

Implementation of a Three-Phase Electronic Watt-Hour Meter Using the MSP430F677x(A)

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ABSTRACT

This application report describes the implementation of a three-phase electronic electricity meter using the Texas Instruments MSP430F677x(A) metering processor. This application report includes the necessary information with regard to metrology software, hardware procedures for this single-chip implementation.

The MSP430F677x source code that is described in this application report can be downloaded from <http://www.ti.com/lit/zip/slaa577>.

The MSP430F677xA source code can be downloaded from <http://www.ti.com/tool/TIDM-THREEPHASEMETER-F6779>.

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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Trademarks

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1 Introduction

The MSP430F677x(A) devices are 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 F677x(A) has a powerful 25-MHz CPU with MSP430CPUX architecture. The analog front-end consists of up to seven independent 24-bit $\Sigma\Delta$ analog to digital converters (ADC) based on a second-order sigma-delta architecture that supports differential inputs. The sigma-delta ADCs (SD24_B) operate independently and are capable of 24-bit results. They can be grouped together for simultaneous sampling of voltages and currents on the same trigger. In addition, it also has an integrated gain stage to support gains up to 128 for amplification of low-output current sensors. 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 MSP430F677x-based software can be downloaded from <http://www.ti.com/lit/zip/slaa577>. The MSP430F677xA-based software can be downloaded from <http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD>.

2 System Diagrams

Figure 1 shows typical connections for one-phase electronic electricity (energy/e-) meters in real life applications. For poly-phase meters, the connection in **Figure 1** is duplicated for each phase. The ac voltages supported are 120 V/230 V at 50/60 Hz with the associated currents. The labels Line (L) and Neutral (N) are interchangeable and are indicative of ac mains voltage source from the energy utilities.

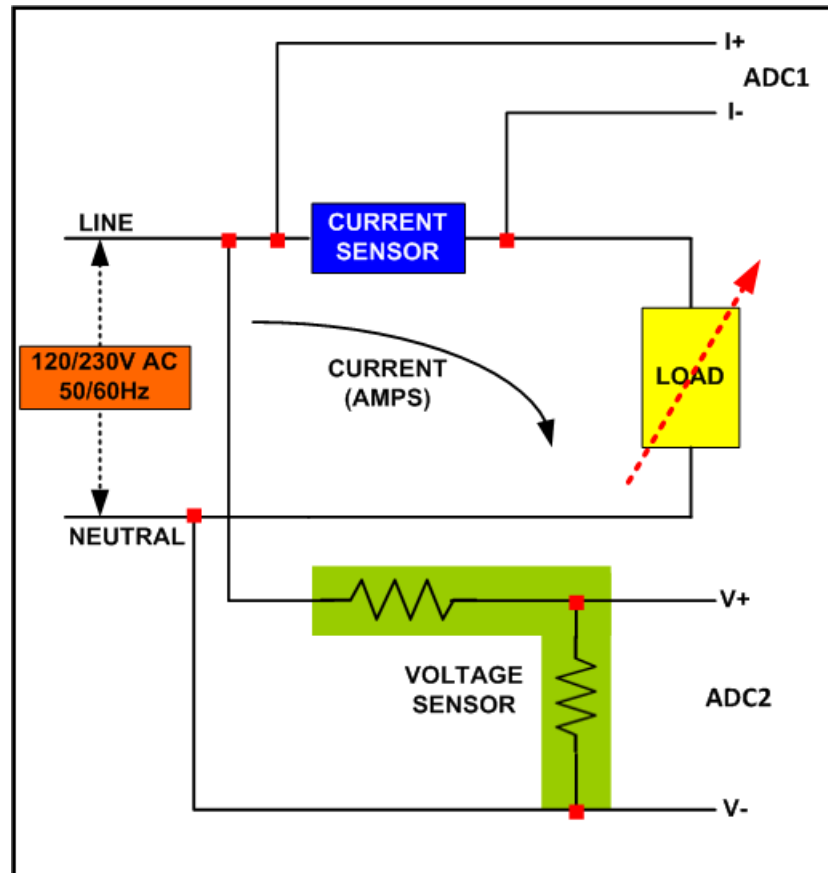


Figure 1. Typical Per-Phase Connections Inside an Electronic Meter

The following sections provide more information on the current and voltage sensors, ADCs, and other features.

Figure 2 shows a block diagram of the high level interface used for a three-phase energy meter application using the F677x(A). 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 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 $\Sigma\Delta 24$. See the *MSP430x5xx and MSP430x6xx Family User's Guide* (SLAU208) and the device-specific data sheet for these values.

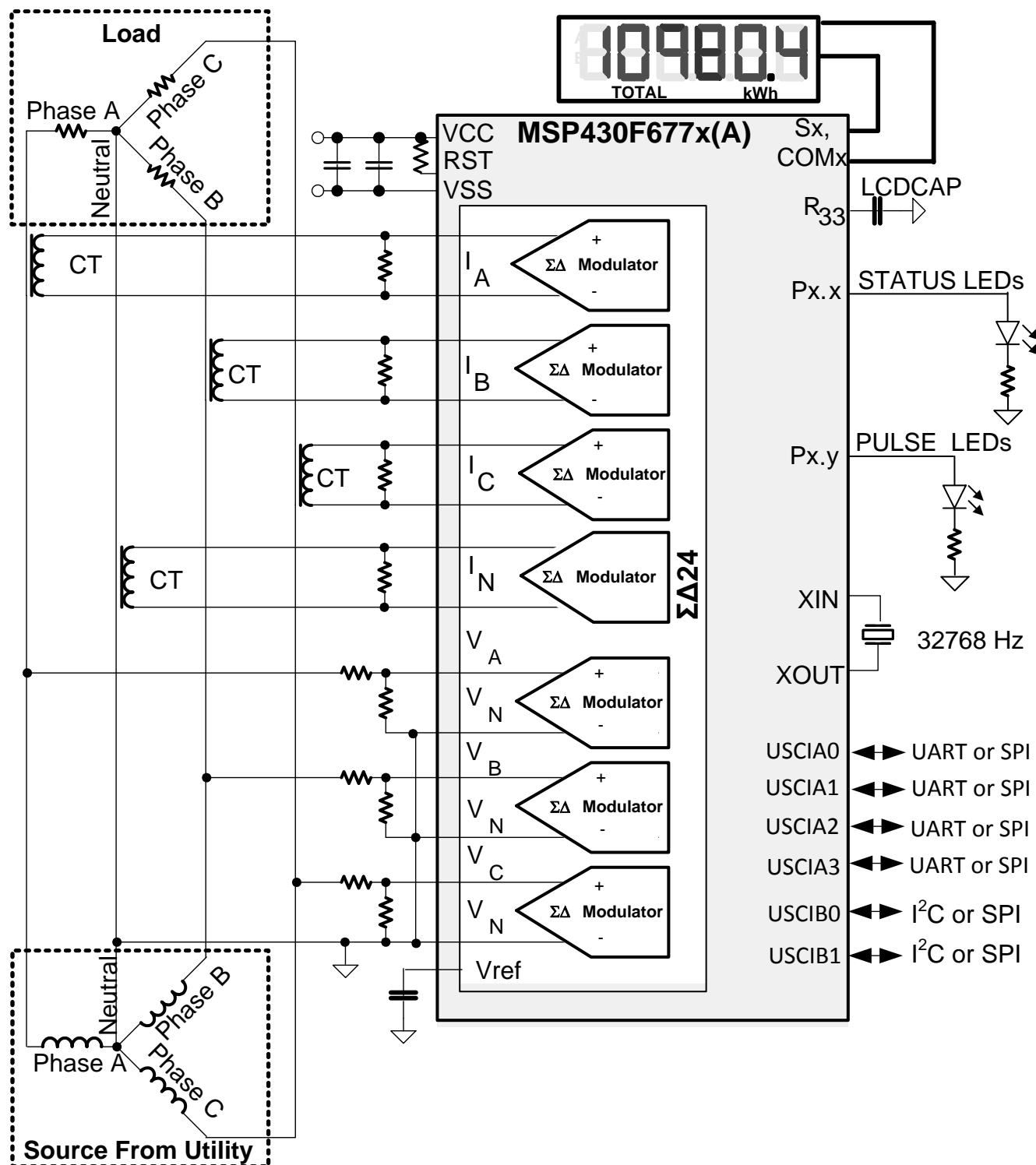


Figure 2. 3-Phase 4-Wire Star Connection Using MSP430F677x(A)

Other signals of interest in Figure 2 are the PULSE LEDs. They are used to transmit active and reactive energy pulses used for accuracy measurement and calibration. In addition, the pulses are used to transmit the active power consumed for each individual phase.

3 Hardware Implementation

This section describes the hardware for the design of a working 3-phase energy meter that uses the F677x(A).

3.1 Power Supply

The MSP430™ family of devices comprises ultralow-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 3 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.

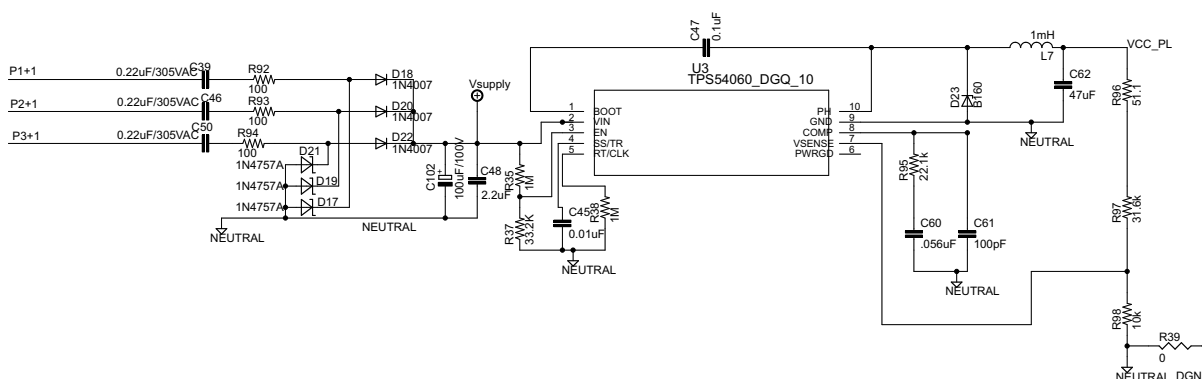


Figure 3. Simple Capacitive Power Supply for the MSP430 Energy Meter

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 4 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 pad LINE 3 on the hardware and P3+1 on the schematic. 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.

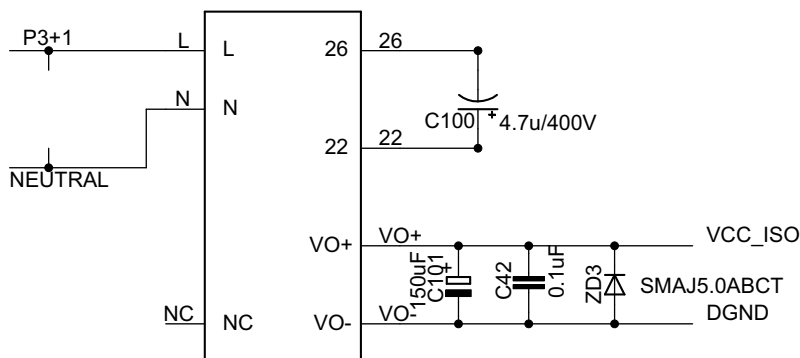


Figure 4. Switching-Based Power Supply for the MSP430 Energy Meter

3.2 Analog Inputs

The MSP430 analog front end, which consists of the $\Sigma\Delta$ ADC, is differential and requires that the input voltages at the pins do not exceed ± 930 mV (gain = 1). To meet this specification, the current and voltage inputs must be divided down. In addition, the $\Sigma\Delta 24$ allows a maximum negative voltage of -1 V. Therefore, ac signals from mains can be directly interfaced without the need for level shifters. This section describes 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 a range of 930 mV. The analog front end for voltage consists of spike protection varistors followed by a simple voltage divider and an RC low-pass filter that acts like an anti-alias filter.

