TI Designs
Two-Phase Embedded Metering

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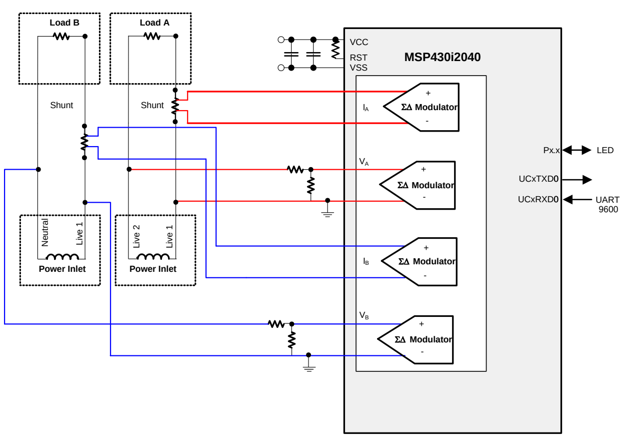
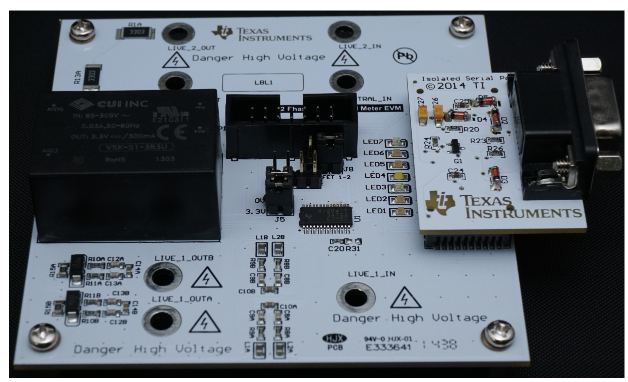
Design Features

- Two-Phase Measurement of Voltage, Current, Power, and so on
- Supports Two Phases of Different Configuration
- Built-In Power Supply and Debugging Interface
- Onboard Connector to External Communication

Featured Applications

- Home Appliances
- Power Supplies
- Home Security and Automation





An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 System Overview

1.1 Cautions and Warnings

The EVM is designed to operate by professionals who received appropriate technical training, yet it is designed to operate from AC supply. Read the safety related documents that come with the EVM package and the user guide before operating this EVM.

CAUTION

Read user guide before use.

CAUTION

Do not leave the EVM powered when unattended.

CAUTION

HOT SURFACE: Contact may cause burns. Do not touch.

CAUTION

HIGH VOLTAGE: Electric shock possible when connecting board to live wire. The board should be handled with care by a professional. For safety, use isolated equipment with overvoltage and overcurrent protection.

1.2 System Description

This document discuss a two-phase power measurement application using a simple low-cost Texas Instruments microcontroller (MCU) MSP430i2040. The MSP430i2040 is a mixed signal MCU that integrates with four differential input, 24-bit Sigma-Delta (SD24) analog-to-digital converters (ADCs) with a programmable gain amplifier, a 16-bit hardware multiplier, an eUSCI_A0 supported UART, SPI communication interface, an eUSCI_B0 supported SPI, an I2C, two 16-bit timers, and 12 I/O pins in a 28-pin TSSOP or 16 GPIO pins in a 32-pin QFN package. The peripheral set is a good combination for electricity power measurement.

In this document, all descriptions of the setup, operations, features, behaviors, functions, and interfacing are based on the default firmware and the original hardware design. Proper functionality is not guaranteed if changes are made to the hardware or firmware.

2 Design Features

2.1 Basic Operations

In this design, all four SD24 ADCs on the MCU are used: Two for the two-phase voltage and two for the current of each phase. The Sigma-Delta ADCs run at approximately a 1.024-MHz modulator frequency fixed by the hardware. The sample frequency is derived from the modulator frequency divided by 256 equals 4 kHz, which give a Nyquist bandwidth of 2 kHz. This bandwidth is sufficient to cover the 31st harmonic for 60-Hz AC and 40th harmonic for 50-Hz AC frequency.

Figure 1 shows the system functional diagram, the four SD24 ADCs take samples from two voltage and two current channels with the calibrated and programmed fractional delay. The samples then pass through a DC removal filter. Each DC removal filter dynamically tracks the DC offset of the ADC (and the signal) by analyzing each sample and removing any DC before passing the sample to AC processing.

The current samples and the voltage samples then perform a square and accumulate to get the root mean square current (I_{rms}) and voltage (V_{rms}). The current samples will also multiply and accumulate with the voltage sample of its phase with proper additional phase delay (if needed) to get the active power (P_{active}) and with the corresponding 90-degree shifted sample to get the reactive power ($P_{reactive}$).

After eight AC cycles, the system sets a flag to show results that need to process. Triggered by this flag, the system then performs the scaling and converts those accumulated values into values of proper units (V, A, W, and so on).

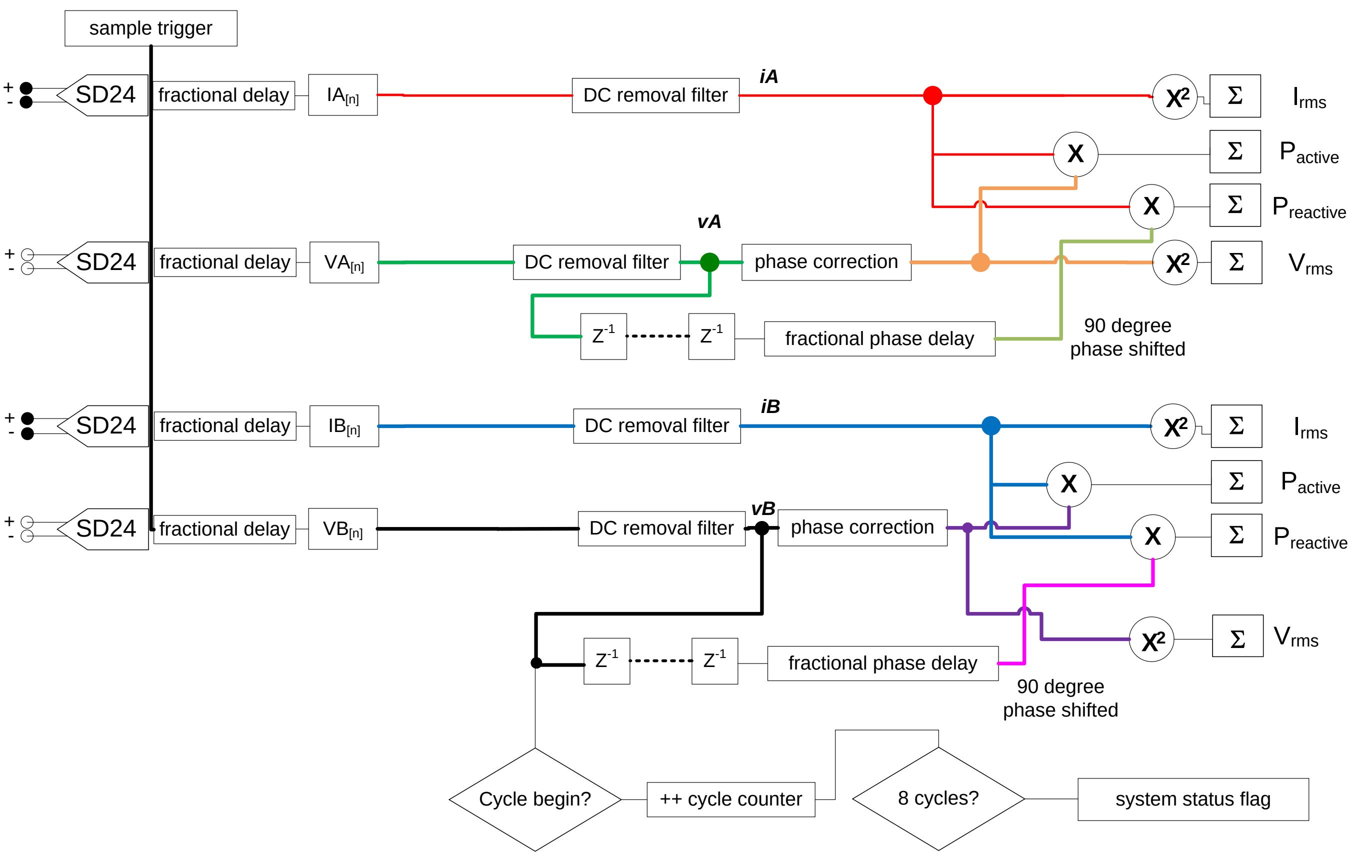


Figure 1. System Functional Diagram

2.2 Board Overview

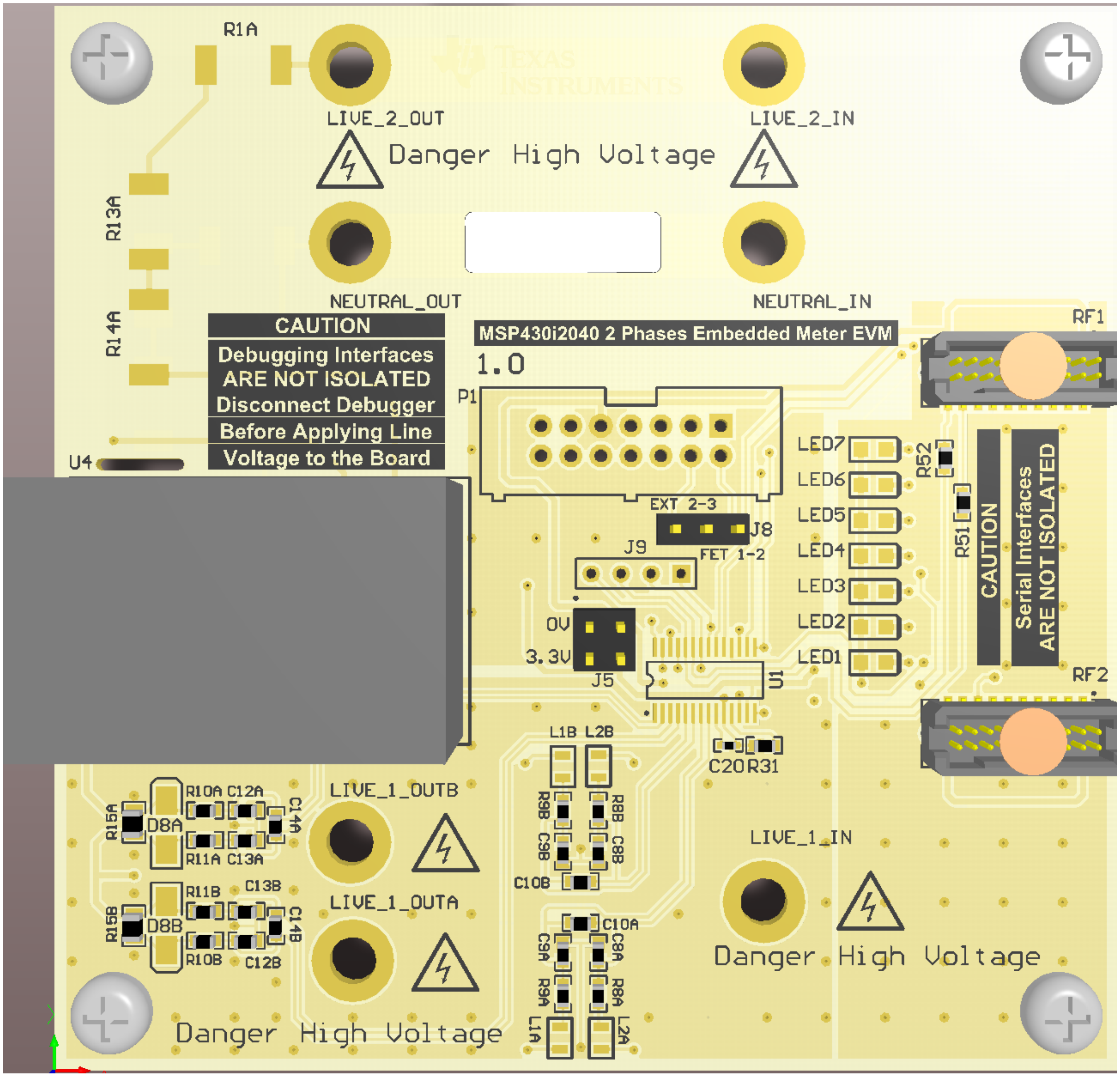


Figure 2. Board Overview

3 Block Diagram

Figure 3 is the block diagram of the system.

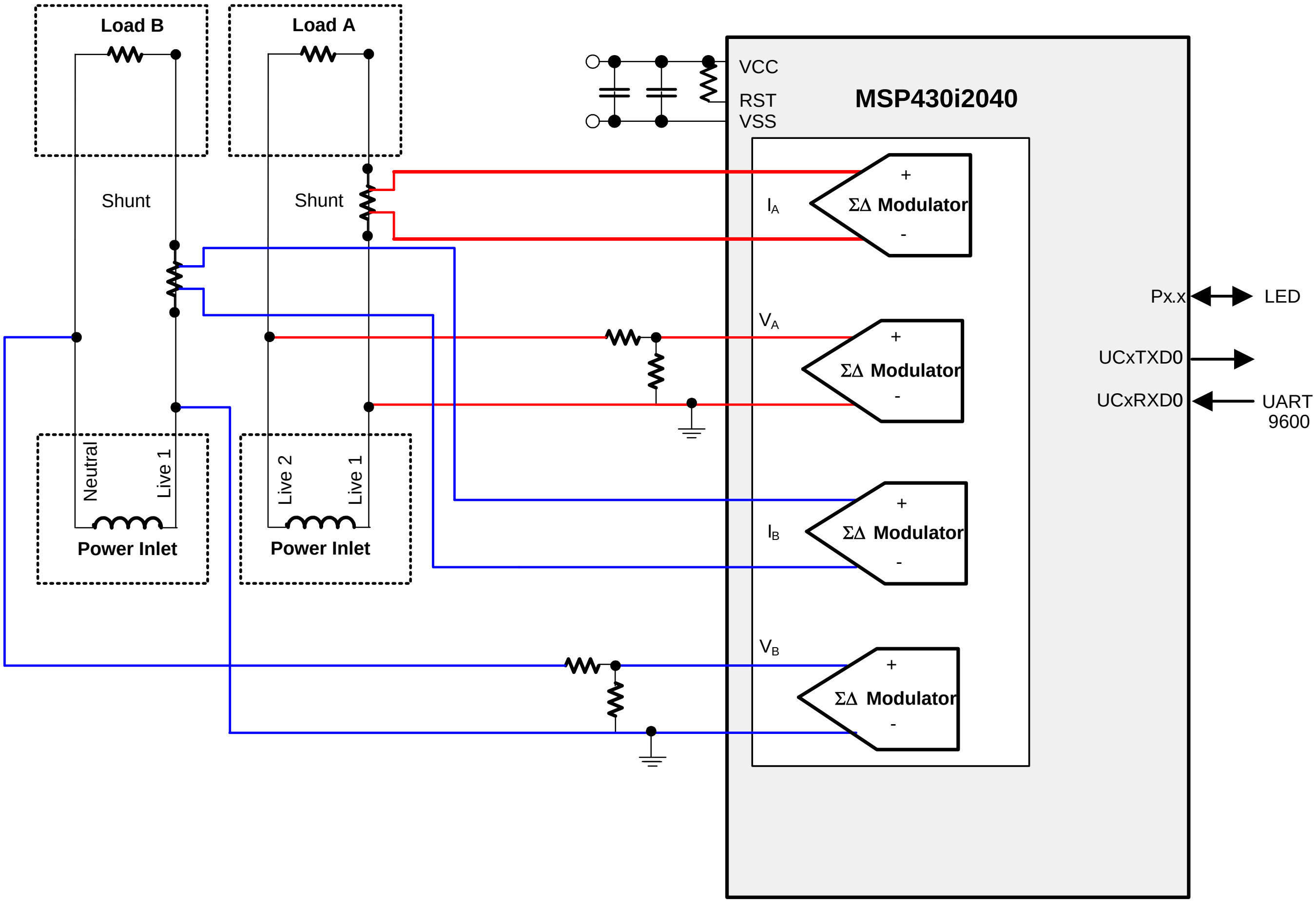


Figure 3. System Block Diagram

4 Circuit Design and Component Selection

The design of this metering circuit can be divided into several sub-systems. This design guide only discusses the design of the sensor sub-system.

