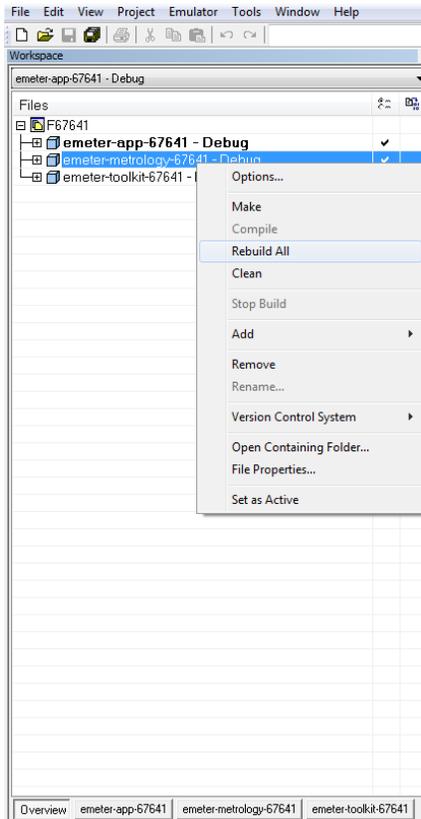


Figure 18. Metrology Project Compilation

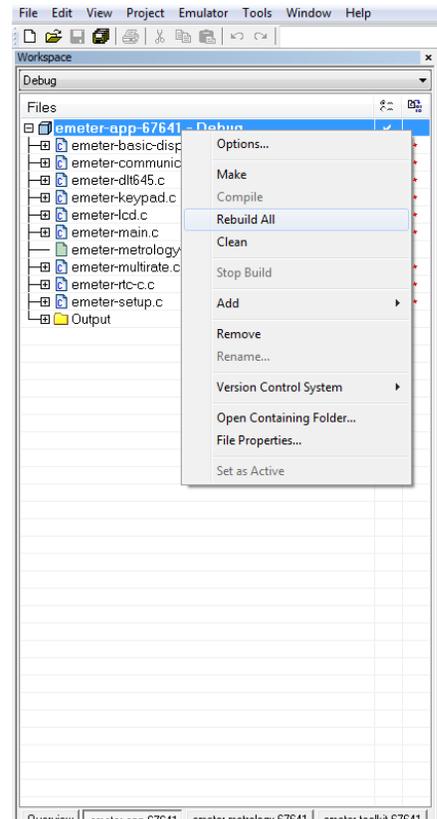


Figure 19. Application Project Compilation

6 Results and Calibration

6.1 Viewing Results on the LCD

The LCD display scrolls between metering parameters every two seconds. For each metering parameter that is displayed on the LCD, three items are usually displayed on the screen: a symbol used to denote the phase of the parameter, text to denote which parameter is being displayed, and the actual value of the parameter. The phase symbol is displayed at the top of the LCD and denoted by a triangle shape. The orientation of the symbol determines the corresponding phase. Figure 20 shows the mapping between the different orientations of the triangle and the phase descriptor:



Figure 20. Phase Symbols

Aggregate results (such as cumulative active and reactive power) and parameters that are independent of phase (such as time and date) are denoted by clearing all of the phase symbols on the LCD.

The bottom line of the LCD is used to denote the value of the parameter being displayed. The text to denote the parameter being shown is displayed on the top line of the LCD. Table 2 shows the different metering parameters that are displayed on the LCD and the associated units in which they are displayed. The "Designation" column shows which characters correspond to which metering parameter.

Table 2. Displayed Parameters

Parameter Name	Designation	Units	Comments
Active Power	ACPo	Watt (W)	This parameter is displayed for each phase. The aggregate active power is also displayed.
Reactive Power	REPo	Volt-Ampere Reactive (var)	This parameter is displayed for each phase. The aggregate reactive power is also displayed.
Apparent Power	APPo	Volt-Ampere (VA)	This parameter is displayed for each phase.
Power Factor	PF	Constant between 0 and 1	This parameter is displayed for each phase.
Voltage	UnS	Volts (V)	This parameter is displayed for each phase.
Current	InS	Amps (A)	This parameter is displayed for each phase.
Frequency	FREQ	Hertz (Hz)	This parameter is displayed for each phase.
Total Consumed Active Energy	ACEn	kWh	This parameter is displayed for each phase.
Total Consumed Reactive Energy	REEn	kVarh	This parameter is displayed for each phase. This displays the sum of the reactive energy in quadrant 1 and quadrant 4.
Time	time	Hour:Minute:Second	This parameter is only displayed when the sequence of aggregate readings is displayed. It is not displayed once per phase.
Date	date	Year:Month:Day	This parameter is only displayed when the aggregate readings are displayed. It is not displayed once per phase.

Figure 21 shows an example of phase A's measured frequency of 49.99 Hz displayed on the LCD.

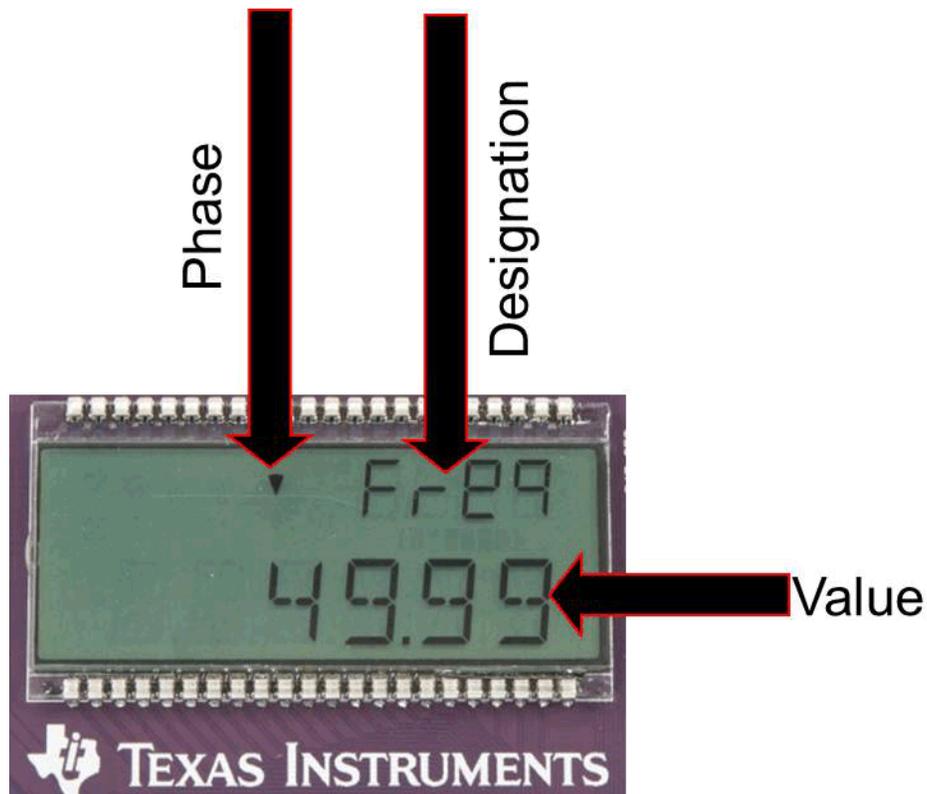


Figure 21. LCD Display

6.2 View Results Using RF Technology (ZigBee™)

The CC2530 Evaluation Module (EM) ([CC2530EMK](#)) is an add-on (plug-in) daughter card that can be purchased separately for ZigBee (IEEE Std 802.15.4) RF applications in the 2.4-GHz unlicensed ISM band. The communication interface to any host or application processor is by UART. The instantaneous power consumption is sent periodically to the ZigBee module for wireless transmission.

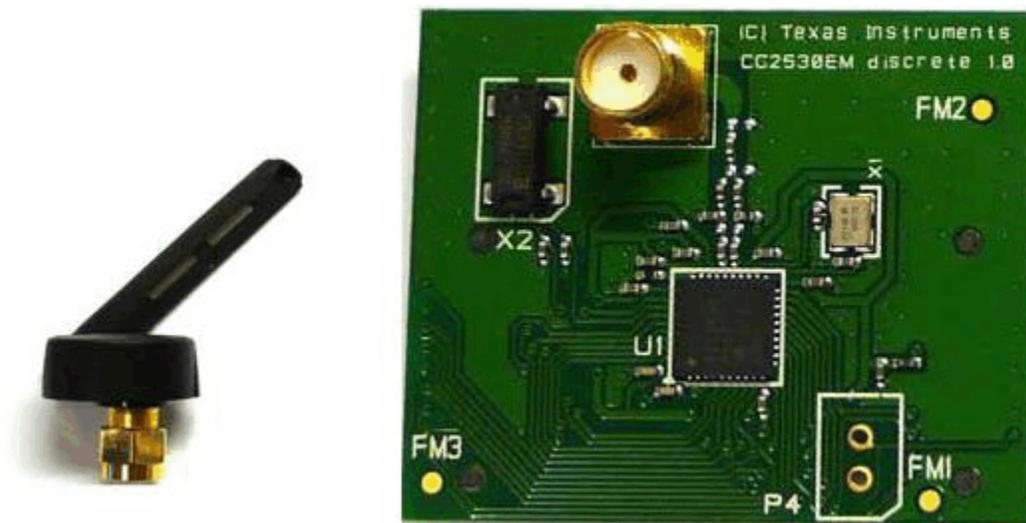


Figure 22. ZigBee Radio

This ZigBee module is connected by the UART, which is configured to 115.2 kbaud to the MSP430F67641 on the transmit portion and the MSP430F4618 on the receive portion (IHD430).

