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Three-Phase Metrology With Enhanced ESD Protection and Tamper Detection

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Design Resources

TIDM-3PHMTR-TAMP-ESD	Design Folder
MSP430F67791A	Product Folder
TPS54060	Product Folder
CC2530 `	Product Folder
CC2530EMK	Tools Folder
TIDM-LOWEND-IHD	Tools Folder

TI E2E™ Community

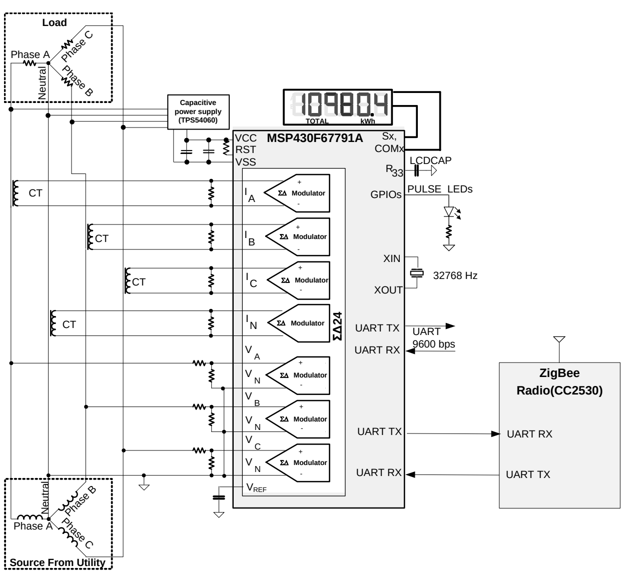
ASK Our E2E Experts
WEBENCH® Calculator Tools

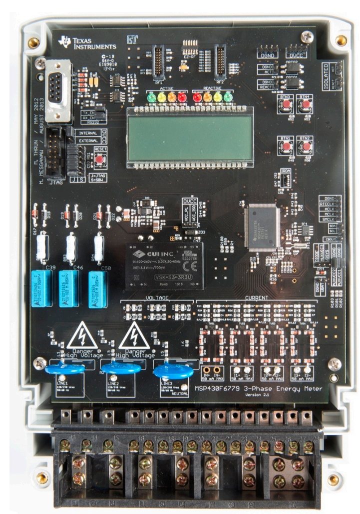
Design Features

- Three-Phase Meter With Tamper Detection Which Exceeds Class 0.2 Accuracy Requirements from ANSI and IEC
- Passed IEC 61000-4-2 Level-4 Air Discharge Tests [1] (See Below for Details)
- TI Energy Library Firmware Calculates All Energy Measurement Parameters Including Active and Reactive Power and Energy, RMS Current and Voltage, Power Factor, and Line Frequency
- Support for ZigBee® Communication to In Home Display or Connections to Wi-Fi®, Wireless M-Bus, and IEEE-802.15.4g Add-On Communications Modules
- Automated or Manual Switching Between Main and Auxiliary Power Sources for Metrology Engine

Featured Applications

- Metering
- Street Lighting





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1 System Description

This design implements an ANSI/IEC Class 0.2 three-phase energy meter with enhanced ESD protection. The design also features tamper detection to limit the feasibility of energy theft and communications through ZigBee™ connectivity. The e-meter system on chip SoC is used to perform all metrology functions and sends active power results to the CC2530EM add-on board. Developers can use the companion In Home Display TI design (TIDM-LOWEND-IHD) to display results remotely [2].

The design guide has a complete metrology source code provided as a downloadable zip file.

1.1 MSP430F67791A

For sensing and calculating the metrology parameters, the MSP430F67791A e-meter SoC is used. This device is the latest metering system on chip (SoC) that belongs to the MSP430F67xxA family of devices. This MSP430F67xxA family of devices offer enhancements when compared to the previous non-A MSP430F67xx devices such as the MSP430F67791. One of these enhancements addresses improved ESD robustness (see the *Differences Between MSP430F67xx and MSP430F67xxA Devices* application note for more details on this change as well as other changes compared to the non-A MSP430F67xx devices). These ESD enhancements can enable increased ESD immunity when compared to the previous meters based on the non-A MSP430F67xx devices.

In regard to metrology, the MSP430F67791A energy library software has support for calculation of various parameters for up to three-phase energy measurement. The key parameters calculated during energy measurements are: RMS current and voltage; active power, reactive power, and energies; power factor; and frequency. These parameters can be viewed either from the calibration graphical user interface (GUI) or liquid crystal display (LCD).

1.2 CC2530

For ZigBee communication, the CC2530EMK evaluation kit is used. Place the board of the kit into the EVMs RF connector to enable ZigBee communication. The F67791A e-meter software automatically packages the active power readings into a packet. This packet is then sent to the CC2530 that is connected to the RF connector of the design.

The TIDM-LOWEND-IHD TI design can be used as a receiver. When this receiver is used, the CC2530 on the IHD430 receives the packet from the CC2530 on the design and displays the packet on the IHD430 LCD.

1.3 TPS54060

The TPS54060 is used in the power supply to help provide a 3.3-V output from an input mains voltage of 120/230-V RMS AC at 50/60 Hz. Figure 8 shows how the TPS54060 is used to create the 3.3-V output from the 120/230-V RMS AC input.

2 Block Diagram

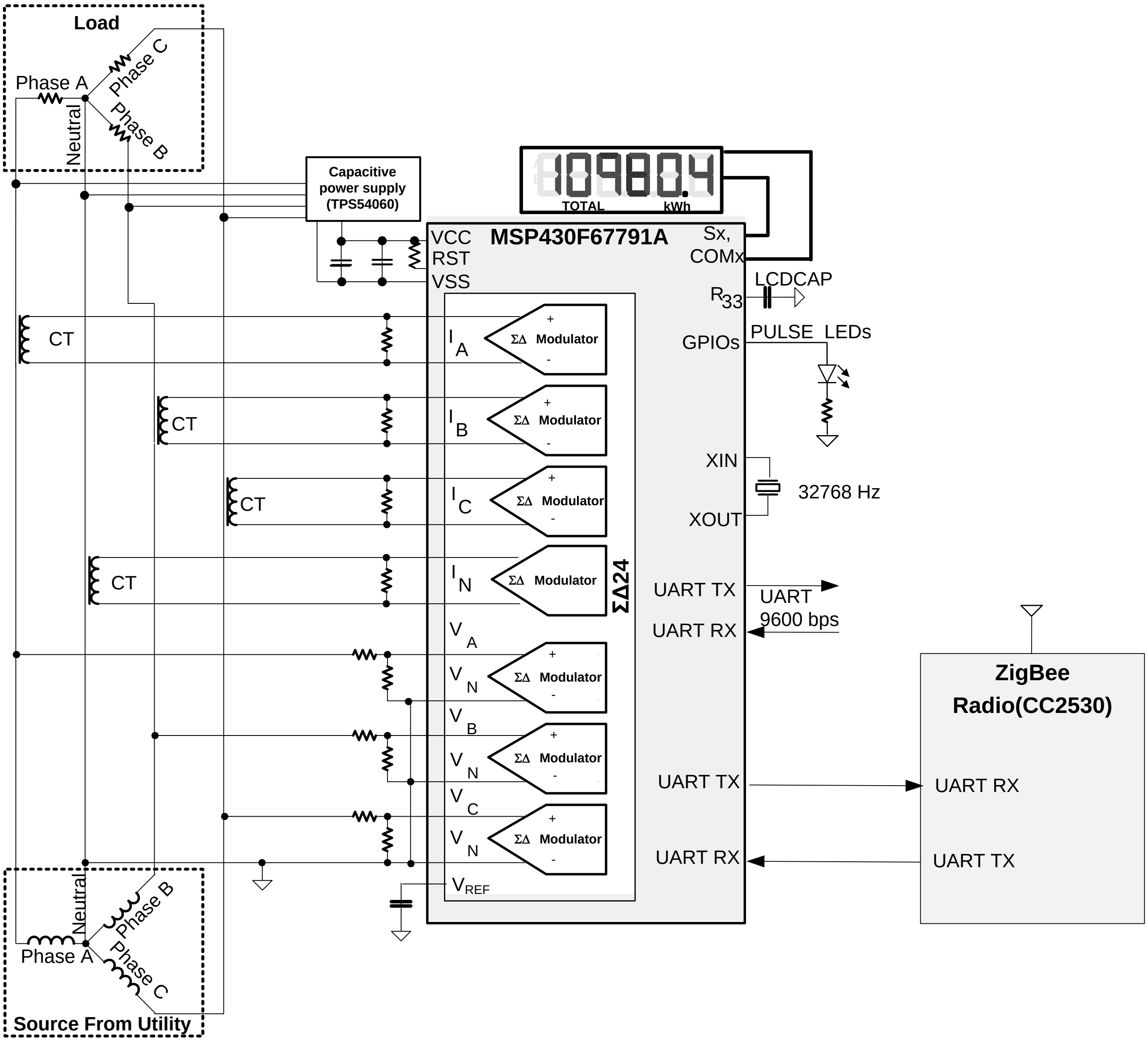


Figure 1. TIDM-3PHMTR-TAMP-ESD System Block Diagram

Figure 1 shows a block diagram that displays the high-level interface used for a three-phase energy meter application that uses the MSP430F67791A device. A three-phase four-wire star connection to the AC mains is shown in this case. In the diagram, a current sensor connects to the current channel and a simple voltage divider is used for the corresponding voltage. The CT has an associated burden resistor that must be connected at all times to protect the measuring device. The selection of the CT and the burden resistor is made based on the manufacturer and current range required for energy measurements. The CTs can easily be 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 adhere to the normal input ranges that are valid for the MSP430s SD24_B ADCs. Refer to the MSP4305xx/6xx user's guide [3] and device specific datasheet [4] for these numbers.

Other signals of interest in Figure 1 are the PULSE LEDs (PULSE1 and PULSE2), which are used to transmit active and reactive energy pulses used for accuracy measurement and calibration. The pulses are also used to transmit the active power consumed for each individual phase. In addition, the user can add ZigBee communication to an in-home display by connecting a CC2530EM board into the RF connectors of the design and flashing the CC2530 with the proper software.

2.1 Highlighted Products

2.1.1 MSP430F67791A

Similar to the MSP430F67791, the MSP430F67791A belongs to the powerful 16-bit MSP430F6xx platform. This chip is intended for energy measurement applications and it has the necessary architecture to perform this application. The MSP430F67791A has a powerful 25-MHz CPU with MSP430CPUx architecture. The analog front-end consists of seven independent 24-bit ΣΔ analog-to-digital converters (ADC) based on a second order sigma-delta architecture that supports differential inputs. The sigma-delta ADCs (ΣΔ24_B) operate independently and are capable of 24-bit results. The sigma-delta ADCs can be grouped together for simultaneous sampling of voltages and currents on the same trigger. In addition, the sigma-delta ADC also has an integrated gain stage to support gains up to 128 for amplification of low-output current sensors. A 32-bit × 32-bit hardware multiplier on this chip can be used to further accelerate math-intensive operations during energy computation.

Figure 2 shows a block diagram of the chip that displays the features of the MSP430F67791A.

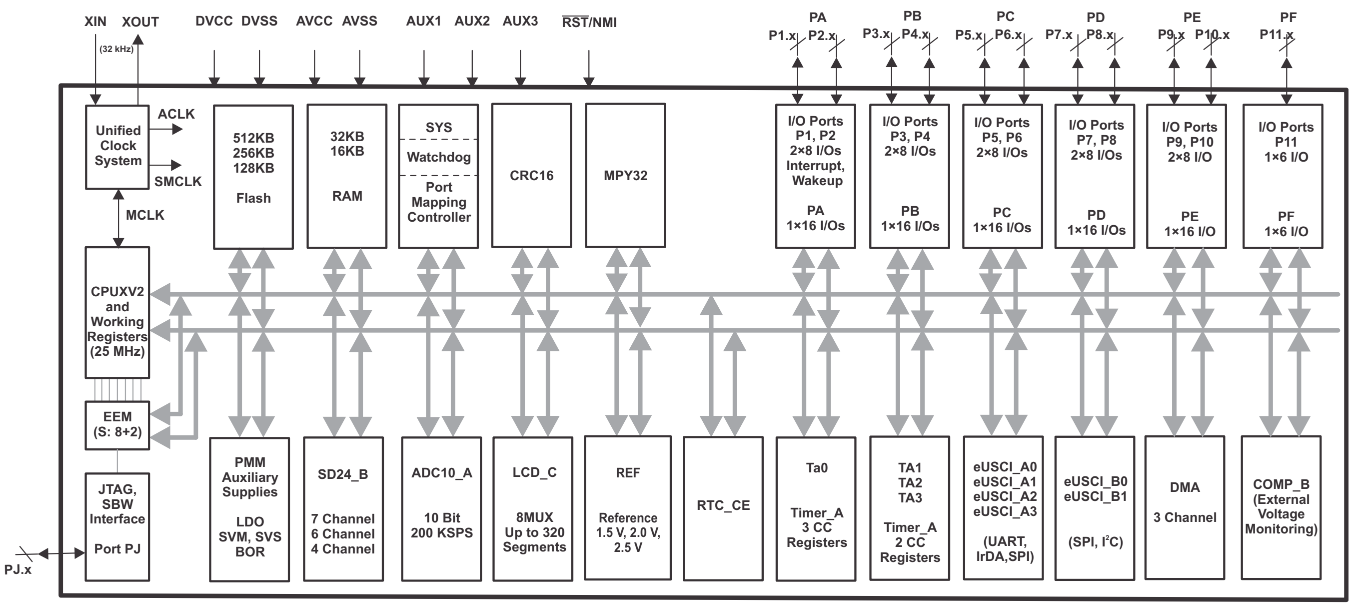


Figure 2. MSP430F67791A Block Diagram

2.1.2 CC2530 Features

The CC2530 device is a true system-on-chip (SoC) solution for IEEE 802.15.4, ZigBee, and Radio Frequency for Consumer Electronics (RF4CE) applications. The CC2530 enables robust network nodes to be built with very-low bill-of-material costs. The CC2530 combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8051 MCU, in-system programmable flash memory, 8-KB RAM, and many other powerful features. The CC2530 comes in four different flash versions: CC2530F32/64/128/256, with 32/64/128/256KB of flash memory, respectively. The CC2530 has various operating modes, making it highly suited for systems where ultra-low power consumption is required. Short transition times between operating modes further ensure low energy consumption. Combined with the industry-leading and golden-unit-status ZigBee protocol stack (Z-Stack™) software from Texas Instruments, the CC2530F256 provides a robust and complete ZigBee solution.