4.1 Interface Circuit

In the design of a metering circuit, a key success factor to yield sufficient accuracy very much depends on a good sampling circuit. The four SD24 ADCs on the MSP430i2040, together with the on-chip programmable gain amplifier, provide the critical hardware for getting high quality AD conversion result from both current and voltage sensor. Moreover, the interface circuit, the component selection, and the circuit layout also play a crucial role for a successful design.

Due to the nature of a Sigma-Delta ADC and of the voltage and current signal being measured, the design needs an external interface circuit to interface the voltage and current to keep the Sigma-Delta ADC working properly and provide proper filtering for the band of interest.

The hardware of the interface circuit is simple, which composes of basically passive components apart from the protection diode. Figure 4 shows the interface circuit designed. The two sets of circuit are exactly the same for the shunt resistors and interface to voltage sensor.

In the current sensor interface circuit with R6 (A, B) being the shunt sensor, D1 (A, B) is the optional protection diode. The protection diode is not required unless, for example, a high shunt resistor value or a current transformer is in use instead of the current sensor and the user anticipates a significant current surge to send enough voltage across the sensor high to damage the MCU.

L1 (A, B), R9 (A, B), and C9 (A, B) form a low-pass filter having a bandwidth of a few MHz. The purpose of this filter is to reject radio frequency interference from going into the SD24 ADC. The filter formed by L2 (A, B), R8 (A, B), and C8 (A, B) has the same characteristic, which is balanced for the differential signal. The filter formed by R9 (A, B), R8 (A, B), and C10 (A, B) is a filter that gives a bandwidth of about 10 kHz, which is the filter for the band of interest.

The order of magnitude of these capacitors should be observed although the actual value of the capacitance is not that critical.

The voltage sensor interface is a resistor ladder. The ratio of the resistance in the resistor ladder allows up to 265-V AC and 420-V DC to be measured. The current sensor filter is similar except that the value of R10 (A, B) is 100 Ω, not 1 kΩ. The reason for this is the voltage divider circuit has an equivalent source resistance $1.5k \times \frac{990k}{(1.5k + 990k)} = 1.5k$ in series with R10. To balance the filter for the differential signal, the sensor uses a small R10 (A, B) value. The combined effect is of similar value to R11 (A, B). Although there is a slight mismatch using the designed value, this effect has no observable impact to accuracy.

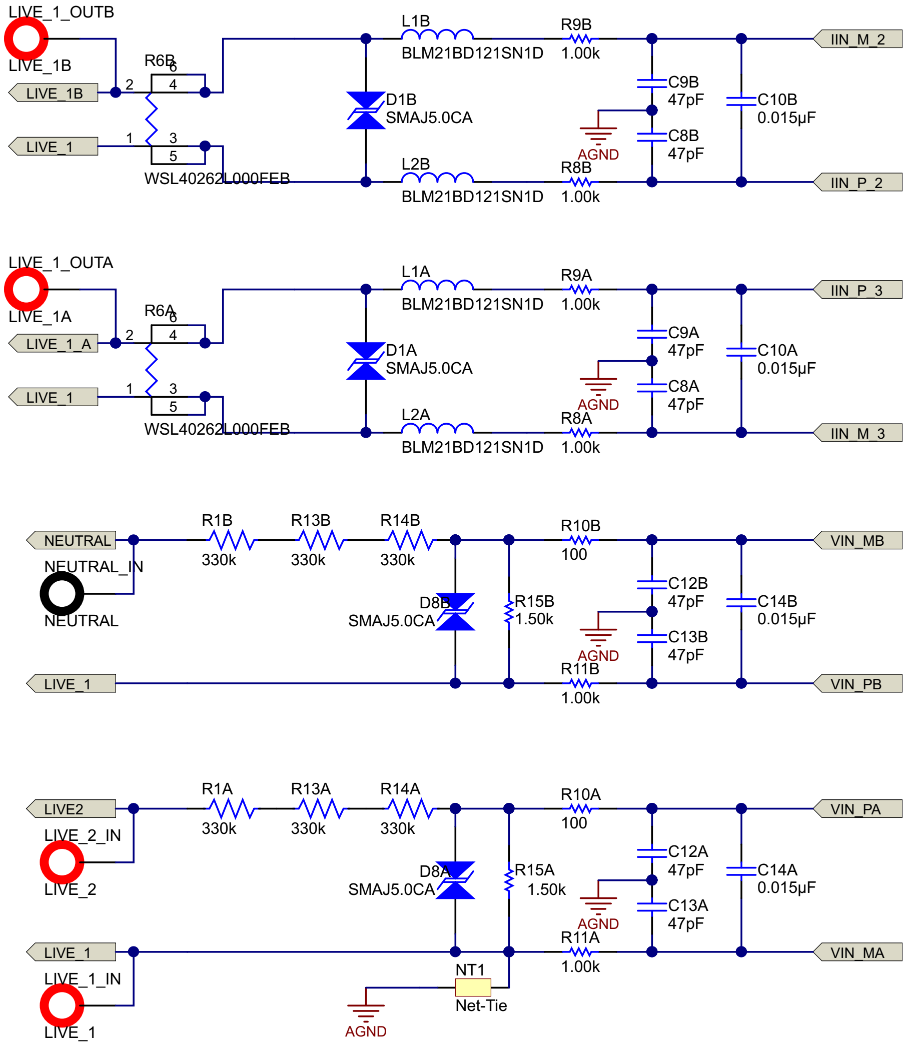


Figure 4. Voltage and Current Sensor Interface Circuit

4.2 Component Considerations

4.2.1 Shunt Resistor

For accurate measurements, the choice of shunt is another important factor. In practice, a shunt of smaller value (<1 mΩ) is a better choice than a larger value (>2 mΩ). A smaller shunt value benefits the power dissipated on the shunt and the respective rise in temperature. The lower rise in temperature reduces the need for a very low temperature coefficient shunt resistor to sustain the accuracy. However, small value shunts also have drawbacks. The signal-to-noise ratio (SNR) of a small value shunt is worse than using a larger value one. In this sense, there may be chance that a shunt of higher value is desired, such as when measuring a very small current and the range of the current to be measured is also small. Therefore, a design needs to consider these factors: the maximum current, the current dynamic range, the heat generated on the shunt, and the ventilation of that heat.

In this application, the maximum current for each socket is 30 A, and the desired dynamic range of current keeping flat error percentage is 1000:1 (30 A : 30 mA). The power dissipated on the shunt resistor should be as small as possible.

To achieve the best accuracy, have the ADC meet its maximum input amplitude (900-mV peak) when presented with the maximum current of the design (30 A_{rms}). Because the SD24 ADC has an input range of approximately 900 mV at x1 gain, using a x8 gain the input range for AC root mean square is

$$\frac{\left(\frac{900}{8}\right)}{\sqrt{2}} = 79.55\ mV_{rms} \tag{1}$$

With this number, a 2-mΩ shunt resistance should be good for this input range with the give maximum current (at 30 A, 2 mΩ gives a 60-mV signal amplitude) still leaving about 10 A in head room.

In addition to value, the physical size of the shunt is also an important factor to accuracy—not the size directly, but the heat generated when current flows. A smaller sized shunt heats up more easily due to the limited surface area and volume. If there is significant current to flow though the shunt, have a large enough sized shunt and sufficient ventilation on the PCB to prevent heat from accumulating. This design uses a 4026-sized shunt. At 2 mΩ, the power dissipated on the shunt at maximum current is $30^2 \times 2 = 1.8$ W, which is about 60% the rated power of a 4026-sized 3-W shunt resistor.

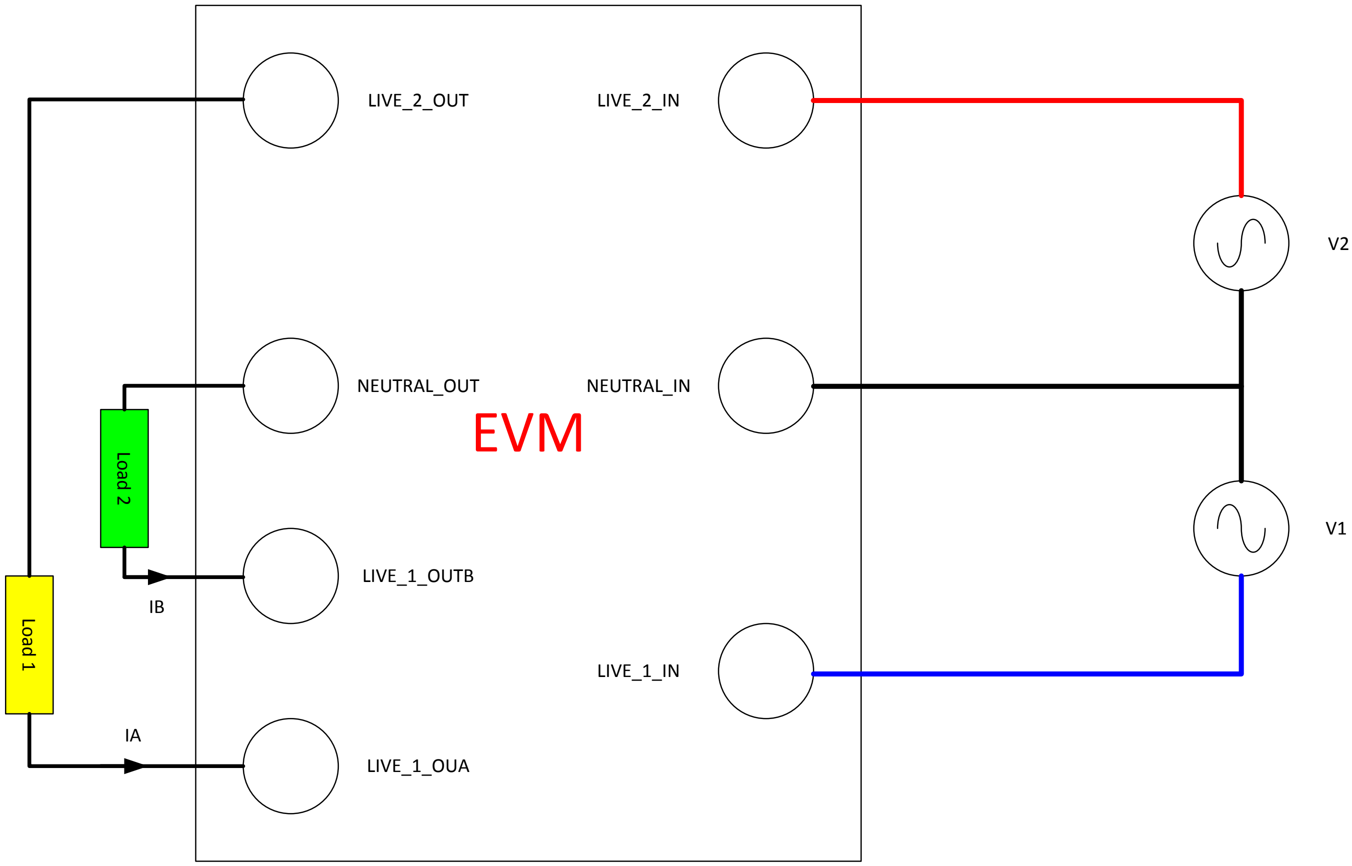
4.2.2 Voltage Divider Circuit

For the voltage sensor circuit, the matter is a little simpler. In this design, the major consideration is that the voltage divider should be able to prevent arcing between the terminals. To reduce the voltage difference between resistor terminals, this design uses four resistors (instead of two) to form the voltage divider [R1 (A, B), R13 (A, B), and R14 (A, B) are 330 kΩ, and R15 (A, B) is 1.5 kΩ]. Then the voltage across R1, R13, and R14 each take about one-third of the AC voltage. Now at a 220-V input, each resistor has a voltage drop of about 75 V across. Using the 2512 resistor for R1, R13, and R14 then further separates the live voltage and R15.

The installation of D8 (A, B) in the voltage sensor circuit is more important than D1 (A, B) in the current circuit. The reason is that the resistor ladder on the voltage sensor circuit is more likely to see a voltage surge across R15 high enough to damage the MCU. If R15 is open circuit or in bad contact, causing a higher resistance the voltage across the input of the voltage channel ADC also damages the MCU.