6.2.1 In-Home Display (IHD)

Most IHDs have their own setup mechanism and all of them tend to join the ZigBee network when they are turned on. In this section, it is assumed that TI's IHD430 (http://www.ti.com/tool/TIDM-LOWEND-IHD_) is used as the in-home display. The IHD430 has a MSP430F461x as an application and host processor.

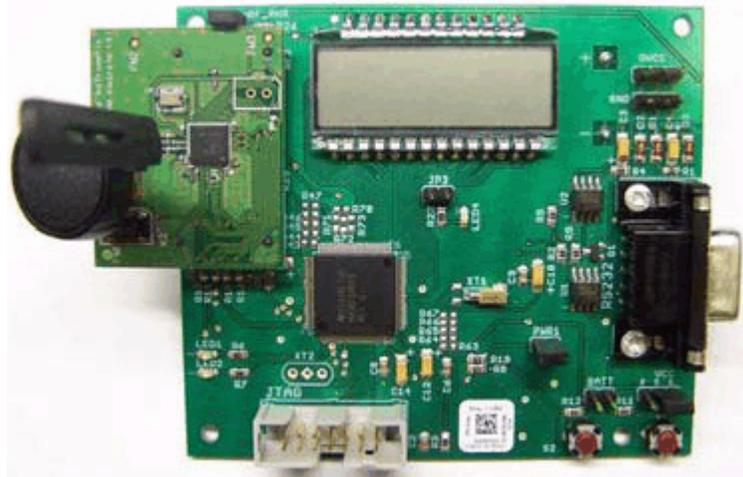


Figure 23. TI Designed IHD430

6.2.1.1 View cumulative three-phase active power readings on the IHD430

Place a CC2530 module in the RF connector socket of the meter (EVM430-F67641). Make sure that it is properly oriented. This CC2530 should be flashed with code to act as a transmitter. The IHD430 also has a corresponding CC2530 flashed to act as a receiver.

6.2.1.2 Initialize the IHD430

Power must be provided by two AAA batteries or by an external supply. The power source is selected by configuring jumpers on VCC and BATT headers and the power is supplied to the on-board MSP430 by placing a jumper on **PWR1** header. The power setup options are:

- Jumper settings to provide Battery power are:
 - Place a jumper on the BATT header.
 - Place a jumper on the PWR1 header.
- Jumper settings to provide Flash emulation tool power are:
 - Place a jumper on pins [1-2] on VCC 3-pin header.
 - Place a jumper on the PWR1 header.
- Jumper settings to provide External power are:
 - Place a jumper on pins [2-3] on the VCC 3-pin header.
 - Place a jumper on the PWR1 header.
- Place a jumper on the RF_PWR header, which enables or disables power to CC2530.

For the MSP430F67641 software to communicate the cumulative three-phase active power to the IHD430, the IHD430_SUPPORT macro must be defined in the emeter-template.h file. When this macro is enabled, the cumulate three-phase active power reading is sent to the on-board CC2530 transmitter via 8N1 UART communication at a rate of 115.2 kbaud. The CC2530 then sends the data to the CC2530 receiver. IHD430 receives the active power readings and displays them on the LCD. Note that the transmitter (meter) must be turned on before the receiver to ensure proper ZigBee communication. In addition, modifications can be made to MSP430F67641 software to send different parameters for display onto the IHD430.

6.3 Calibrate and View Results With a PC

6.3.1 GUI Execution

To run the GUI:

1. Connect the EVM to a PC via an RS-232 cable.
2. Open the /Source/GUI folder and open calibration-config.xml in a text editor.
3. Change the "port name" field within the "meter" tag to the COM port connected to the meter. In [Figure 24](#), 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 24. GUI Config File Changed to Communicate With Meter

4. Run calibrator.exe in the /Source/GUI folder. If the COM port in calibration-config.xml was changed in the previous step to the com port connected to the EVM, the GUI opens (see [Figure 25](#)).

If the GUI connects properly to the EVM, 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.

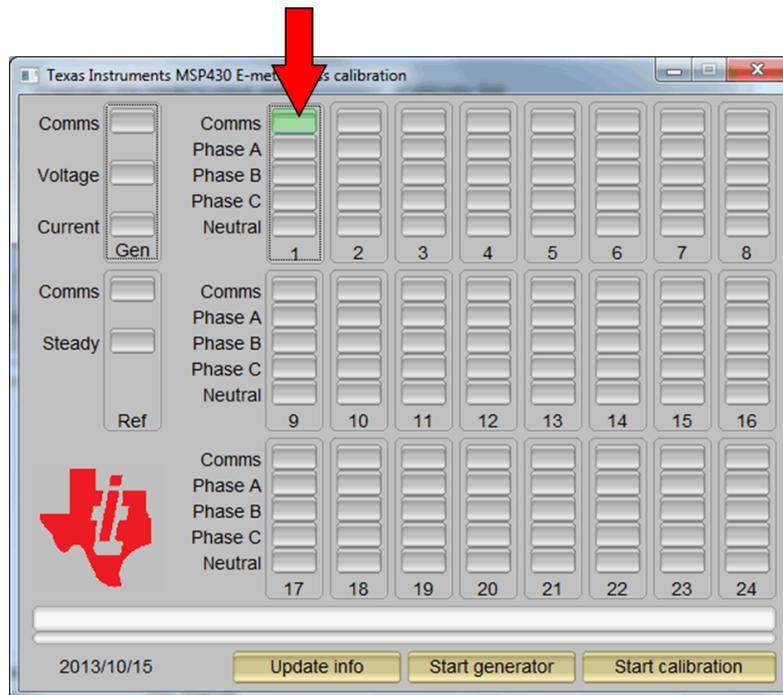


Figure 25. GUI Startup Window

6.3.2 View Results

When you click on the green button, the results window opens (see [Figure 26](#)). Note that there is a trailing "L" or "C" on the Power factor values to indicate an inductive or capacitive load, respectively.

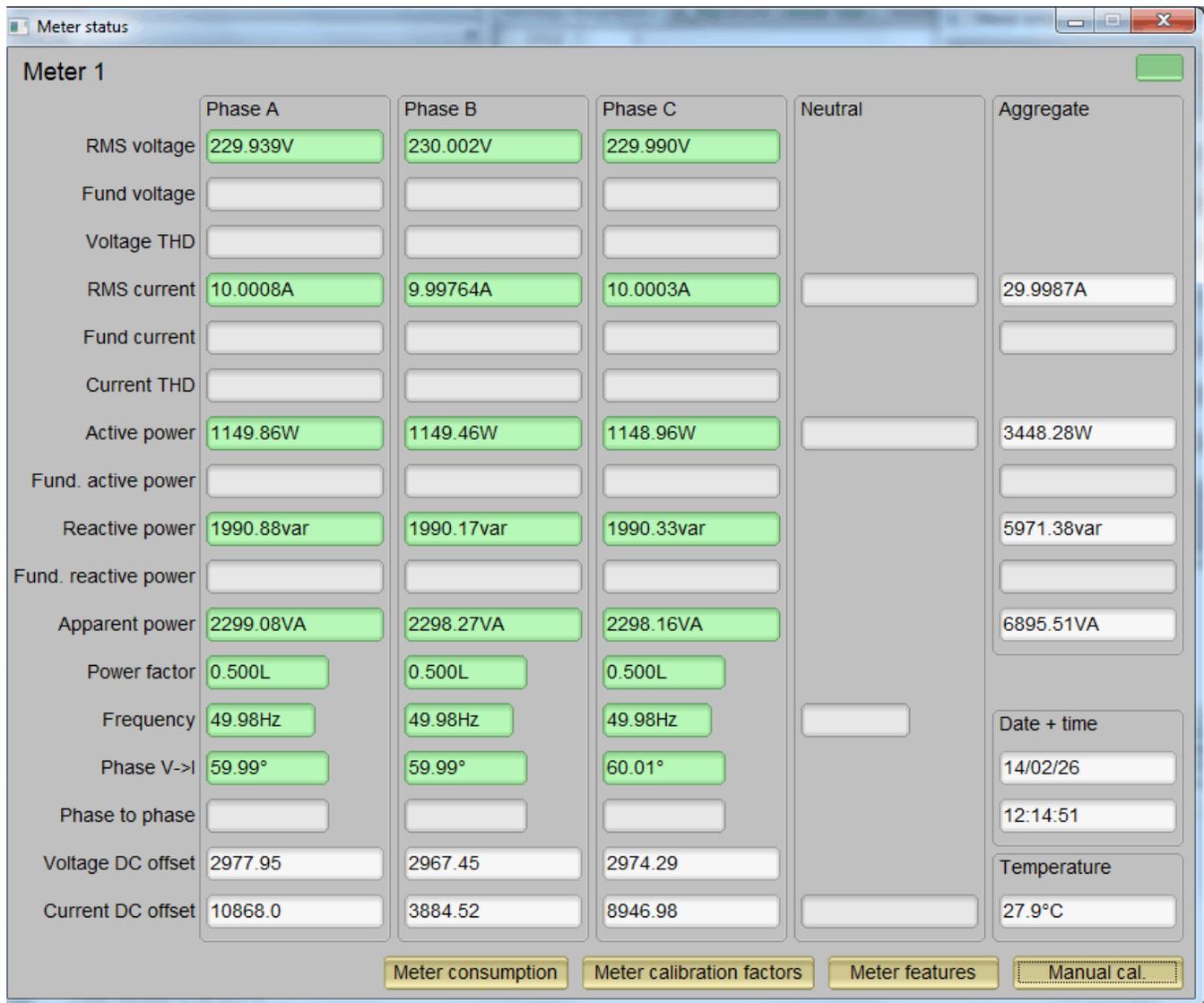


Figure 26. Results Window

From the results window, the total-energy consumption readings and sag/swell logs can be viewed by pressing the "Meter Consumption" button. When this button is pressed, the meter events and consumption window opens (see [Figure 27](#)).