2.1.3 TPS54060 Features

The TPS5401 device is a 42-V, 0.5-A, step-down regulator with an integrated high-side MOSFET. Current-mode control provides simple external compensation and flexible component selection. A low-ripple pulse-skip mode reduces the supply current to 116 µA when outputting regulated voltage without a load. Using the enable pin, shutdown supply current reduces to 1.3 µA when the enable pin is low.

Undervoltage lockout is internally set at 2.5 V, but can be increased using the enable pin. The slow-start pin controls the output voltage start-up ramp. The output voltage start-up ramp is controlled by the slow-start pin that can also be configured for sequencing or tracking. In addition, an open-drain power-good signal indicates the output is within 94% to 107% of its nominal voltage

3 System Design Theory

3.1 ESD Introduction

Electrostatic discharge (ESD) is a single-event rapid transfer of electrostatic charge between two objects that are at different voltages. ESD events can have a negative effect on electronic systems such as e-meters. There can be many sources for ESD. For an e-meter in particular, a charged person that is in contact with the meter (such as the operator of a meter) can potentially subject the meter to ESD. Depending on the humidity of the environment, and the material used to charge the charged person, the voltage at which the person is charged varies. Figure 3 shows the electrostatic voltages in relation to the humidity of the environment.

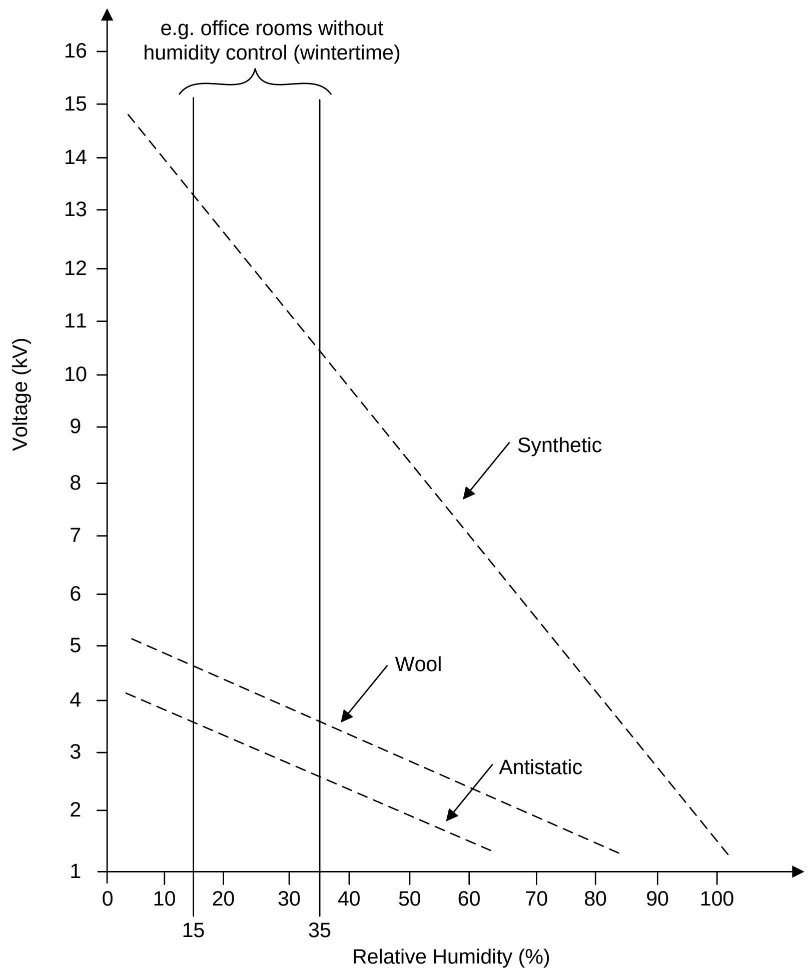


Figure 3. Maximum Values of Electrostatic Voltages People Can Be Charged to When in Contact With Different Materials [1]

Because these devices are used in billing applications and should always remain functional, e-meters must be designed with ESD immunity in consideration. The IEC 62052-11 standard accounts for this consideration by requiring all e-meters that adhere to this standard to pass ESD immunity tests according to IEC 61000-4-2.

The purpose of the IEC 61000-4-2 standard is to ensure that systems are tolerant of ESD exposure that may be present while a system is operating. The scope of the standard is to test electrical and electronic equipment that may be subjected to ESD from operators directly or from personnel to adjacent objects [1]. Depending on the equipment and environment in which the equipment operates, the amount of ESD exposure can vary. The IEC 61000-4-2 defines multiple levels to cover the different types of exposure levels. There are four standard levels; however, depending on special requirements, testing beyond these conditions may be conducted. The level for testing is selected based on the purpose of the implemented system and the environment where the tests are to be deployed. For each test, a special unit (sometimes referred to as an ESD gun), generates an ESD event that is meant to simulate the necessary ESD waveform. Figure 4 shows an example of such an ESD waveform. Figure 5 shows this ESD gun, along with the entire setup for IEC 61000-4-2.

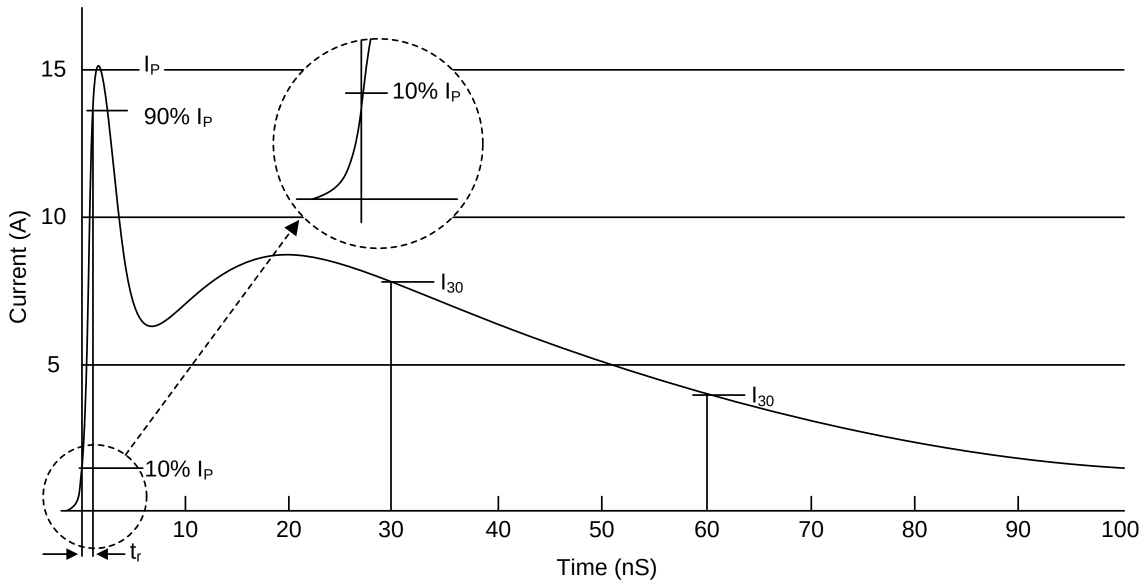


Figure 4. Ideal Contact Discharge Current Waveform at 4 kV (Taken from IEC 61000-4-2) [1]

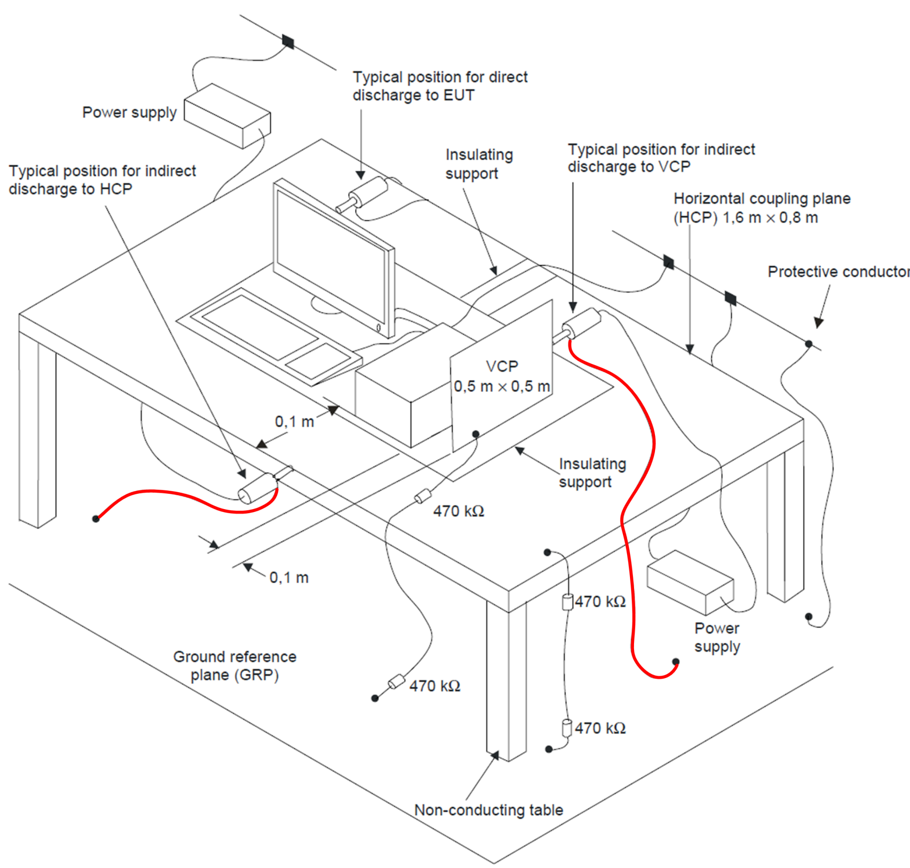


Figure 5. ESD Test Bench for Powered Condition (Taken from IEC 61000-4-2) [1]

For e-meters, IEC 62052-11 specifically mentions that IEC 61000-4-2 should be conducted with contact discharges (if applicable) of 8 kV and air discharges of 15 kV with ten discharge pulses at a rate of 1 Hz. However, based on different region requirements, sometimes a meter may have more stringent requirements and must pass immunity testing at higher ESD voltage levels or larger number of discharge pulses.

3.2 Design Hardware Implementation

3.2.1 Analog Inputs

The MSP430 analog front end consists of ΣΔ ADCs. Each converter is differential and requires that the input voltages at the pins does not exceed ±930 mV (gain = 1) for optimum results. To meet this input voltage specification, the current and voltage inputs must be divided down. In addition, the SD24 allows a maximum negative voltage of −1 V; therefore, AC signals from mains can be directly interfaced without the need for level shifters. This sub-section describes the analog front end used for voltage and current channels.

3.2.1.1 Voltage Inputs

The voltage from the mains is usually 230 V or 120 V and is usually scaled down for optimal accuracy within 930 mV. In the analog front end for voltage, there consists a spike protection varistor, electromagnetic interference (EMI) filter beads (which help for ESD testing), a voltage divider network, and a RC low-pass filter that functions as an anti-alias filter.

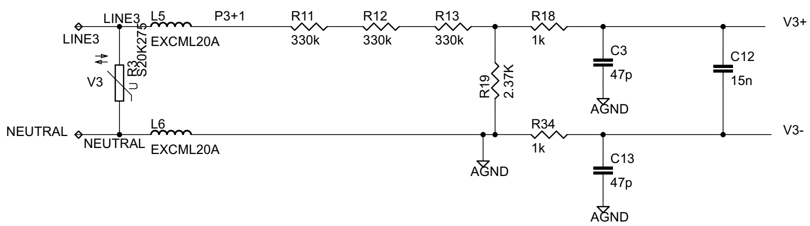


Figure 6. Analog Front End for Voltage Inputs

Figure 6 shows the analog front end for voltage inputs for a mains voltage of 230 V. The voltage is brought down to approximately 549-mV RMS, which is 779 mV at the peak, and fed to the positive input. This voltage is within the MSP430ΣΔ analog limits by a safety margin greater than 15%. This margin allows accurate measurements even during voltage spike conditions. Additionally, it is important to note that the anti-alias resistors on the positive and negative sides are different because the input impedance to the positive terminal is much higher; therefore, a lower value resistor is used for the anti-alias filter. If this is not maintained, a relatively large phase shift occurs.

3.2.1.2 Current Inputs

The analog front-end for current inputs is slightly different from the analog front end for the voltage inputs. Figure 7 shows the analog front end used for a current channel. The analog front end for current consists of diodes and transorbs for transient voltage suppression. In addition, the front-end consists of EMI filter beads (which help for ESD testing), burden resistors for current transformers, and also an RC low-pass filter that functions as an anti-alias filter.

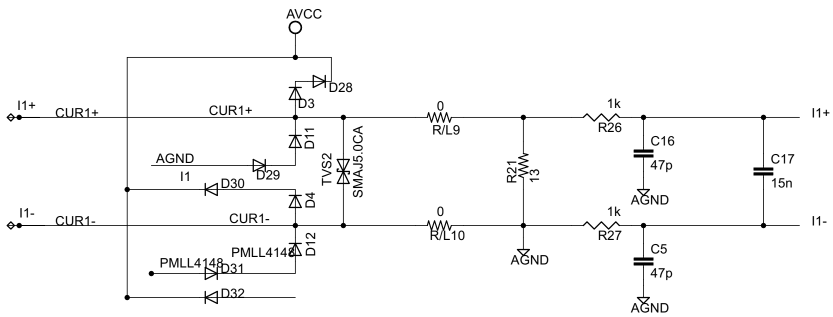


Figure 7. Analog Front End for Current Inputs

As Figure 7 shows, resistor R21 is the burden resistor selected based on the current range used and the turns ratio specification of the CT (this design uses CTs with a turns ratio of 2000:1). The value of the burden resistor for this design is around 13 Ω. The antialiasing circuitry, consisting of resistors and capacitors, follow the burden resistor. Based on this EVMs maximum current of 100 A, CT turns ratio of 2000:1, and burden resistor of 13 Ω, the input signal to the converter is a fully differential input with a voltage swing of ±919 mV maximum when the maximum current rating of the meter (100 A) is applied. In addition, footprints for suppressant inductors are also available. Figure 7 shows these inductor footprints as R/L9 and R/L10, which are populated by default with 0-Ω resistors.

3.2.2 Power Supply

The MSP430 family of microcontrollers support a number of low-power modes in addition to low-power consumption during active (measurement) mode when the CPU and other peripherals are active. Because an energy meter is always interfaced to the AC mains, deriving the DC supply required for the measuring element (MSP430F67791A) is easily derived using an AC to DC conversion mechanism. The reduced power requirements of this device family allow design of power supplies to be small, extremely simple and cost-effective. The power supply allows the operation of the energy meter by being powering it directly from the mains. The next sub-sections discuss the various power supply options that are available to users to support their design.

3.2.2.1 Resistor Capacitor (RC) Power Supply

Figure 8 shows a capacitor power supply that provides a single output voltage of 3.3 V directly from the mains of 120-V to 230-V RMS AC at 50/60 Hz.