4.3 Configurations

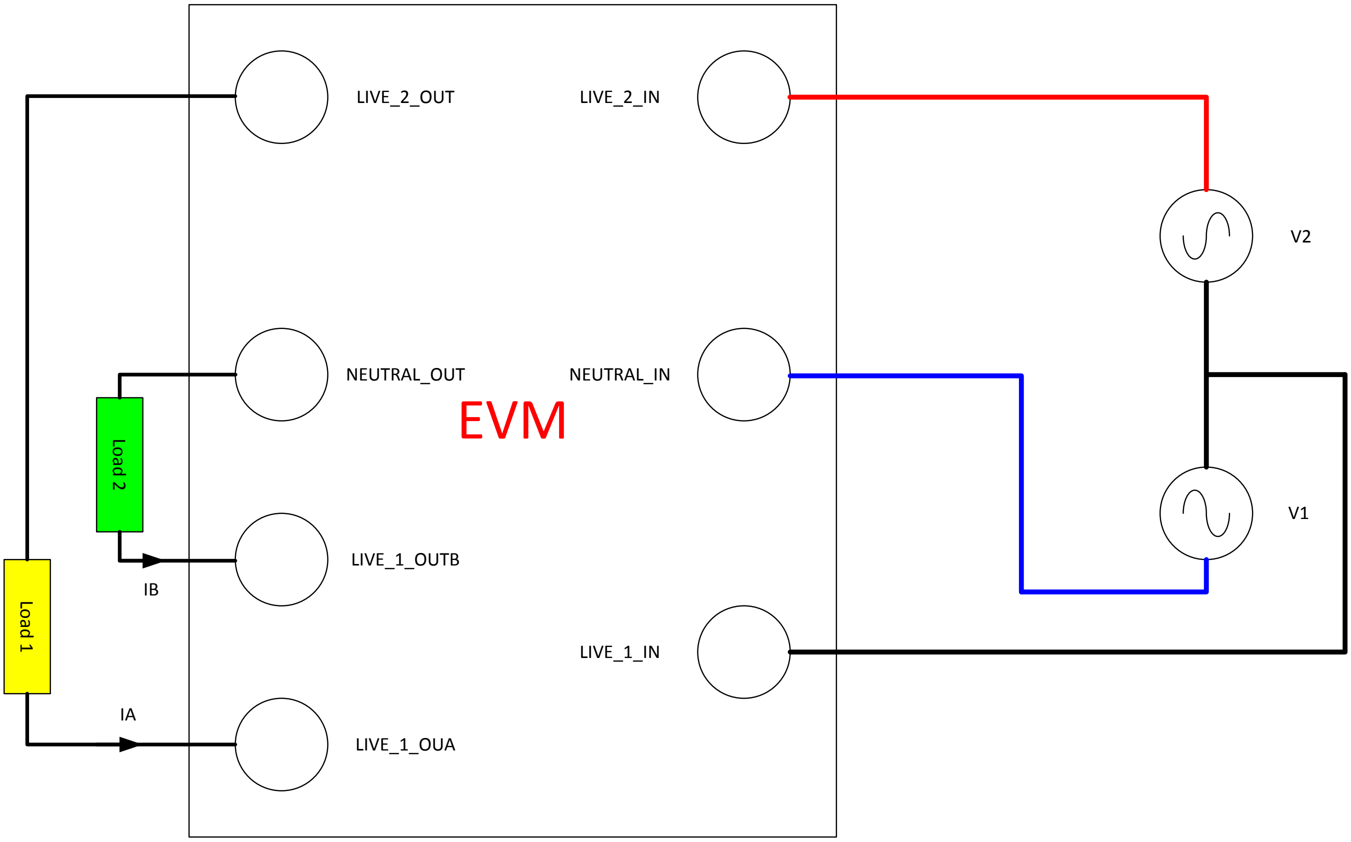
This design allows different connections to the EVM so different measurement configurations can be set for different application needs. The two configurations are show in Figure 5 and Figure 6:



$$P_A = \int (V_2(t) - V_1(t)) \times I_A dt$$

$$P_B = \int (V_1(t)) \times I_B dt$$

Figure 5. Configuration 1



$$P_A = \int (V_2(t)) \times I_A dt$$

$$P_B = \int (V_1(t)) \times I_B dt$$

Figure 6. Configuration 2

5 Software Description

5.1 Firmware Structure

The firmware comes with the this design package is designed to use a layered approach, isolating the user from the details of metrology and the associated computations involved so that the programming work is simplified. In users view the firmware is partitioned into 3 main blocks The application, which performs : system setup and initialization, main loop, communication protocol and command handling, non-volatile parameters preset and manipulation. The toolkit packaged, which is packed into a library named “emeter-toolkit-i2041.r43”, contains low level computation routines.

The firmware is designed to use a layered approach, isolating the user from the details of metrology and the associated computations involved to simplify the programming work.

In the user's view, the firmware is partitioned into three main blocks:

- The application, which performs the system setup and initialization, main loop, communication protocol and command handling, non-volatile parameters preset, and manipulation
- The toolkit packaged, which is packed into a library named “emeter-toolkit-i2041.r43”, contains low-level computation routines
- The metrology computation engine, which is packaged into a library named “emeter-metrology-i2041-2-phase.r43”, contains the function for ADC setup and initialization, sample-based background processing, reporting cycle-based foreground processing, and result reading API

NOTE: This package does not include the source code of this library. Contact a local Texas Instruments Sales Team if the source code is needed.

5.2 Metrology Computation Engine

The metrology computation engine performs the actual sampling and computation based on the information collected from the voltage and current ADC channels. The engine acts in a time-critical background process and a less time-critical foreground process.

The background process is triggered by the ADC at the sample rate. This process runs in the interrupt services routine of the ADC and is processed automatically.

The foreground process is triggered by the completion of background process at the reporting and update rate. The background process sets the flag PHASE_STATUS_NEW_LOG in the variable phase_state to indicate that data is ready to be processed by the foreground. The application then needs to monitor this flag to trigger the foreground process by calling to calculate_phase_readings ().

In the actual computation, use the following formulas in the metrology computation:

$$V_{RMS} = VGAIN \times \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_{samp(i)} \times V_{samp(i)}} \quad (2)$$

$$I_{RMS} = IGAIN \times \sqrt{\frac{1}{N}\sum_{i=1}^{N} I_{samp(i)} \times I_{samp(i)}} \quad (3)$$

$$P_{active} = PGAIN \times \frac{1}{N}\sum_{i=1}^{N} V_{samp(i)} \times I_{samp(i)} \quad (4)$$

$$P_{reactive} = PGAIN \times \frac{1}{N}\sum_{i=1}^{N} V_{samp,90(i)} \times I_{samp(i)} \quad (5)$$

$$P_{apparent} = \sqrt{P^2_{active} \times P^2_{reactive}} \quad (6)$$

$$PF = \cos\varphi = \frac{P_{active}}{P_{apparent}} \quad (7)$$

5.2.1 Background Process

The background performs a straight-forward, time-critical, sample-based process. The process starts by an SD24 interrupt trigger at the sample rate. The background process then

- Captures data from voltage and current ADC channels
- Performs voltage sample processing
- Performs current sample processing
- Performs power processing
- Performs line frequency processing
- Triggers the foreground process

5.2.2 Foreground Process

After reaching the report cycle, the background sets the flag PHASE_STATUS_NEW_LOG. The user main loop checks the status of this flag and calls to the foreground process calculate_phase_readings () to compute the rest and deliver the measurement readings. The foreground process then calculates the active power, reactive power, apparent power, RMS voltage, RMS current, power factor, and frequency of the AC line.

6 Test Setup

6.1 Apparatus

The following list of instruments help calibrate and test the EVM (See instrument link in Section 9):

- AC meter test set
- A reference meter that could read AC parameters based on the voltage, current, and phase setting from the AC meter test set

6.2 Setup

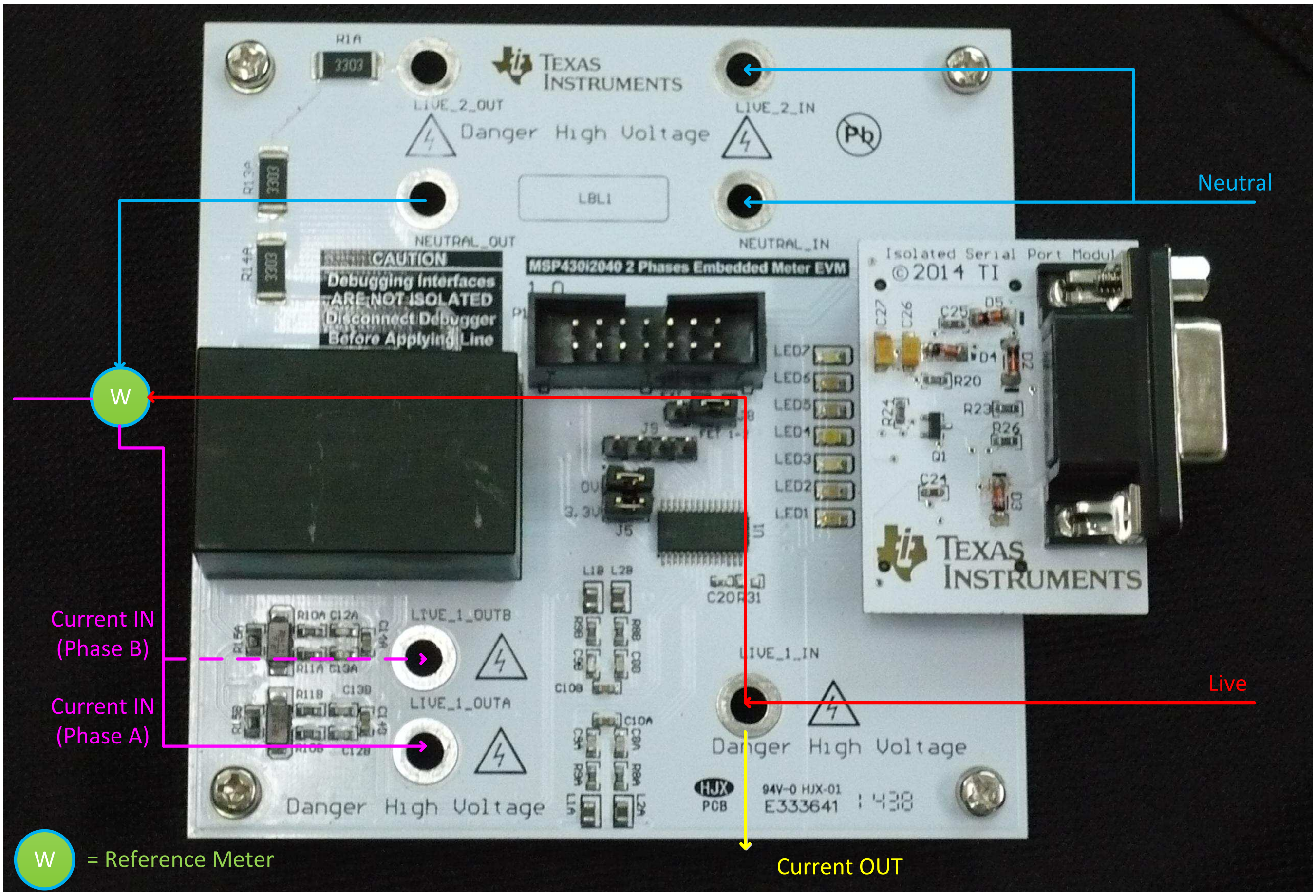


Figure 7. Connection to AC Meter Test Set

7 Test Results

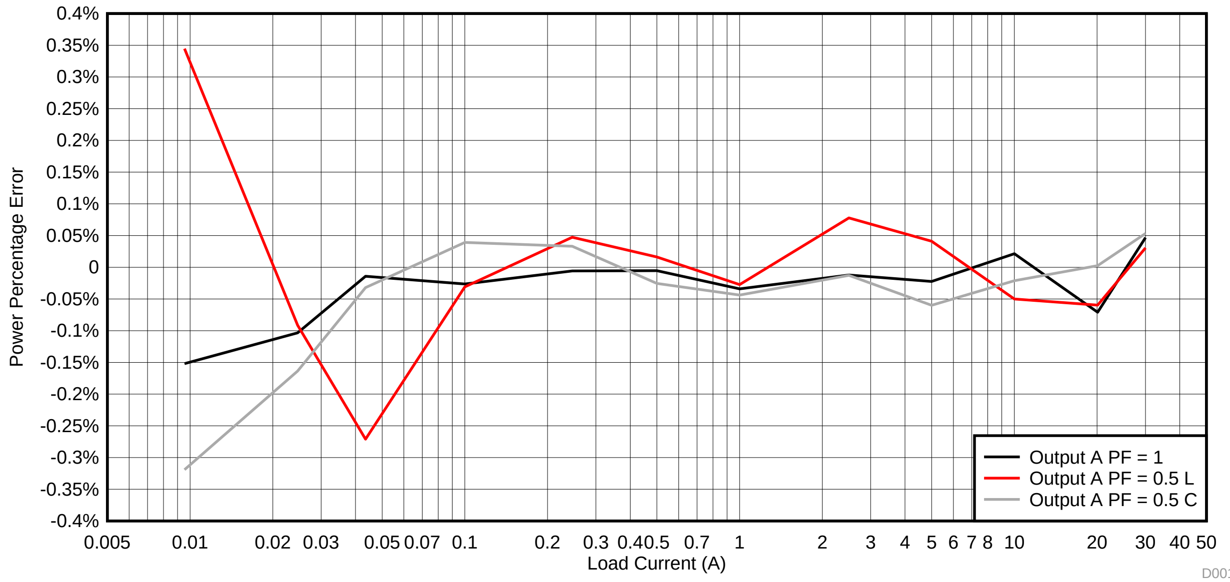


Figure 8. Phase A Accuracy Test Results

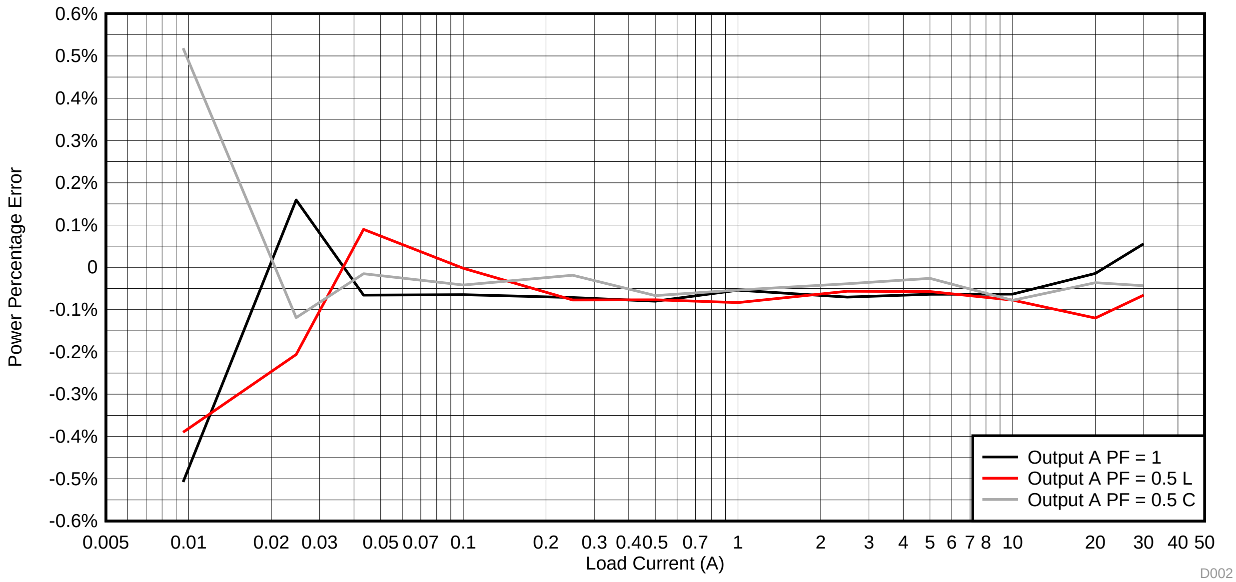


Figure 9. Phase B Accuracy Test Results

7.1 Test Summary

With the test settings and proper calibration, this design achieves an accuracy of <0.2% error over a 30-mA to 30-A range and <0.5% error over a 10-mA to 30-A range. The higher percentage error in the low current range is due to noise seen on the shunt resistor. The effect of noise diminished as the test current increased.

8 Design Files

8.1 Schematics

To download the schematics, see the design files at TIDM-2PHASE-SUBMTR.