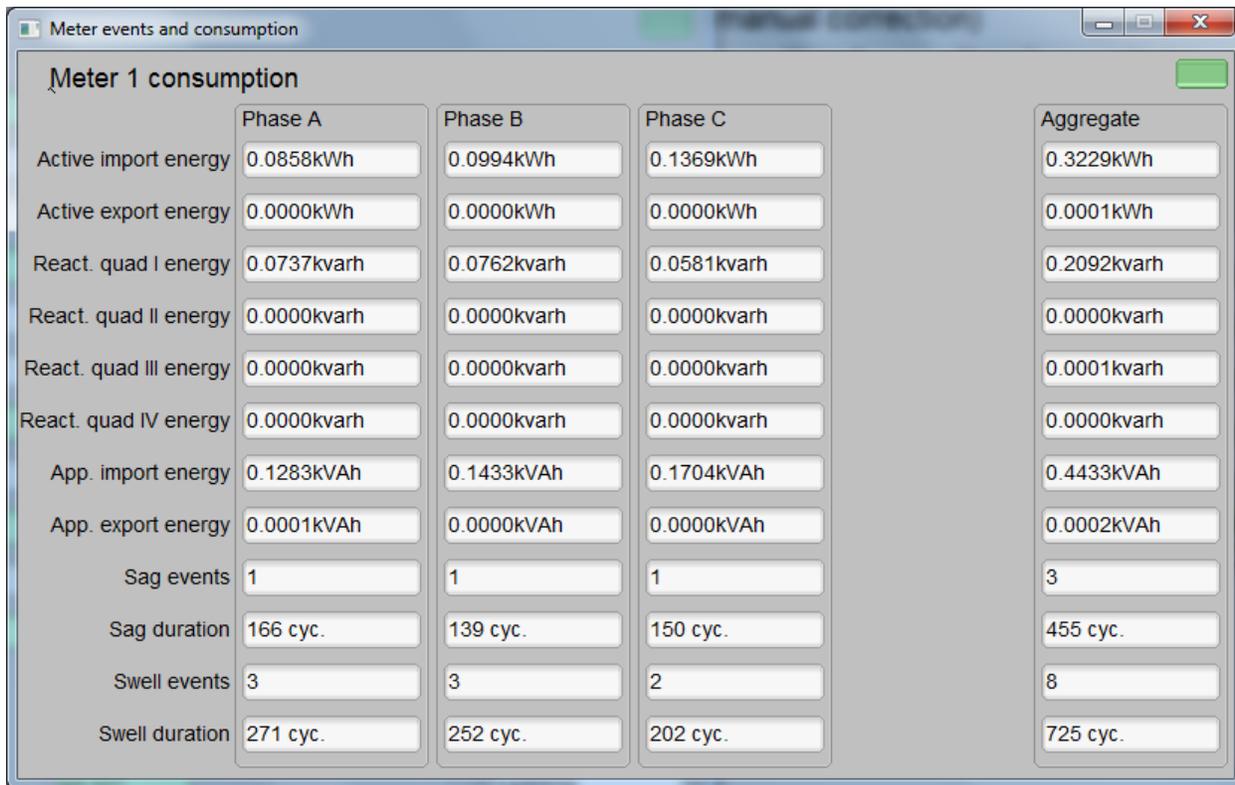


Figure 27. Meter Events and Consumption Window

6.3.3 Calibration

Calibration is key to any meter's performance, and it is absolutely necessary for every meter to go through this process. Initially, every meter exhibits different accuracies due to silicon-to-silicon differences, sensor accuracies, and other passive tolerances. To nullify the effects of these differences, every meter must be calibrated. For calibration to be performed accurately, an accurate AC test source and a reference meter must be available. The source should be able to generate any desired voltage, current, and phase shift (between V and I). To calculate errors in measurement, the reference meter acts as an interface between the source and the meter that is being calibrated. This section describes a simple and effective method of calibration of this three-phase EVM.

The GUI that is used for viewing results can also be used to calibrate the EVM. During calibration, parameters called calibration factors are modified in software to give least error in measurement. For this meter, there are six main calibration factors for each phase: voltage scaling factor, voltage AC offset, current scaling factor, current AC offset, 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 voltage AC offset and current AC offset are used to eliminate the effect of Additive White Gaussian Noise associated with each channel. This noise is orthogonal to everything except itself. As a result, it is present only when calculating RMS voltages and currents. The last calibration factor is the phase compensation factor, which is used to compensate any phase shifts introduced by the current sensors and other passives. 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 meter software is flashed with the code (available in the zip file), default calibration factors are loaded into these calibration factors (see Section 4.4.1 for the macros associated with each calibration factor). These values will be modified via the GUI during calibration. The calibration factors are stored in INFO_MEM, and therefore, would remain the same if the meter is restarted. However, if code is re-flashed during debug, the calibration factors will be replaced and the meter must be recalibrated. One way to save the calibration values is by clicking on the "Meter calibration factors" button shown in Figure 28. The meter

calibration factors window displays the latest values and this could be used to directly replace the macro definition of these factors in the source code. The "Voltage", "Voltage AC off", "Current", "Current AC offset", and "Active Power" calibration factors shown in the calibration factors window could be copied directly into the corresponding macros in the source code. However, for phase correction, a conversion must be made from microseconds to register units since the software's phase correction parameters are in units of modulation clock cycles instead of microseconds. To convert the value displayed by the GUI into a value that can be used by the associated macro in emeter-template, multiply the "Phase correction" variable on the GUI by 8.338608, round the resulting number to the nearest integer, and then right-shift by 3.

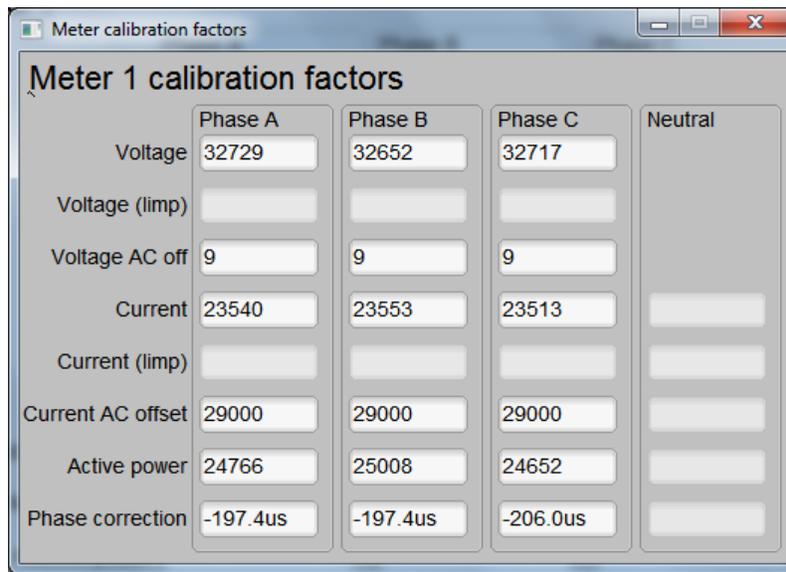


Figure 28. Calibration Factors Window

Calibrating any of the scaling factors is referred to as gain correction. Calibrating any of the phase compensation factors is referred to as phase correction. Calibrating the offset is referred to as offset calibration. For the entire calibration process, the AC test source must be on, meter connections must be made as shown in [Section 5.1.1](#), and the energy pulses must be connected to the reference meter.

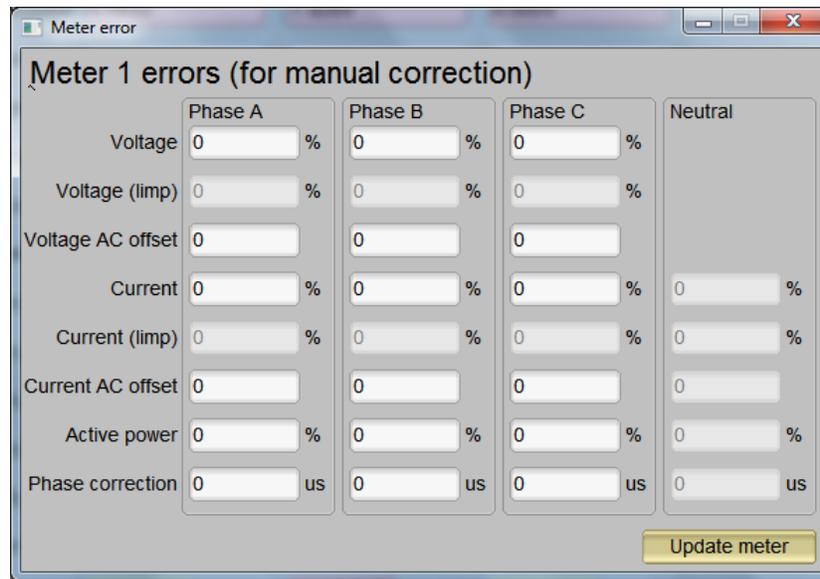
6.3.3.1 Gain Calibration

Usually gain correction for voltage and current can be done simultaneously for all phases. However, energy accuracy (%) from the reference meter for each individual phase is needed for gain correction for active power. Also, when performing active power calibration for any given phase, the other two phases must be turned off. Typically, switching off only the currents is good enough to disable a phase.