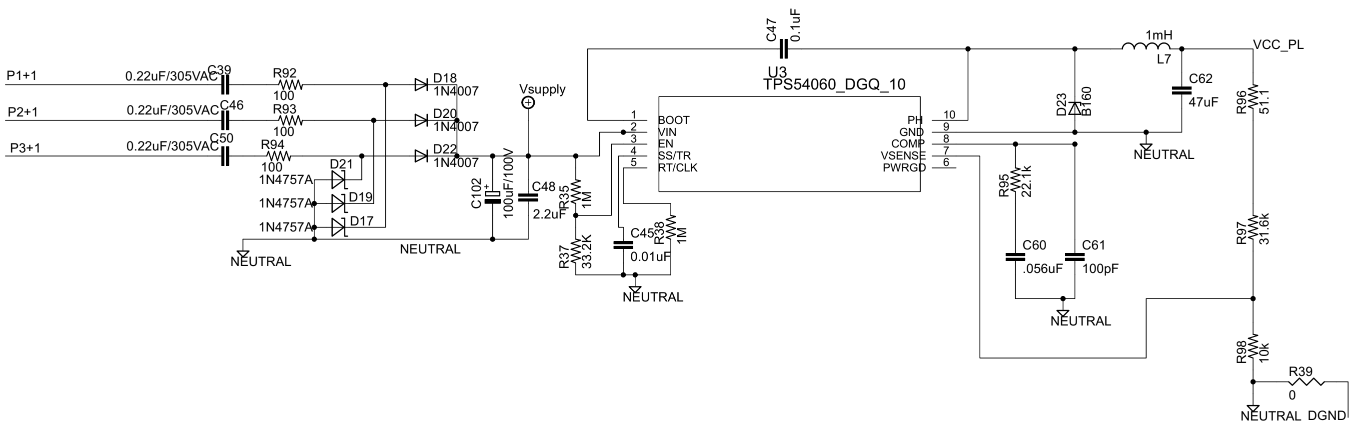


Figure 8. Simple Capacitive Power Supply for the MSP430 Energy Meter

The appropriate values of resistors (R92, R93, and R94) and capacitors (C39, C46, and C50) in Figure 8 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 circuitry to provide a DC voltage for the operation of the MSP430 device. 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* [5].

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 an even higher output drive is required, the same circuitry can be used followed by an NPN output buffer. Another option is to replace the above circuitry with a transformer/switching based power supply.

3.2.2.2 Switching-Based Power Supply

Figure 9 shows a switching-based power supply that provides a single output voltage of 3.3 V directly from the AC mains 100- to 230-V RMS. As the Figure 9 configuration shows, the meter is powered as long as there is AC voltage on Phase C, corresponding to pad “LINE 3" on the hardware and P1/P3+1 on the schematic. The internal circuitry of a switching power supply is omitted from this application note. For the drive of the power supply, refer to the documentation of the power supply module.

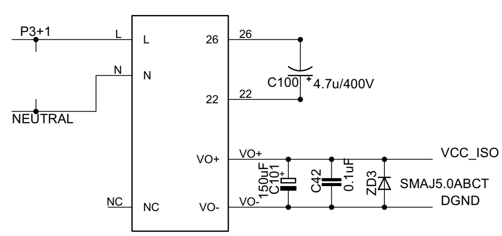


Figure 9. Switching-Based Power Supply for the MSP430 Energy Meter

3.3 Metrology Software Implementation

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

3.3.1 Peripherals Setup

The major peripherals of the MSP430F67791A are the 24-bit sigma delta (ΣΔ24_B) ADC, clock system, timer, LCD, watchdog timer (WDT), and so forth.

3.3.1.1 ΣΔ24 Setup

For a three-phase system, at least six ΣΔs are necessary to independently measure three voltages and currents. The code accompanying this application note addresses the metrology for a three-phase system with limited discussion to anti-tampering; however, the code supports the measurement of the neutral current. The clock to the ΣΔ24 (f_M) is derived from system clock configured to run at 16 MHz. The sampling frequency is defined as $f_s = f_M / OSR$; 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 4096 samples per second. The ΣΔ24s are configured to generate regular interrupts every sampling instant.

The following are the ΣΔ channels associations:

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

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

3.3.1.2 Real Time Clock (RTC_C)

The RTC_C is a real-time clock module that is configured to give precise one second interrupts. Based off these one second interrupts, the time and date are updated in software, as necessary.

3.3.1.3 LCD Controller (LCD_C)

The LCD controller on the MSP430F67791A device can support up to 8-mux displays and 320 segments. The LCD controller 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.

3.3.2 Foreground Process

The foreground process includes the initial setup of the MSP430 hardware and software immediately after a device RESET. Figure 10 shows the flowchart for this process. The initialization routines involve the setup of the ADC, clock system, general purpose input and output (GPIO) port pins, RTC module for clock functionality, LCD, and the USCI_A1 for universal asynchronous receiver and transmitter (UART) functionality. In addition, if ZigBee™ communication is enabled, USCI_A2 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 the processed current, voltage, and active and reactive quantities that have been accumulated for one second. This accumulation is equivalent to the accumulation of 50 or 60 cycles of data synchronized to the incoming voltage signal. In addition, a sample counter keeps tracks 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 data samples set consist of processed current, voltage, active and reactive energy. Processed voltages accumulate in a 48-bit register. 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 calculated values of active and reactive power from the foreground, 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 3.3.2.1.

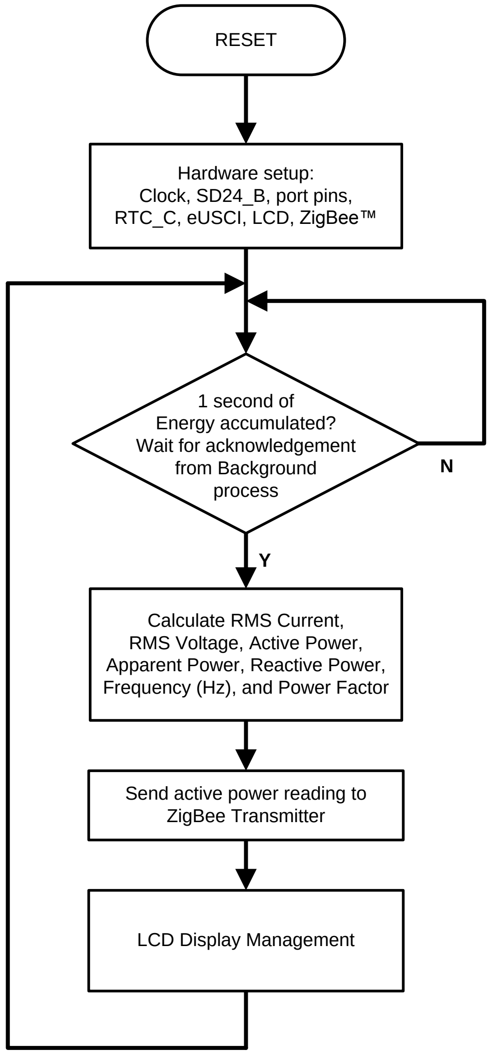


Figure 10. Foreground Process

3.3.2.1 Formulae

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

As described in the previous sections, voltage and current samples are obtained from the ΣΔ converters at a sampling rate of 4096 Hz. All of the samples that are taken in 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:

$$V_{RMS,ph} = K_{v,ph} \times \sqrt{\frac{\sum_{n=1}^{\text{Sample count}} v_{ph}(n) \times v_{ph}(n)}{\text{Sample count}}} \qquad I_{RMS,ph} = K_{i,ph} \times \sqrt{\frac{\sum_{n=1}^{\text{Sample count}} i_{ph}(n) \times i_{ph}(n)}{\text{Sample count}}} \tag{1}$$

where

- ph= Phase whose parameters are being calculated (i.e. 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. (2)

Power and energy are calculated for a 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 via the following formulas:

$$P_{ACT,ph} = K_{ACT,ph} \frac{\sum_{n=1}^{\text{Sample count}} v(n) \times i_{ph}(n)}{\text{Sample count}} \qquad P_{REACT,ph} = K_{REACT,ph} \frac{\sum_{n=1}^{\text{Sample count}} v_{90}(n) \times i_{ph}(n)}{\text{Sample count}} \qquad P_{APP,ph} = \sqrt{P_{ACT,ph}^{2} + P_{REACT,ph}^{2}}$$

where

- v_{90} (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 (3)

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

$$P_{ACT,\,Cumulative} = \sum_{ph=1}^{3} P_{ACT,ph} \qquad P_{REACT,\,Cumulative} = \sum_{ph=1}^{3} P_{REACT,ph} \tag{4}$$

Please note that 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 measurement method specified by IEC and ANSI standards

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Since the frequency of the mains varies, it is important to first measure the mains frequency accurately in order to phase shift the voltage samples accordingly (refer to Section 3.3.3.3 *Frequency measurement and cycle tracking*). 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 fractional delay filter (refer to Section 3.3.3.2 *Phase compensation*).

Using the calculated powers, energies are calculated by the following equations:

$$E_{ACT,\,ph} = P_{ACT,\,ph} \times \text{Sample count}$$
$$E_{REACT,\,ph} = P_{REACT,\,ph} \times \text{Sample count} \quad (5)$$

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

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

The background process calculates the frequency in terms of samples per Mains cycle. The foreground process then converts this to Hertz by the following formula:

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

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:

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

3.3.3 Background Process

The background process uses the ΣΔ interrupt as a trigger to collect voltage and current samples (seven values in total). These samples are used to calculate intermediate results. Since 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. Active power and reactive power are also accumulated in 64-bit registers.

The background function deals mainly with timing critical events in software. Once sufficient samples (approximately one seconds 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/lag conditions. Figure 11 shows the flow diagram of the background process.

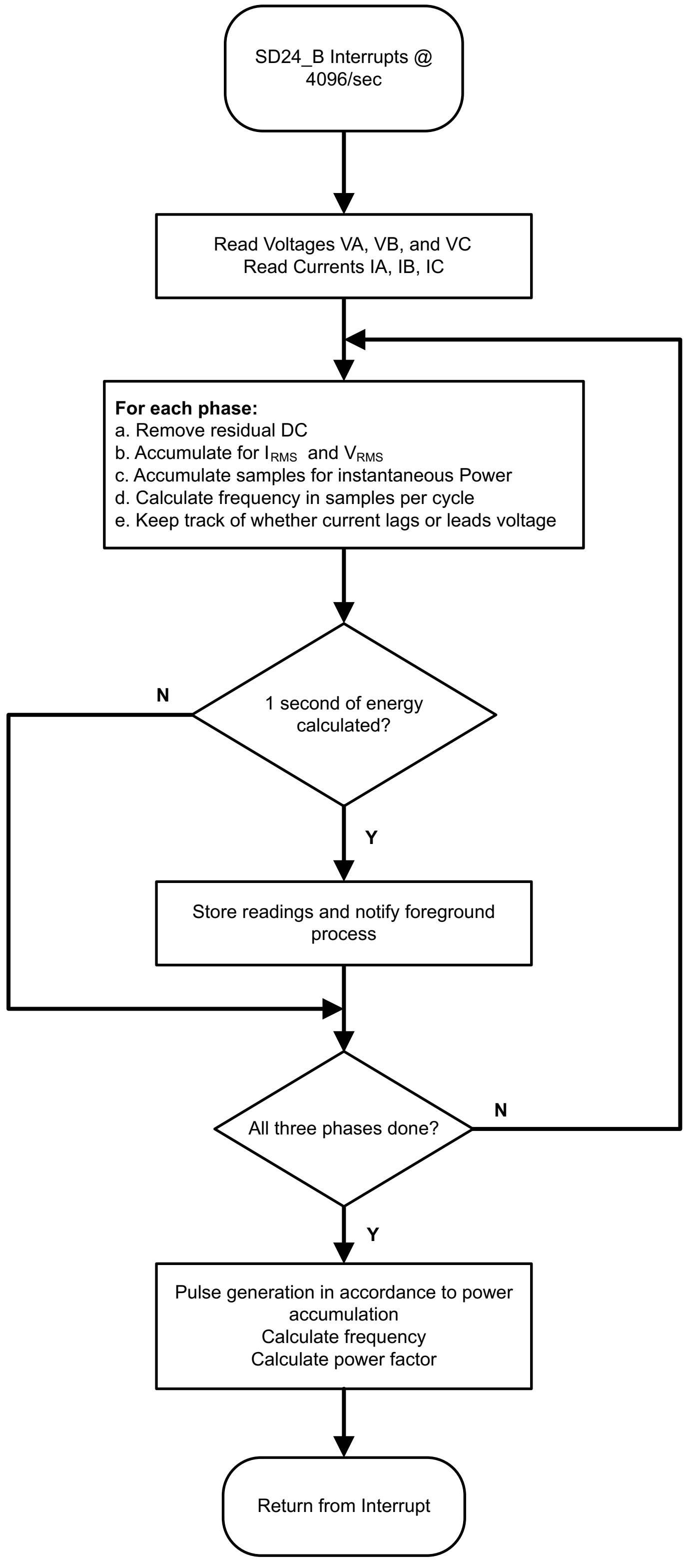


Figure 11. Background Process

3.3.3.1 Voltage and Current Signals

The ΣΔ Converter has fully differential input architecture and each ΣΔ 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 ΣΔ is a signed integer and any stray DC or offset value on these ΣΔs are removed using a DC tracking filter. A separate DC estimate for all voltages and currents is obtained using the filter, voltage, and current samples respectively. This estimate is 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 energy
- Accumulated energy samples using current and 90° phase shifted voltage to calculate reactive energy

The foreground process processes these accumulated values.

3.3.3.2 Phase Compensation

When a current transformer (CT) is used as a sensor, it introduces additional phase shift on the current signals. Also, the passive components of the voltage and current input circuit may introduce another phase shift. The user must compensate the relative phase shift between voltage and current samples to ensure accurate measurements. The ΣΔ converters have programmable delay registers (ΣΔ24PREx) that can be applied to a particular channel. The use of this built-in feature (PRELOAD) is to provide the required phase compensation. Figure 12 shows the usage of PRELOAD to delay sampling on a particular channel.