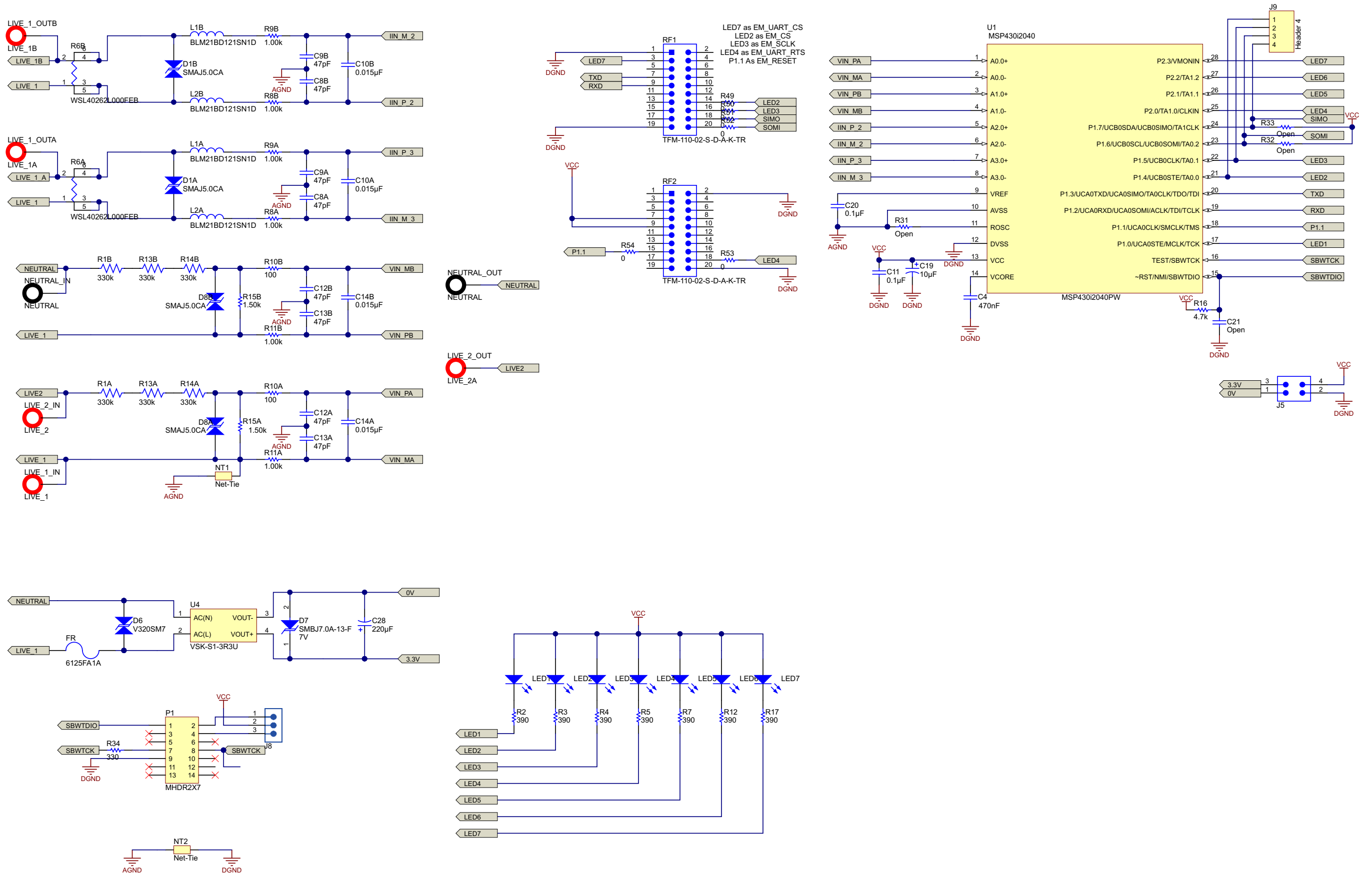


Figure 10. TIDM-2PHASE-SUBMTR Main Board

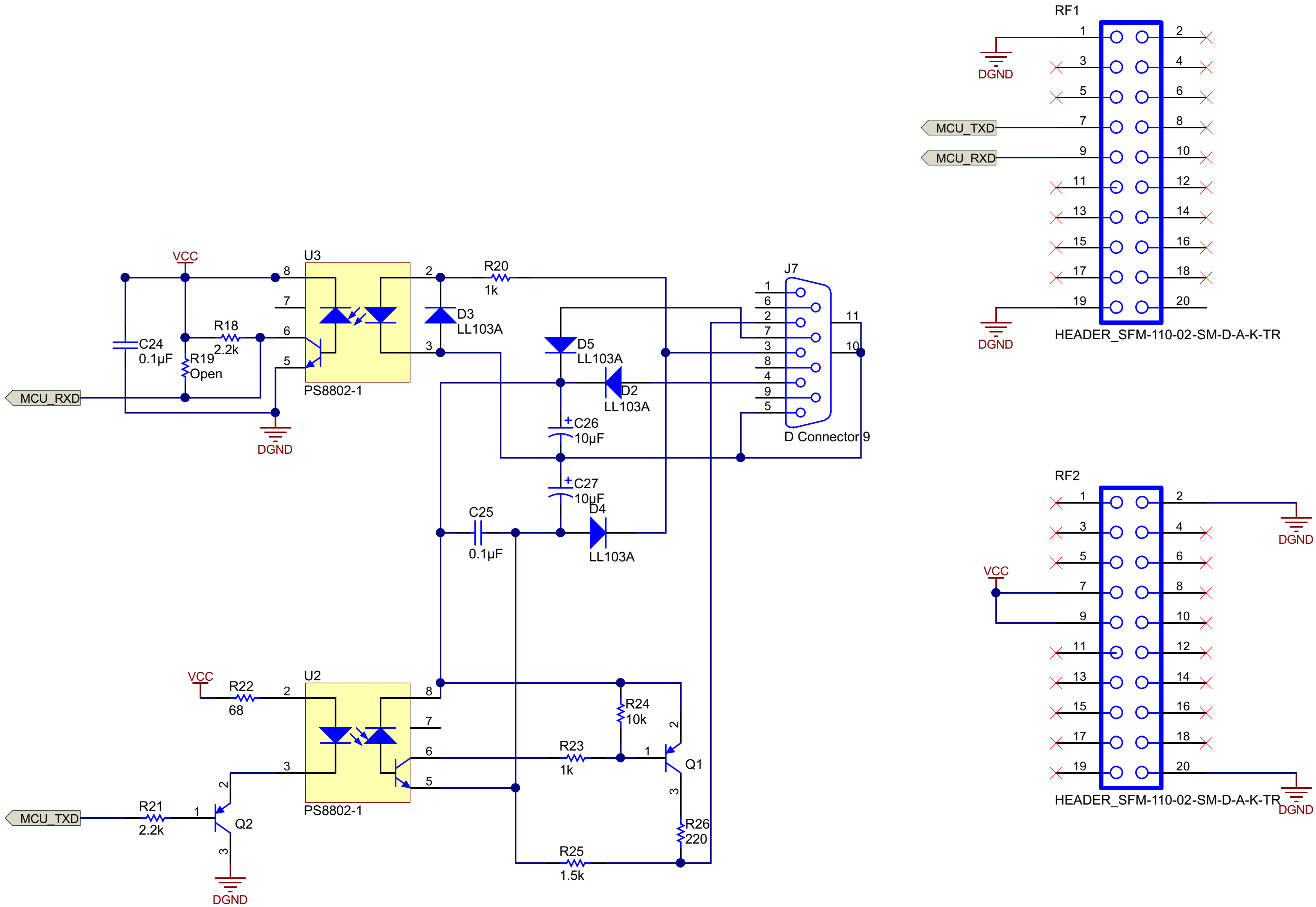


Figure 11. Isolated Serial Board

8.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDM-2PHASE-SUBMTR.

Table 1. TIDM-2PHASE-SUBMTR Main Board BOM

QTY	DESIGNATOR	VALUE	DESCRIPTION	MANUFACTURER	PARTNUMBER	FOOTPRINT
1	C19	10 µF	CAP, TANT, 10 µF, 10 V, ±20%, 2.5 Ω, 3528-21 SMD	Vishay-Sprague	293D106X0010B2TE3	3528-21
1	C28	220 µF	CAP, TANT, 220 µF, 6.3 V, ±10%, 0.6 Ω, 7343-31 SMD	Vishay-Sprague	293D227X96R3D2TE3	7343-31
4	H5, H6, H7, H8		Standoff, Hex, 0.5"L #4-40 Nylon	Keystone	1902C	Keystone_1902C
8	C8A, C8B, C9A, C9B, C12A, C12B, C13A, C13B	47 pF	CAP, CERM, 47 pF, 50 V, ±5%, C0G/NP0, 0603	AVX	06035A470JAT2A	0603
1	FR		Fuse, 1 A,125 V, SMD	Cooper Bussman	6125FA1A	6125FA
1	C21	DNA	CAP, CERM, 2200 pF, 50 V, ±10%, X7R, 0603	Kemet	C0603X222K5RACTU	0603
2	C11, C20	0.1 µF	CAP, CERM, 0.1 µF, 10 V, ±10%, X5R, 0402	TDK	C1005X5R1A104K	0402
1	C4	470 nF	CAP, CERM, 470 nF, 16 V, [TempCo], xx%, [PackageReference]	Taiyo Yuden	EMK107F474ZA-T	0603
6	R8A, R8B, R9A, R9B, R11A, R11B	1.00 k	RES, 1.00 kΩ, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00FKEA	0603
1	R16	4.7 k	RES, 4.7 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06034K70JNEA	0603
2	R15A, R15B	1.50 k	RES, 1.50 kΩ, 1%, 0.125 W, 0805	Vishay-Dale	CRCW08051K50FKEA	0805
2	R10A, R10B	100	RES, 100 Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603100RFKEA	0603
1	R34	330	RES, 330 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW0603330RJNEA	0603
6	R49, R50, R51, R52, R53, R54	0	RES, 0 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06030000Z0EA	0603
4	C10A, C10B, C14A, C14B	0.015 µF	CAP, CERM, 0.015 µF, 16 V, ±10%, X7R, 0603	MuRata	GRM188R71C153KA01D	0603
1	J9		Header, 4-Pin			3-644456-4
2	NEUTRAL_IN, NEUTRAL_OUT			N/A	Used in BOM report	Hole for Banana Socket
1	LIVE_1_IN			N/A	Used in BOM report	Hole for Banana Socket
1	LIVE_1_OUTA			N/A	Used in BOM report	Hole for Banana Socket
1	LIVE_1_OUTB			N/A	Used in BOM report	Hole for Banana Socket
1	LIVE_2_IN			N/A	Used in BOM report	Hole for Banana Socket
1	LIVE_2_OUT			N/A	Used in BOM report	Hole for Banana Socket
4	L1A, L1B, L2A, L2B		Inductor, Ferrite Chip 120 Ω 0805	Murata Electronics	BLM21BD121SN1D	YW0805

Table 1. TIDM-2PHASE-SUBMTR Main Board BOM (continued)

QTY	DESIGNATOR	VALUE	DESCRIPTION	MANUFACTURER	PARTNUMBER	FOOTPRINT
2	LED1, LED5		Red	Lite-On Inc	LTST-C170KRKT	0805-LED
2	LED2, LED6		Green	Lite-On Inc	LTST-S220KGKT	0805-LED
2	LED3, LED7		Blue	Lite-On Inc	LTST-C170TBKT	0805-LED
1	LED4		White	Lite-On Inc	LTW-170TK	0805-LED
1	P1		Header, 7-Pin, Dual row	TE Connectivity	A104860-ND	2X7BOXHEADER
1	U1		MSP430i2040	Texas Instruments	MSP430i2040PW	TSSO10x6-G28
4	H1, H2, H3, H4		Machine Screw, Round, #4-40 × 1/4, Nylon, Philips panhead	B&F Fastener Supply	NY PMS 440 0025 PH	NY PMS 440 0025 PH
1	J8	1×3	Header, TH, 100-mil, 1×3, Gold plated, 230 mil above insulator	Sullins Connector Solutions	PBC03SAAN	PBC03SAAN
1	!PCB		Printed Circuit Board	Any		
6	R1A, R1B, R13A, R13B, R14A, R14B	330 k	Resistor, 330 kΩ, 1 W, 1%	TE Connectivity	1-2176071-0	R2512
7	R2, R3, R4, R5, R7, R12, R17	390	RES, 390 Ω, 5%, 0.1 W, 0603	Yageo America	RC0603JR-07390RL	0603
3	R31, R32, R33	DNA	RES, Open Ω, x%, xW, 0603 RES, xxx Ω, x%, xW, [PackageReference] RES, xxx Ω, x%, xW, [PackageReference]	Used in BOM report	Used in BOM report	0603
4	D1A, D1B, D8A, D8B			Littelfuse Inc	SMAJ5.0CA	DSO-C2/X1.8
1	D7	7 V	Diode, TVS, Uni, 7 V, 600 W, SMB	Diodes Inc.	SMBJ7.0A-13-F	SMB
2	RF1, RF2		CONN SHRD HDR HDR 20 POS 1.27 MM SLDR ST SMD	Samtec	TFM-110-02-S-D-A-K-TR	Samtec_TFM-110-02-S-D-A-K
1	LBL1		Thermal Transfer Printable Labels, 0.650" W × 0.200" H - 10,000 per roll	Brady	THT-14-423-10	Label_650x200
1	J5		Header, TH, 100-mil, 2×2, Gold plated, 230 mil above insulator	Samtec, Inc.	TSW-102-07-G-D	TSW-102-07-G-D
2	R6A, R6B		Shunt Resistor	Vishay Dale	WSL40262L000FEB	Current Sensing Pad
1	D6			Littelfuse Inc	V320SM7	V320SM7
1	U4		Onboard block power supply	CUN Inc	VSK-S1-3R3U	VSK-S1

Table 2. Isolated Serial Board BOM

QTY	DESIGNATOR	COMMENT	DESCRIPTION	LIBREF	PARTNUMBER	FOOTPRINT
2	C24, C25	C1608X7R1H104K	CAP, CERM, 0.1 µF, 50 V, ±10%, X7R, 0603	C1608X7R1H104K	C1608X7R1H104K	0603
2	C26, C27	T495A106K010ATE1K8	CAP, TA, 10 µF, 10 V, ±10%, 1.8 Ω, SMD	T495A106K010ATE1K8	T495A106K010ATE1K8	3216-18
4	D2, D3, D4, D5	LL103A		LL103A	LL103A	SOD-80
1	J7	D Connector 9	Receptacle Assembly, 9 Position, Right Angle	D Connector 9		DSUB9-F
2	Q1, Q2	BC857C-7-F	Transistor, PNP, 45 V, 0.1 A, SOT-23	BC857C-7-F, Diodes Inc.	BC857C-7-F	SOT-23
2	R18, R21	2.2k	RES, 2.2 kΩ, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
1	R19	Open	RES, Open Ω, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
2	R20, R23	1k	RES, 1 kΩ, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
1	R22	68	RES, 68 Ω, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
1	R24	10k	RES, 10 kΩ, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
1	R25	1.5k	RES, 1.5 kΩ, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
1	R26	220	RES, 220 Ω, x%, xW, [PackageReference]	Resistor	Used in BOM report	0603
2	RF1, RF2	HEADER_SFM-110-02-SM-D-A-K-TR	Header, SMT 10×2 pin, Shrouded	HEADER_TFM-110-02-SM-D-A-K-TR	SFM-110-02-SM-D-A-K-TR	HEADER_TFM-110-02-SM
2	U2, U3	PS8802-1		PS8802-1	PS8802-1	SO-8

8.3 PCB Layout

To download the layer plots, see the design files at TIDM-2PHASE-SUBMTR.