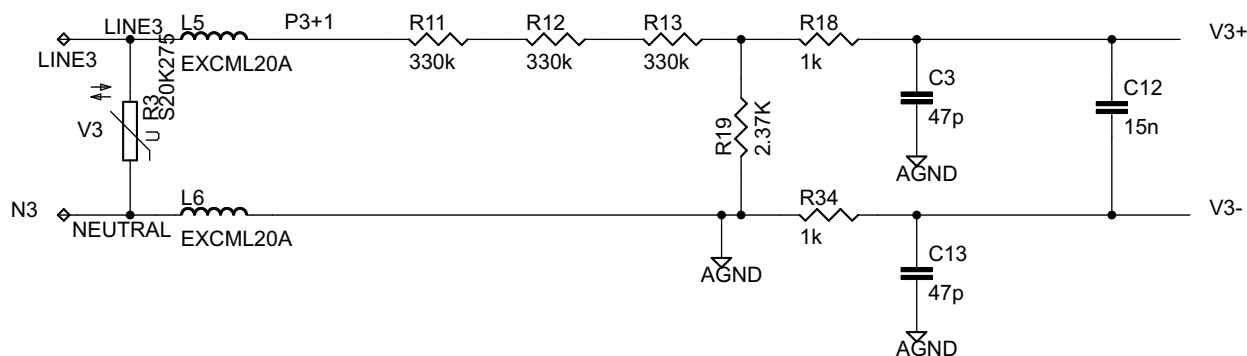


Figure 5. Analog Front End for Voltage Inputs

Figure 5 shows the analog front end for the voltage inputs for a mains voltage of 230 V. The voltage is brought down to approximately 549 mV RMS, which is 779 mV peak, and fed to the positive input. This voltage is within the MSP430 $\Sigma\Delta$ analog limits by a safety margin greater than 15%. This margin allows accurate measurements even during voltage spike conditions.

3.2.2 Current Inputs

The analog front-end for current inputs is slightly different from the analog front end for the voltage inputs. Figure 6 shows the analog front end used for a current channel.

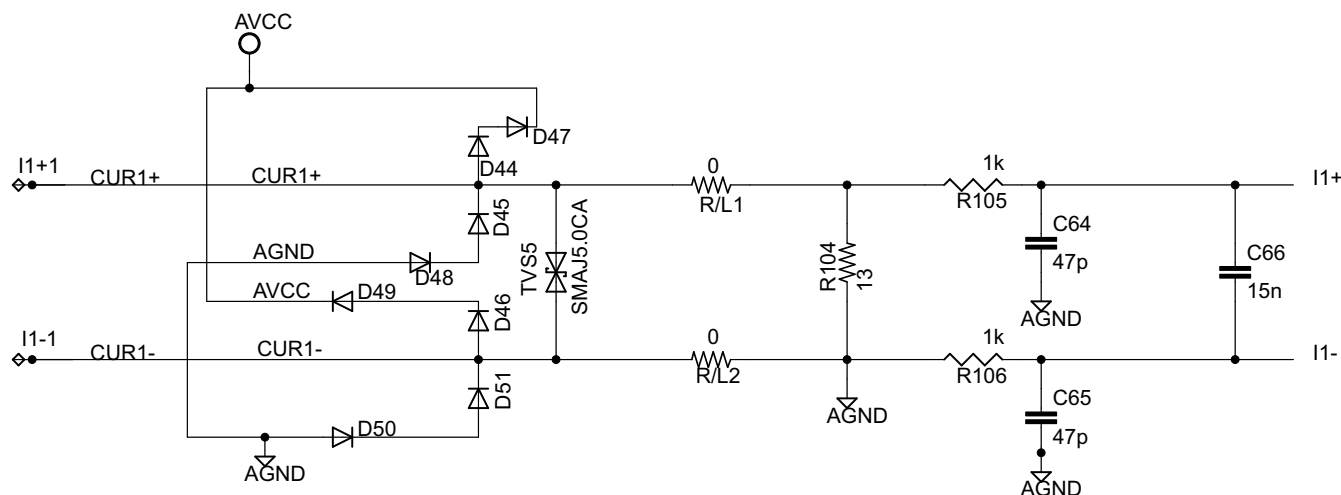


Figure 6. Analog Front End for Current Inputs

Resistor R104 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 approximately 13 Ω . The antialiasing circuitry, which consists of resistors and capacitors, follows the burden resistor. The input signal to the converter is a fully differential input with a voltage swing of ± 919 mV maximum when the gain of the converter is set to 1.

4 Software Implementation

The software for the implementation of 3-phase metrology is described in this section. The [Section 4.1](#) describes the setup of various peripherals of the MSP430. Next, the entire metrology software is described as two major processes: the foreground process (see [Section 4.2](#)) and background process (see [Section 4.3](#)).

4.1 Peripherals Setup

The major peripherals are the 24-bit sigma delta (SD24_B) ADC, clock system, timer, LCD, and watchdog timer (WDT).

4.1.1 $\Sigma\Delta 24$ Setup

The F677x(A) family has up to seven independent sigma delta data converters. For a three-phase system, at least six $\Sigma\Delta$ s are necessary to independently measure three voltages and currents. The code that accompanies this application report is designed for the metrology of a 3-phase system with limited anti-tampering features. However, the code supports the measurement of the neutral current. The clock to the $\Sigma\Delta 24$ (f_M) is derived from system clock, which is configured to run at 16 MHz. The sampling frequency is defined as $f_s = f_M / \text{OSR}$, the OSR is chosen to be 256 and the modulation frequency f_M , is chosen as 1.048576 MHz, resulting in a sampling frequency of 4.096 ksp/s. The $\Sigma\Delta 24$ s are configured to generate regular interrupts every sampling instance.

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

- A0.0+ and A0.0- \rightarrow Voltage V1
- A1.0+ and A1.0- \rightarrow Voltage V2
- A2.0+ and A2.0- \rightarrow Voltage V3
- A4.0+ and A4.0- \rightarrow Current I1
- A5.0+ and A5.0- \rightarrow Current I2
- A6.0+ and A6.0- \rightarrow Current I3

Optional neutral channel can be processed via channel A3.0+ and A3.0-.

4.1.2 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.

4.1.3 LCD Controller

The LCD controller on the MSP430F677x(A) 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 ACLK/64, which is 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 7](#) shows the flowchart for this process

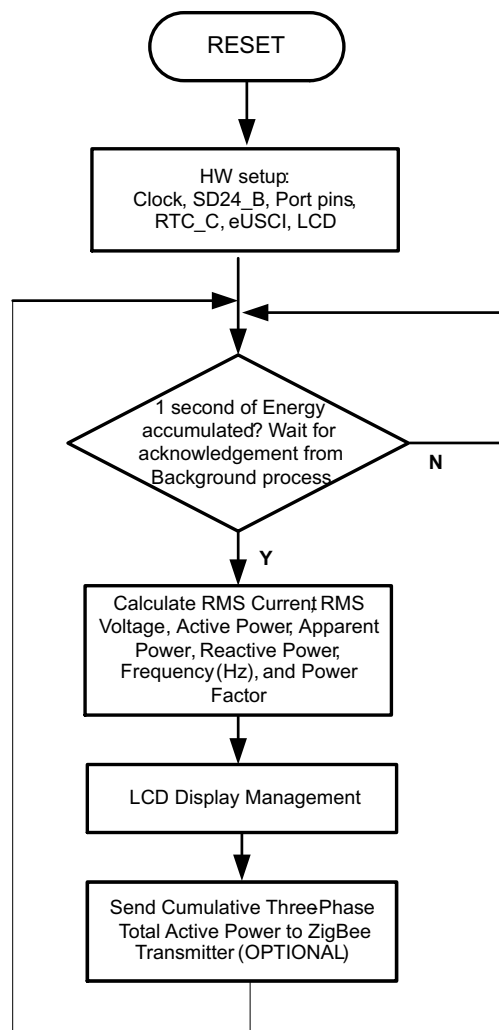


Figure 7. Foreground Process

The initialization routines involve the setup of the analog to digital converter, clock 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_A3 is configured.

After the hardware is setup, the foreground process waits for the background process to notify it to calculate new metering parameters. This notification is done through a status flag every time a frame of data is available for processing. The data frame consists of processed current, voltage, active energy, and reactive energy accumulated for one second. 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 set of data samples consists of processed current, voltage, active energy, and reactive energy. Processed voltages are accumulated in 48-bit registers. In contrast, processed currents, active energies, and reactive energies 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](#).

4.2.1 Computation Formulas

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

4.2.1.1 Voltage and Current

As described in the previous sections, simultaneous voltage and current samples are obtained from seven independent $\Sigma\Delta$ converters at a sampling rate of 4096 Hz. All of the samples that are taken in 1 second are kept and used to obtain the RMS values for voltage and current for each phase. The RMS values are obtained by the following formulas:

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

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

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

$i_{ph}(n)$ = Each current sample at a sample instant n

Sample count = Number of samples in one second

$K_{v,ph}$ = Scaling factor for voltage

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

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](#).

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

$$P_{REACT,ph} = K_{REACT,ph} \frac{\sum_{n=1}^{Sample\ count} v_{90}(n) \times i_{ph}(n)}{Sample\ count} \quad (2)$$

Where,

$v_{90,ph}(n)$ = Voltage sample at a sample instant n shifted by 90 degrees, and

$K_{ACT,ph}$ = Scaling factor for active power

$K_{REACT,ph}$ = Scaling factor for reactive power

Active energy is calculated from the active power by [Equation 3](#).

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

$$E_{REACT,ph} = P_{REACT,ph} \times SampleCount \quad (3)$$

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

1. It allows accurate measurement of the reactive power for very small currents.
2. 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 4.3.3](#)).

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:

$$P_{APP,ph} = \sqrt{P_{ACT,ph}^2 + P_{REACT,ph}^2} \quad (4)$$

In addition to calculating the per-phase active and reactive power and energy, the cumulative sum of these parameters are calculated by .

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

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

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

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

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 5](#).

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

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 and a negative power factor corresponds to an inductive load. The sign of the internal representation of power factor is determined by whether the current leads or lags voltage, which is determined in the background process. Therefore, the internal representation of power factor is calculated by the following formula:

$$\text{Internal Representation of Power Factor} = \begin{cases} \frac{P_{Act}}{P_{Apparent}}, & \text{if capacitive load} \\ -\frac{P_{Act}}{P_{Apparent}}, & \text{if inductive load} \end{cases} \quad (6)$$

4.3 Background Process

The background process uses the $\Sigma\Delta$ interrupt as a trigger to collect voltage and current samples (seven values in total). These samples are used to calculate intermediate results. 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.

The background function deals mainly with timing critical events in software. After sufficient samples (approximately one second's worth) have been accumulated, then the foreground function is triggered to calculate the final values of V_{RMS} , I_{RMS} , active, reactive, and apparent powers, active, reactive, and apparent energy, frequency, and power factor. The background process is also wholly responsible for the calculation of energy proportional pulses, frequency (in samples/cycle), and determining current lead and lag conditions. [Figure 8](#) shows the flow diagram of the background process.

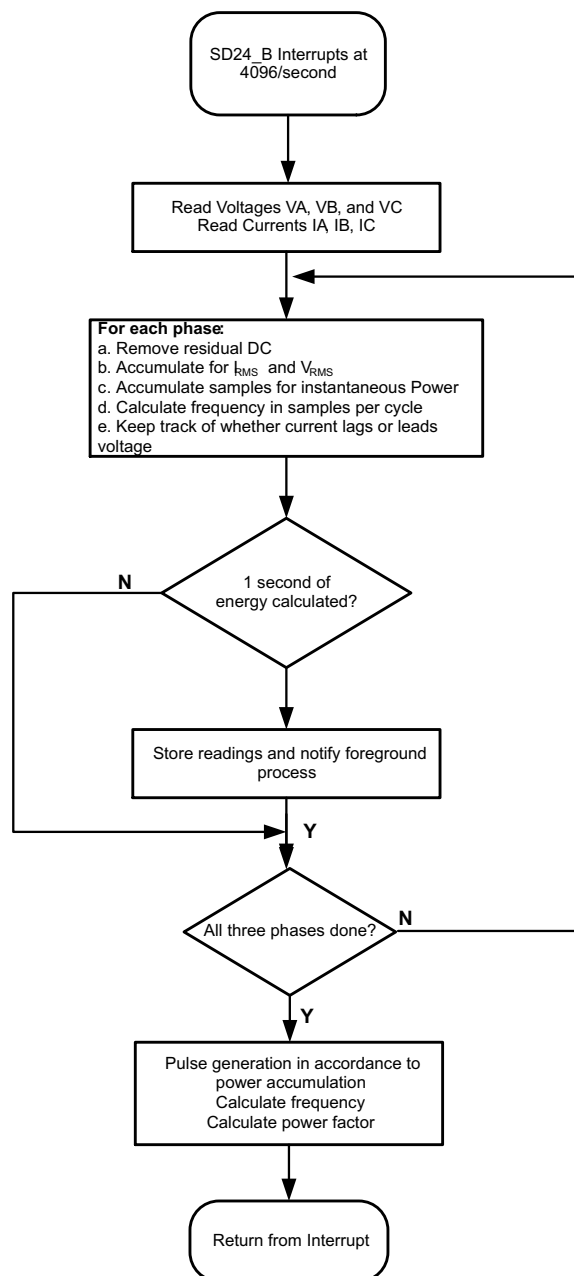


Figure 8. Background Process

The following sections describe the various elements of electricity measurement in the background process.