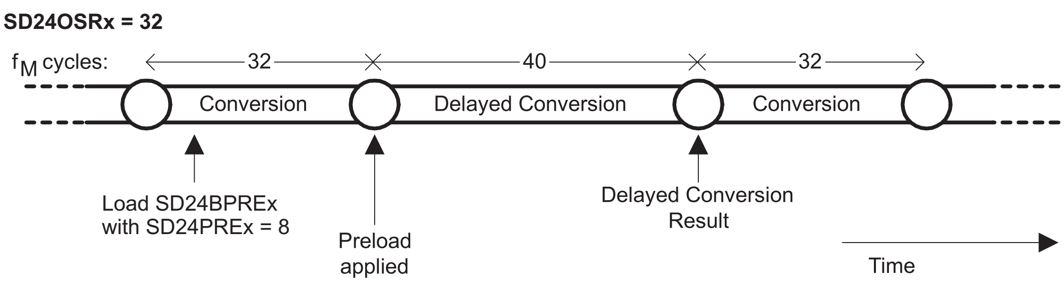


Figure 12. Phase Compensation using PRELOAD Register

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

$$\text{Delay resolution}_{Deg} = \frac{360^o \times f_{IN}}{OSR \times f_S} = \frac{360^o \times f_{IN}}{f_M} \quad (9)$$

In the current application, for an input frequency of 60 Hz, OSR of 256, and sampling frequency of 4096, the resolution for every bit in the preload register is about 0.02° with a maximum of 5.25° (maximum of 255 steps).

3.3.3.3 Frequency Measurement and Cycle Tracking

The instantaneous voltage is accumulated in a 48-bit register. 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 seconds 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 because it produces very stable results.

For frequency measurements, a straight line interpolation is used between the zero crossing voltage samples. Figure 13 shows the samples near a zero cross and the process of linear interpolation.

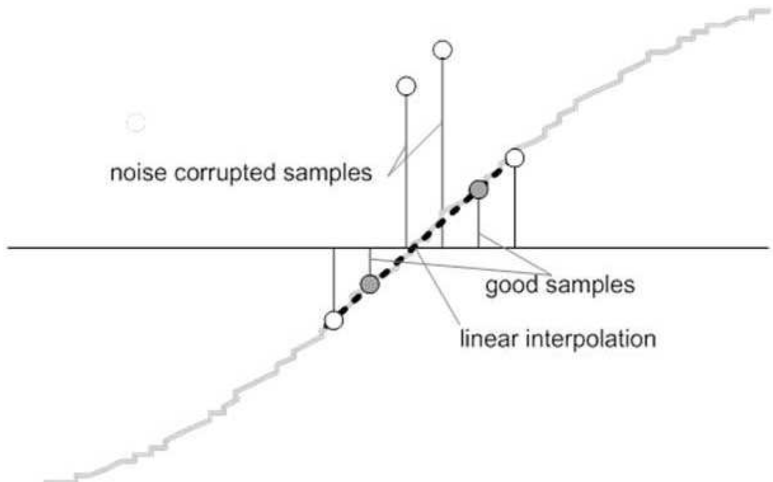


Figure 13. Frequency Measurement

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 genuine zero crossing points. For example, with two negative samples, a noise spike can make one of the samples positive, thereby making the negative and positive pair appear as if there is a zero crossing.

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

3.3.3.4 LED Pulse Generation

In electricity meters, the energy consumption of the load is normally measured in a fraction of kilowatt-hour (KWh) pulses. This information can be used to accurately calibrate any meter for accuracy measurement. Typically, the measuring element (MSP430) is responsible for generating pulses proportional to the energy consumed. Although, time jitters are not an indication of bad accuracy, time jitters give a negative indication of the overall accuracy of the meter. The jitter must be averaged out due to this negative indication of accuracy.

This application uses average power to generate these energy pulses. The average power (calculated by the foreground process) accumulates at every ΣΔ interrupt, thereby spreading the accumulated energy from the previous one-second time frame evenly for each interrupt in the current one-second time frame. This accumulation process is equivalent to converting power to energy. Once 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 the threshold in the next interrupt cycle. Because the average power tends to be a stable value, this way of generating energy pulses is very steady and free of jitter.

The threshold determines the energy “tick” specified by meter manufacturers and is a constant. The “tick” is usually defined in pulses/kWh or just in KWh. One pulse must be generated for every energy “tick”. For example, in this application, the number of pulses generated/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 through light-emitting diodes (LEDs) on the board. GPIO pins are used to produce the pulses. Figure 14 shows the flow diagram for pulse generation.

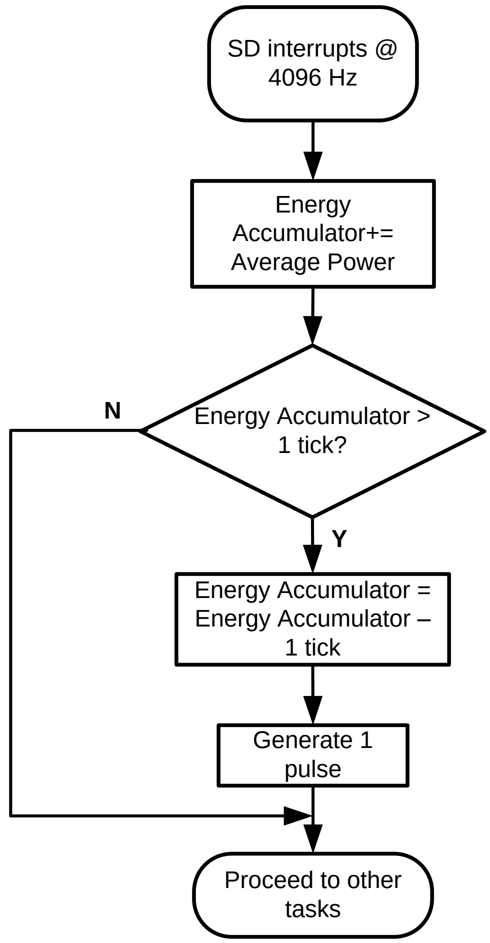


Figure 14. Pulse Generation for Energy Indication

The average power is in units of 0.01 W and a 1-KWh threshold is defined as:

1-KWh threshold = 1 / 0.01 × 1 KW × (Number of interrupts/sec) × (Number of seconds in 1 hour) = 100000 × 4096 × 3600 = 0x15752A00000

3.4 ESD Testing Software

When exposing equipment to ESD testing, failures can be classified into three categories:

- Temporary loss of function or degradation of performance that ceases after the disturbance ceases. The equipment under test recovers its normal performance without operator intervention. This is an acceptable failure for an e-meter in IEC 62052-11, assuming the energy readings were not affected by an amount greater than a certain threshold.
- Temporary loss of function or degradation of performance. Recovery requires operator intervention.
- Temporary loss of function or degradation of performance that is not recoverable.

To better diagnose ESD failures from passes (and also distinguish the different failures into the three types of failures), a separate code example was loaded on the MSP430F67791A when performing ESD testing. In this code example, the RST/NMI pin is configured to NMI mode. Additionally, whenever a brownout reset occurs, the red light of the EVM blinks three times before staying ON. Afterward, the green LED of the EVM constantly blinks. If this green LED stops blinking, this indicates that the meter has temporarily stopped working. If the red LED starts blinking again after previously being ON, then a brownout reset event has reoccurred.

4 Getting Started

4.1 Hardware

For testing this design, the EVM430-F6779 is used and its MSP430F67791 is replaced with a MSP430F67791A. The following figures of the EVM best describe the hardware: Figure 15 is the top view of the energy meter and Figure 16 then shows the location of various pieces of the EVM based on functionality.

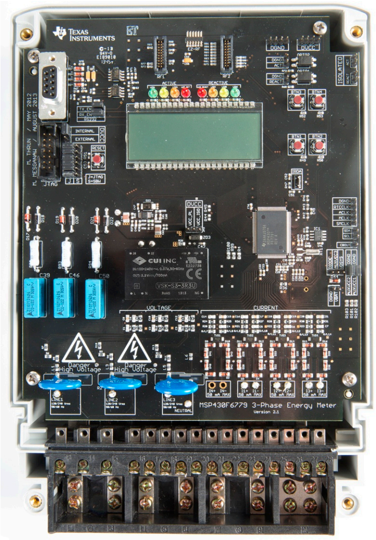


Figure 15. Top View of the Three Phase Energy Meter EVM

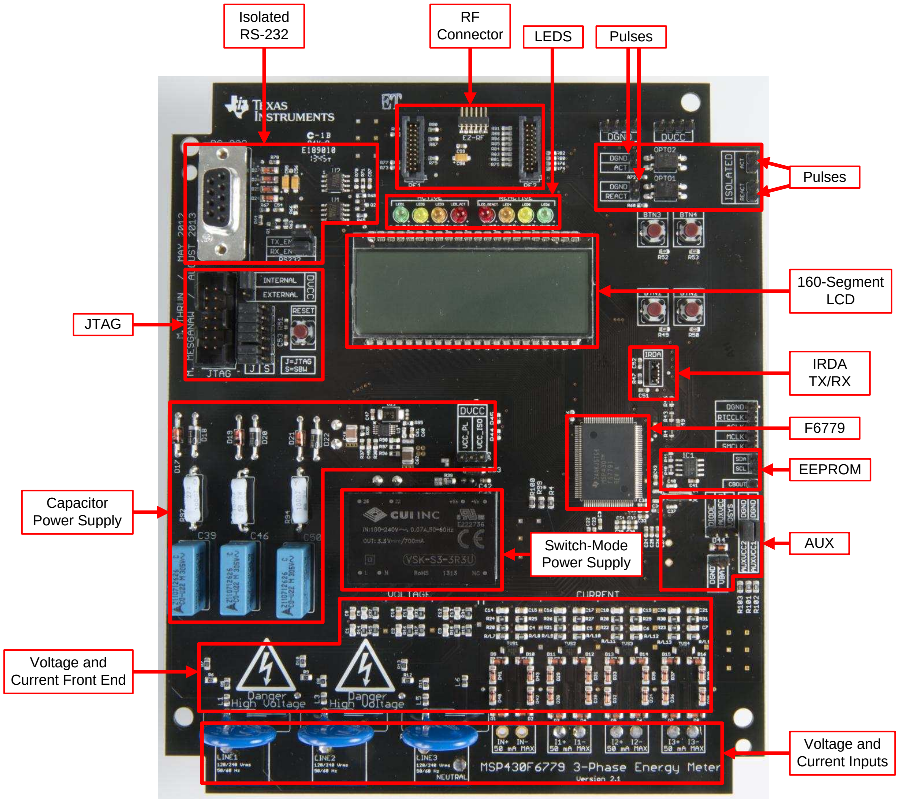


Figure 16. Top View of the Three Phase Energy Meter EVM with Components Highlighted

4.1.1 Connections to the Test Setup for AC Voltages

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 must not exceed 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 the voltages 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 the voltages 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 the voltages across I3+ and I3- does not exceed 930mV. *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 the voltages across IN+ and IN– does not exceed 930 mV. *This is currently NOT connected to a CT on the EVM*.

Figure 17 and Figure 18 show the various connections that must be made to the test setup for proper functionality of the EVM. When a test AC source must be connected, the connections have to be made according to the EVM design. Figure 17 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 18 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 phases B; 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 EVM obtained from Texas Instruments does not have a sensor connected to the neutral ADC channel.

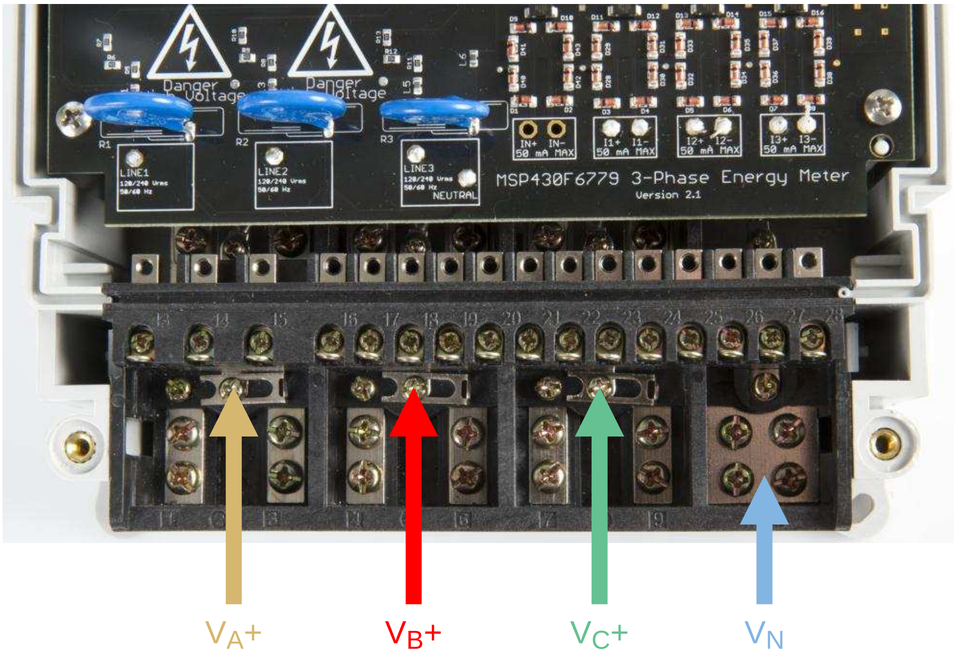


Figure 17. Top View of the EVM With Test Setup Connections

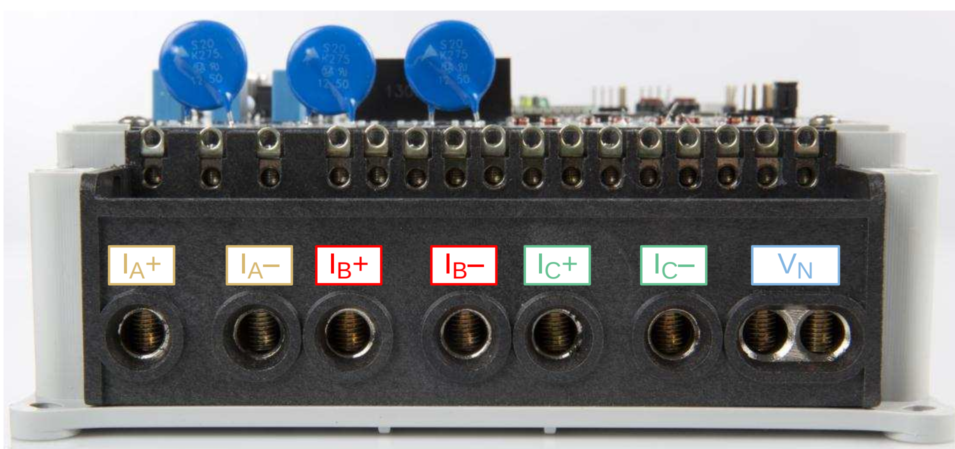


Figure 18. Front View of the EVM With Test Setup Connections

4.1.2 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

HEADER AND 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 will have to 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 Isolated ACT 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 back-up power supply to the MSP430. To do so, simply 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 super capacitor.	--
AUXVCC2 (not isolated, do not probe)	2-pin jumper/ header	AUXVCC2 selection and 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 back-up power supply to the MSP430. To do so, simply connect the alternative power supply to this header and configure the software to use this backup power supply as needed.	
AUXVCC3 (not isolated, do not probe)	2-pin jumper/ header	AUXVCC3 selection and external power **(WARNING)**	To power the RTC externally regardless of whether 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 (continued)

HEADER AND 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 pption **(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 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 has 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.
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

Table 1. Header Names and Jumper Settings (continued)

HEADER AND HEADER OPTION NAME	TYPE	MAIN FUNCTIONALITY	VALID USE-CASE	COMMENTS
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 Isolated REACT 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 will have to be modified to output RTCCLK.
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 that jumpers must be placed at to select a JTAG communication. 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	I^2C / 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	I^2C / 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 will have to 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 could still be powered when the voltage at DVCC is removed.	--

4.2 Firmware

The source code is developed in the IAR environment using the IAR Embedded Workbench® Integrated Development Environment (IDE) Version 6.30.1 for the MSP430 IDE and Version 7.2.0.3640 for IAR common components. Earlier versions of IAR cannot open the project files. When the project is loaded in IAR version 6.x or later, the IDE may prompt the user to create a backup. Click “YES” to proceed. There are three 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 and application code that is used for the host-processor functionality of the meter (that is communication, LCD display, RTC setup, and so forth)
- The GUI that is used for calibration

Figure 19 shows the contents of the source folder.