8.3.1 TIDM-2PHASE-SUBMTR

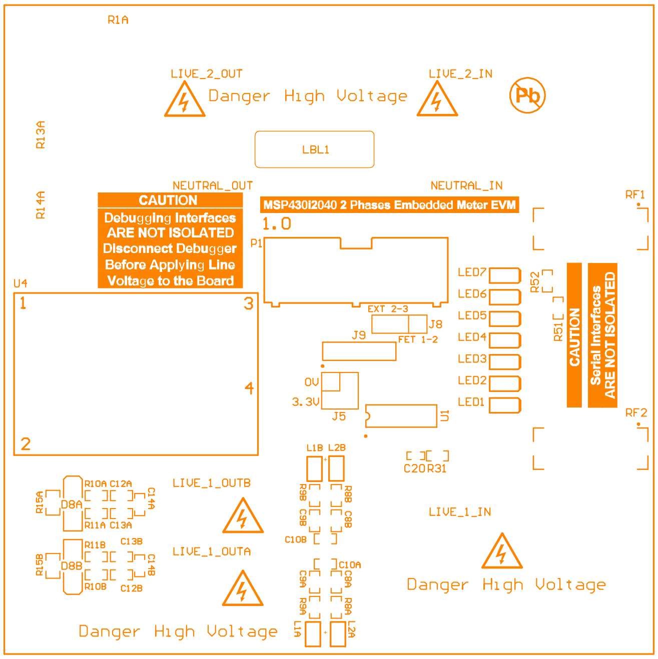


Figure 12. Top Overlay

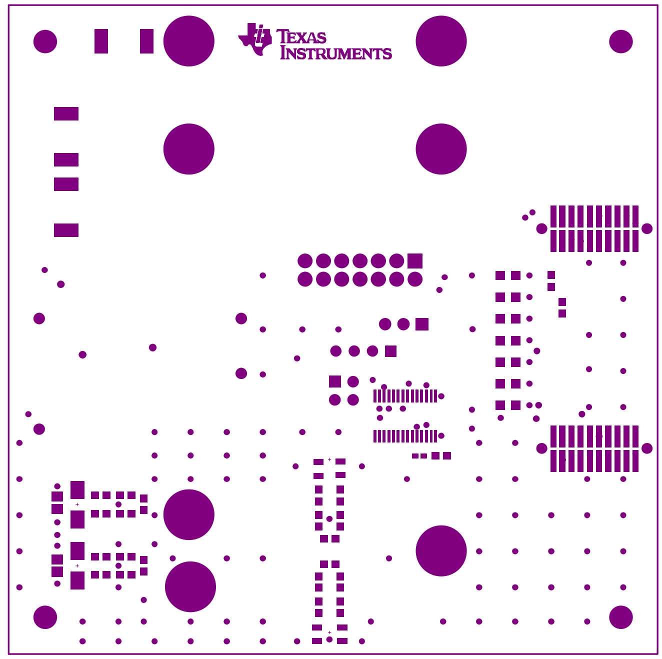


Figure 13. Top Solder

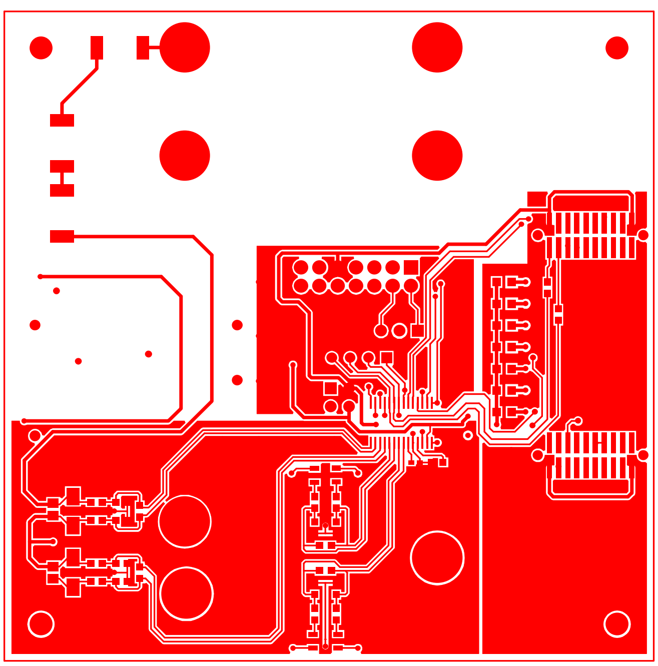


Figure 14. Top Layer

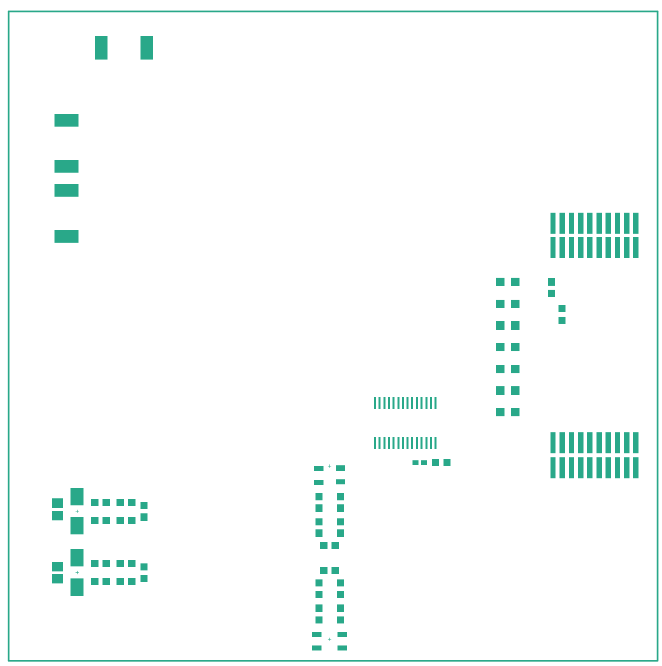


Figure 15. Top Paste

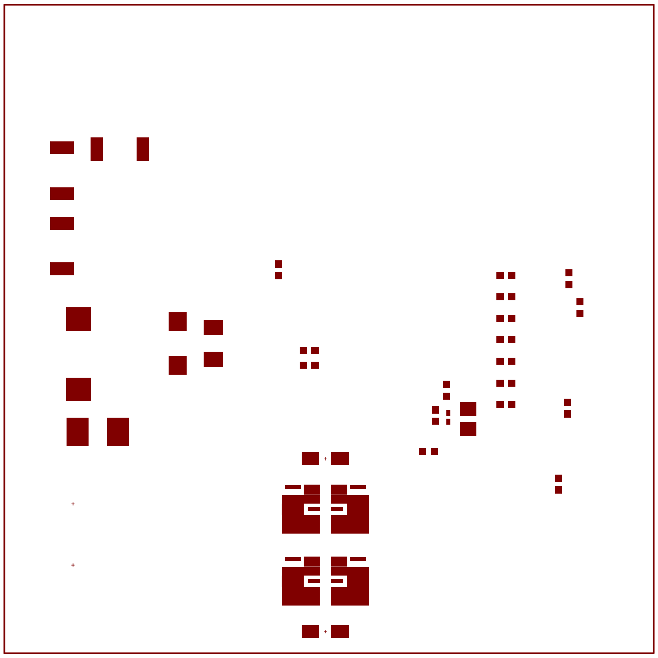


Figure 16. Bottom Paste

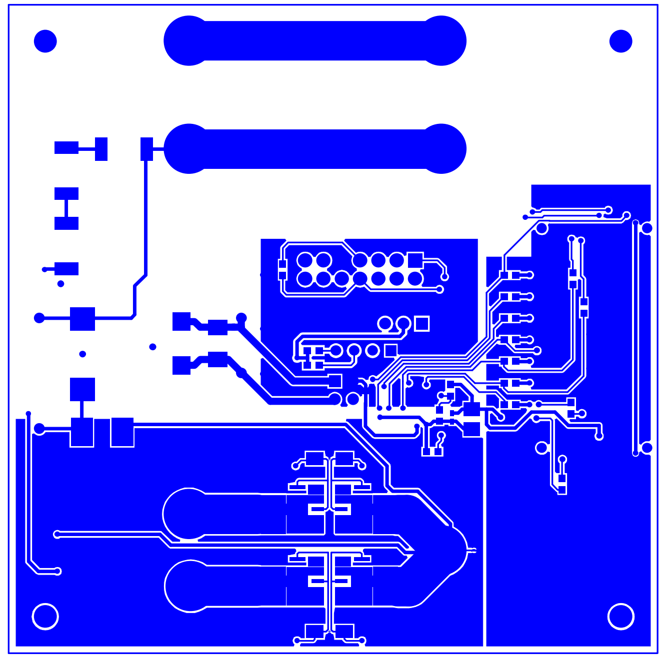


Figure 17. Bottom Layer

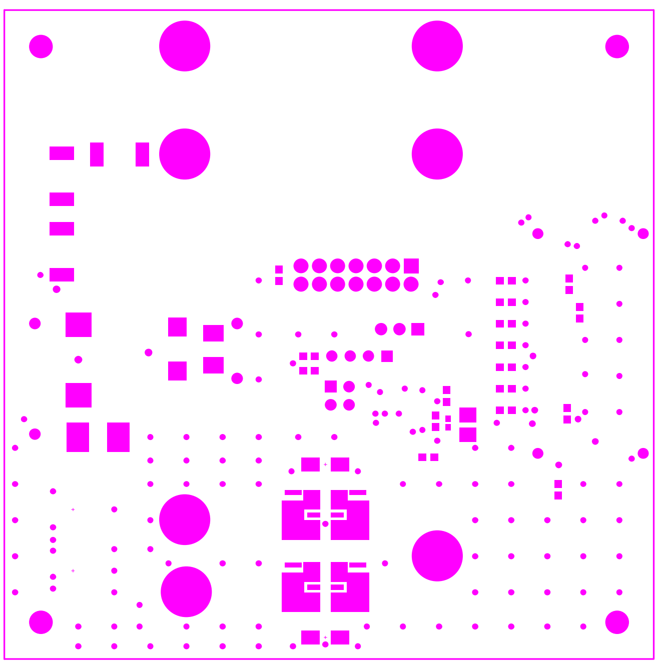


Figure 18. Bottom Solder

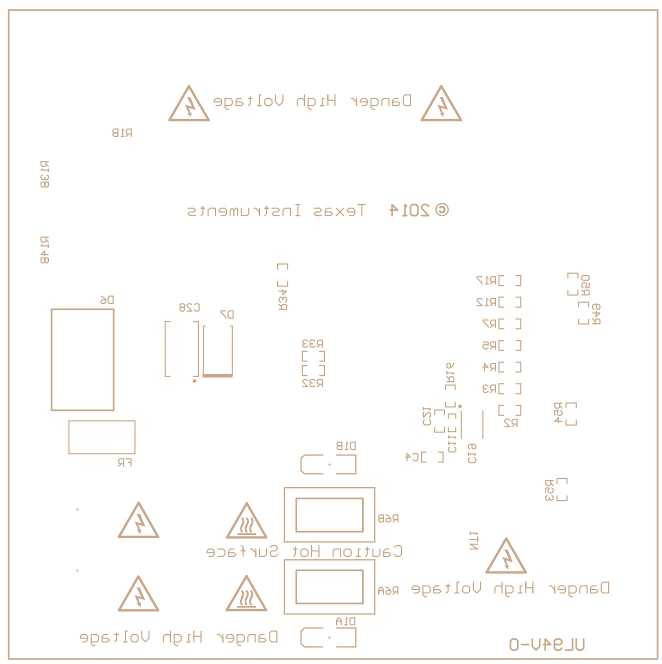


Figure 19. Bottom Overlay

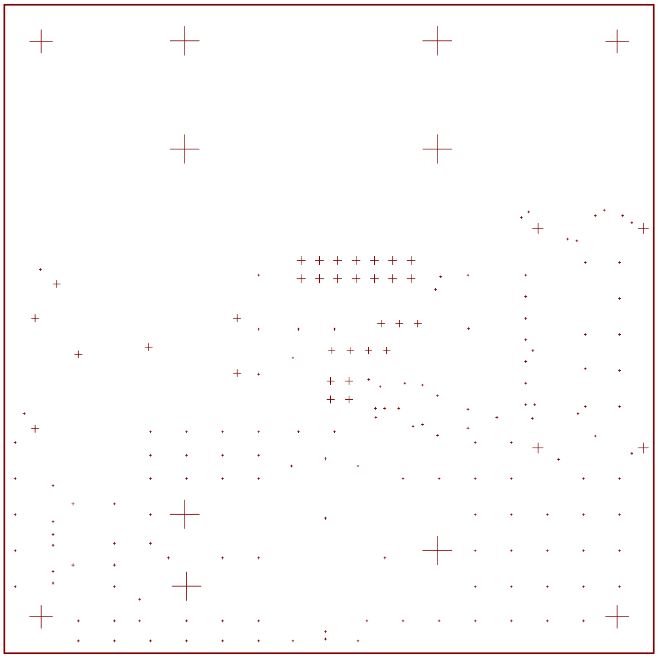


Figure 20. Drill Guide

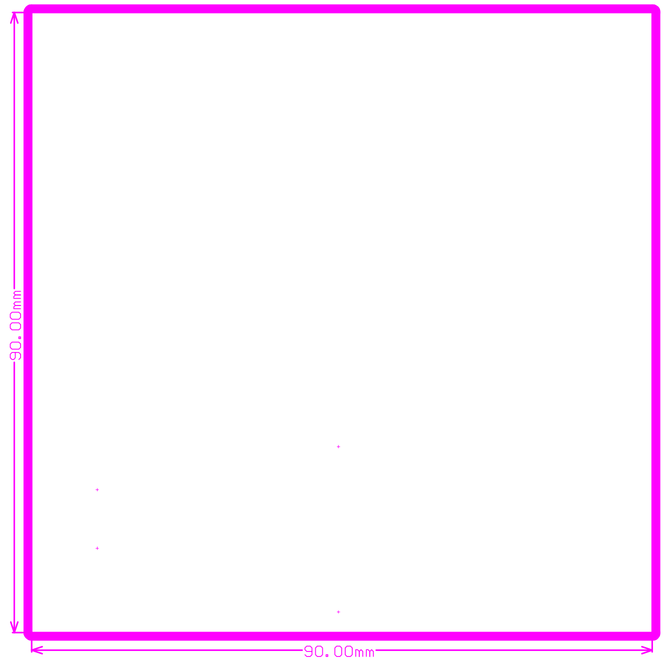


Figure 21. Board Dimensions

8.3.2 Isolated Serial Board

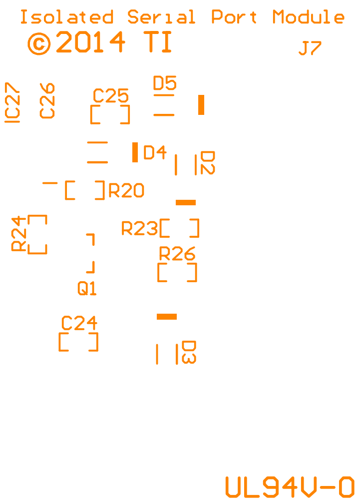


Figure 22. Top Overlay

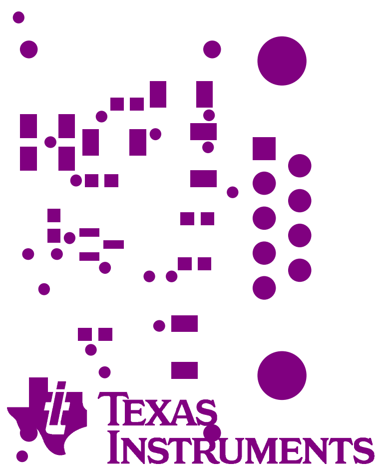


Figure 23. Top Solder

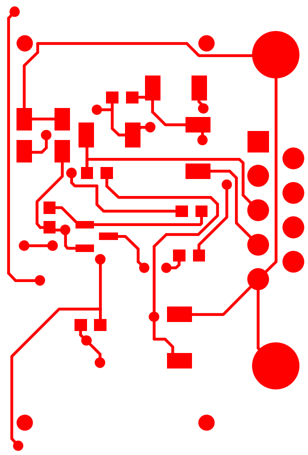


Figure 24. Top Layer

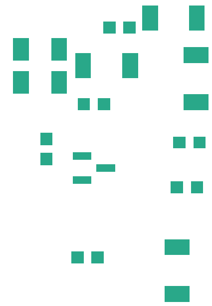


Figure 25. Top Paste

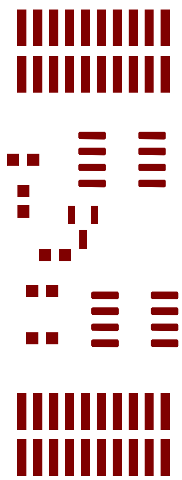


Figure 26. Bottom Paste

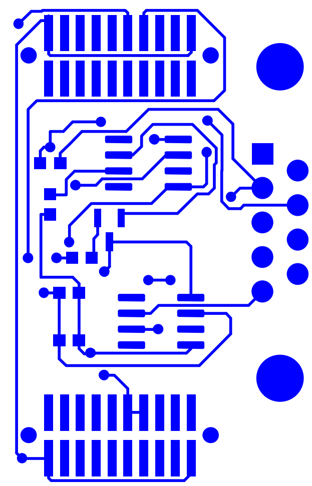


Figure 27. Bottom Layer

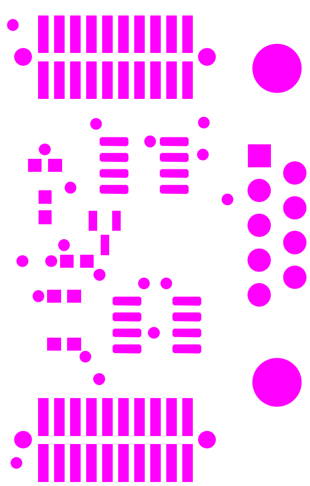


Figure 28. Bottom Solder

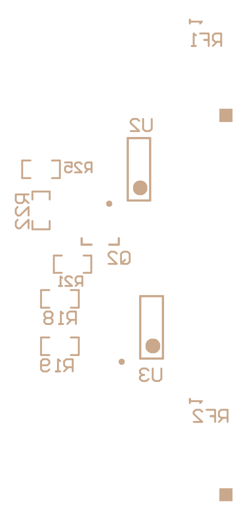


Figure 29. Bottom Overlay

Figure 30. Board Outline

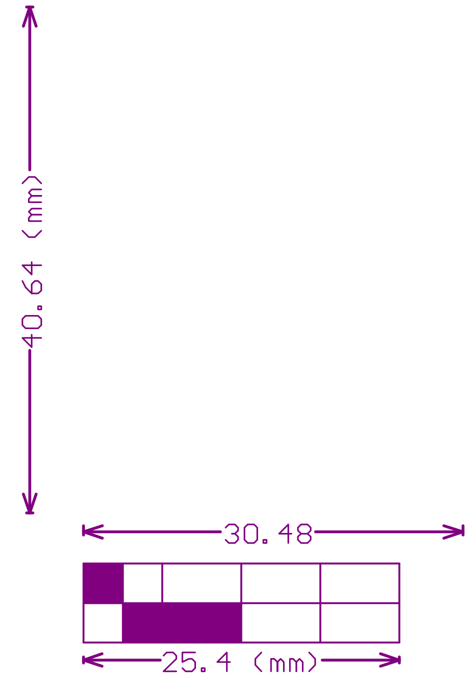


Figure 31. Board Dimensions

8.4 Altium Project

To download the Altium project files, see the design files at TIDM-2PHASE-SUBMTR.

8.5 Gerber Files

To download the Gerber files, see the design files at TIDM-2PHASE-SUBMTR.

8.6 Assembly Drawings

8.6.1 TIDM-2PHASE-SUBMTR

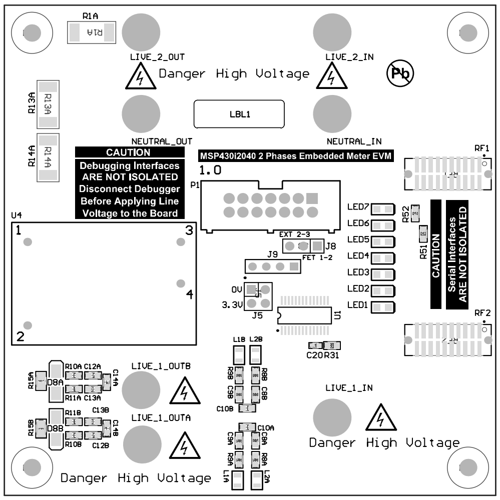


Figure 32. Top Assembly Drawing

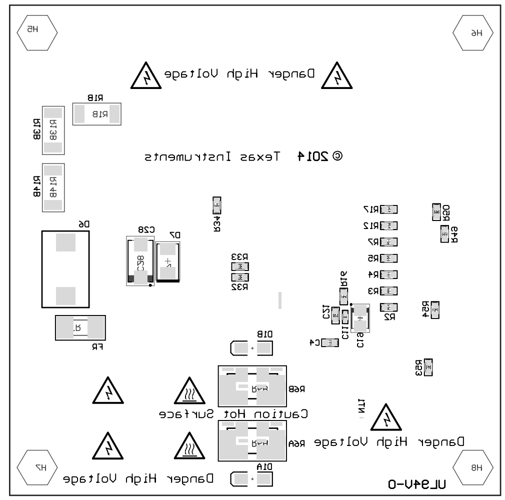


Figure 33. Bottom Assembly Drawing

8.6.2 Isolated Serial Board

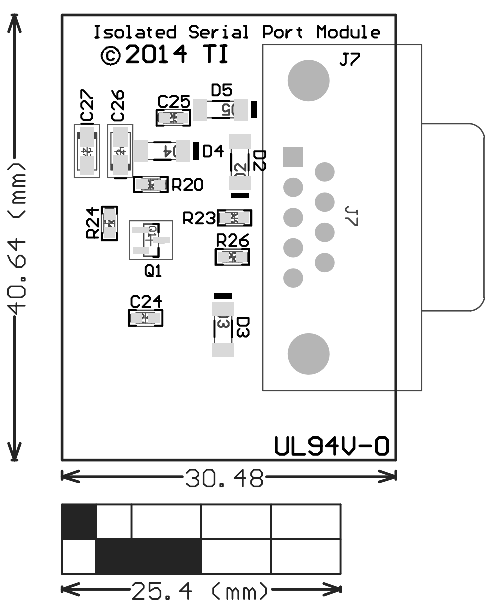


Figure 34. Top Assembly Drawing

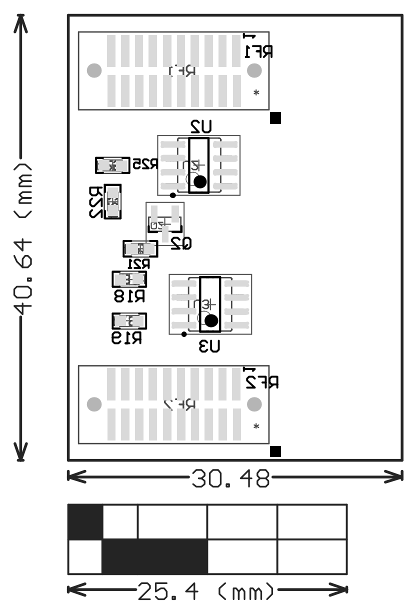


Figure 35. Bottom Assembly Drawing

8.7 Software Files

To download the software files, see the design files at TIDM-2PHASE-SUBMTR.