4.3.1 Voltage and Current Signals

The $\Sigma\Delta$ converter has fully differential input architecture and each $\Sigma\Delta$ pin can accept negative inputs; therefore, no level-shifting is necessary for the incoming ac voltage (unlike single-ended or pseudo-differential converters).

The output of each $\Sigma\Delta$ is a signed integer and any stray dc or offset value on these $\Sigma\Delta$ s 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 results:

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

These accumulated values are processed by the foreground process.

4.3.2 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. The relative phase shift between voltage and current samples must be compensated to ensure accurate measurements. The $\Sigma\Delta$ converters have programmable delay registers ($\Sigma\Delta 24PREx$) that can be applied to a particular channel. This built-in feature (PRELOAD) is used to provide the phase compensation required. Figure 9 shows the use of PRELOAD to delay sampling on a particular channel.

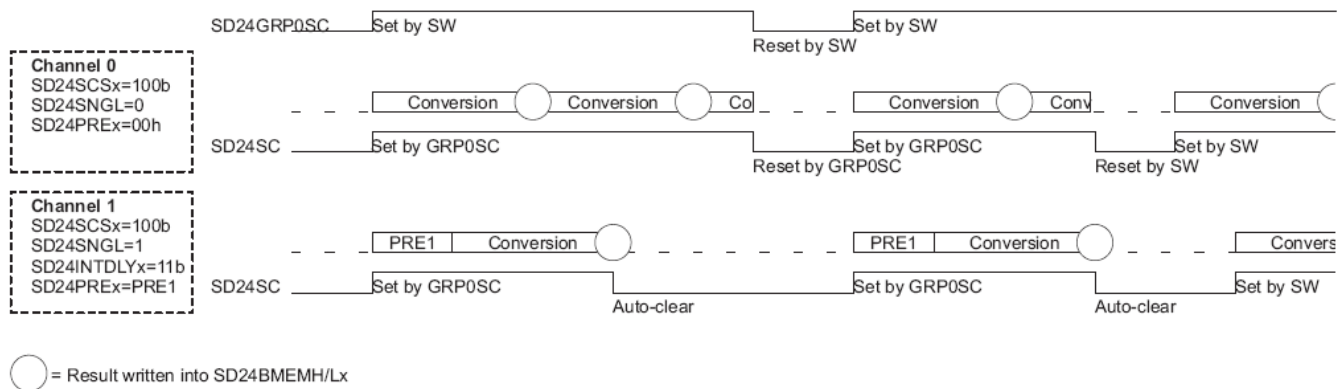


Figure 9. Phase Compensation Using PRELOAD Register

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

$$\text{Delay resolution}_{Deg} = \frac{360^\circ \times f_{IN}}{OSR \times f_S} = \frac{360^\circ \times f_{IN}}{f_M} \quad (7)$$

In this application, for input frequency of 60 Hz, OSR of 256, and sampling frequency of 4096, the resolution for every bit in the preload register is approximately 0.02° with a maximum of 5.25° (maximum of 255 steps). Because the sampling of the seven channels are group triggered, a commonly used method is to apply 128 steps of delay to all channels and then increase or decrease from this base value. This allows adding or subtracting a delay time to compensate for phase lead or lag. This puts the practical limit in the current design to $\pm 2.62^\circ$. 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.

4.3.3 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 stores these accumulation registers and notifies the foreground process to produce the average results such as RMS and power values. Cycle boundaries are used to trigger the foreground averaging process 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.

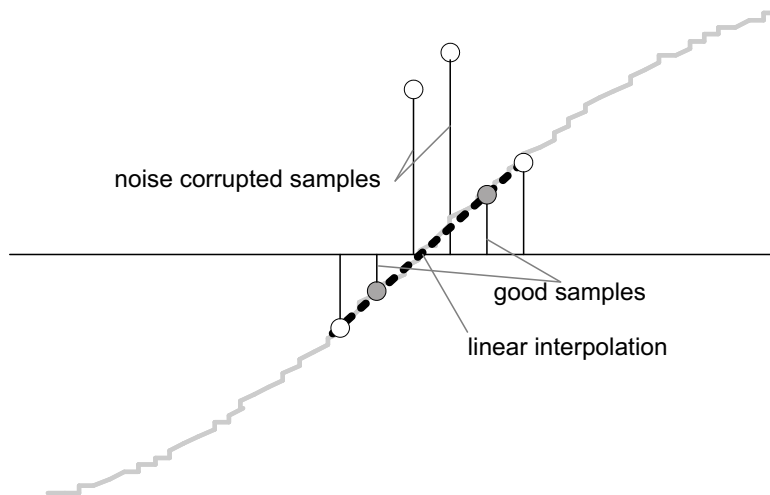


Figure 10. Frequency Measurement

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.

4.3.4 LED Pulse Generation

In electricity meters, the 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 6400 for active and reactive energies. The energy "tick" in this case is 1 kWh/6400. 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 LED1, LED2, LED3, and LED_ACT correspond to the active energy consumption for phase A, phase B, phase C, and the cumulative three-phase sum, respectively. LED_REACT 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.

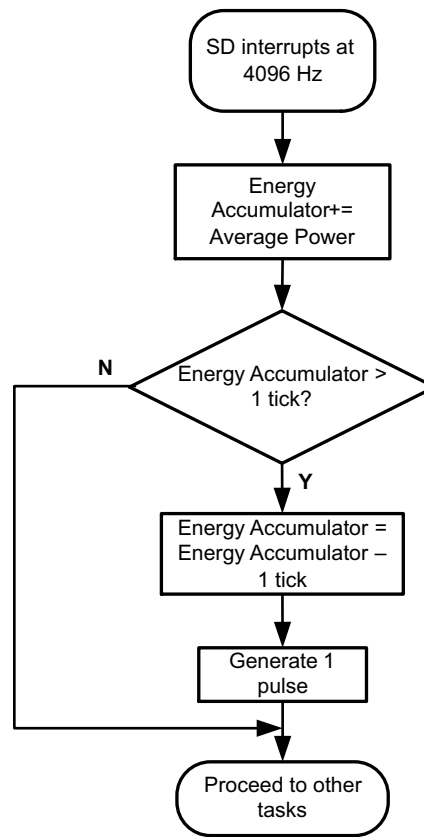


Figure 11. Pulse Generation for Energy Indication

The average power is in units of 0.01 W and the 1 kWh threshold is defined as:

$$\begin{aligned}
 1 \text{ kWh threshold} &= (1 / 0.01) \times 1 \text{ kW} \times (\text{number of interrupts per second}) \times (\text{number of seconds in one hour}) \\
 &= 100000 \times 4096 \times 3600 = 0x15752A00000
 \end{aligned}$$

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 file that needs modification is `emeter-3ph-neutral-6779(A).h`, which is in the parent directory `emeter-ng`. This file includes macro definitions that are used during the normal operation of the meter.

1. **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](#).
2. **SERIAL_CALIBRATION_SUPPORT**: This macro allows the meter to be calibrated using the GUI provided and RS-232 interface to the PC.
3. **MAINS_FREQUENCY_SUPPORT**: The macro configures the meter to measure the frequency of the ac mains.
4. **MAINS_NOMINAL_FREQUENCY**: The macro defines the default ac mains frequency
5. **TOTAL_ENERGY_PULSES_PER_KW_HOUR**: This macro defines the total number of pulses per 1 kWh of cumulative three-phase energy. In this application it is defined to 6400. It is important to note that this value is not a standard. There could be a practical limit set on this number due to the reference meter's ability to accept fast pulses (due to large currents). This number is true for total three phase energy only.
6. **PHASE_ENERGY_PULSES_PER_KW_HOUR**: This macro defined the total number of pulses per 1 kWh of energy at each phase. In this application it is defined to 6400 if pulses generation for each

individual phase has been enabled.

7. **INHIBIT_NEGATIVE_PHASE_POWER_ACCUMULATION:** This macro prevents negative energy from being accumulated at individual phases. Negative energy could be a result of reversed connection at the voltage or current but not both at any of the phases.
8. **INHIBIT_NEGATIVE_TOTAL_POWER_ACCUMULATION:** This macro prevents negative energy from being accumulated for the three phases combined. Negative energy could be a result of reversed connection at the voltage or current but not both at any of the phases.
9. **ENERGY_PULSE_DURATION:** This macro defines the duration of the LED ON time for an energy pulse. This is measured in ADC samples (that is, increments of 1/4096 s). The maximum allowed is 255, giving a pulse of approximately 62.5 ms, while 163 gives a 40-ms pulse. This duration might be too large with adjacent pulses overlapping when very high currents are measured. It is recommended that this value be changed to a smaller number such as 20 if overlap is seen at the pulse outputs.
10. **RESIDUAL_POWER_CUTOFF:** Very low power levels should not be recorded at all, as they might just be rounding errors, noise, or the consumption of the meter itself. This value is the cutoff level, in 0.01-W increments. In this application, it is set to 250, resulting in a start-energy of approximately 2.5 W.
11. **NEUTRAL_MONITOR_SUPPORT:** This macro enables support for neutral monitoring. The seventh SD24_B is used for this purpose.
12. **VRMS_SUPPORT:** This macro is used to configure the meter to calculate V_{RMS} from the voltage samples.
13. **IRMS_SUPPORT:** This macro is used to configure the meter to calculate I_{RMS} from the current samples.
14. **REACTIVE_POWER_SUPPORT:** This macro is used to configure the meter to calculate the reactive power from the voltage and current samples.
15. **REACTIVE_POWER_BY_QUADRATURE_SUPPORT:** This macro is used to configure the meter to calculate the reactive power from the delayed voltage samples by 90 degrees and current samples instead of using the power triangle method.
16. **APPARENT_POWER_SUPPORT:** This macro is used to configure the meter to calculate the apparent power.
17. **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.
18. **TOTAL_ACTIVE_ENERGY_SUPPORT:** This macro is used to configure the meter to calculate the total 3-phase active energy consumption.
19. **PER_PHASE_ACTIVE_ENERGY_SUPPORT:** This macro is used to configure the meter to calculate the active energy consumption for individual phases in addition to the total 3-phase active energy.
20. **TOTAL_REACTIVE_ENERGY_SUPPORT:** This macro is used to configure the meter to calculate the total 3-phase reactive energy consumption.
21. **PER_PHASE_REACTIVE_ENERGY_SUPPORT:** This macro is used to configure the meter to calculate the reactive energy consumption for individual phases in addition to the total 3-phase reactive energy.
22. **RTC_SUPPORT:** This macro is used to configure the meter to support a real-time clock. A software RTC is implemented for this purpose.
23. **CURRENT_PHASE_GAIN:** This macro defines the gain of the SD24_B's internal programmable gain amplifier (PGA) for all the three currents. In this application it is set to 1.
24. **CURRENT_NEUTRAL_GAIN:** This macro defines the gain of the SD24_B's internal PGA for neutral current monitoring. In this application it is set to 16.
25. **VOLTAGE_GAIN:** This macro defines the gain of the SD24_B's internal programmable gain amplifier (PGA) for all the three voltages. In this application it is set to 1.
26. **PHASE_REVERSED_DETECTION_SUPPORT:** This macro configures the meter to detect reversed power condition.
27. **PHASE_REVERSED_IS_TAMPERING:** This macro configures the meter to treat phase reversed connections as tampering.

28. `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.
29. `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.
30. `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.
31. `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.
32. `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.
33. `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.
34. `DEFAULT_P_SCALE_FACTOR_A_LOW`: 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.
35. `DEFAULT_P_SCALE_FACTOR_B_LOW`: 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.
36. `DEFAULT_P_SCALE_FACTOR_C_LOW`: 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.
37. `DEFAULT_I_RMS_SCALE_FACTOR_NEUTRAL`: This macro holds the scaling factor for current at neutral. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
38. `DEFAULT_P_SCALE_FACTOR_NEUTRAL`: This macro holds the scaling factor for active power at neutral. Set this factor to an approximately correct value, and it will be fine tuned during calibration.
39. `DEFAULT_BASE_PHASE_A_CORRECTION_LOW`: This macro holds the value for phase correction to compensate for the delay coming from the current transformer 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.
40. `DEFAULT_BASE_PHASE_B_CORRECTION_LOW`: This macro holds the value for phase correction to compensate for the delay coming from the current transformer 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.
41. `DEFAULT_BASE_PHASE_C_CORRECTION_LOW`: This macro holds the value for phase correction to compensate for the delay coming from the current transformer 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.
42. `DEFAULT_NEUTRAL_BASE_PHASE_CORRECTION`: This macro holds the value for phase correction to compensate for the delay 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.