6.3.3.1.1 Voltage and Current Gain Calibration

To calibrate the voltage and current readings:

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's voltage and current. For example: 230V, 10A, 0° (PF = 1). Typically, these values are the same for every phase.
3. Click the Manual cal. button in the Results window (see [Figure 26](#)) to open the window shown in [Figure 29](#).



Meter 1 errors (for manual correction)

	Phase A	Phase B	Phase C	Neutral
Voltage	0 %	0 %	0 %	
Voltage (limp)	0 %	0 %	0 %	
Voltage AC offset	0	0	0	
Current	0 %	0 %	0 %	0 %
Current (limp)	0 %	0 %	0 %	0 %
Current AC offset	0	0	0	0
Active power	0 %	0 %	0 %	0 %
Phase correction	0 us	0 us	0 us	0 us

Update meter

Figure 29. Manual Calibration Window

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

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

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

- After calculating Correction(%) for all voltages and currents, input these values as is (\pm) for the fields "Voltage" and "Current" for the corresponding phases.
- Click Update meter and the observed values for the voltages and currents on the GUI settle to the desired voltages and currents.

6.3.3.1.2 Active Power Gain Calibration

Note that this example is for one phase. Repeat these steps for other phases.

After performing gain correction for voltage and current, gain correction for active power must be done. Gain correction for active power is different from voltage and current correction. Although, conceptually, calculating Correction(%) using Step 4 with Active power readings (displayed on the AC test source) can be done, it is not the most accurate method and should be avoided.

The best option to find the Correction(%) is directly from the reference meter's measurement error of the active power. This error is obtained by feeding energy pulses to the reference meter. This error must be recorded for each phase individually with the other phases disabled.

To perform active power calibration:

- Turn off the meter and connect the meter's energy pulse output to the reference meter. Configure the reference meter to measure the active power error based on these pulse inputs.
- Turn on the AC test source.
- Repeat Steps 1 to 3 from [Section 6.3.3.1.1](#) with the identical voltages, currents, and 0° phase shifts that were used for the voltage and current gain calibration.
- Disable the other phases that are not currently being calibrated by setting the current of these phases to 0 A.
- Obtain the % error in measurement from the reference meter. Note that this value may be negative.

6. Enter the error obtained in the above step into the "Active" field under the corresponding phase in the GUI window. This error is already the Correction(%) value and does not need to be calculated.
7. Click Update meter and the error values on the reference meter settle to a value close to zero.

6.3.3.2 Phase Correction

Note that this example is for a given phase. Repeat these steps for other phases.

After performing power gain correction, phase calibration must be performed. Similar to active power gain calibration, to perform phase correction on one phase, the other phases must be disabled. To perform phase correction calibration, perform the following steps:

1. If the AC test source has been turned OFF or reconfigured, perform steps 1-3 from the voltage and current gain section using the identical voltages and currents used in that section.
2. Disable all other phases that are not currently being calibrated by setting the current of these phases to 0 A.
3. Modify only the phase-shift of the calibrated phase to a non-zero value; typically, +60° is chosen. The reference meter will now display a different % error for active power measurement. Note that this value may be negative.
4. Using the % error readings provided by your reference meter (denoted as %_{error} below), the phase shift supplied by your source meter (denoted as φ_{desired} below), and the line frequency fed into the meter (denoted as f_{Mains} below), calculate the correction factor (in units of microseconds) by using the below equations. For these equations, note that φ_{desired} and φ_{error} must be in units of degrees while f_{Mains} must be in units of Hertz.

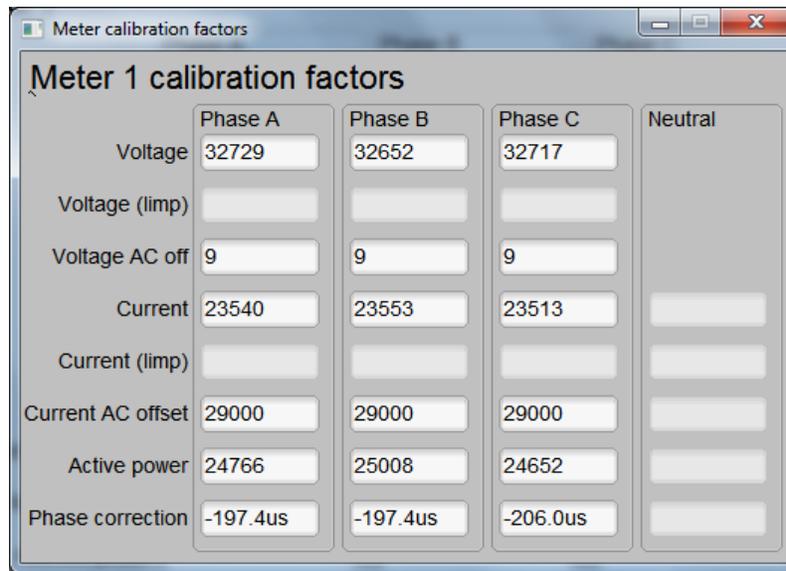
$$\varphi_{\text{error}} = \arccos\left(\left(\frac{\%_{\text{error}}}{100} + 1\right) * \cos(\varphi_{\text{desired}})\right) - \varphi_{\text{desired}}$$

$$\text{correction} = \frac{-\varphi_{\text{error}} \times 10^6}{f_{\text{Mains}} \times 360} \quad (12)$$

5. Enter the calculated correction into the "Phase" field for the phase that is being calibrated.
6. Click Update meter.
7. If this error is not close to zero, or is unacceptable, fine-tune the phase correction by following these steps:
 - (a) Enter a small value as an update for the "Phase" field for the phase that is being calibrated. Usually, a small positive or negative integer should be entered to bring the error close to zero. Additionally, for a phase shift greater than 0 (for example, +60°), a positive (negative) error would require a positive (negative) number as correction.
 - (b) Click Update meter and monitor the error values on the reference meter.
 - (c) If this measurement error (%) is not accurate enough, fine tune by incrementing or decrementing by a value of 1 based on Step 4a and 4b. Note: When the error is very close to zero, changing the fine-tuning value by 1 can result in the error oscillating on either side of zero. Select the value that has the smallest absolute error.
 - (d) Change the phase to -60° and check if this error is still acceptable. Ideally, errors should be symmetric for same phase shift on lag and lead conditions.

After performing phase correction, calibration is complete for one phase. **Note that the gain calibration and phase calibration are completed in sequence for each phase before moving on to other phases. These two procedures must be repeated for each phase, unlike voltage and current calibration.**

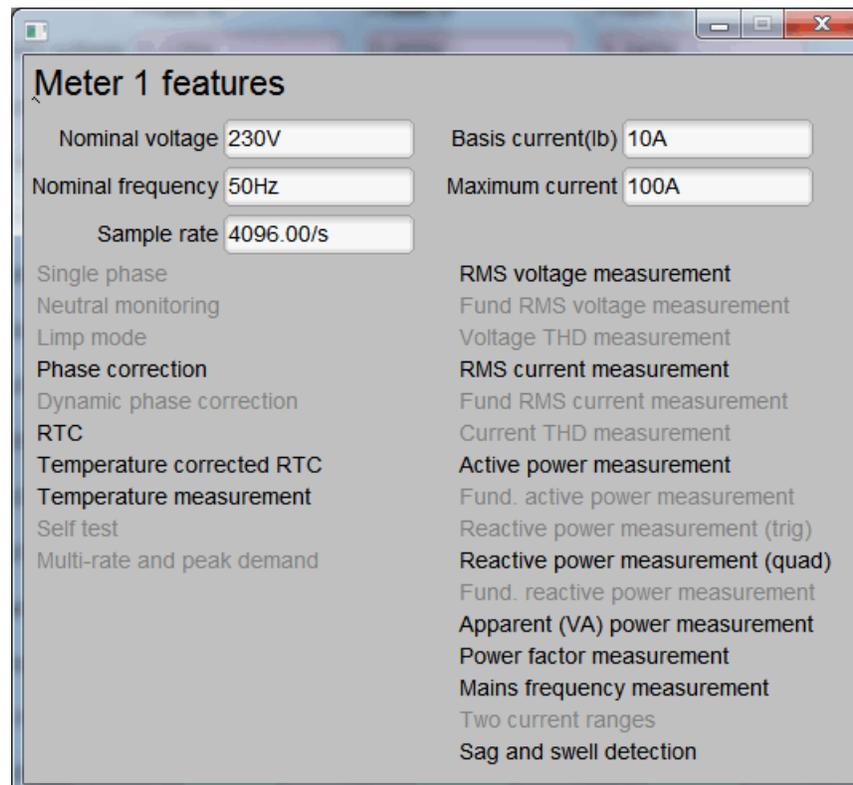
This completes calibration of voltage, current, and power for all three phases. View the new calibration factors by clicking the Meter Calibration factors button of the GUI metering results window (see [Figure 30](#)).



	Phase A	Phase B	Phase C	Neutral
Voltage	32729	32652	32717	
Voltage (limp)				
Voltage AC off	9	9	9	
Current	23540	23553	23513	
Current (limp)				
Current AC offset	29000	29000	29000	
Active power	24766	25008	24652	
Phase correction	-197.4us	-197.4us	-206.0us	

Figure 30. Calibration Factors Window

The configuration of the meter can also be viewed by clicking Meter features to open the screen shown in [Figure 31](#) (this is only an example).