9 References

1. Kaipu Electronic AC Meter Test Set (http://en.3gcnkaipu.com/index.html)
2. Hsiang Cheng Electric Corp. Reference Meter (http://www.hc.com.tw/index.php)

10 About the Author

MARS LEUNG received his bachelor of engineering in Hong Kong Polytechnic University and his master of science at the Chinese University of Hong Kong. He has been a field application engineer specialized in MCU application support and development; senior smartcard application engineer specialized in smart card payment system definition and implementation; staff engineer specialized in MCU and new module definition; staff engineer in analog system application specialized in digital system; and video processing of dynamic LED backlight control. He is now staff engineer in Texas Instruments' smart grid application team specialized in embedded electricity metering application.

Appendix A Example Application Code

A.1 Introduction

Project structure:

- emeter-communication.c – source code for low level UART communication routines including UART port setup, write and read from UART, interrupt services routine for byte-wise send and receive
- emeter-dlt645.c – source code for the polling mode protocol implementation
- emeter-main.c – source code for system initialization, main loop, callback functions implementation and interrupt vector placement
- emeter-metrology-i2041-2-phase.r43 – embedded metering library object code
- emeter-setup.c – source code for low level system initialization
- emeter-template.h – source code for configuration
- metrology-calibration-default.c – source code to put the user defined default calibration parameter into a proper data structure (do not modify this file)
- metrology-calibration-template.h – source code of user defined default calibration parameter

A.2 Preparing the Application Code to Run

1. Launch the IAR5.5 Embedded Workbench IDE and click on *File→Open→Workspace.*
2. Select *emeters.eww* when prompted to open *Workspace*.