5 Energy Meter Demo

The energy meter evaluation module (EVM) associated with this application report has the MSP430F677x(A) 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.

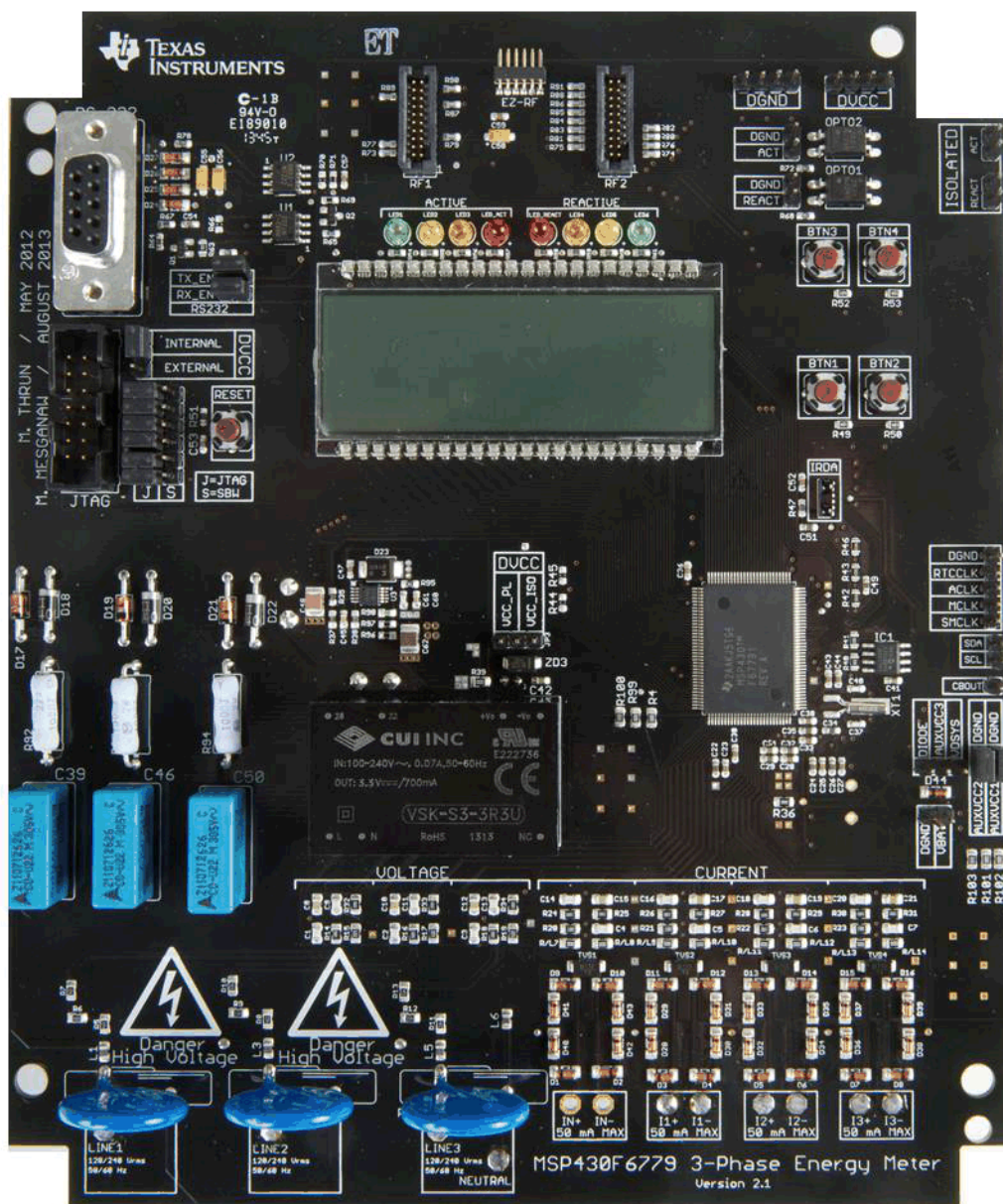


Figure 12. Top View of the Three Phase Energy Meter EVM

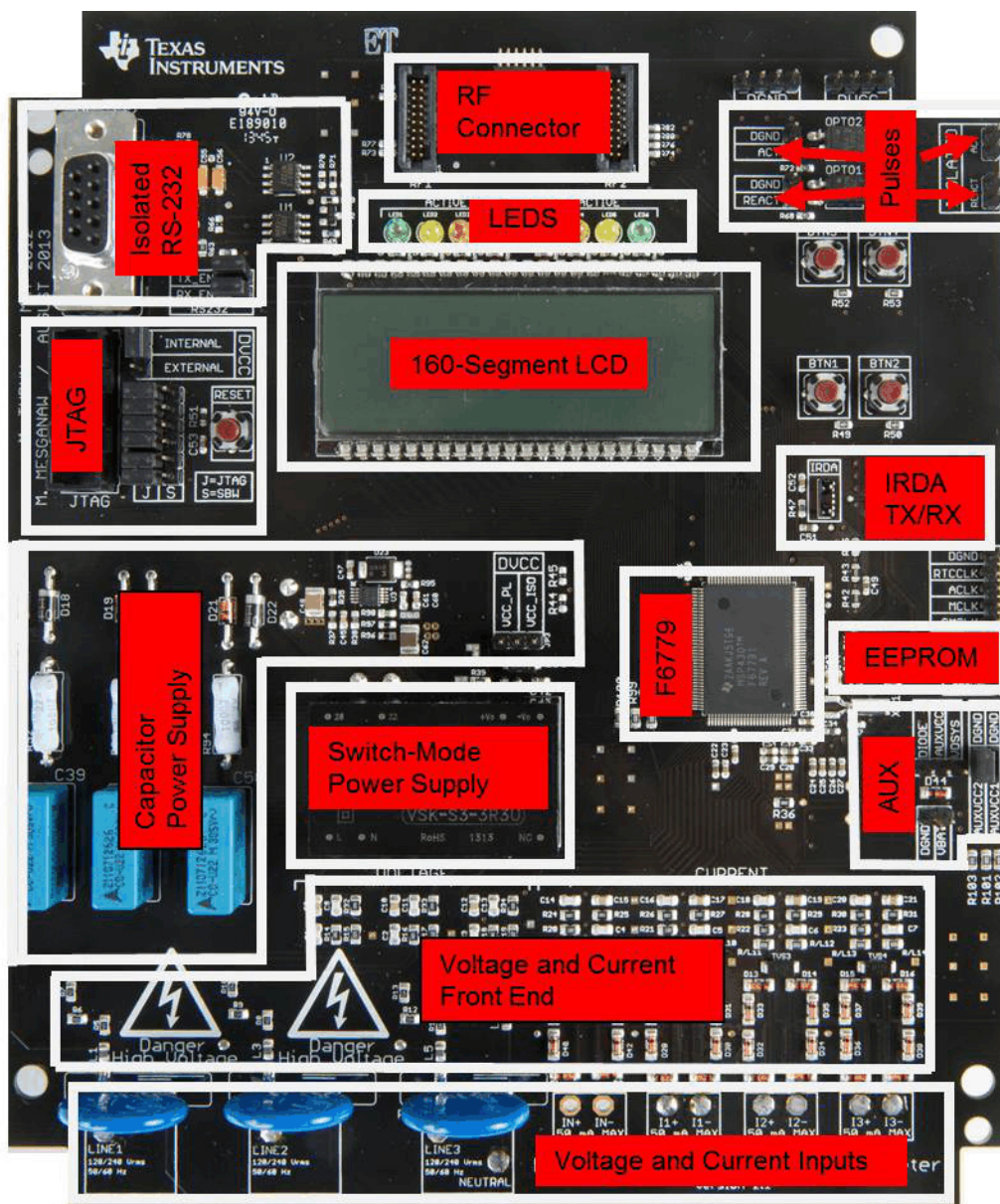



Figure 13. Top View of the EVM With Components Highlighted

	<p>Danger High Voltage</p>	<p>Electric shock is possible when connecting the board to live wires. The board should be handled with care by a professional.</p> <p>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 LINE1 corresponds to the line connection for phase A.
- Pad LINE2 corresponds to the line connection for phase B.
- Pad LINE3 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 930 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 930 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 930 mV. THIS IS CURRENTLY CONNECTED TO A CT ON THE EVM.
- IN+ and IN- are the current inputs after the sensors for the neutral current. When a current sensor is used, make sure that the voltage across IN+ and IN- does not exceed 930 mV. THIS IS CURRENTLY NOT CONNECTED TO 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. V_A+ , V_B+ , and V_C+ corresponds to the line voltage for phases A, B, and C, respectively. V_N corresponds to the neutral voltage from the test ac source.

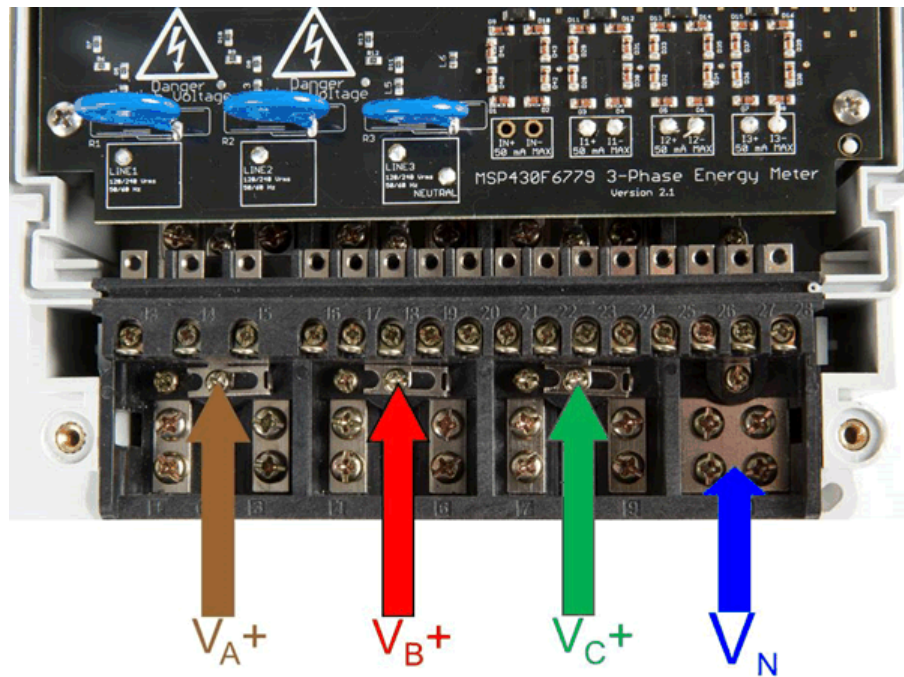


Figure 14. Top View of the EVM With Test Setup Connections

Figure 15 shows the connections from the front view. I_A+ and I_A- correspond to the current inputs for phase A, I_B+ and I_B- correspond to the current inputs for phase B, and I_C+ and I_C- correspond to the current inputs for phase C. V_N corresponds to the neutral voltage from the test setup. Although the EVM hardware and software supports measurement for the neutral current, the EVMs obtained from Texas Instruments do not have a sensor connected to the neutral ADC channel.

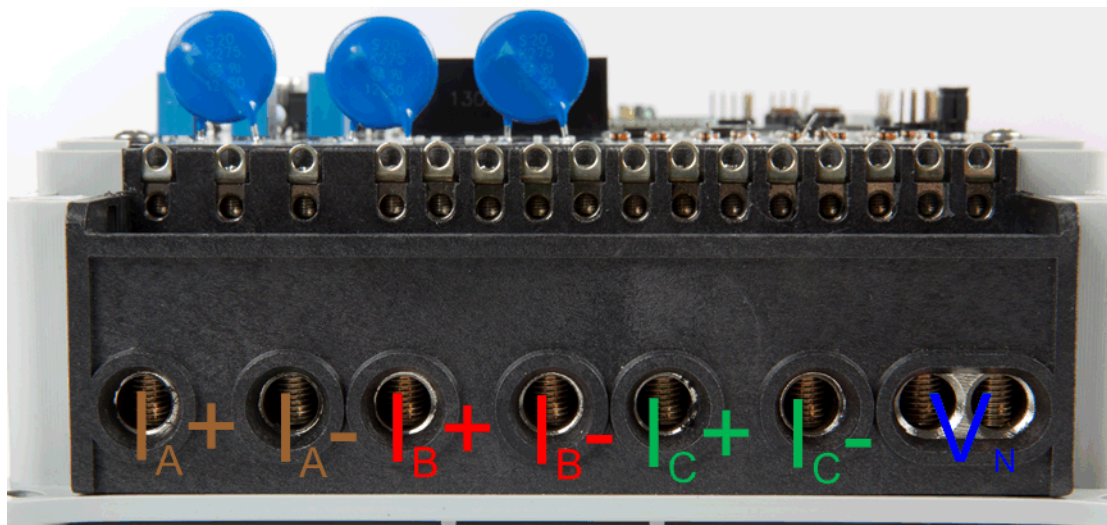


Figure 15. Front View of the EVM With Test Setup Connections

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](#) indicates the functionality of each jumper on the board and the associated functionality.