Meter 1 features	
Nominal voltage	230V
Nominal frequency	50Hz
Sample rate	4096.00/s
Basis current(lb)	10A
Maximum current	100A
Single phase	RMS voltage measurement
Neutral monitoring	Fund RMS voltage measurement
Limp mode	Voltage THD measurement
Phase correction	RMS current measurement
Dynamic phase correction	Fund RMS current measurement
RTC	Current THD measurement
Temperature corrected RTC	Active power measurement
Temperature measurement	Fund. active power measurement
Self test	Reactive power measurement (trig)
Multi-rate and peak demand	Reactive power measurement (quad)
	Fund. reactive power measurement
	Apparent (VA) power measurement
	Power factor measurement
	Mains frequency measurement
	Two current ranges
	Sag and swell detection

Figure 31. Meter Features Window

6.3.4 Metrology Results

In this section, metrology results are shown for the cumulative three-phase active energy, cumulative three-phase reactive energy, and individual active energy. [Figure 32](#) shows the cumulative active energy results over a current dynamic range of 2000:1. [Table 3](#) shows the values for the error. Similarly, [Figure 33](#) shows the cumulative reactive energy results over a current dynamic range of 2000:1, and [Table 4](#) shows the values for the error.

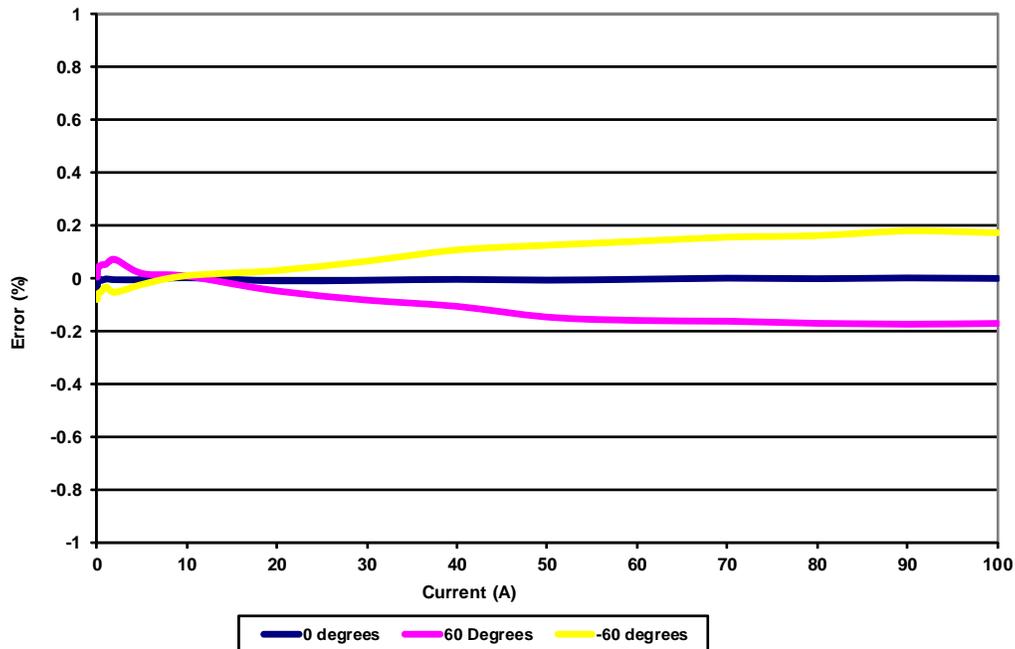


Figure 32. Cumulative Phase Active Energy Measurement Error

Table 3. Cumulative Phase Active Energy Measurement Error (%)

Current (A)	0°	60°	-60°
0.05	-0.04	0.005	-0.08
0.1	-0.004	0.043	-0.06
0.25	-0.003	0.044	-0.055
0.5	-0.008	0.051	-0.05
1	-0.002	0.053	-0.033
2	-0.00533	0.071667	-0.053
5	-0.00533	0.018333	-0.02333
10	0.002	0.008333	0.01
20	-0.00967	-0.048	0.029667
30	-0.00767	-0.08267	0.065
40	-0.004	-0.106	0.107667
50	-0.00733	-0.14667	0.125
60	-0.00367	-0.15967	0.14
70	0.000333	-0.16233	0.155667
80	-0.00133	-0.17033	0.161333
90	0.001333	-0.17367	0.179333
100	-0.00033	-0.17067	0.172

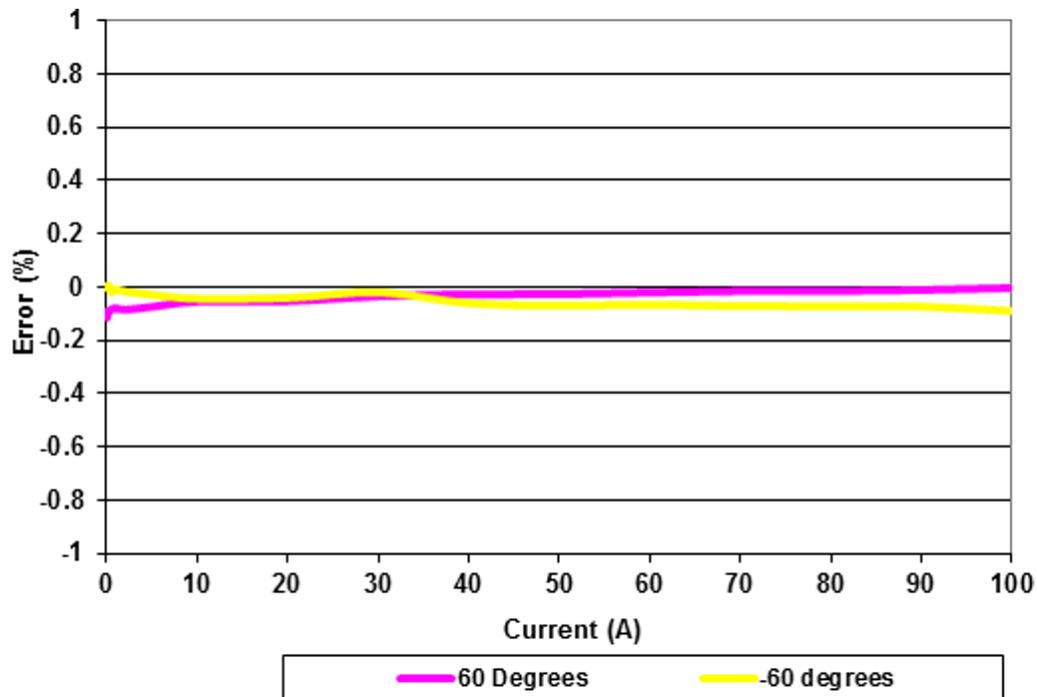


Figure 33. Cumulative Phase Reactive Energy Measurement Error

Table 4. Cumulative Phase Reactive Energy Measurement Error (%)

Current (A)	60°	-60°
0.05	-0.114	0.006
0.1	-0.089	-0.004
0.25	-0.0945	0.006
0.5	-0.083	-0.018
1	-0.079	-0.0085
2	-0.0845	-0.016
5	-0.0735	-0.028
10	-0.0545	-0.043
20	-0.0525	-0.04
30	-0.034	-0.019
40	-0.027	-0.06
50	-0.026	-0.069
60	-0.02	-0.0655
70	-0.0147	-0.0707
80	-0.0147	-0.0717
90	-0.0105	-0.0733
100	-0.003	-0.089

Figure 34, Figure 35, and Figure 36 show the active error over a current dynamic range of 2000:1 for phases A, B, and C, respectively. Table 5, Table 6, and Table 7 show the corresponding error for phases A, B, and C, respectively.