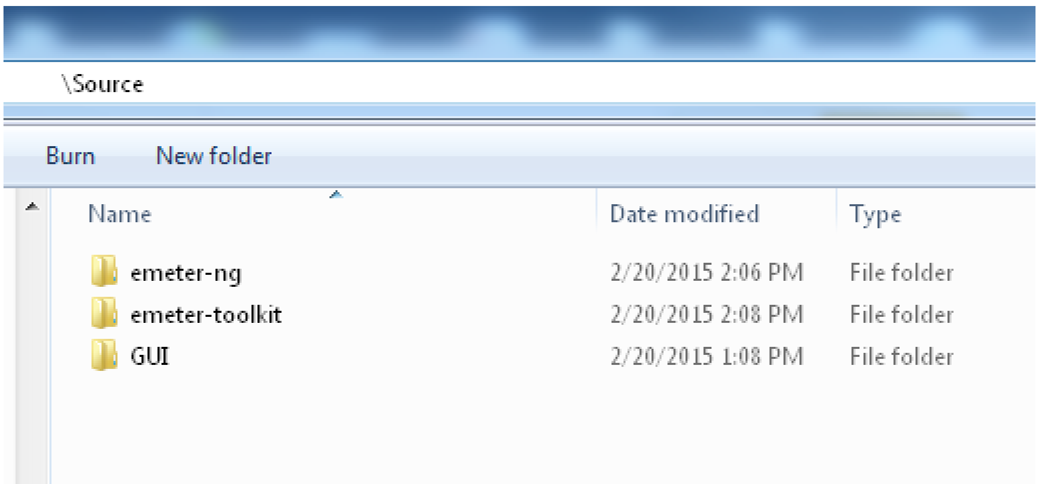


Figure 19. Source Folder Structure

The *emeter-ng* folder contains multiple project files and for this application, the *emeter-6779A.ewp* project file is to be used. The folder *emeter-toolkit* has corresponding project file *emeter-toolkit-6779A.ewp*. For first time use, TI recommends completely rebuilding both of the projects by performing the following steps:

1. Open the IAR IDE.
2. Load the *emeter_toolkit_6779A.ewp* project.
3. Click the *Rebuild All* option as shown in Figure 20.
4. Close the existing workspace and open the main project *emeter-6779A.ewp*.
5. Click *Rebuild All* (see Figure 21) and load this project onto the MSP430F67791A.

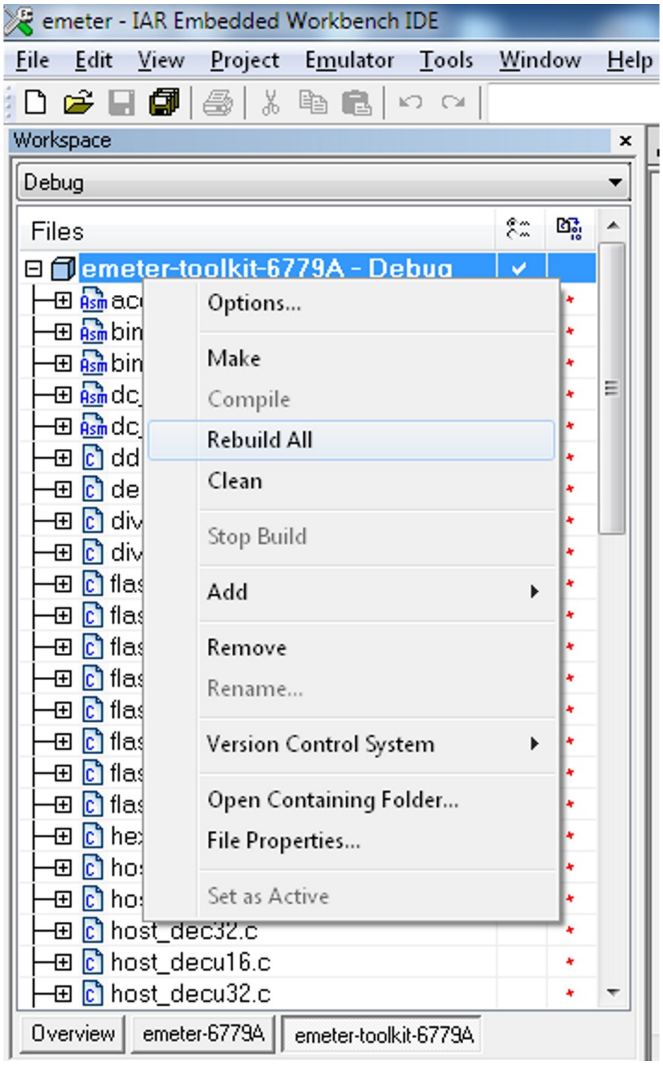


Figure 20. Toolkit Compilation in IAR

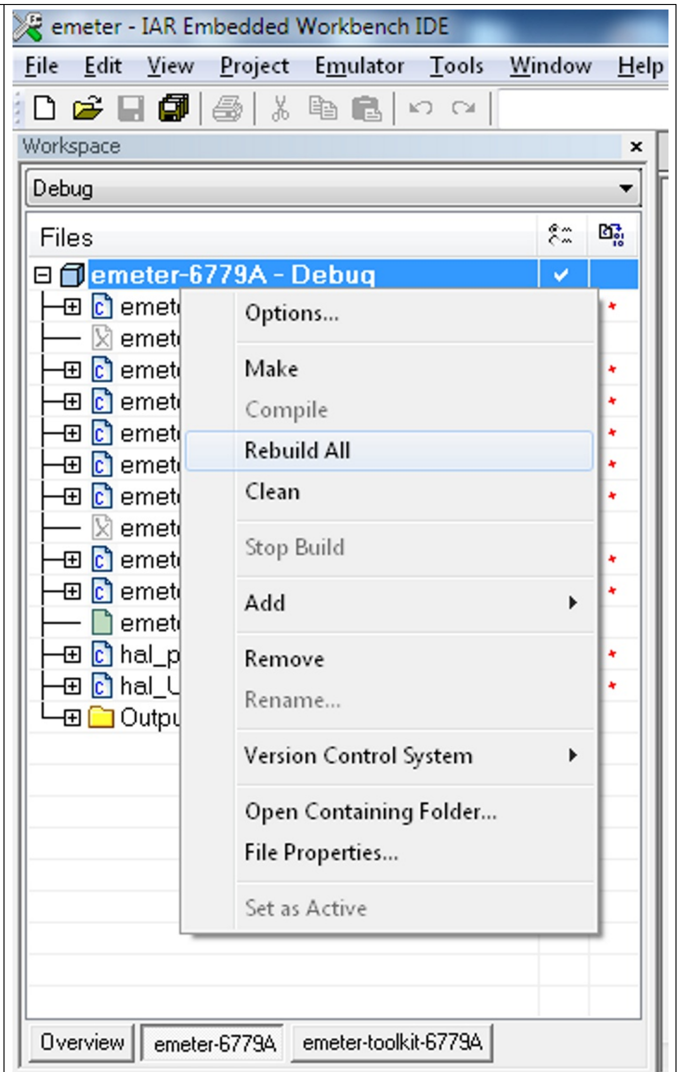


Figure 21. Metrology Project Build in IAR

5 Test Setup

5.1 Metrology Test Setup

For performing metrology testing, a source generator was used to provide the voltage and current to the meter at the proper locations (see Section 4.1.1). The design tests used a nominal voltage of 230 V, calibration current of 10 A, and nominal frequency of 50 Hz. In the tests, current is varied from 50 mA to 100 A. For each current, a phase shift of 0°, 60°, and −60° is applied between the voltage and current.

When voltage and current are applied to the meter, the meter outputs active energy pulses at a rate of 6400 pulses/kWh. This pulse output feeds into a reference meter that determines the active energy % error (for the equipment used in this test, the reference meter was integrated in the same equipment used for the source generator). The active energy % error is based on the actual energy provided to the meter and the measured energy as determined by the active energy output pulse of the meter. Based on this energy pulse measurement, a plot of active energy % error versus current is created for 0°, 60, and -60° phase shifts as shown in Section 7.2.

5.2 ESD Test Setup

When performing ESD testing, both a MSP430F67791-based meter and MSP430F67791A-based meter were tested to show the ESD improvements of the MSP430F67791A. Both meters use the same board (EVM430-F6779). The only differences between the meters would be whether a MSP430F67791 or MSP430F67791A was actually populated on the boards. Although this test shows the comparative behavior of the MSP430F67791 against the MSP430F67791A, please note that ESD testing for e-meters is a system-level test. Therefore, improvements from selecting the MSP430F67791A varies based on layout and overall system design. Adhering to good ESD layout guidelines allows for maximum ESD immunity. The presence of the MSP430F67791A cannot compensate for significant design weaknesses because the ESD testing is on a system level.

Each meter was tested by applying discharges on the coupling plane. The discharge was applied in the same location for both meters. For each test point, ten strikes were applied. The tested ESD voltages were 2 kV to kV in 2-kV increments with both positive and negative polarity.

To easily diagnose the state of the MSP430F67791A device when performing ESD testing, the EVM was loaded with software performing the functions in Section 3.4. Using the software, the state of the MSP430F67791A can be determined from the EVM's LEDs. In addition, the current drawn by the microcontrollers were monitored to determine between latch-up or lock-up conditions.

Section 7.1 shows the results of these ESD tests.

6 Viewing Metrology Readings and Calibration

The values of the metrology parameters can be viewed on the LCD or the GUI. In addition, the active power reading can be viewed from an in-home display that communicates with the meter through ZigBee.

6.1 Viewing Results Through LCD

The LCD display scrolls between metering parameters approximately every two seconds. For each metering parameter that shows on the LCD, three items are actually displayed on the screen: the corresponding phase of the parameter, a 1 or 2 character symbol, which is used to distinguish the parameter being displayed and the actual value of that parameter. The phase of the parameter displays 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 shows on the left side of the second line of the LCD. The actual value of the parameter shows just to the right of the parameter symbol. 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 in Table 2 shows which characters correspond to which metering parameter. The COMMENTS column of Table 2 provides a brief interpretation of the displayed metering parameters.

Table 2. Displayed Parameters

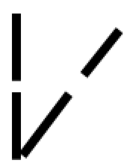
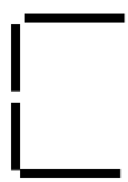
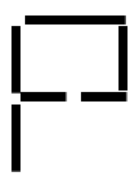
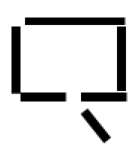
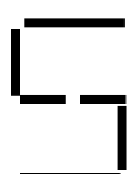
PARAMETER NAME	SYMBOL	UNITS	COMMENTS
Voltage		Volts (V)	--
Current		Amps (A)	--
Active power		Watt (W)	--
Reactive power		Volt-ampere reactive (var)	--
Apparent power		Volt-ampere (VA)	--

Table 2. Displayed Parameters (continued)

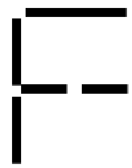
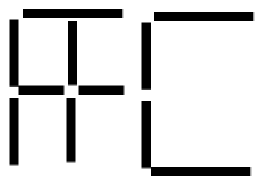
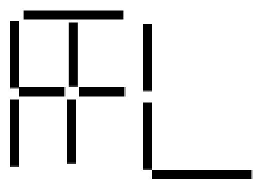
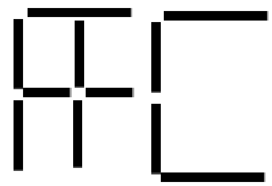
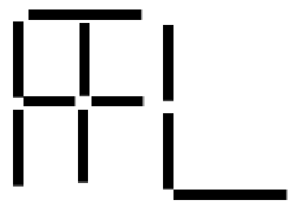
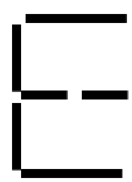
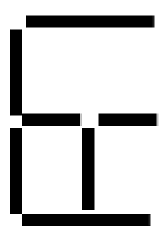
PARAMETER NAME	SYMBOL	UNITS	COMMENTS
Frequency		Hertz (Hz)	--
Power factor	 or 	Constant between 0 and 1	The characters  are used if the load is determined to be a capacitive load. The characters  are used if the load is determined to be an inductive load.
Total consumed active energy		100 “ticks”	Every 10 ticks increments the tenths place by 1.
Total consumed reactive energy		100 “ticks”	Every 10 ticks increments the tenths place by 1.

Figure 22 shows an example of phase A’s measured frequency of 49.99 Hz being displayed on the LCD.

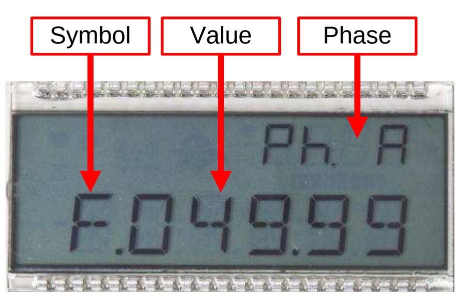


Figure 22. LCD Display

6.2 Viewing Results Using RF Technology (ZigBee)

The CC2530 Evaluation Module (EM) is an add-on and plug-in daughter card for ZigBee and IEEE 802.15.4 radio frequency (RF) applications in the 2.4-GHz, unlicensed industrial, scientific, and medical (ISM) band (see Figure 23). The communication interface to any host/application processor is through UART. The instantaneous power consumption sends periodically to the ZigBee module for wireless transmission.