Table 1. Header Names and Jumper Settings on the F677x(A) EVM

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
ACLK (Not isolated, do not probe)	1-pin Header	ACLK Output (WARNING)	Probe here to measure the frequency of ACLK.	The software does not output ACLK by default and must be modified to output ACLK. This header is not isolated from ac voltage so do not connect any measuring equipment.
ACT (Not isolated, do not probe)	1-pin Header	Active Energy Pulses (WARNING)	Probe between here and ground for cumulative three-phase active 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 ACT header, instead.
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 and configure the software to use the backup power supply as needed. In addition, on the bottom of the board, a footprint is present that allows the addition of a supercap.	
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, 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.	
AUXVCC3 (Not isolated, do not probe)	2-pin Jumper Header	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 here 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.	
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.

Table 1. Header Names and Jumper Settings on the F677x(A) EVM (continued)

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
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.
MCLK (Not isolated, do not probe)	1-pin Header	MCLK Output (WARNING)	Probe here to measure the frequency of MCLK.	The software does not output MCLK by default and will have to be modified to output MCLK. Probe only when ac mains is isolated.
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.
RTCCLK	1-pin Header	RTCCLK Output	Probe here to measure the frequency of RTCCLK, which is used for calibrating the RTC.	The software does not output RTCCLK by default, and it must be modified to output RTCCLK.
RX_EN	Jumper Header	RS-232 Receive enable	Place a jumper here to enable receiving characters using RS-232.	--

Table 1. Header Names and Jumper Settings on the F677x(A) EVM (continued)

Header, Header Option Name	Type	Main Functionality	Valid Use Case	Comments
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.
SMCLK (Not isolated, do not probe)	1-pin Header	SMCLK Output (WARNING)	Probe here to measure the frequency of SMCLK.	The software does not output MCLK by default and must be modified to output SMCLK. Probe only when ac mains is isolated.
TX_EN	Jumper Header	RS-232 Transmit Enable	Place a jumper here to enable RS-232 transmissions.	--
VBAT	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 is still powered when the voltage at DVCC is removed.	

5.2 Loading the Example Code

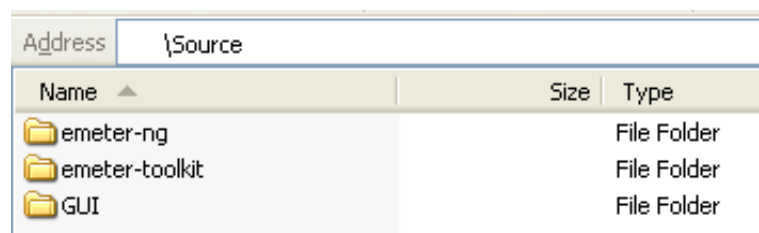
The source code is developed in the IAR environment using IAR compiler version 6.x. Earlier versions of IAR cannot open the project files. When the project is loaded in IAR version 6.x or later, the IDE prompts you to create a backup. Click YES to proceed. There are three parts to the energy metrology software.

- The toolkit that contains a library of mostly mathematics routines
- The main code that is made of the source and include files
- The GUI that is used for calibration

In this software package, there are two sets of directories: one for the MSP430F6779 and one for the MSP430F6779A. Depending on the utilized device, open the proper directory. [Section 5.2.1](#) describes how to compile a project for the MSP430F6779 option. A similar set of instructions can be followed to compile a project for the MSP430F6779A option.

5.2.1 Opening the Project

[Figure 16](#) shows the contents of the Source folder.



Name	Size	Type
emeter-ng		File Folder
emeter-toolkit		File Folder
GUI		File Folder

Figure 16. Source Folder Structure

The emeter-ng folder contains multiple project files and for this application, the emeter-6779.ewp project file is to be used. The folder emeter-toolkit has corresponding project file emeter-toolkit-6779.ewp. For first time use, it is recommended that both the projects be completely rebuild by performing the following steps:

1. Open the IAR IDE.
2. Load the emeter_toolkit_6779.ewp project.
3. Click the Rebuild All option as shown in [Figure 17](#).
4. Close the existing workspace and open the main project emeter-6779.ewp.
5. Click rebuild All as shown in [Figure 18](#) and load this project onto the MSP430F6779.

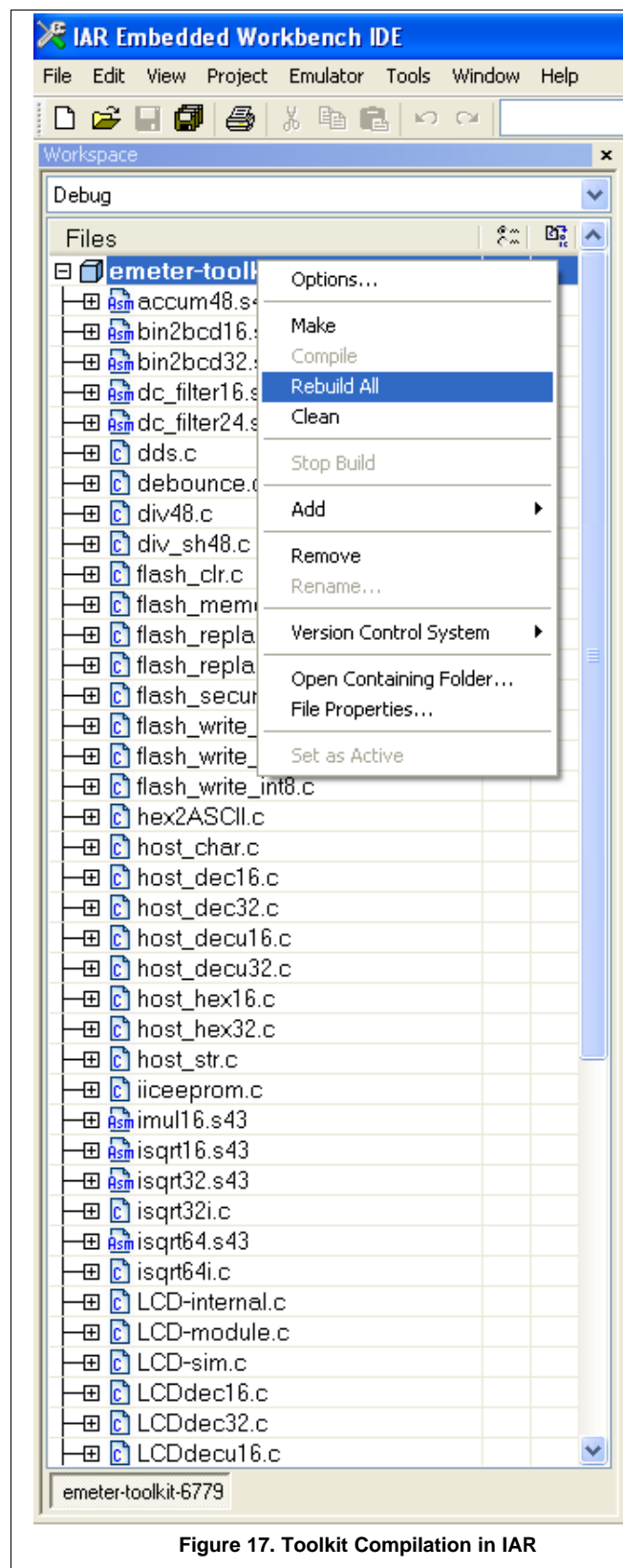


Figure 17. Toolkit Compilation in IAR

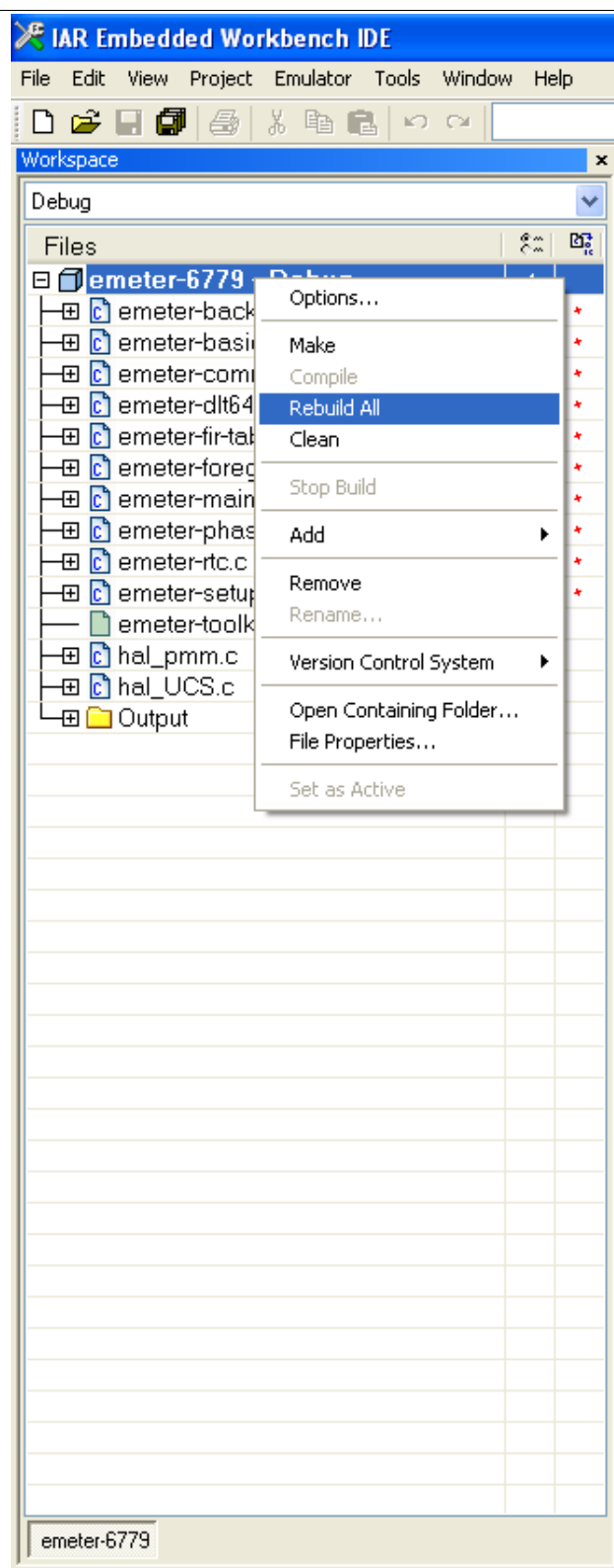


Figure 18. Metrology Project Build in IAR

6 Results and Calibration

6.1 Viewing Results via LCD

The LCD display scrolls between metering parameter approximately every two seconds. For each metering parameter that is displayed on the LCD, three items are actually displayed on the screen: the corresponding phase of the parameter, a one or two character symbol used to distinguish which parameter is being displayed, and the actual value of the parameter. The phase of the parameter is displayed on the top line of the LCD. This may take the values of A, B, C, and t for phase A, phase B, phase C, and the aggregate-sum of these phases, respectively. The parameter symbol is displayed on the left of the second line of the LCD. To the right of the parameter symbol is the actual value of the parameter.

Table 2 shows the different metering parameters that are displayed on the LCD and the associated units in which they are displayed. The Symbol column shows which characters correspond to which metering parameter. The Comments column provides a brief interpretation of the displayed metering parameters.

Table 2. Displayed Parameters







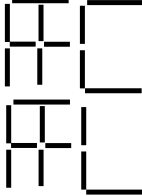




Parameter Name	Symbol	Units	Comments
Voltage		Volts (V)	--
Current		Amps (A)	
Active Power		Watt (W)	--
Reactive Power		Volt-Ampere Reactive (var)	--
Apparent Power		Volt-Ampere (VA)	--
Frequency		Hertz (Hz)	--
Power Factor		Constant between 0 and 1	<p>The characters  are used if the load is determined to be a capacitive load.</p> <p>The characters  are used if the load is determined to be an inductive load.</p>
Total Consumed Active Energy		100 "Tick"	Every 10 ticks increments the tenths place by 1.
Total Consumed Reactive Energy		100 "Tick"	Every 10 ticks increments the tenths place by 1.