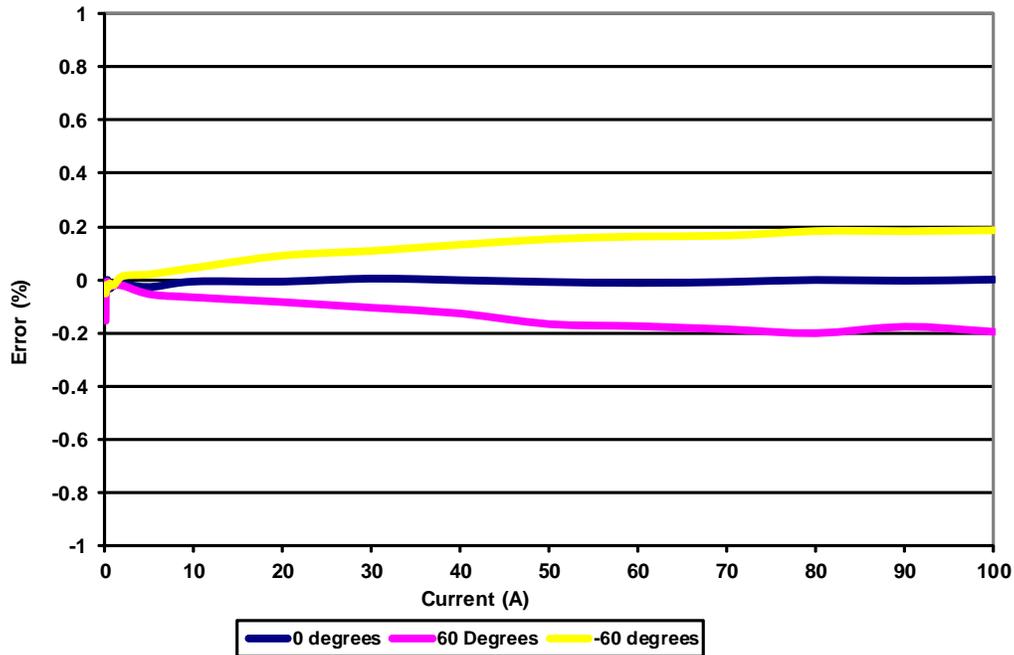
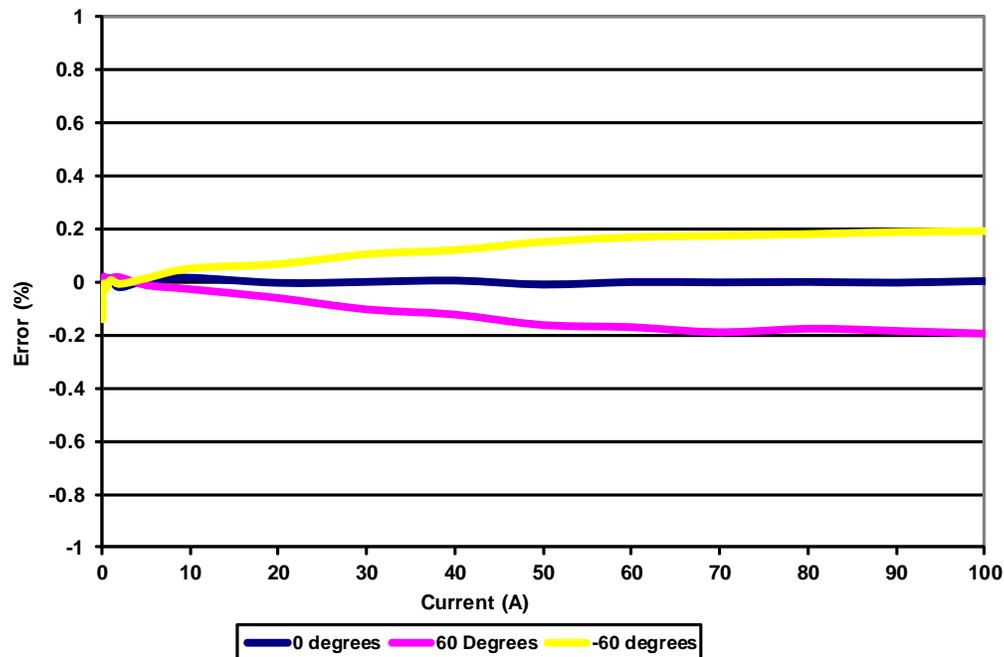


Figure 34. Phase A Active Energy Measurement Error

Table 5. Phase A Active Energy Measurement Error

Current (A)	0°	60°	-60°
0.05	-0.038	-0.153	-0.051
0.1	-0.019	-0.038	-0.019
0.25	0	-0.006	-0.032
0.5	-0.032	-0.025	-0.013
1	-0.019	-0.019	-0.019
2	-0.01467	-0.021	0.015
5	-0.02667	-0.05333	0.021333
10	-0.00567	-0.06533	0.045333
20	-0.00633	-0.083	0.091667
30	0.005333	-0.104	0.109333
40	-0.001	-0.12567	0.132667
50	-0.00767	-0.166	0.153667
60	-0.01133	-0.17367	0.163
70	-0.00767	-0.18533	0.166333
80	0	-0.2	0.183667
90	-0.003	-0.17533	0.183333
100	0.001667	-0.19467	0.186667


Figure 35. Phase B Active Energy Measurement Error
Table 6. Phase B Active Energy Measurement Error

Current (A)	0°	60°	-60°
0.05	-0.019	-0.038	-0.141
0.1	0.019	-0.019	-0.051
0.25	0	0.019	-0.006
0.5	0.007	0	-0.025
1	0.013	0.013	0.007
2	-0.021	0.017333	-0.00833
5	0.004333	-0.01267	0.013
10	0.015	-0.02767	0.050333
20	-0.00433	-0.06133	0.066667
30	-0.00067	-0.104	0.104
40	0.004667	-0.12333	0.119333
50	-0.01067	-0.163	0.150333
60	-0.00133	-0.171	0.167667
70	-0.00233	-0.19033	0.173333
80	-0.001	-0.17667	0.179333
90	-0.00333	-0.18533	0.187333
100	0.002667	-0.195	0.191

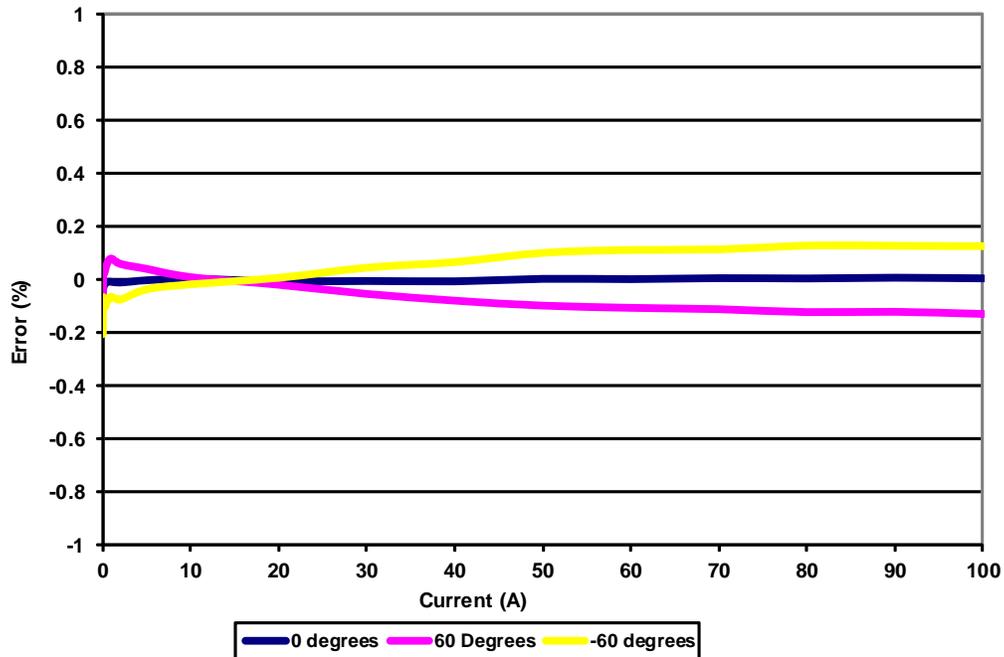


Figure 36. Phase C Active Energy Measurement Error

Table 7. Phase C Active Energy Measurement Error

Current (A)	0°	60°	-60°
0.05	-0.047	-0.072	-0.205
0.1	-0.032	0.02	-0.069
0.25	-0.015	0.028	-0.103
0.5	-0.008	0.058	-0.085
1	-0.008	0.08	-0.064
2	-0.011	0.059667	-0.075
5	-0.002	0.041	-0.03633
10	0.003	0.009667	-0.01767
20	-0.00633	-0.019	0.007
30	-0.005	-0.05333	0.045333
40	-0.00633	-0.07867	0.066333
50	0.003	-0.09767	0.101
60	0.002	-0.106	0.111667
70	0.005667	-0.11133	0.114
80	0.004667	-0.12233	0.128333
90	0.007333	-0.121	0.127667
100	0.005	-0.129	0.126

Figure 37 shows the cumulative active energy results when varying the 230-V nominal voltage by $\pm 10\%$ at different currents and power factors. Table 8 shows the corresponding error.

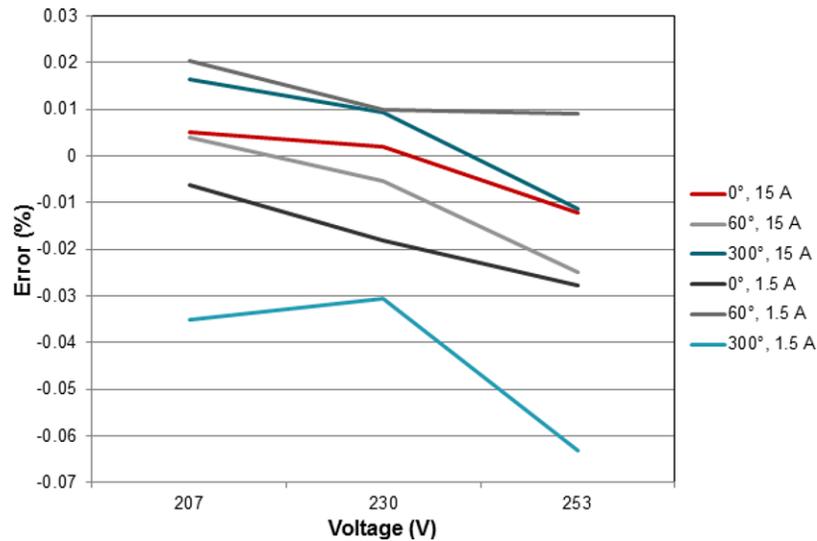


Figure 37. Cumulative Active Energy Measurement Error, $\pm 10\%$ Nominal Voltage

Table 8. Cumulative Active Energy Measurement Error, $\pm 10\%$ Nominal Voltage

Voltage (V)	0°, 15 A	60°, 15 A	300°, 15 A	0°, 1.5 A	60°, 1.5 A	300°, 1.5 A
207	0.005	0.004	0.0165	-0.0063	0.0205	-0.035
230	0.002	-0.0055	0.0095	-0.018	0.01	-0.0305
253	-0.0123	-0.025	-0.0113	-0.0277	0.009	-0.063

Figure 38 shows the active energy results from 100 V to 270 V, and Table 9 shows the corresponding errors. Note that no changes were made to the EVM to produce these results. Figure 39 shows the active energy results from 100 V to 320 V, and Table 10 shows its corresponding error.