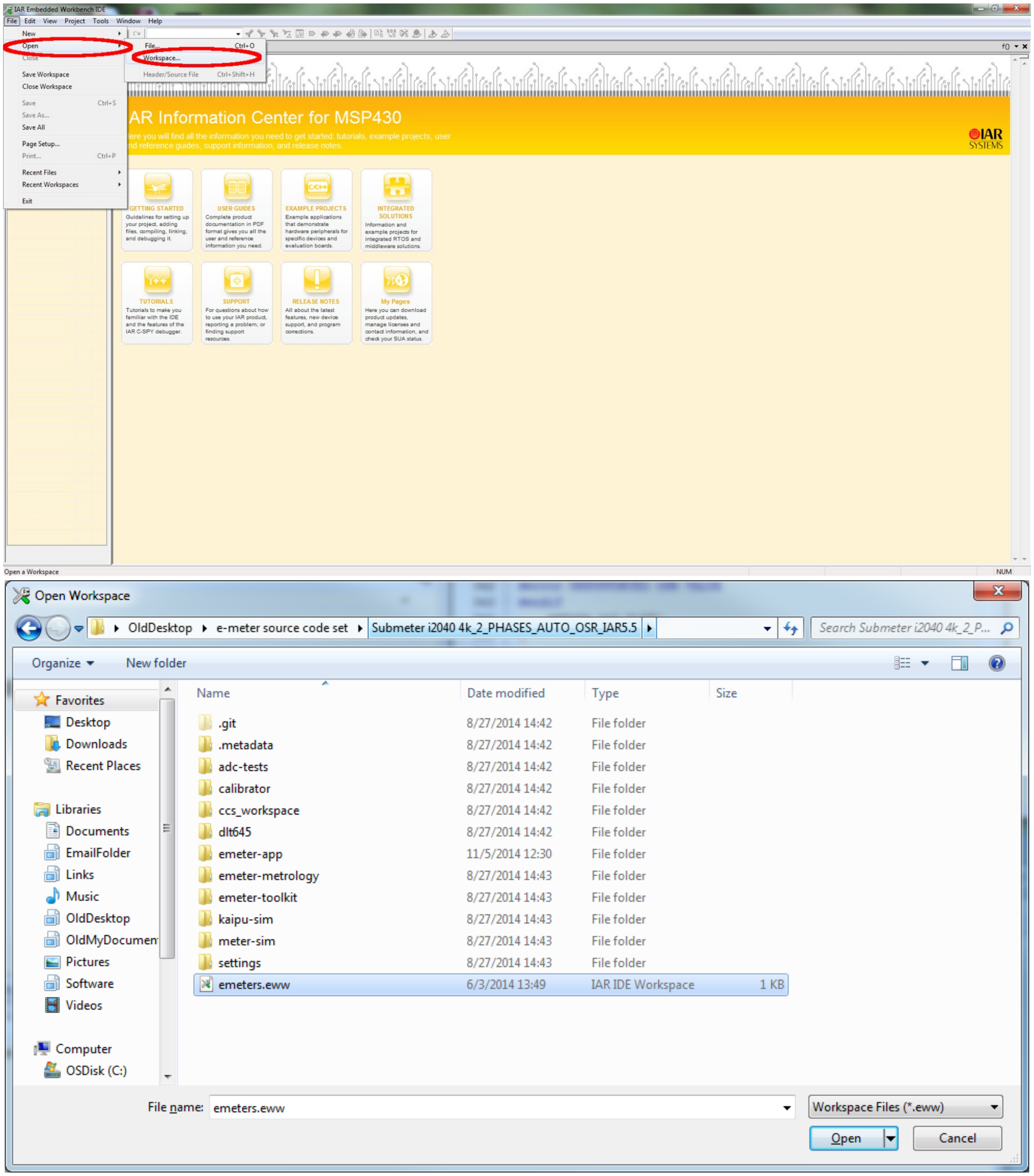


Figure 36. Opening Workspace

3. Select the *emeter-app-i2041* project tab at the bottom of the *Workspace* window.

4. Check project options by right clicking the project name and select *Options…* from the pop-up menu (see Figure 37).

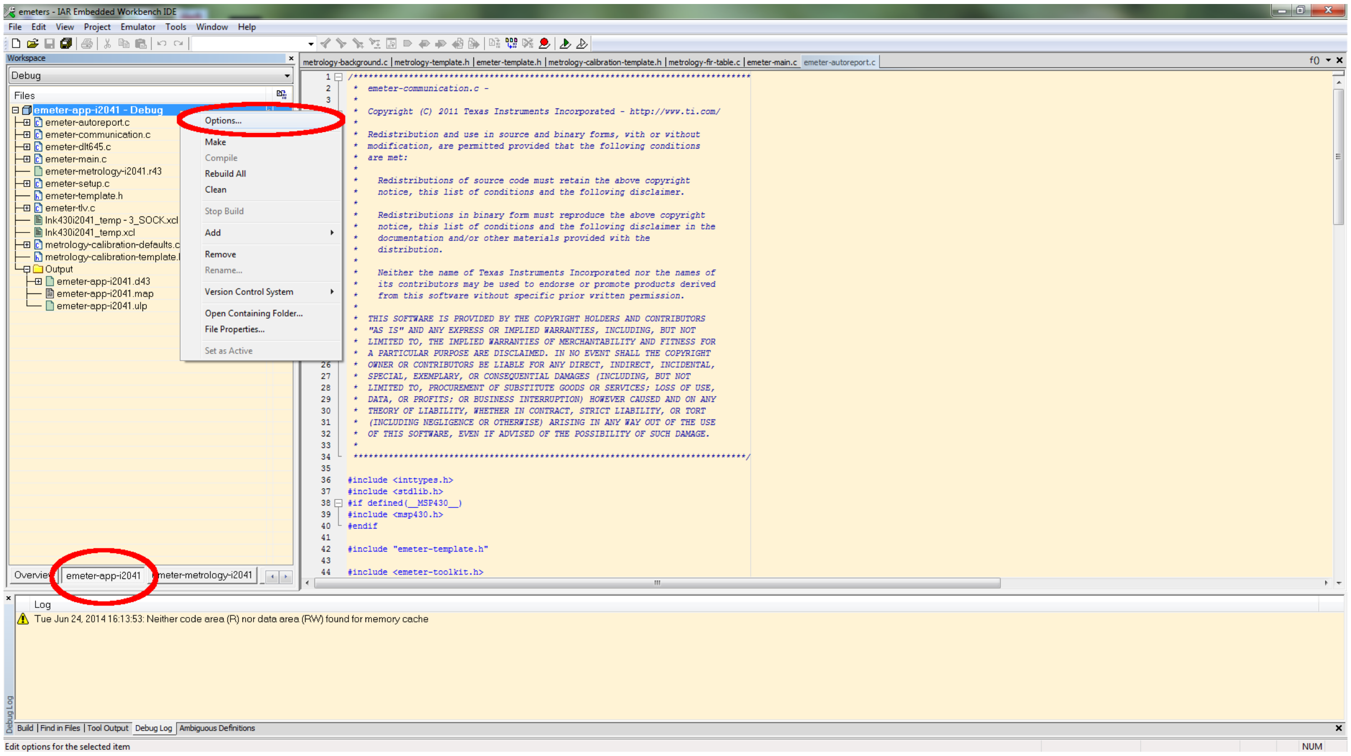


Figure 37. Project Tab

5. When the options appear, select *C/C++ Compiler* on the left-hand column. Then select the *Optimizations* tab on the right-hand side and check the optimization settings as shown in Figure 38.

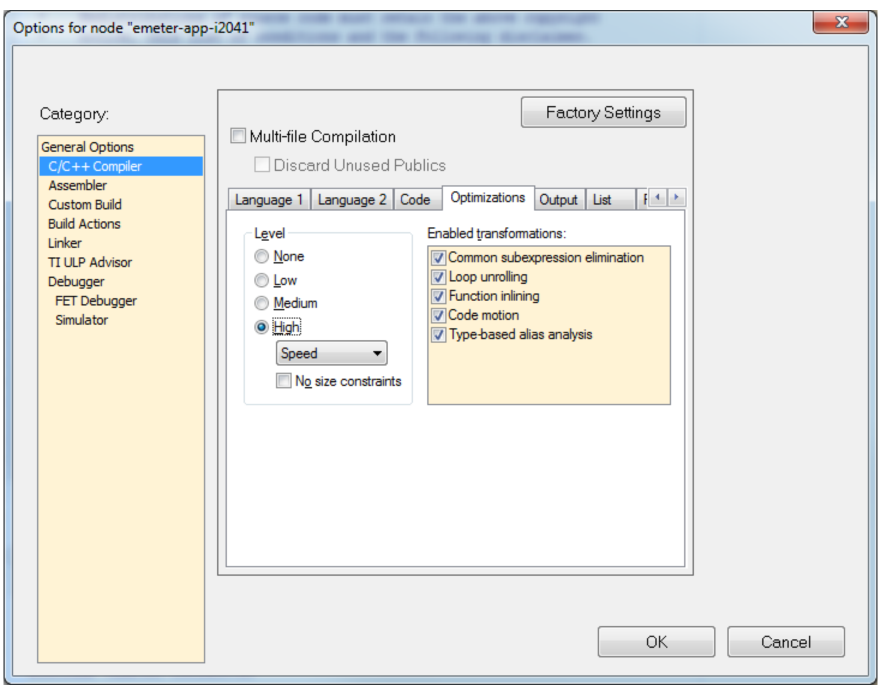


Figure 38. Optimization Options

6. Select *FET Debugger* on the left-hand column, then select the *Setup* tab. The EVM uses Spy-Bi-Wire for its code downloading and debugging. Check to make sure the options are as shown in Figure 39.

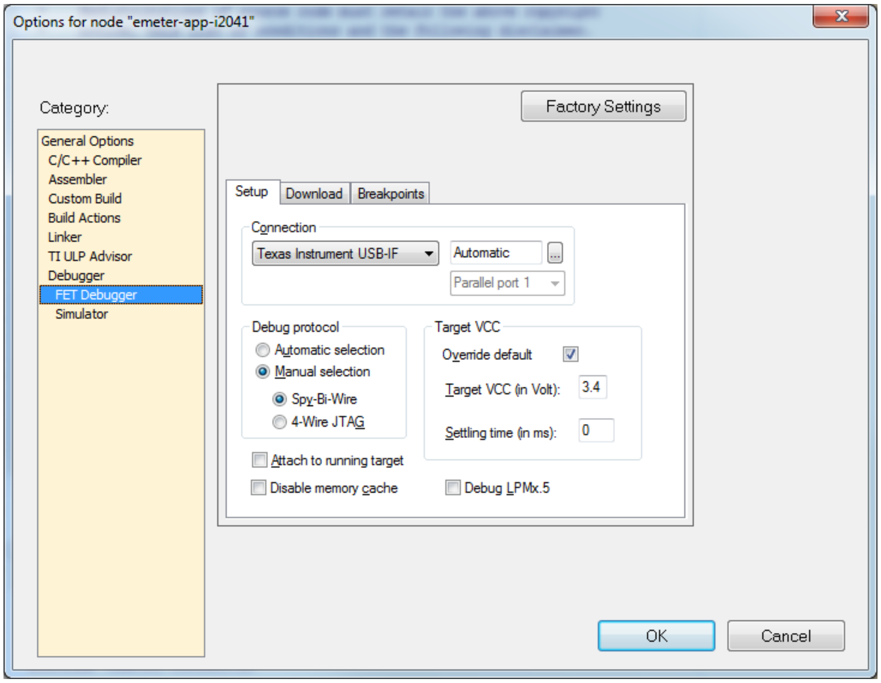


Figure 39. Debugger Options

7. Select the *Download* tab. Under *Flash erase*, do not choose *Erase main memory and Information memory*; this option erases both sets of data and cannot be recovered. Instead, choose *Erase main memory* as the download option to preserve these factory parameters: system clock calibration, ADC calibration, and internal reference calibration (see Figure 40). However, metrology calibration stored in the main memory, such as VGAIN, IGAIN, PGAIN, and so on, are always erased after downloading.

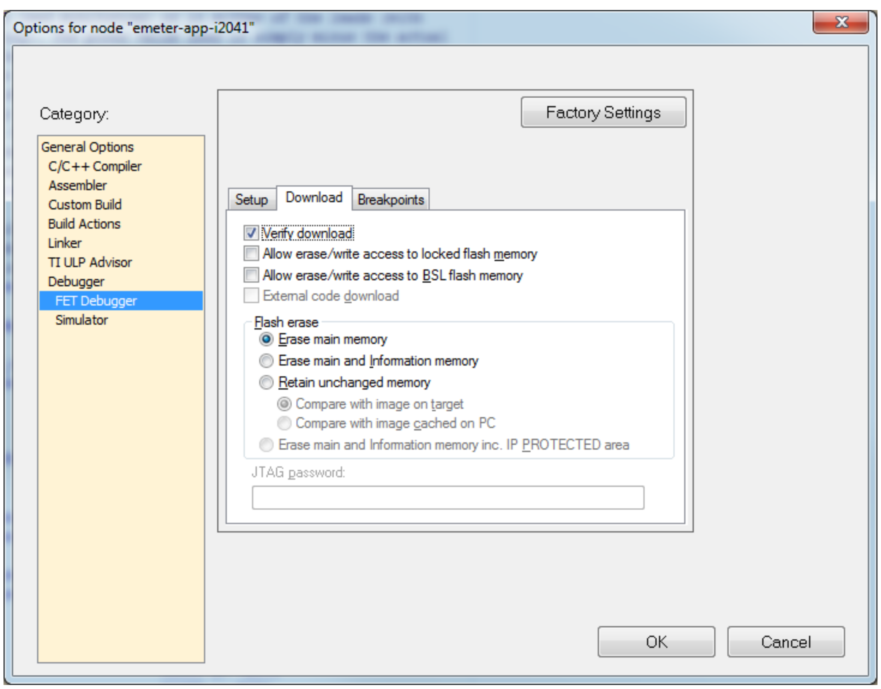


Figure 40. Download Options

8. Click *OK* after completing all of the changes.

9. Rebuild the project by right-clicking on the project and select *Rebuild All* from the pop-up menu (see Figure 41). Three warnings will be reported during rebuilding (see Figure 42), which are safe to ignore. To open the project workspace and modify, compile, and download the code, the user must have IAR Embedded Workbench 5.5 installed with a valid license. If a valid license is not available, the user can still download the object code. See Section A.3 for downloading procedures.

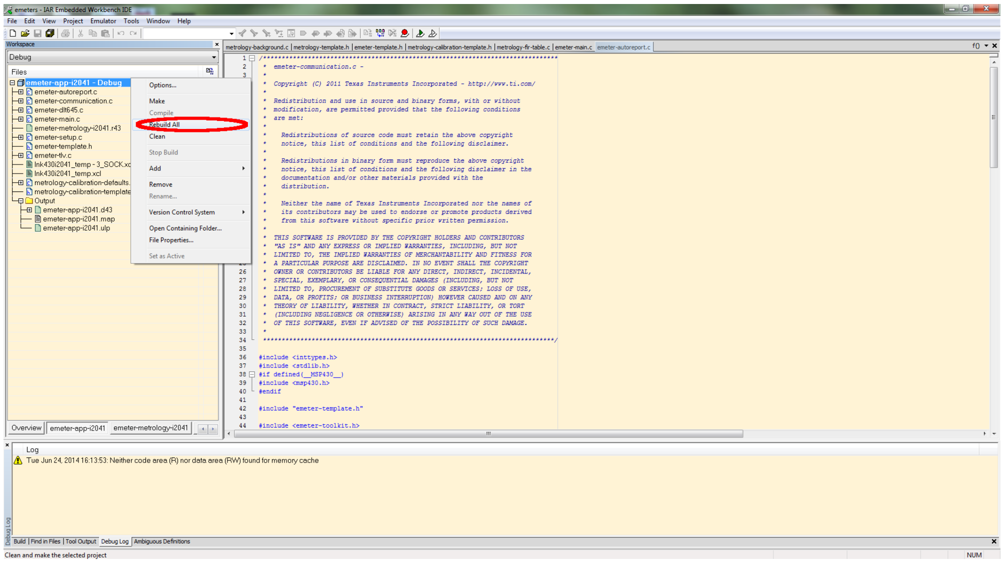


Figure 41. Compiling the Application

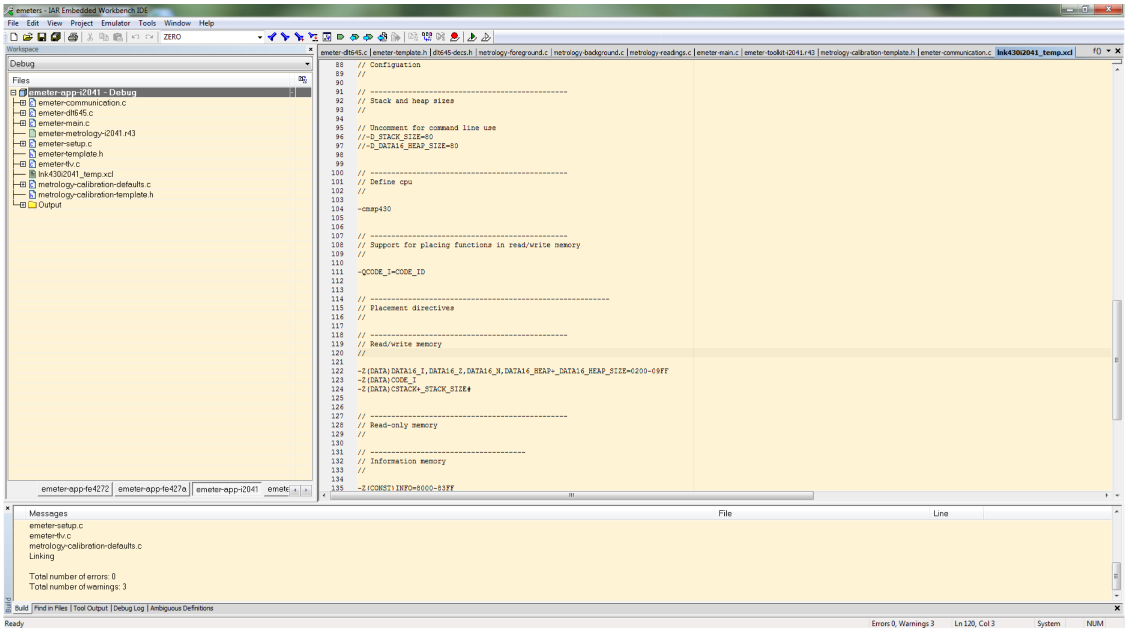


Figure 42. Warnings

10. Make sure the jumper on J8 is short properly. Connect the 14-pin connector P1 to MSP-FET430UIF by a flat cable as shown in Figure 43.

CAUTION

The debugging interface is not isolated. Make sure to properly isolate between the EVM and the PC used for debugging with AC or DC high voltage connected.

NOTE: Connection to debugging interface is optional for the operation of the EVM. The EVM can operate without a debugger connected.