Figure 19 shows an example of phase A's measured frequency of 49.99 Hz displayed on the LCD.

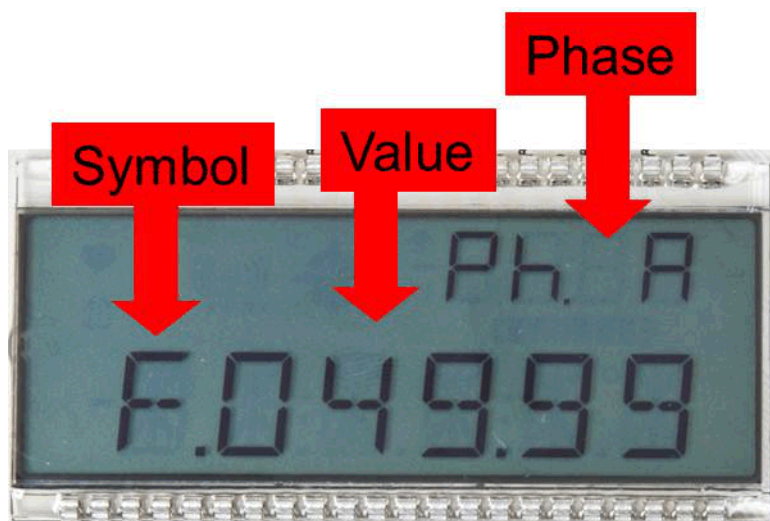


Figure 19. LCD Display

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.

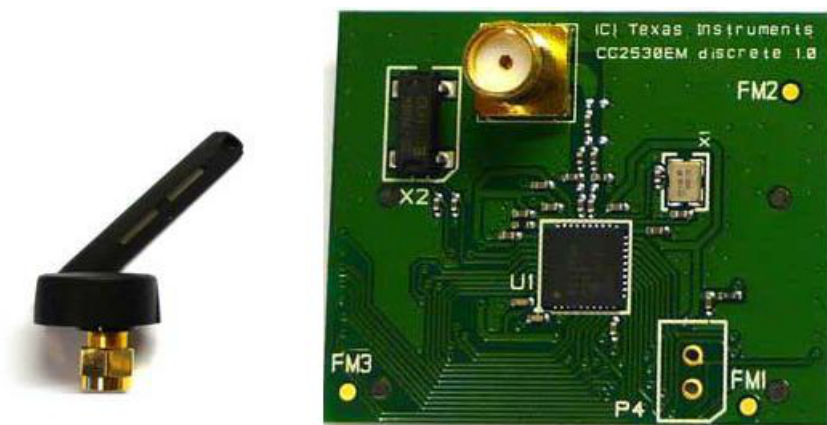


Figure 20. ZigBee Radio

This ZigBee module is connected by the UART, which is configured to 115.2 kbaud to the MSP430F6779(A) 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 is used as the in-home display. The IHD430 has a MSP430F461x as an application and host processor.

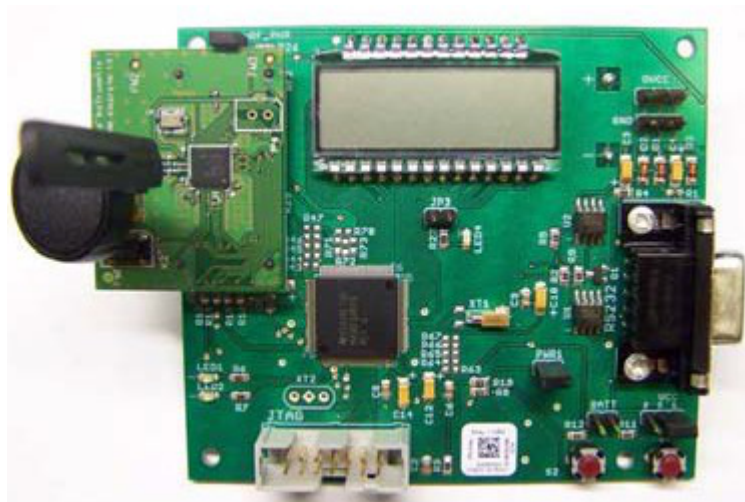


Figure 21. TI Designed IHD430

View cumulative three-phase active power readings on the IHD430

Place a CC2530 module in the RF connector socket of the meter (EVM430-F6779). 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.

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:

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

For the MSP430F677x(A) software to communicate the cumulative three-phase active power to the IHD430, the IHD430_SUPPORT macro must be defined in the emeter-3ph-neutral-6779(A).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 MSP430F677x(A) 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 22](#), this field is changed to COM2.

```

343 <step current="25.000" phase="0.0" gain="1.0"/>
344 <step current="30.000" phase="0.0" gain="1.0"/>
345 <step current="35.000" phase="0.0" gain="1.0"/>
346 <step current="40.000" phase="0.0" gain="1.0"/>
347 <step current="45.000" phase="0.0" gain="1.0"/>
348 <step current="50.000" phase="0.0" gain="1.0"/>
349 <step current="55.000" phase="0.0" gain="1.0"/>
350 </correction>
351 </phase>
352 <temperature/>
353 <rtc/>
354 </cal-defaults>
355 <meter position="1">
356 <port name="\\.\com2" speed="9600"/>
357 </meter>

```

Figure 22. 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 23](#)).

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.

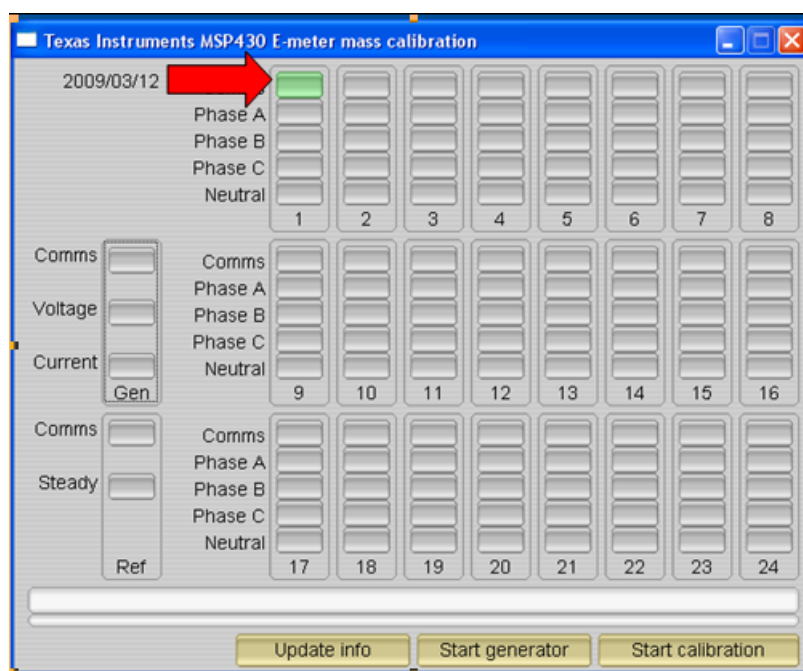


Figure 23. GUI Startup Window

6.3.2 View Results

When you click on the green button, the results window opens (see [Figure 24](#)). Note that there is a trailing "L" or "C" on the Power factor values to indicate an inductive or capacitive load, respectively.

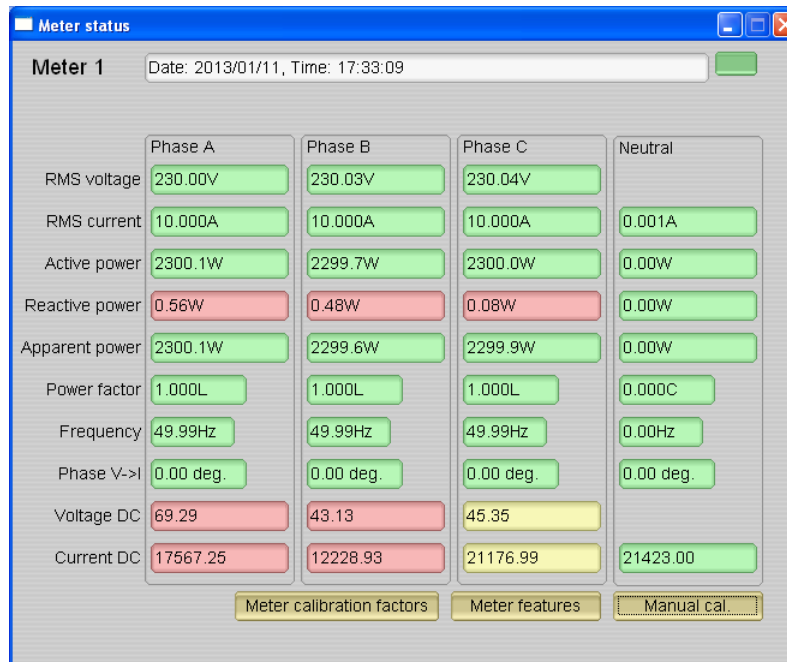


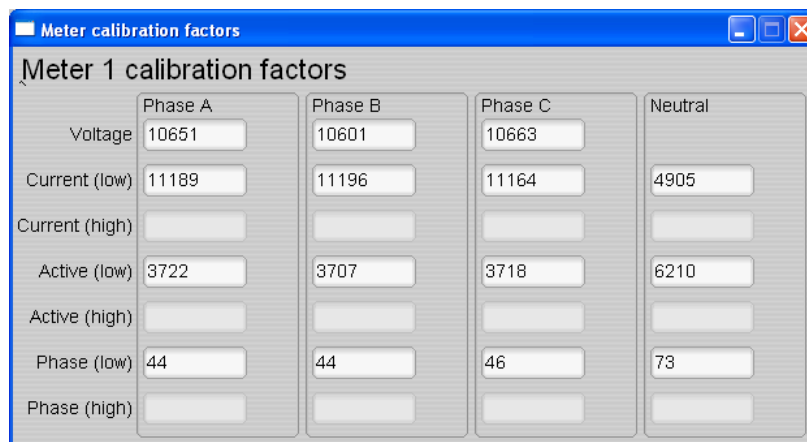
Figure 24. Results Window

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 3-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 four main calibration factors for each phase: voltage scaling factor, current scaling factor, 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 phase compensation factor is used to compensate any phase shifts introduced by the current sensors and other passives.

When the meter software is flashed with the code (available in the zip file), default calibration factors are loaded into these calibration factors (see items 28 to 42 in [Section 4.4](#) for the macro definitions). 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 24](#). 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.



	Phase A	Phase B	Phase C	Neutral
Voltage	10651	10601	10663	
Current (low)	11189	11196	11164	4905
Current (high)				
Active (low)	3722	3707	3718	6210
Active (high)				
Phase (low)	44	44	46	73
Phase (high)				

Figure 25. 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. 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.

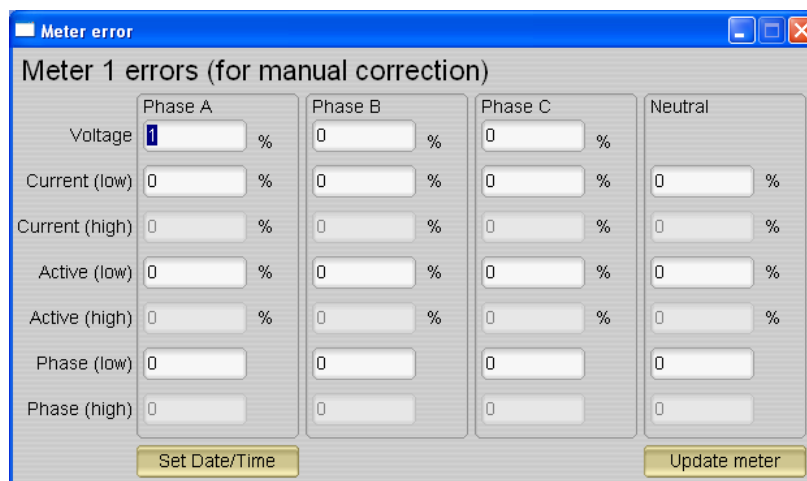
6.3.3.1 Gain Calibration

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: 230 V, 10 A, 0° (PF = 1). Typically, these values are the same for every phase.
3. Click the "Manual cal." button in the Results window (see [Figure 24](#)) to open the window shown in [Figure 26](#).