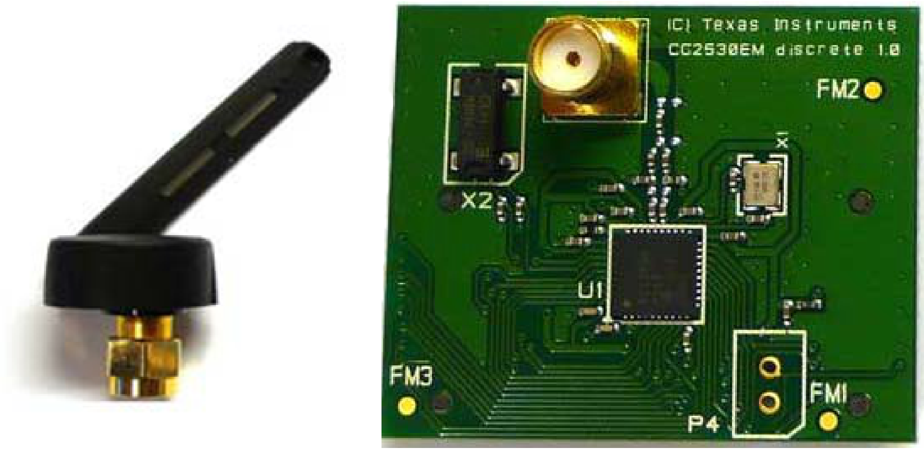


Figure 23. ZigBee Radio

This ZigBee module connects through the UART, which is configured to 115.2 kbaud on the transmit portion of the MSP430F67791A and the receive portion of the MSP430F4618 (IHD430).

6.2.1 In-Home Display

Most IHDs have their own setup mechanism and all of them tend to join the ZigBee network when turned ON. This section describes the in-home display using TI's IHD430 (TIDM-LOWEND-IHD), which Figure 24 shows. The IHD430 has an MSP430F461x device as an application/host processor.

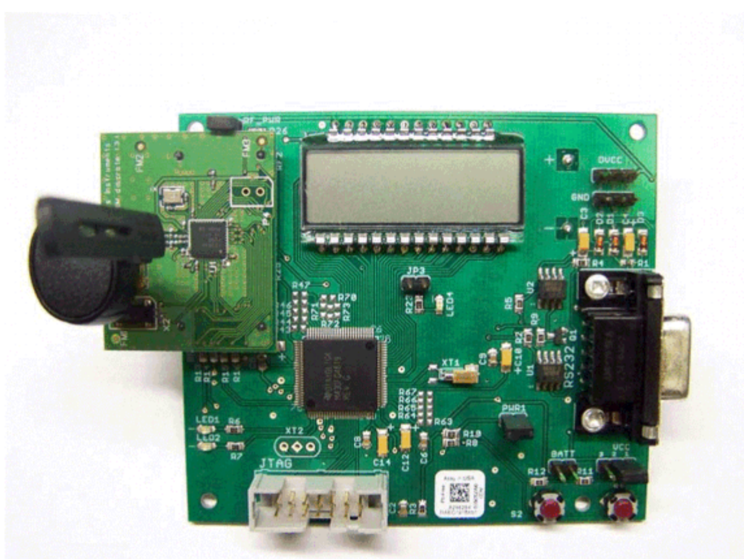


Figure 24. TIDM-LOWEND-IHD

Viewing active power readings on the IHD430

Place a CC2530 module in the RF connector socket of the meter EVM430-F6779, making sure that the module is properly oriented. This CC2530 is flashed with code to act as a transmitter. The IHD430 also has a corresponding CC2530 module that has been flashed to act as a receiver.

Initializing the IHD430

Power must be provided by 2 AAA batteries or an external supply. The power source is selected by configuring jumpers on the VCC and BATT headers and the power is supplied to the on-board MSP430 by placing a jumper on the PWR1 header. The power setup options are provided in the following list.

1. Jumper settings to provide battery power are:
   (a) Place jumper on BATT header
   (b) Place jumper on PWR1 header
2. Jumper settings to provide flash emulation tool power are:
   (a) Place jumper on pins [1-2] on VCC 3-pin header
   (b) Place jumper on PWR1 header
3. Jumper settings to provide external power are:
   (a) Place jumper on pins [2-3] on VCC 3-pin header
   (b) Place jumper on PWR1 header
4. Ensure jumper is placed on RF_PWR header, which has been provided to enable and disable power to CC2530

The “IHD430_SUPPORT” macro must be defined in the *emeter-3ph-neutral-6779(A).h* file for the MSP430F67791A software to communicate the active power to the IHD430. When this macro is enabled, the active power reading sends to the on-board CC2530 transmitter through 8N1 UART communication at a baud rate of 115.2 k. The CC2530 then sends the data to the CC2530 receiver. The IHD430 receives the active power readings and displays it on the LCD. Please note, the transmitter (meter) must be turned ON before the receiver to ensure proper ZigBee communication. In addition, modifications can be made to the MSP430F67791A software to send different parameters for display onto the IHD430.

6.3 Calibrating and Viewing Results Through PC

6.3.1 Viewing Results

To view the metrology parameter values through the GUI, utilize the following steps:

1. Connect the EVM to a PC through an RS-232 cable.
2. Open “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 25, this field shows COM2.

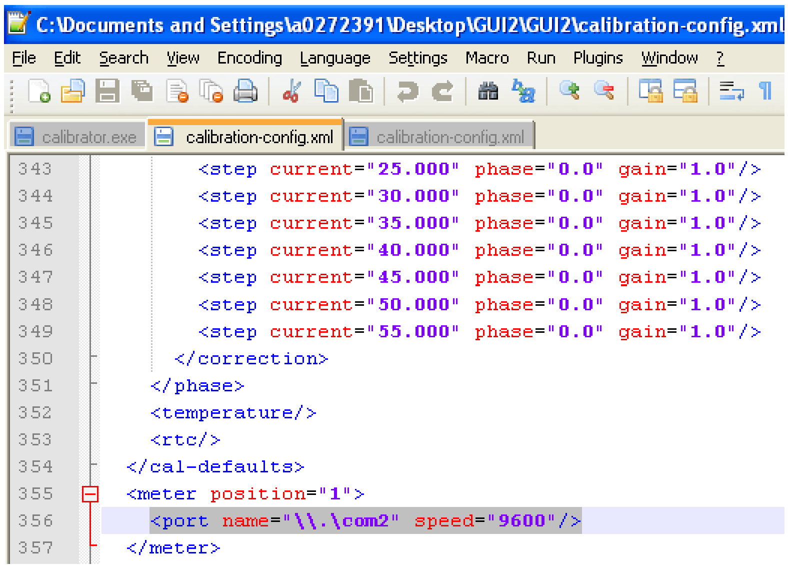


Figure 25. GUI Config File Changed to Communicate With Meter

4. Run calibrator.exe, which is located in the GUI folder. If the COM port in calibration-config.xml has been changed in the previous step to the COM port connected to the EVM, the GUI opens (see Figure 26). If the GUI connects properly to the EVM, the top left button is green. The button is red if there are problems with connections or if the code is not configured correctly. Click the green button to view the results.

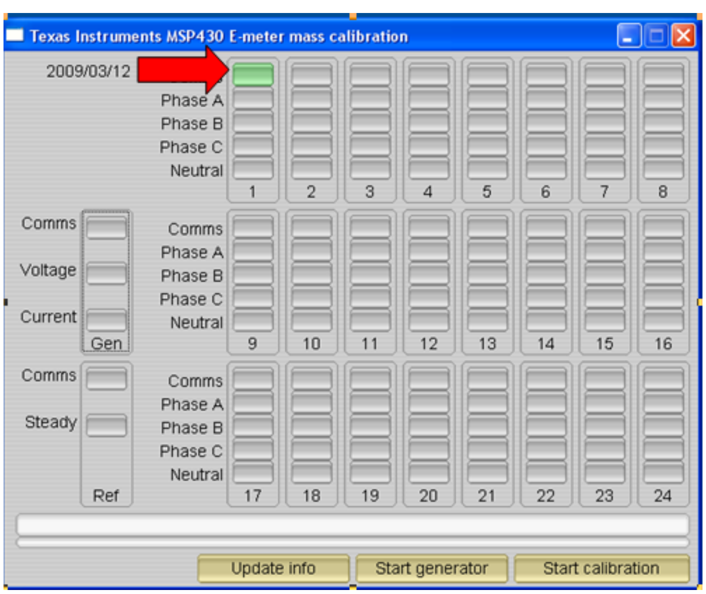


Figure 26. GUI Startup Window

Upon clicking on the green button, the results window opens (see Figure 27). In Figure 27, there is a trailing "L" or "C" on the "Power factor" values to indicate an inductive or capacitive load, respectively.

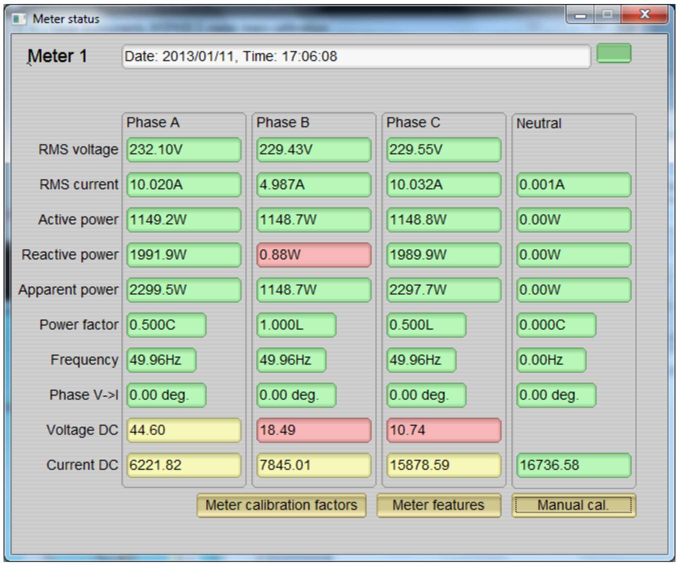


Figure 27. GUI Results Window

From the GUI results window, the user can either view the meter settings by clicking the“Meter features” button, view the meter calibration factors by clicking the “Meter calibration factors” button, or open the window used for calibrating the meter by clicking the “Manual cal.” button.

6.3.2 Calibration

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

The GUI used for viewing results can easily be used to calibrate the EVM. Parameters called calibration factors are modified in the software during the calibration to give the 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, current, 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. The GUI modifies these values during calibration. The calibration factors are stored in INFO_MEM and they remain the same if the meter is restarted. However, if code is re-flashed during debugging operations, the calibration factors are replaced and the meter must be recalibrated. One way to save the calibration values is by clicking on the “Meter calibration factors” button (Figure 27). The meter calibration factors window Figure 28) shows the latest values. This information could be used to directly replace the macro definition of these factors in the source code.

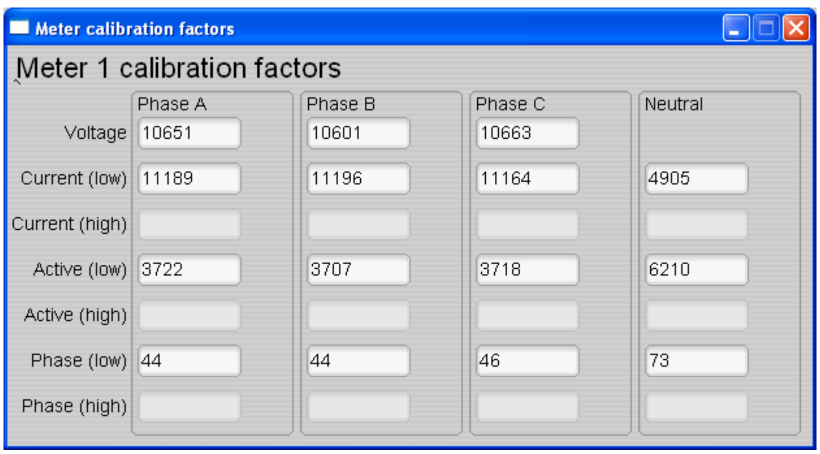


Figure 28. Calibration Factors Window

Calibrating any of the scaling factors is referred to as gain correction. Calibrating the phase compensation factors is referred to as phase correction. For the entire calibration process, the AC test source must be ON, meter connections consistent with *Section 4.1.1*, and the energy pulses must be connected to the reference meter.

6.3.2.1 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 required for gain correction of active power parameters. Also, when performing active power calibration for any given phase, the other two phases must be turned OFF. Typically just switching the currents OFF is sufficient for disabling a phase.

6.3.2.1.1 Voltage and Current Gain Calibration

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

1. Connect the GUI to view results for voltage, current, active power, and the other metering parameters.
2. Configure the test source to supply desired voltage and current for all phases. Ensure that these are the voltage and current calibration points with a zero-degree phase shift between the voltage and current (for example 230 V, 10 A, 0º (PF = 1). Typically, these values are the same for every phase.
3. Click on “Manual cal.” button (see Figure 27). The following screen pops up on the display Figure 29:

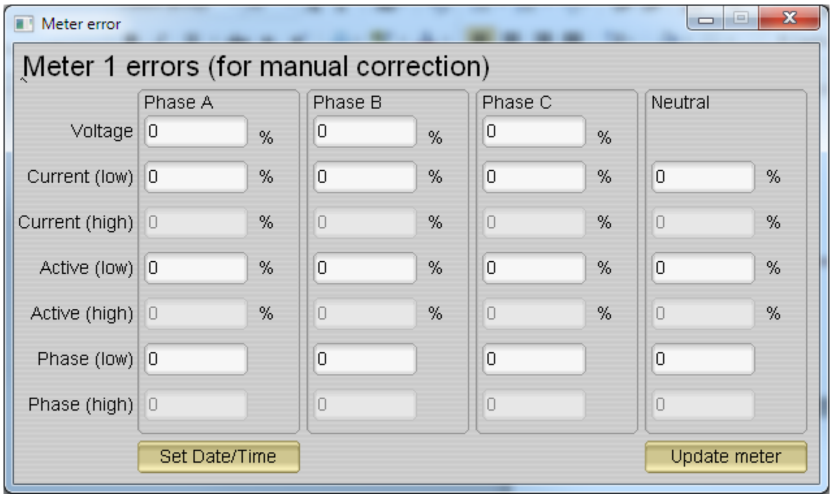


Figure 29. Manual Calibration Window

4. Calculate the correction values for each voltage and current. The correction values that must be entered for the voltage and current fields are calculated 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. (10)

5. After calculating for all voltages and currents, input these values as is (±) for the fields “Voltage” and “Current (low)” for the corresponding phases.
6. Click on “Update meter” and the observed values for the voltages and currents on the GUI update gradually to the desired voltages and currents.