In comparison to the results in Figure 38 and Table 9, the results for Figure 39 and Table 10 were generated with one change made to the hardware. Because 275-V varistors are used in the EVM's voltage front end, these varistors were removed to allow testing beyond 275 V. Other than removing these varistors, no other changes were made to the EVM for generating the results in Figure 39 and Table 10.

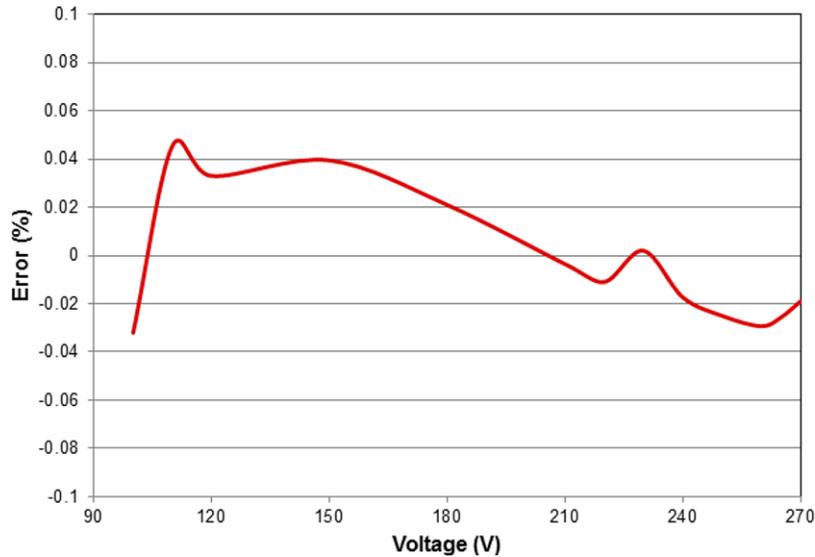


Figure 38. Cumulative Active Energy Measurement Error, 100 V to 270 V, No EVM Modifications

Table 9. Cumulative Active Energy Measurement Error, 100 V to 270 V, No EVM Modifications

Voltage (V)	Error (%)
100	-0.032
110	0.0455
120	0.033
150	0.0395
180	0.021
210	-0.0035
220	-0.011
230	0.002
240	-0.0173
250	-0.025
260	-0.0293
265	-0.0257
270	-0.019

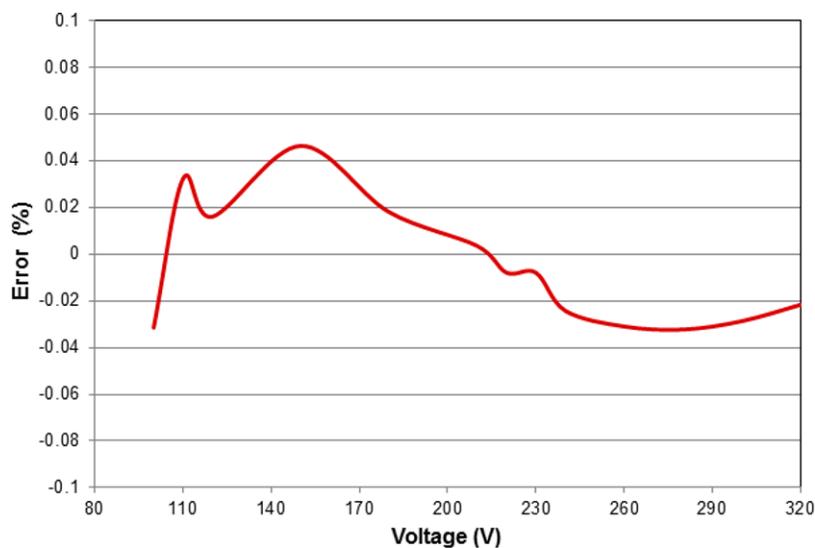
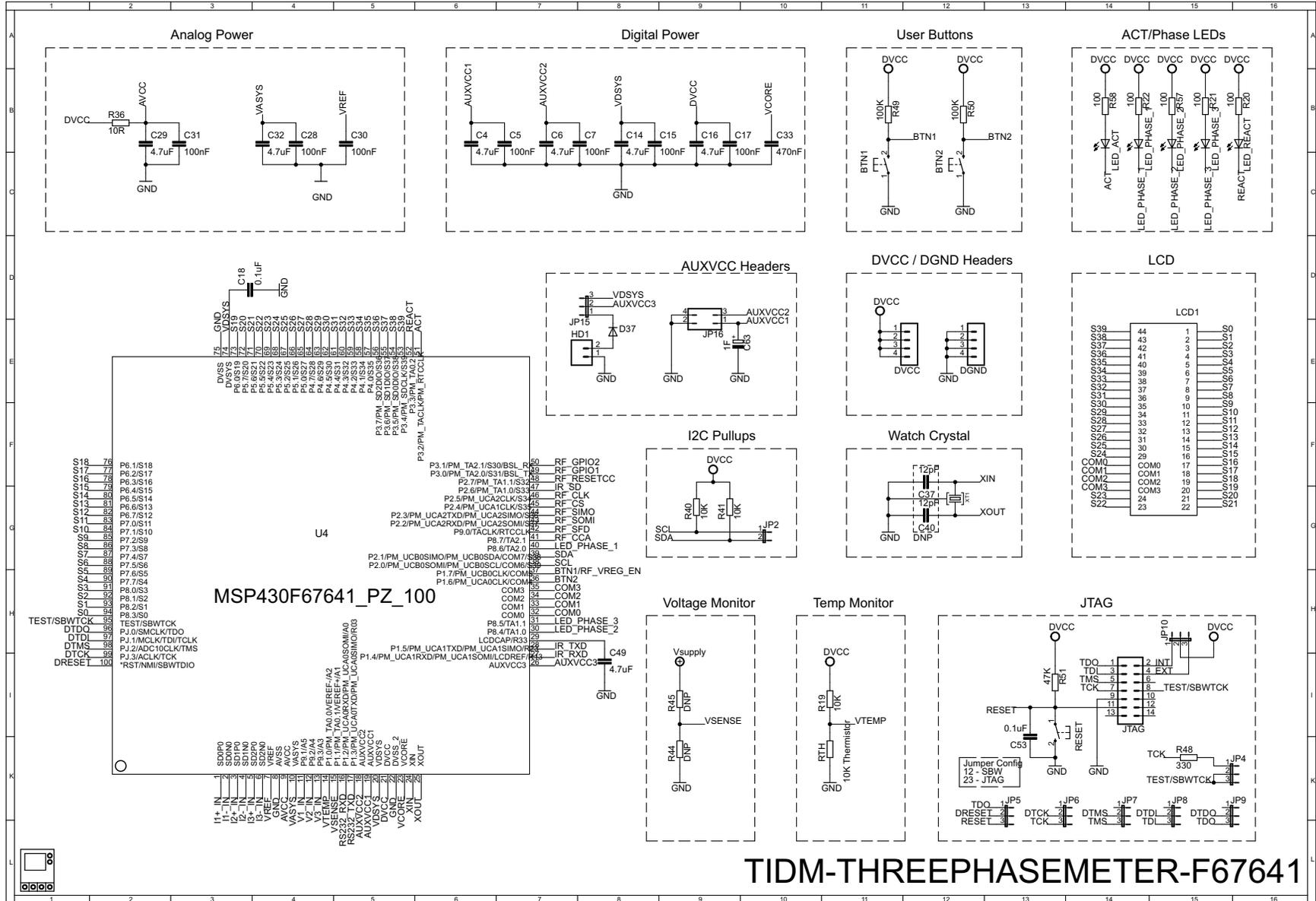


Figure 39. Cumulative Active Energy Measurement Error, 100 V to 320 V, Varistors Removed

Table 10. Cumulative Active Energy Measurement Error, 100 V to 320 V, Varistors Removed