	Phase A	Phase B	Phase C	Neutral
Voltage	1 %	0 %	0 %	
Current (low)	0 %	0 %	0 %	0 %
Current (high)	0 %	0 %	0 %	0 %
Active (low)	0 %	0 %	0 %	0 %
Active (high)	0 %	0 %	0 %	0 %
Phase (low)	0	0	0	0
Phase (high)	0	0	0	0

Set Date/Time Update meter

Figure 26. Manual Calibration Window

4. 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:

$$\text{Correction}(\%) = \left(\frac{\text{value}_{\text{observed}}}{\text{value}_{\text{desired}}} - 1 \right) * 100 \quad (8)$$

Where $\text{value}_{\text{observed}}$ is the value measured by the TI meter, and $\text{value}_{\text{desired}}$ is the calibration point configured in the ac test source.

5. After calculating Correction(%) for all voltages and currents, input these values as is (\pm) for the fields Voltage and Current (low) for the corresponding phases.
6. 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:

1. 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.
2. Turn on the ac test source.
3. 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.
4. Disable the other phases that are not currently being calibrated by setting the current of these phases to 0 A.
5. 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 (low) 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. If this error is not close to zero, or is unacceptable, perform phase correction by following these steps:
 1. Enter a value as an update for the Phase (Low) 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.

2. Click Update meter and monitor the error values on the reference meter.
3. 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.
4. 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 24](#)).

	Phase A	Phase B	Phase C	Neutral
Voltage	10651	10601	10663	
Current (low)	11189	11196	11164	4905
Current (high)				
Active (low)	3722	3707	3718	6210
Active (high)				
Phase (low)	44	44	46	73
Phase (high)				

Figure 27. Calibration Factors Window

The configuration of the meter can also be viewed by clicking Meter features to open the screen shown in [Figure 28](#) (this is only an example).

Single phase	Active power measurement
Neutral monitoring	Reactive power measurement (trig)
Limp mode	Reactive power measurement (quad)
Phase correction	Apparent (VA) power measurement
Dynamic phase correction	RMS voltage measurement
RTC	RMS current measurement
Temperature corrected RTC	Power factor measurement
Temperature measurement	Mains frequency measurement
Self test	Two current ranges
Multi-rate and peak demand	

Figure 28. Meter Features Window

6.3.4 Metrology Results

In this section, metrology results are shown for cumulative three-phase active energy. Figure 29 shows the results over a dynamic range of 2000:1 using the customized CTs that are provided with the EVM430-F6779. Table 3 shows the values for the error. Changing the EVM's CTs may result in better performance. Figure 30 shows the results over the same dynamic range using high-end CTs over the same current range. Table 4 shows the values for the error. All results were calibrated at 230 V, 10 A, 50 Hz.

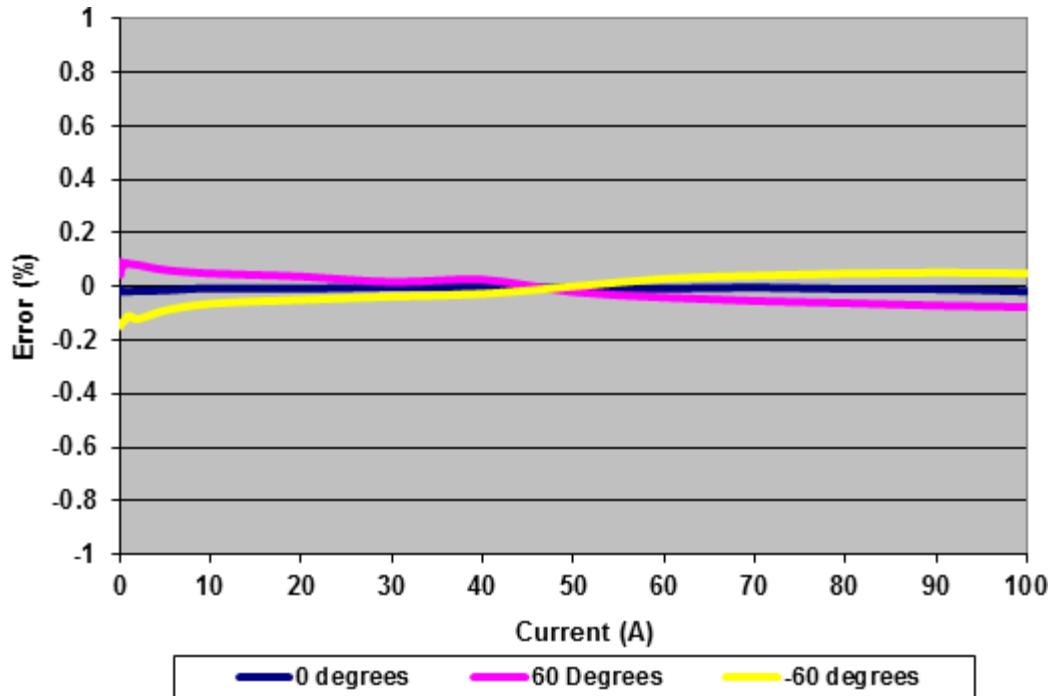


Figure 29. Energy Measurement Error Across Current With Customized CTs on EVM430-F6779

Table 3. Energy Measurement Error With Customized CTs on EVM430-F6779 (%)

Current (A)	0°	60°	-60°
0.05	-0.02	0.0445	-0.147
0.1	-0.011	0.093	-0.1373
0.25	-0.0173	0.073	-0.131
0.5	-0.0187	0.0877	-0.1277
1	-0.0173	0.0853	-0.1077
2	-0.0157	0.0815	-0.1203
5	-0.014	0.0627	-0.0887
10	-0.006	0.0497	-0.0633
20	-0.0073	0.0377	-0.049
30	-0.001	0.018	-0.037
40	0.0003	0.026	-0.027
50	-0.006	-0.0197	0.0013
60	-0.007	-0.04	0.0297
70	-0.003	-0.0533	0.041
80	-0.0083	-0.0613	0.049
90	-0.0093	-0.0707	0.053
100	-0.0177	-0.0763	0.0497

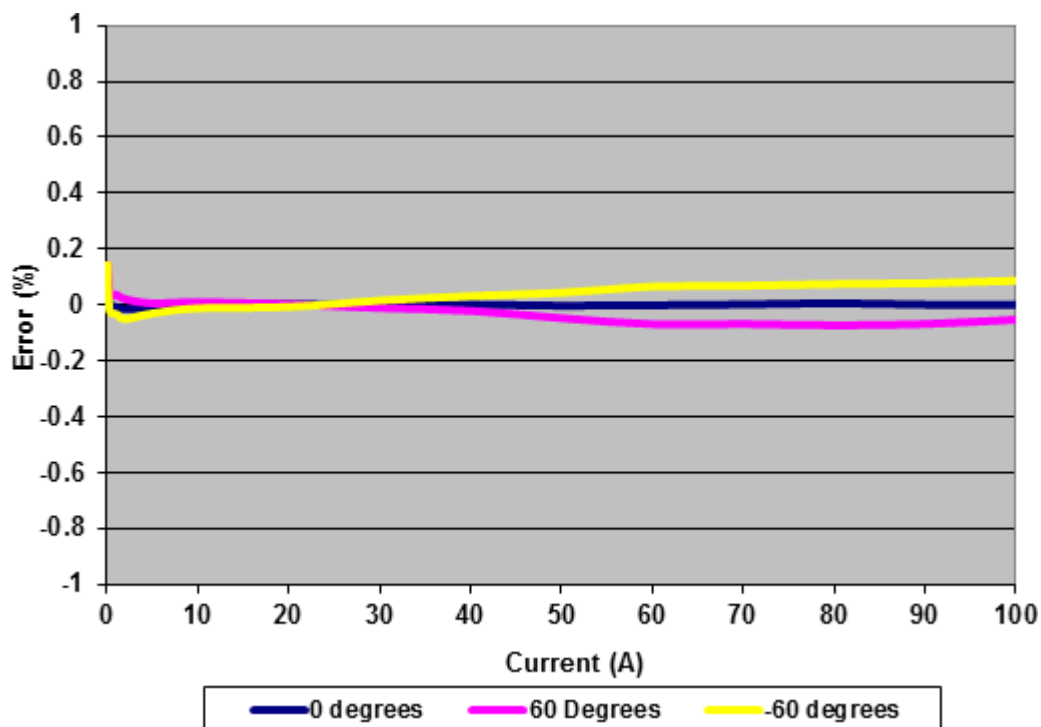


Figure 30. Energy Measurement Error Across Current With High-End CTs

Table 4. Energy Measurement Error With High-End CTs (%)

Current (A)	0°	60°	-60°
0.05	0.048	0.1445	0.144
0.1	0.0857	0.1185	0.0725
0.25	0.011	0.05	-0.02
0.5	-0.006	0.0327	-0.0295
1	-0.0075	0.0365	-0.033
2	-0.015	0.0207	-0.0505
5	-0.009	0.006	-0.03
10	-0.002	0.0097	-0.012
20	0.0027	0.0023	-0.007
30	-0.0017	-0.0107	0.016
40	0.0015	-0.021	0.032
50	-0.003	-0.0473	0.0437
60	-0.001	-0.0687	0.066
70	0.0017	-0.0683	0.069
80	0.006	-0.0727	0.0747
90	0.001	-0.0683	0.078
100	-0.0007	-0.0527	0.0863

7 Schematics

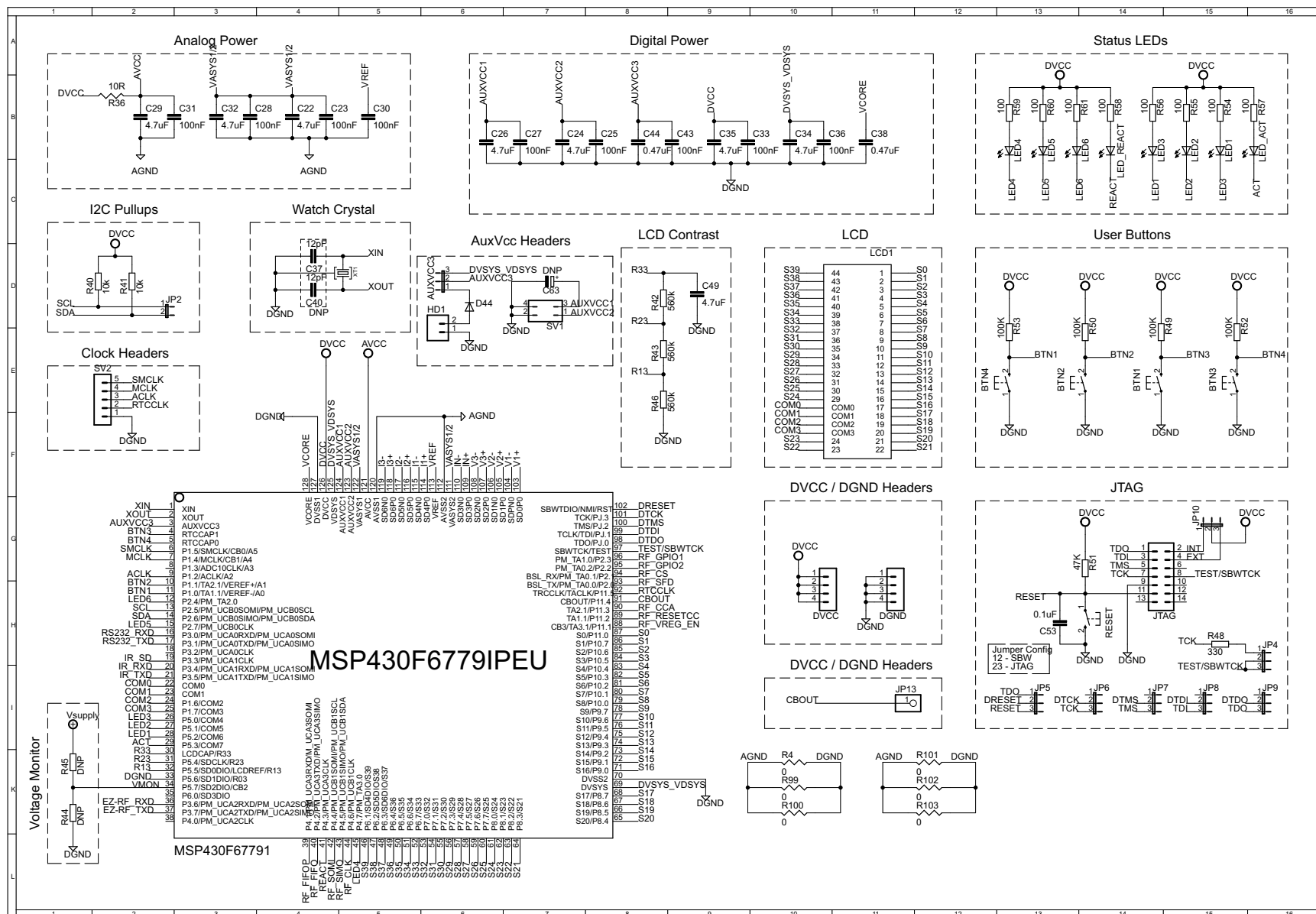


Figure 31. Schematics (1 of 4)