6.3.2.1.2 Active Power Gain Calibration

After performing gain correction for voltage and current, gain correction for active power must be done. Gain correction for active power is done differently in comparison to voltage and current. Although, conceptually, calculating 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 get the Correction(%) is directly from the reference meters measurement error of the active power. This error is obtained by feeding energy pulses to the reference meter. To perform active power calibration, utilize the following steps:

1. Turn off the meter and connect the meters 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 the previous Section 6.3.2.1.1 with the identical voltages, currents, and 0º phase shift that were used in the previous section.
4. Obtain the % error in measurement from the reference meter. Note that this value may be negative.

5. 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 value and does not need to be calculated.
6. Click on “Update meter” and the error values on the reference meter would immediately settle to a value close to zero.

6.3.2.2 Phase Correction

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 to a non-zero value; typically, +60º is chosen. The reference meter now displays 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:
   (a) Enter a value as an update for “Phase (Low)” field . Usually, a small ± integer should be entered to bring the error closer to zero. Additionally, for a phase shift greater than 0 (for example: +60º), a positive (negative) error would require a positive (negative) number as correction.
   (b) Click on “Update meter” and monitor the error values on the reference meter.
   (c) If this measurement error (%) is not accurate enough, fine tune by incrementing/decrementing by a value of one based on the previous Steps 4a and 4b. Please note, after a point, the fine-tuning only results in the error oscillating on either side of zero. The value that has the smallest absolute error must be selected.
   (d) Change the phase now to –60° and check if this error is still acceptable. Ideally, errors must be symmetric for same phase shift on lag and lead conditions.

After performing phase correction, calibration is complete for one phase. Please 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. The new calibration factors as shown in Figure 30 can be viewed by clicking the “Meter Calibration factors” button of the GUI metering results window in Figure 27.

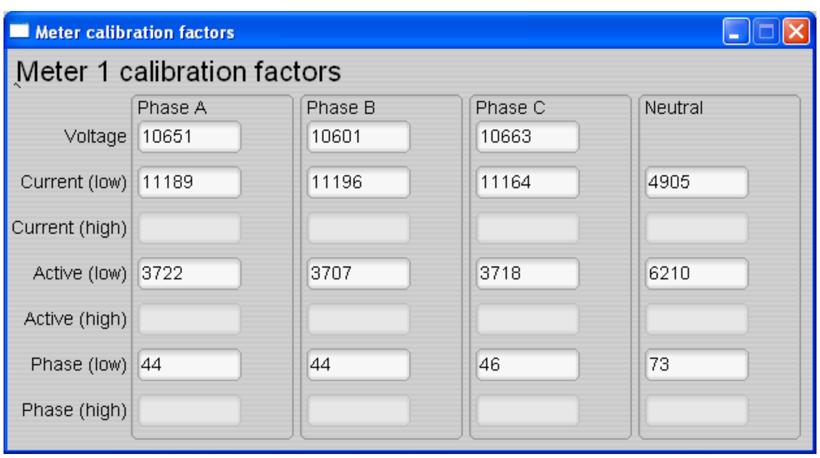


Figure 30. Calibration Factors Window

The configuration of the meter can be viewed by clicking on the “Meter features” button to access screen that Figure 31 shows.

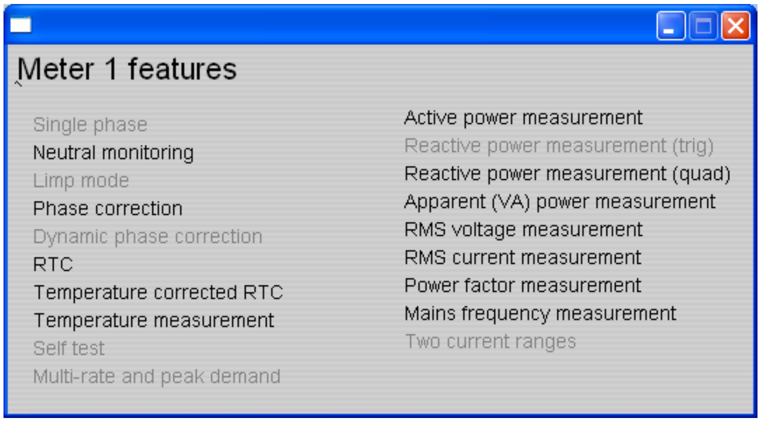


Figure 31. Meter Features Window

7 Test Data

7.1 ESD Results

To test the comparative ESD robustness between the MSP430F67791A and MSP430F67791, an IEC 61000-4-2 test was performed on one EVM430-F6779 that had the MSP430F67791A as the metering SoC and another EVM430-F6779 that had the non-A MSP430F67791 as the metering SoC. Please note that for the EVM430-F6779, some ESD tradeoffs were made to fully support showcasing the features of the silicon and ease-of-use for evaluation purposes. However, the EVM can still be used as a gauge to show the improvements in using the MSP430F67791A devices instead of the MSP430F67791.

For applying the ESD test on the two test EVMs, both positive and negative polarity discharges were applied on both test boards at the same location. In the tests, recoverable failures (a reset, for example), lock-ups, and latch-ups were logged as failures. Table 3 shows the results of these tests. In these tests, voltage levels where both positive and negative polarity tests passed are colored green, tests where only either positive or negative polarity tests passed are colored yellow, and tests where both positive and negative polarity tests failed are colored red.

Table 3. 2 IEC 61000-4-2 Test Results for MSP430F67791 and MSP430F67791A

TEST VOLTAGE	F67791 RESULTS (+POLARITY/ –POLARITY)	F67791A RESULTS (+POLARITY/ –POLARITY)
1 kV		Pass/Pass
2 kV	Pass/Pass	Pass/Pass
4 kV	Pass/Pass	Pass/Pass
6 kV	Pass/Pass	Pass/Pass
8 kV	Pass/Pass	Pass/Pass
10 kV	Fail/Pass	Pass/Pass
12 kV	Fail/Fail	Pass/Pass
14 kV		Pass/Pass
16 kV		Pass/Pass
18 kV		Pass/Pass
20 kV		Pass/Pass

From these results, there is a clear improvement in selecting the MSP430F67791A devices over the MSP430F67791. The MSP430F67791A chips pass up to 20 kV at the location tested, which is an improvement by 8 kV to 10 kV.

7.2 Metrology Result Comparison

Regardless of the improvements made in the MSP430F67791A, metrology performance is still comparable to the non-A MSP430F67791. To show this, an EVM430-F67791 was tested with a MSP430F67791 and a MSP430F67791A. The results for these tests are in Table 4, Figure 32, and Figure 33. These results show that the MSP430F67791A can still meet the class 0.2% accuracy requirements fulfilled by the non-A MSP430F67791.

Table 4. Active Energy % Error for MSP430F67791 and MSP430F67791A

CURRENT (Amps)	MSP430F67791			MSP430F67791A		
	0°	60°	–60°	0°	60°	–60°
0.05	–0.043	–0.086	–0.076	–0.011	–0.024	–0.08
0.1	–0.053	–0.019	–0.068	–0.005	0.077	–0.079
0.25	–0.028	–0.03	–0.057	–0.018	0.005	–0.078
0.5	–0.014	–0.018	–0.04	–0.027	–0.009	–0.058
1	–0.01	–0.004	–0.022	–0.015	0	–0.04
2	–0.0206667	–0.00166667	–0.039	–0.029	0.00166667	–0.0543333
5	–0.018	–0.015	–0.0123333	–0.0216667	–0.0113333	–0.0296667
10	–0.00733333	–0.0233333	0.0143333	–0.0126667	–0.017	–0.00833333
20	–0.00833333	–0.042	0.028	–0.010667	–0.0273333	0.00666667
30	–0.000333333	–0.0646667	0.062	–0.005	–0.043	0.0393333
40	–0.003	–0.091	0.078	–0.00233333	–0.0606667	0.0563333
50	–0.0143333	–0.122	0.0983333	–0.008	–0.101333	0.0786667
60	–0.009	–0.135	0.11333	–0.0106667	–0.113333	0.0863333
70	–0.0123333	–0.148667	0.12	–0.0113333	–0.120667	0.0963333
80	–0.011	–0.15	0.130333	–0.016	–0.131667	0.097
90	–0.014	–0.158667	0.126333	–0.018	–0.136	0.098
100	–0.027	–0.179333	0.119333	–0.0253333	–0.144333	0.0933333

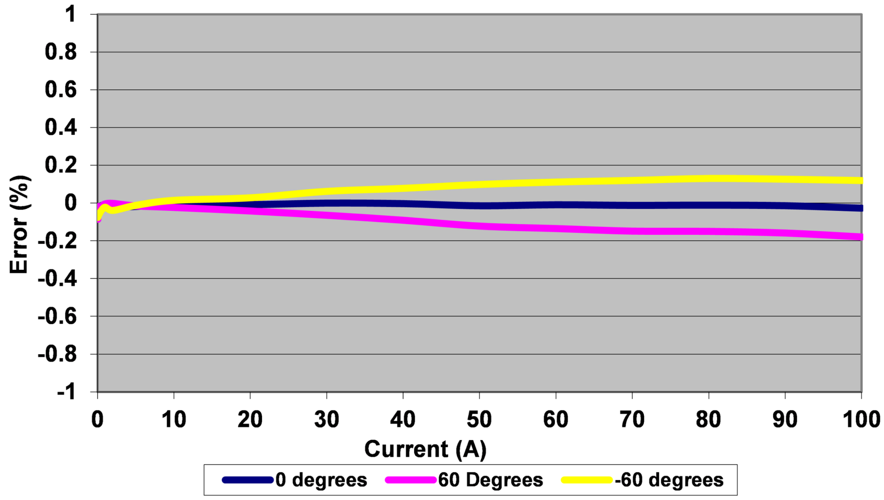


Figure 32. EVM430-F6779 Performance With MSP430F67791

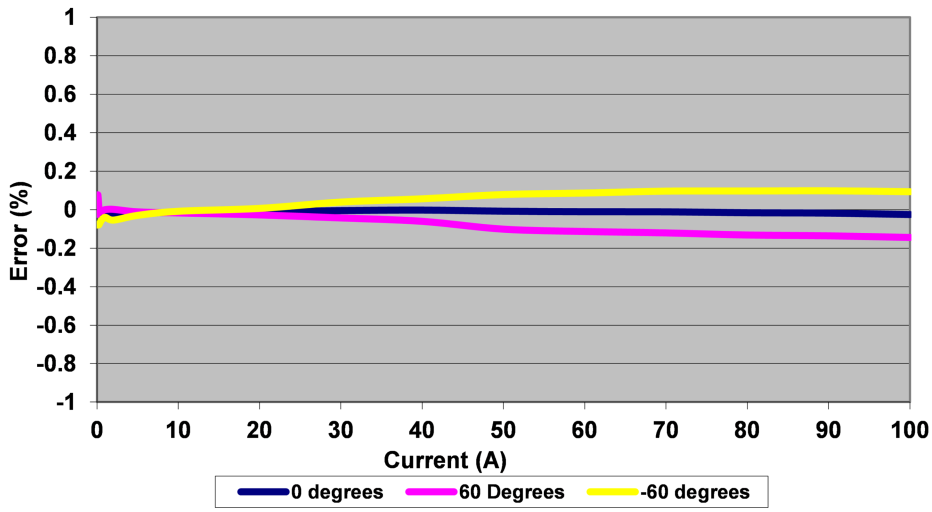


Figure 33. EVM430-F6779 Performance With MSP430F67791A

8 Design Files

8.1 Schematics

To download the Schematics for each board, see the design files at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