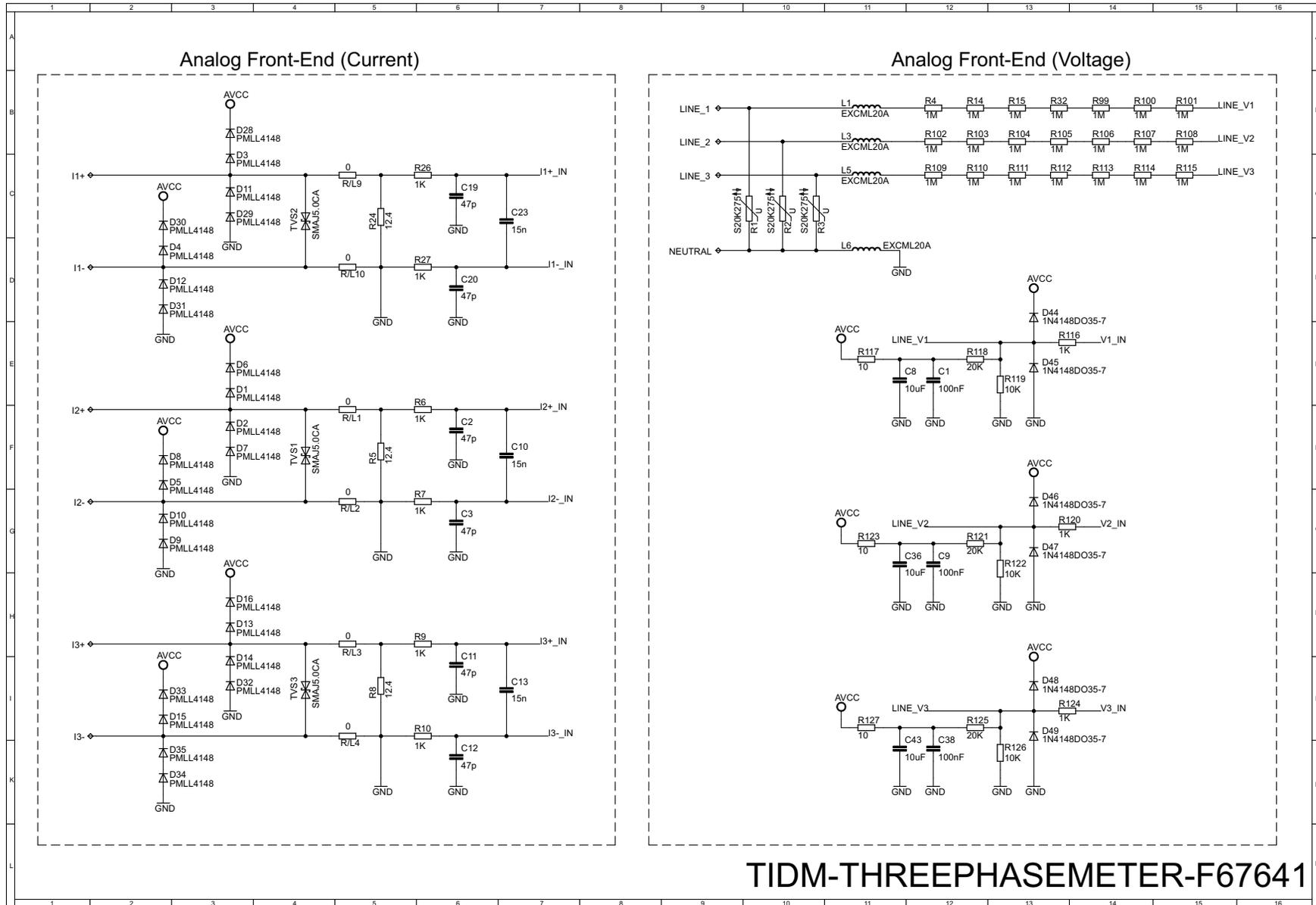
Voltage (V)	Error (%)
100	-0.0315
110	0.0323
120	0.016
150	0.0463
180	0.018
210	0.0035
220	-0.008
230	-0.008
240	-0.0243
260	-0.031
280	-0.0323
300	-0.0287
320	-0.0217

7 Schematics



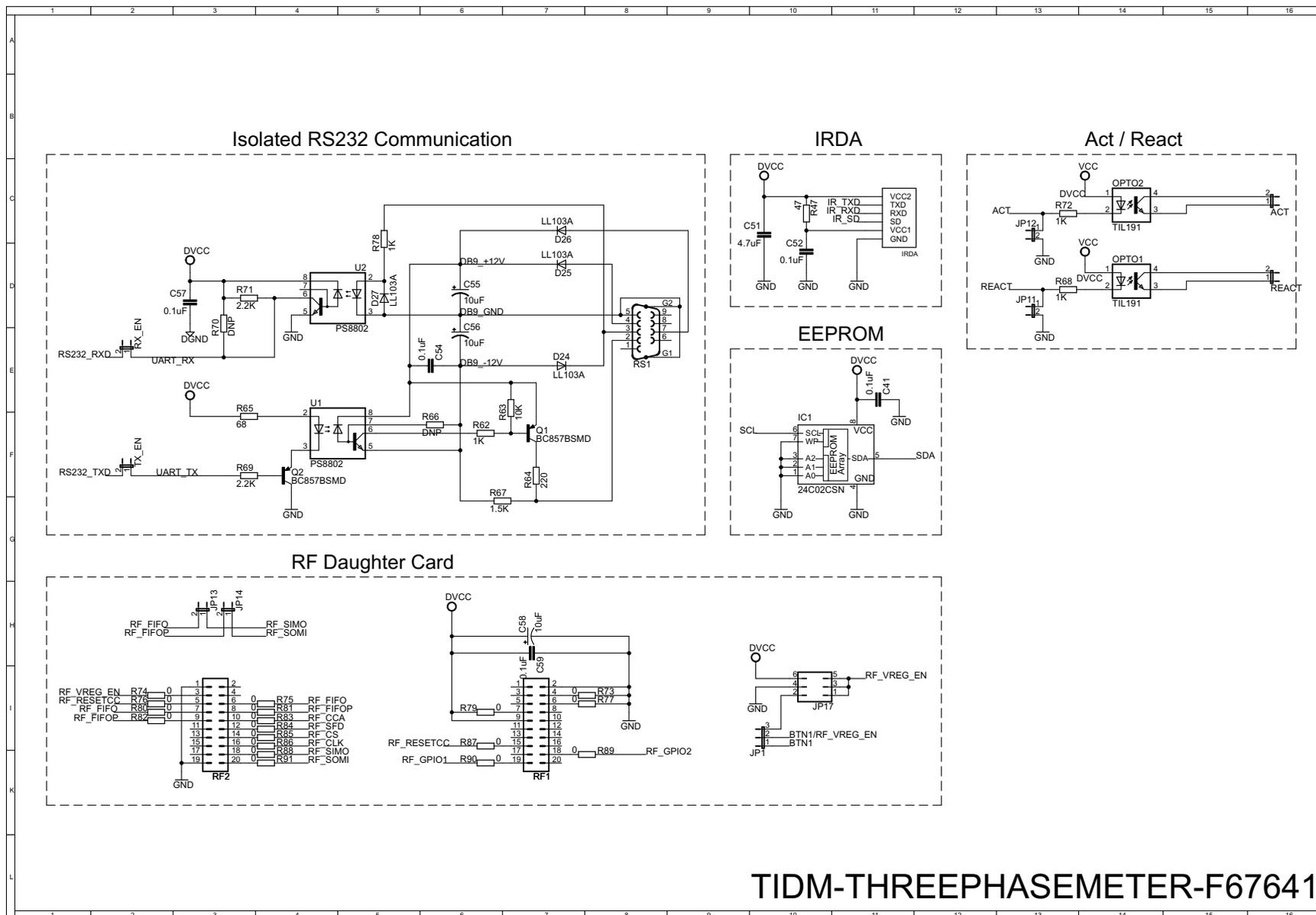
TIDM-THREEPHASEMETER-F67641

Figure 40. Schematics (1 of 4)



TIDM-THREEPHASEMETER-F67641

Figure 41. Schematics (2 of 4)



TIDM-THREEPHASEMETER-F67641

Figure 43. Schematics (4 of 4)

Revision History

Changes from B Revision (September 2014) to C Revision Page

- Updated links and descriptions for associated source code..... 1
 - Updated links to source code..... 3
-

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

General Texas Instruments High Voltage Evaluation (TI HV EVM) User Safety Guidelines



Always follow TI's setup and application instructions, including use of all interface components within their recommended electrical rated voltage and power limits. Always use electrical safety precautions to help ensure your personal safety and those working around you. Contact TI's Product Information Center <http://support/ti.com> for further information.

Save all warnings and instructions for future reference.

Failure to follow warnings and instructions may result in personal injury, property damage, or death due to electrical shock and burn hazards.

The term TI HV EVM refers to an electronic device typically provided as an open-framed unenclosed printed circuit board assembly. It is **intended strictly for use in development laboratory environments, solely for qualified professional users having training, expertise, and knowledge of electrical safety risks in development and application of high voltage electrical circuits. Any other use and/or application are strictly prohibited by Texas Instruments.** If you are not suitably qualified, you should immediately stop from further use of the HV EVM.

1. Work Area Safety

- (a) Keep work area clean and orderly.
- (b) Qualified observer(s) must be present anytime circuits are energized.
- (c) Effective barriers and signage must be present in the area where the TI HV EVM and its interface electronics are energized, indicating operation of accessible high voltages may be present, for the purpose of protecting inadvertent access.
- (d) All interface circuits, power supplies, evaluation modules, instruments, meters, scopes and other related apparatus used in a development environment exceeding 50Vrms/75VDC must be electrically located within a protected Emergency Power Off EPO protected power strip.
- (e) Use stable and nonconductive work surface.
- (f) Use adequately insulated clamps and wires to attach measurement probes and instruments. No freehand testing whenever possible.

2. Electrical Safety

As a precautionary measure, it is always a good engineering practice to assume that the entire EVM may have fully accessible and active high voltages.

- (a) De-energize the TI HV EVM and all its inputs, outputs and electrical loads before performing any electrical or other diagnostic measurements. Revalidate that TI HV EVM power has been safely de-energized.
- (b) With the EVM confirmed de-energized, proceed with required electrical circuit configurations, wiring, measurement equipment connection, and other application needs, while still assuming the EVM circuit and measuring instruments are electrically live.
- (c) After EVM readiness is complete, energize the EVM as intended.

WARNING: WHILE THE EVM IS ENERGIZED, NEVER TOUCH THE EVM OR ITS ELECTRICAL CIRCUITS AS THEY COULD BE AT HIGH VOLTAGES CAPABLE OF CAUSING ELECTRICAL SHOCK HAZARD.

3. Personal Safety

- (a) Wear personal protective equipment (for example, latex gloves or safety glasses with side shields) or protect the EVM in an adequate lucent plastic box with interlocks to protect from accidental touch.

Limitation for safe use:

EVMs are not to be used as all or part of a production unit.

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