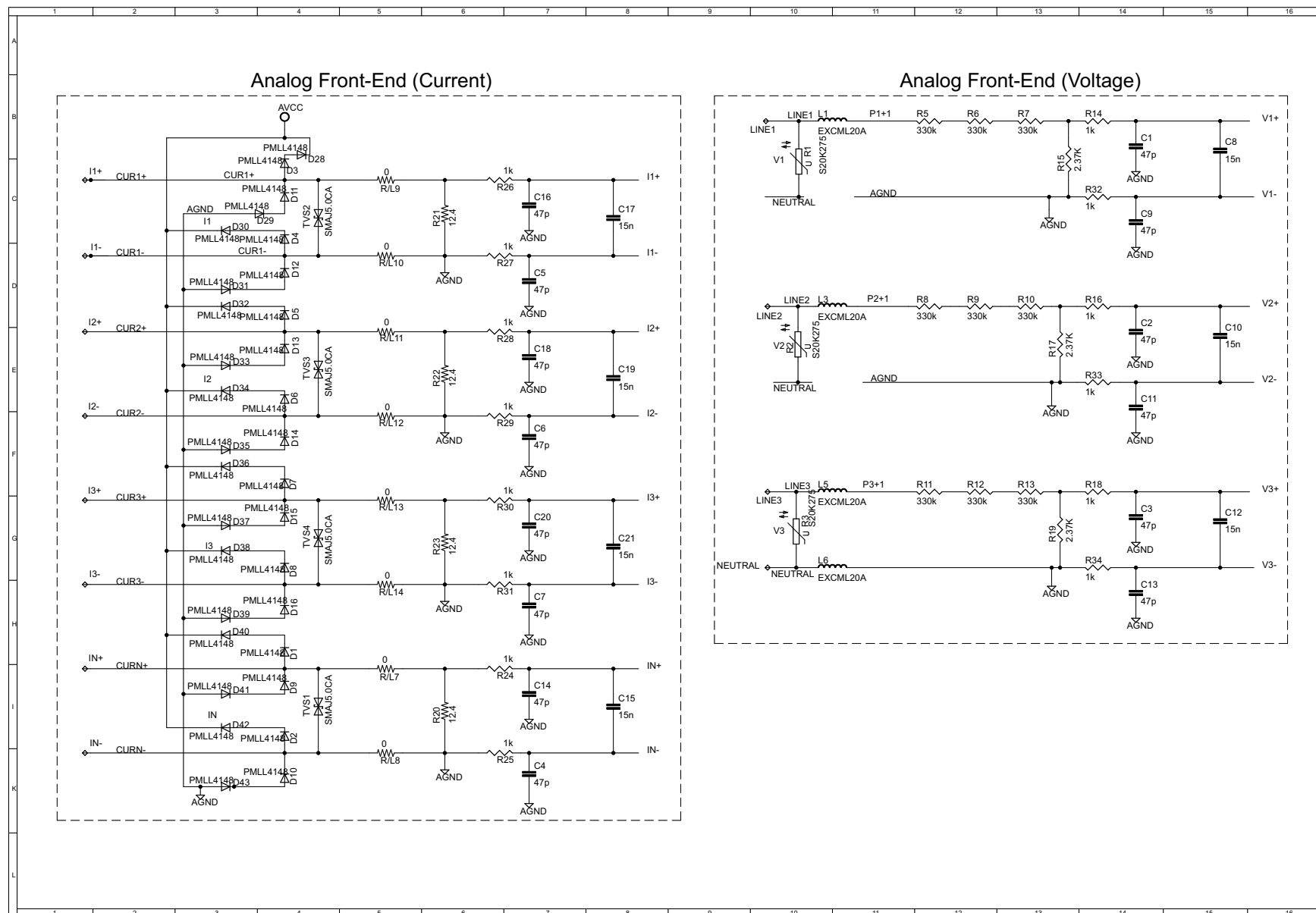


Figure 32. Schematics (2 of 4)

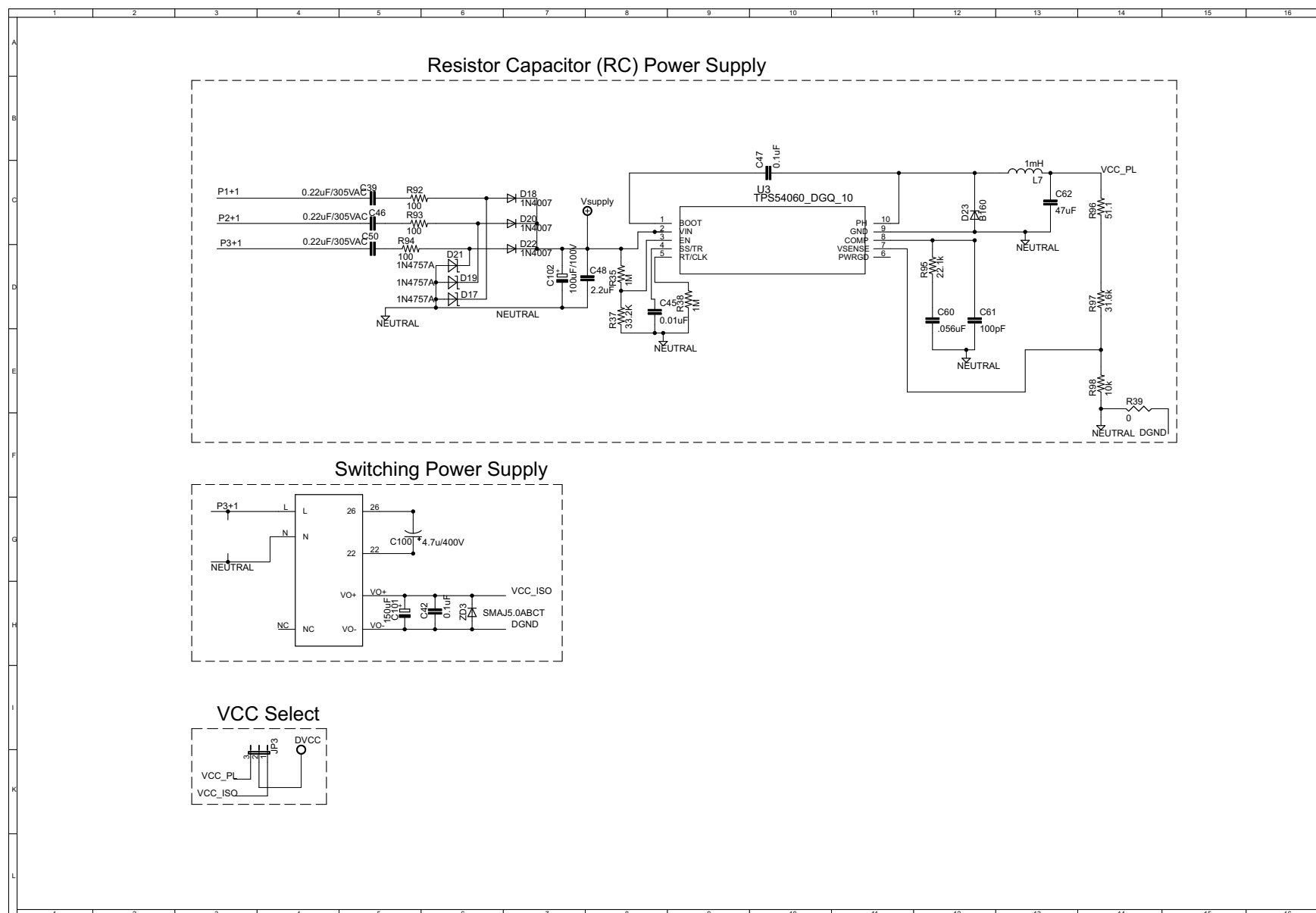


Figure 33. Schematics (3 of 4)

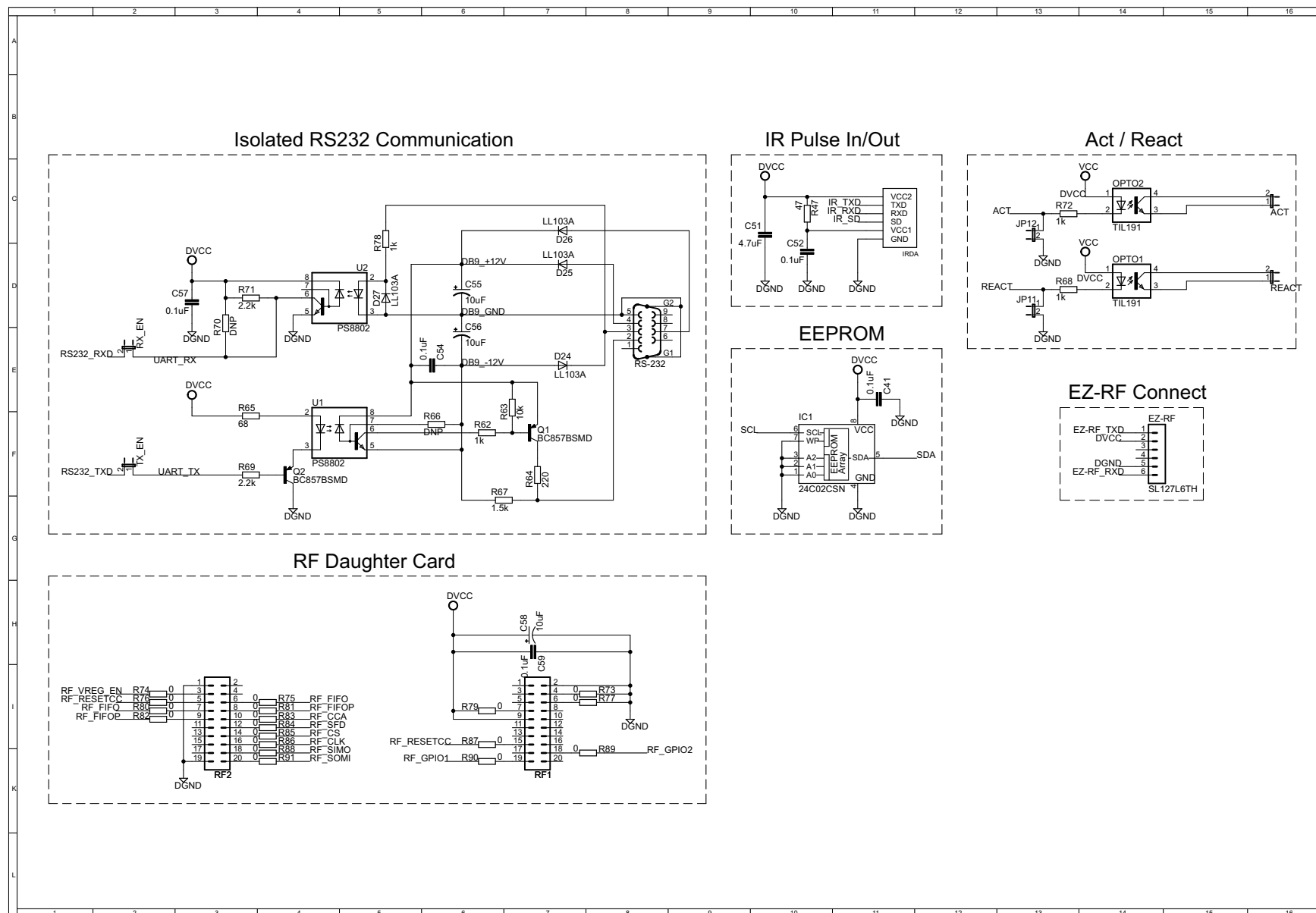


Figure 34. Schematics (4 of 4)

Revision History

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

Changes from F Revision (May 2014) to G Revision	Page
• Updated links and descriptions for associated source code.....	1
• Updated links to source code.....	3

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

1. Keep work area clean and orderly.
2. Qualified observer(s) must be present anytime circuits are energized.
3. 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.
4. 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.
5. Use stable and nonconductive work surface.
6. 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.

1. 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.
2. 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.
3. 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

1. 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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