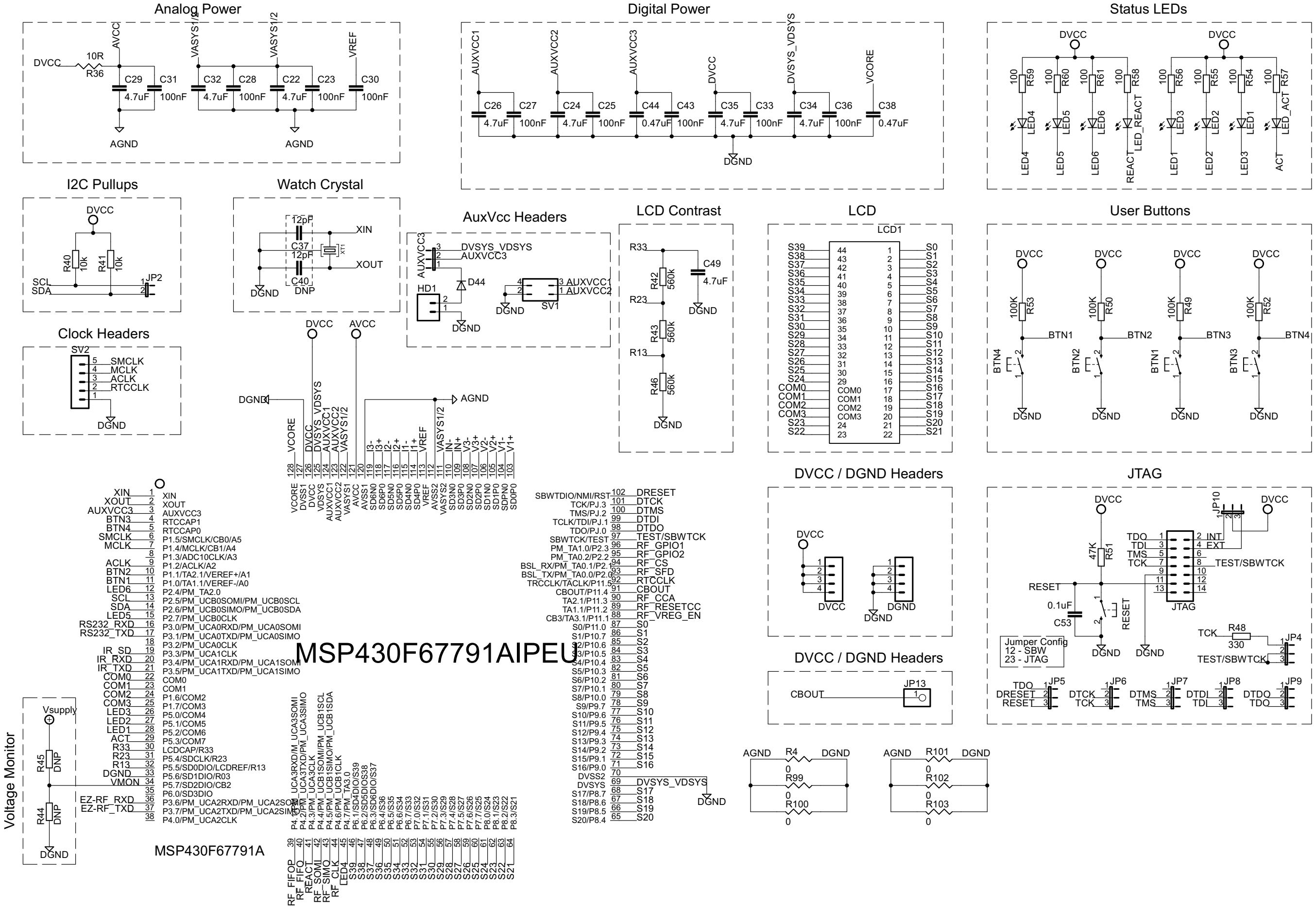


Figure 34. TIDM-3PHMTR-TAMP-ESD Schematic Page 1

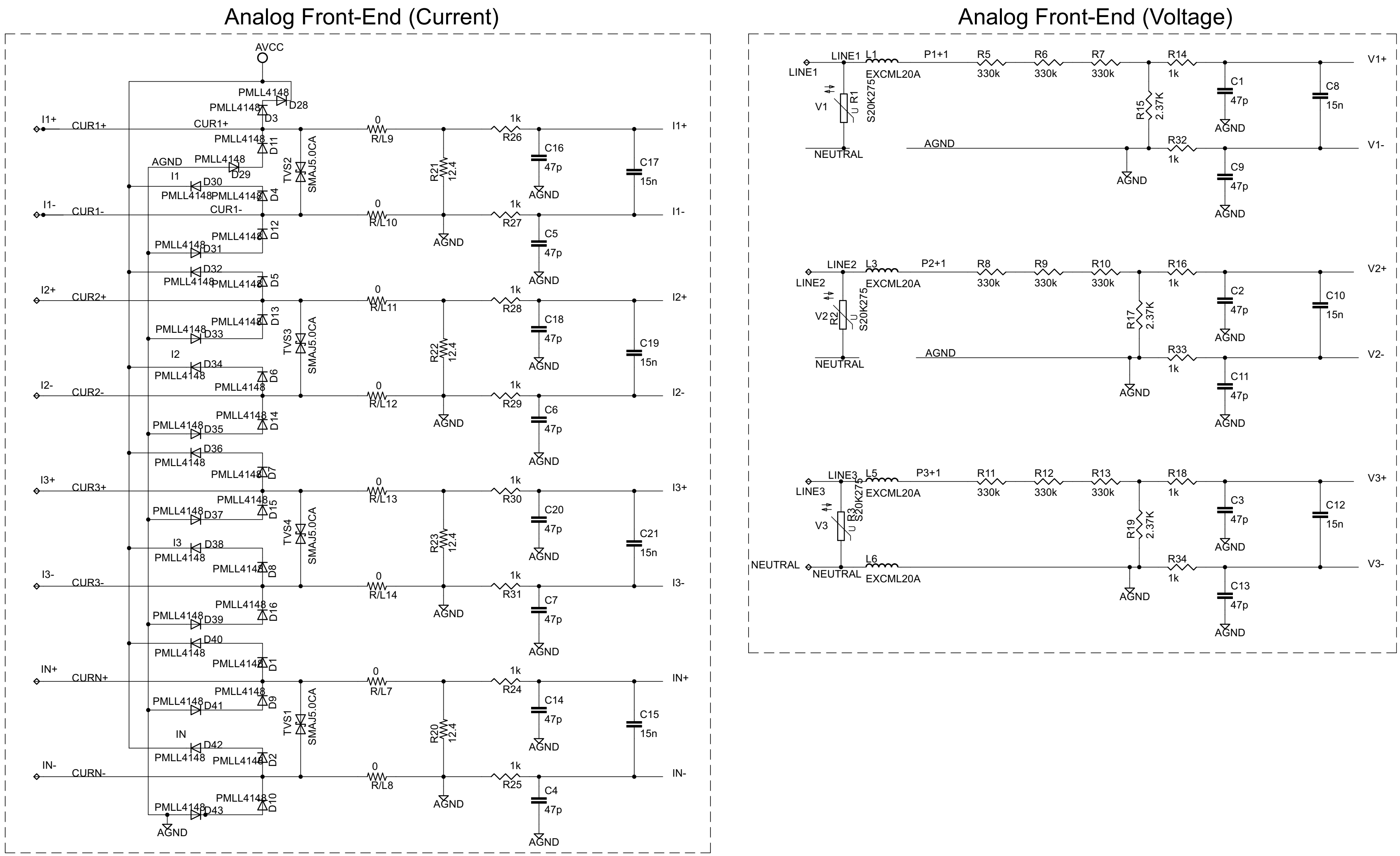
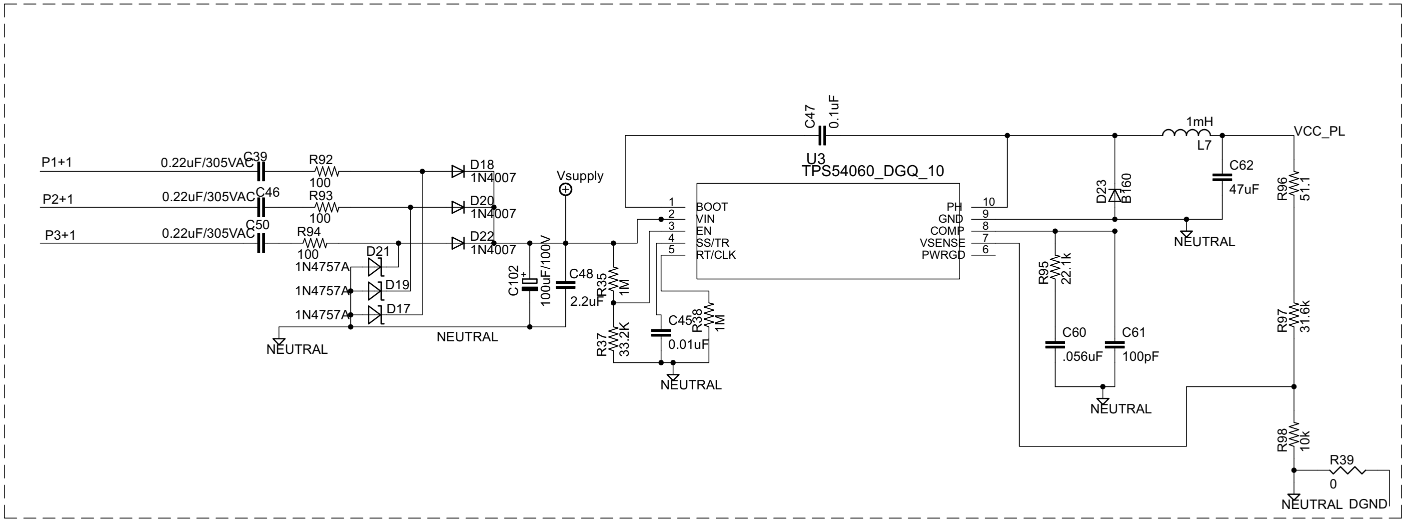
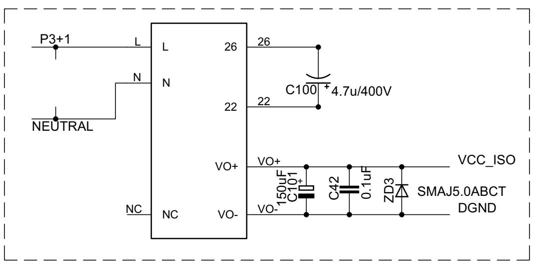


Figure 35. TIDM-3PHMTR-TAMP-ESD Schematic Page 2

Un-isolated VCC from AC Mains



Isolated VCC from AC Mains



VCC Select

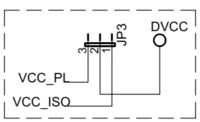


Figure 36. TIDM-3PHMTR-TAMP-ESD Schematic Page 3

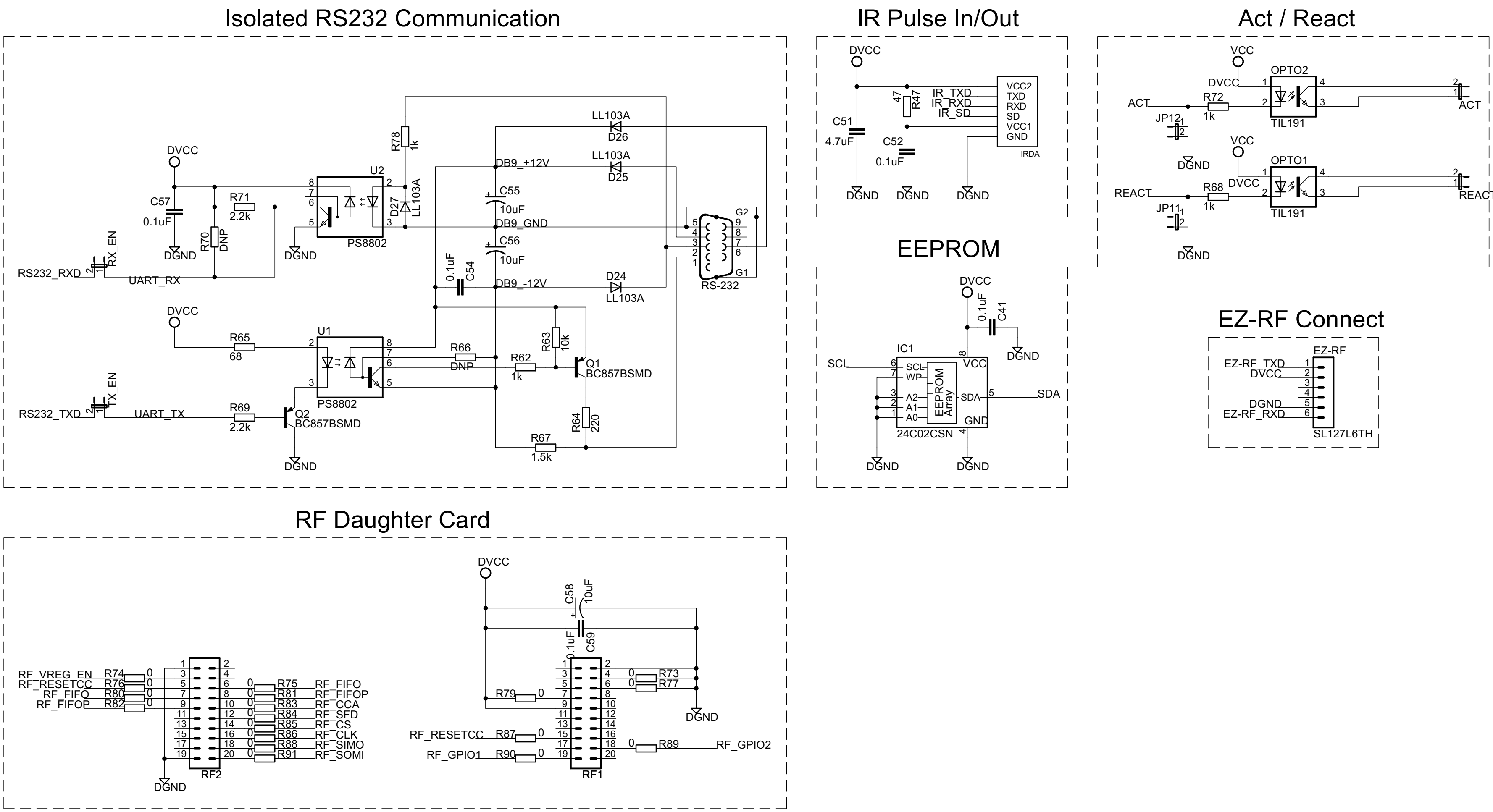


Figure 37. TIDM-3PHMTR-TAMP-ESD Schematic Page 4

8.2 Bill of Materials

To download the Bill of Materials for each board, see the design files at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

8.3 PCB Layout Recommendations

PCB layout is an important factor in a meters ESD immunity performance. The EVM430-F6779 in particular was designed to make it easy to evaluate the MSP430F67791 as an e-meter SoC. As a result, in certain instances, ESD performance was traded off for ease of evaluation of the EVM. However, in general, some PCB layout guidelines for ESD performance are the following:

- Use ground planes instead of ground traces where possible and minimize the cuts in these ground planes(especially for critical traces) in the direction of current flow. Ground planes provide a low-impedance ground path which minimizes induced ground noise. However, cuts in the ground plane can increase inductance. If there are cuts in the ground plane, they should be bridged on the opposite side with a 0-Ω resistor.
- When there is a ground plane on both top and bottom layers of a board (such as in the EVM of this design) ensure there is good stitching between these planes through the liberal use of vias that connect the two planes.
- Keep traces short and wide to reduce trace inductance. If an LCD is used, place it near the microcontroller and prevent long LCD traces to the microcontroller.
- Use wide VCC traces and star-routing for these traces instead of point-to-point routing.
- Minimize the length of the microcontrollers reset trace and other critical edge-triggered traces.
- Isolate sensitive circuitry from noisy circuitry. For example, high voltage and low voltage circuitry must be separated.
- Use transient voltage suppressors, EMI suppressant ferrite beads, and other ESD protection devices to suppress the effects from an ESD discharge. The turn on time of these devices should be small since the rise time of ESD discharge waveform is also small. ESD protection devices can be found at the following link: www.ti.com/esd.
- Keep sensitive circuitry away from PCB edges. If a ground plane is present, put sensitive circuitry near the center of these ground planes.
- Use decoupling capacitors with low effective series resistance (ESR) and effective series Inductance. Place decoupling capacitors close to their associated pins.
- Place connectors all on one edge of the PCB, especially through-hole connectors since they cause breaks in the ground plane.
- Minimize the length of the traces used to connect the crystal to the microcontroller. Place guard rings around the leads of the crystal and ground the crystal housing. In addition, there should be clean ground underneath the crystal and placing any traces underneath the crystal should be prevented. Also, keep high frequency signals away from the crystal.

For more ESD recommendations please refer to SLAA530 [6].

8.4 Layer Plots

To download the layer plots, see the design files at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

8.5 CAD Project

To download the CAD project files, see the design files at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

8.6 Gerber Files

To download the Gerber files for each board, see the design files at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

8.7 Software Files

To download the software files for this reference design, please see the software at http://www.ti.com/tool/TIDM-3PHMTR-TAMP-ESD.

9 References

1. International Electrotechnical Commission, IEC 61000-4-2, Electromagnetic capability (EMC)—Part 4: Testing and measurement techniques – Electrostatic discharge immunity test, Ed. 2.0.
2. Texas Instruments, *Segment LCD-Based Low-End In-Home Display with Wireless RF Communication*, User's Guide, (TIDU203).
3. Texas Instruments, *MSP430x5xx and MSP430x6xx Family*, User's Guide, (SLAU208).
4. Texas Instruments, *MSP430F677x1A, MSP430F676x1A, MSP430F674x1A Polyphase Metering SoCs*, Data Sheet, (SLAS983).
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10 About the Author

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