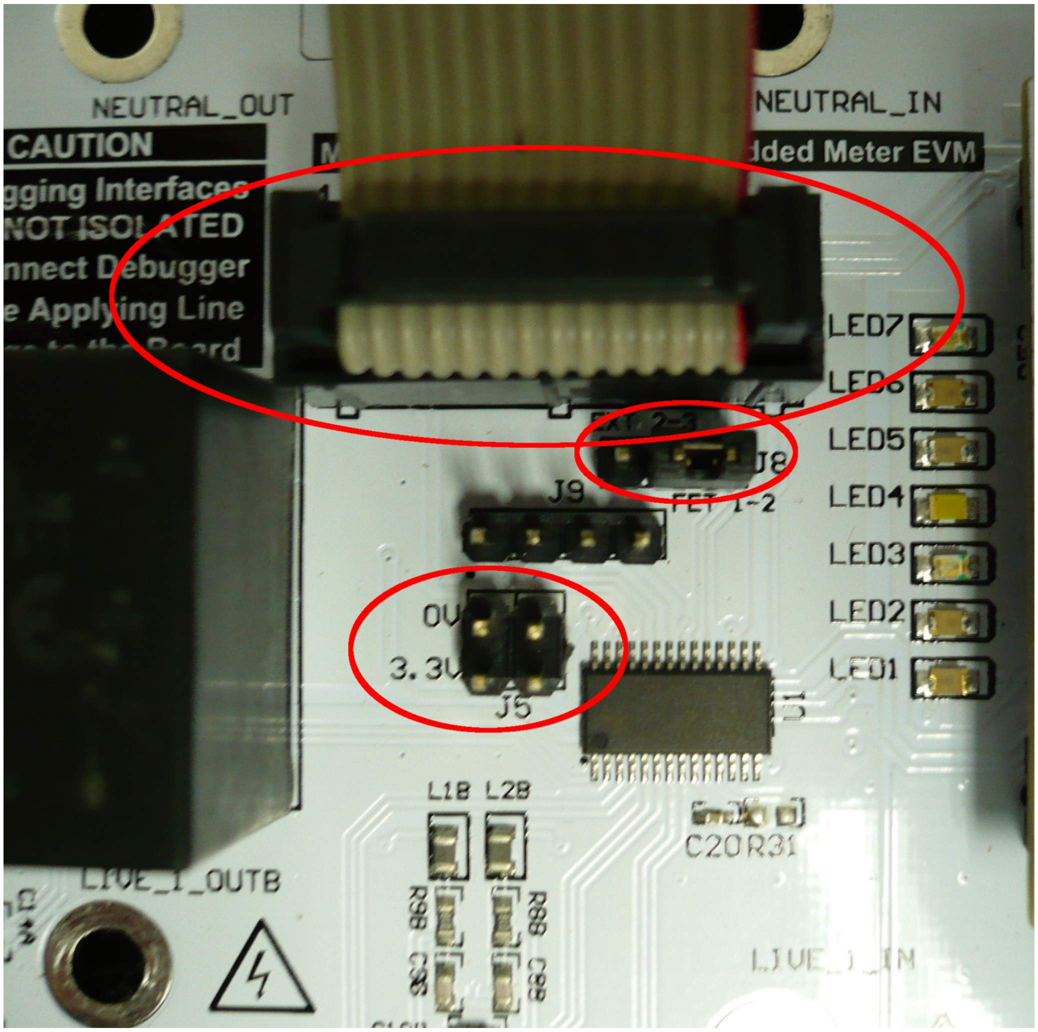


Figure 43. Connecting EVM and FET

11. Click the *Download and Debug* button to download and debug (see Figure 44).

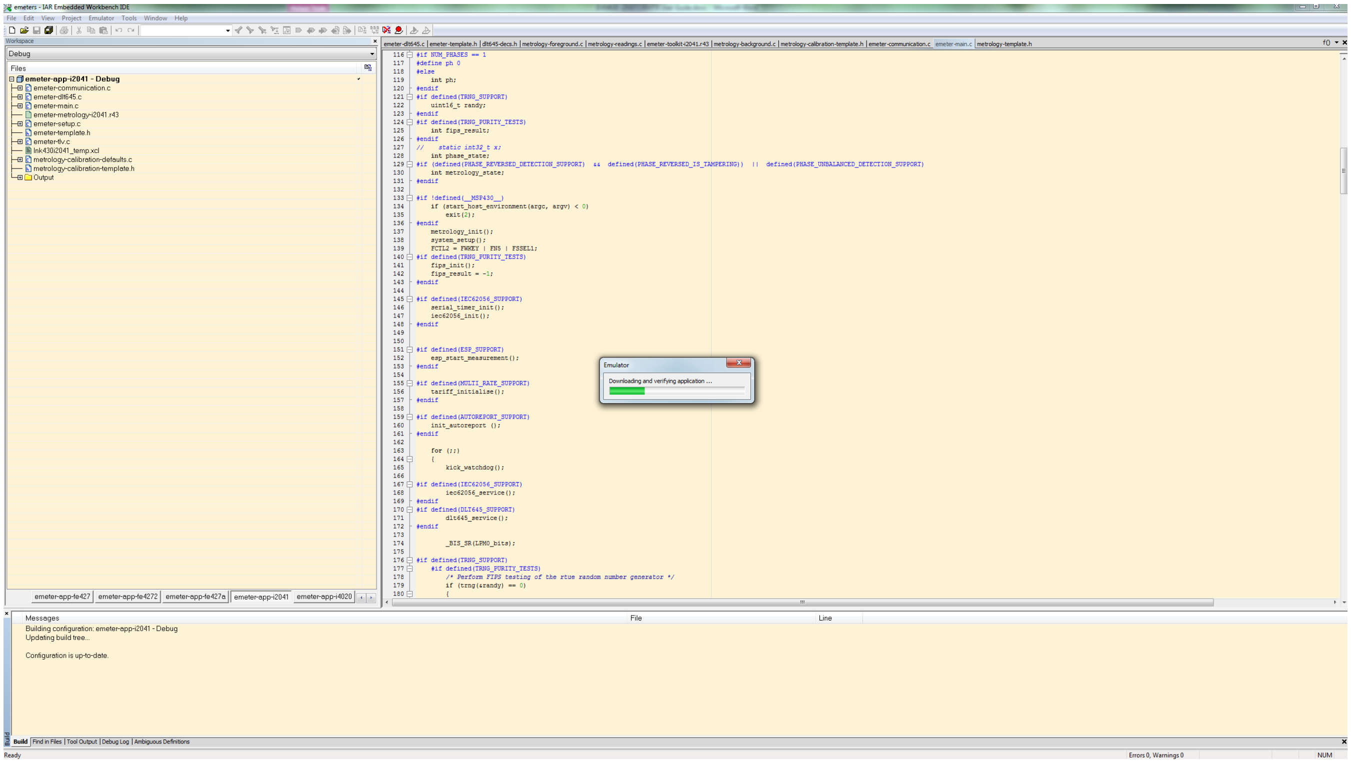


Figure 44. Code Downloading

12. After successfully completing the download, Figure 45 appears. Click *Go* to run the application.

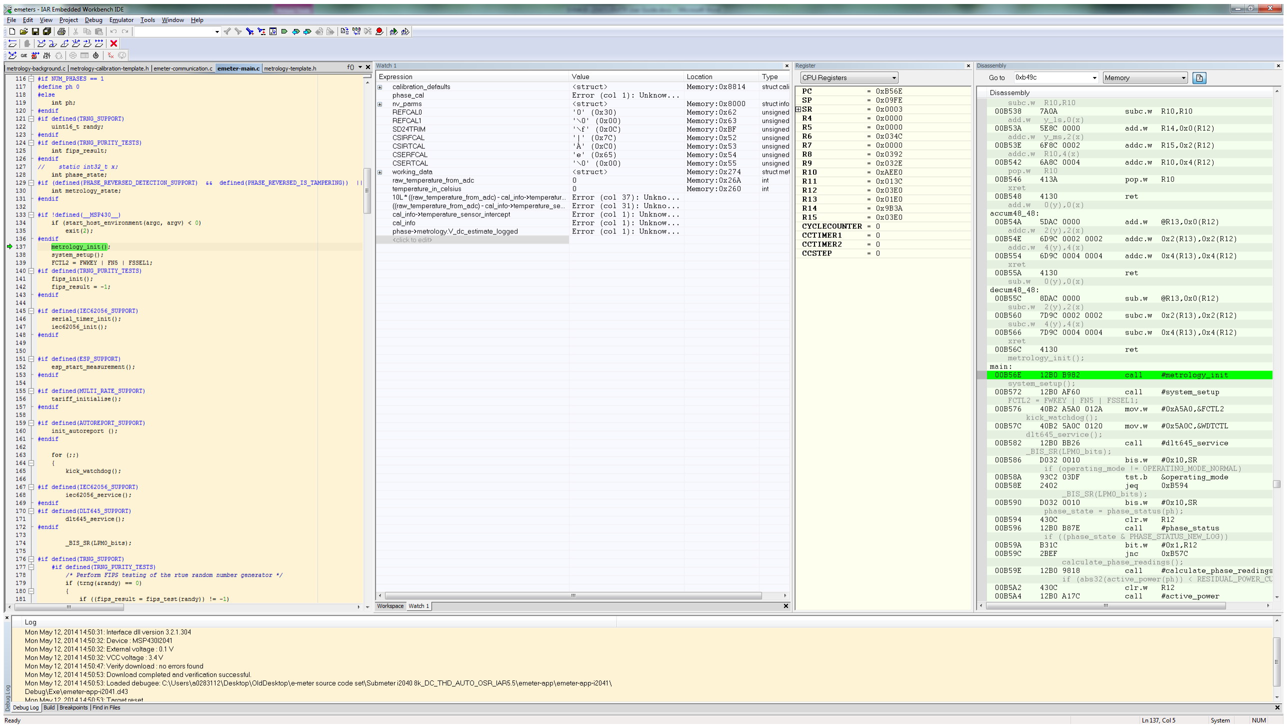


Figure 45. Debugger Screen

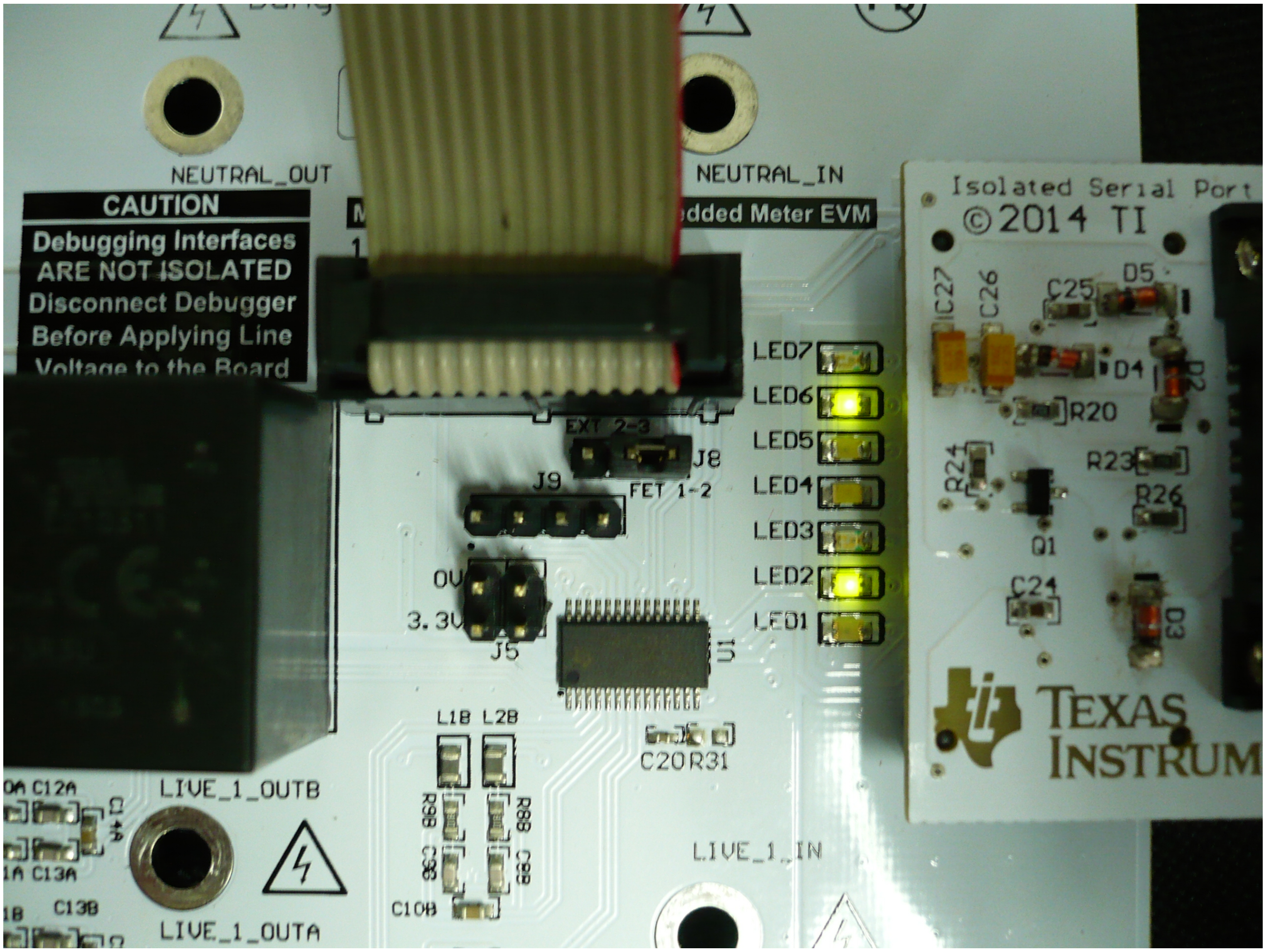


Figure 46. EVM Running

A.3 Downloading Without an IAR License

If a valid IAR Embedded Workbench 5.5 license is not available, download the executable code to the board with the following steps using the installed IAR Embedded Workbench 5.5.

1. Open the project workspace as described in Section A.2, Steps 1 through 7. Then connect the board to the MSP-FET430UIF as described in Step 10 in Section A.2.
2. Select *Project→Download→Download File…* from the menu (see Figure 47).
3. When prompted to select a file, go to the folder *[Submeter i2040 4k_2_PHASES_AUTO_OSR_IAR5.5]\emeter-app\emeter-app-i2041\Debug\Exe* and select the file named “emeter-app-i2041.d43” (Figure 48).

   The executable code will then download to the board.

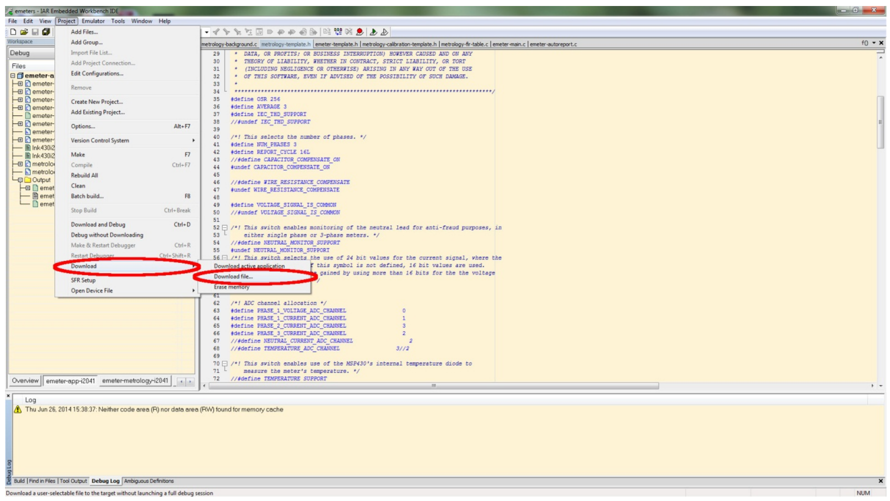


Figure 47. Download Executable File

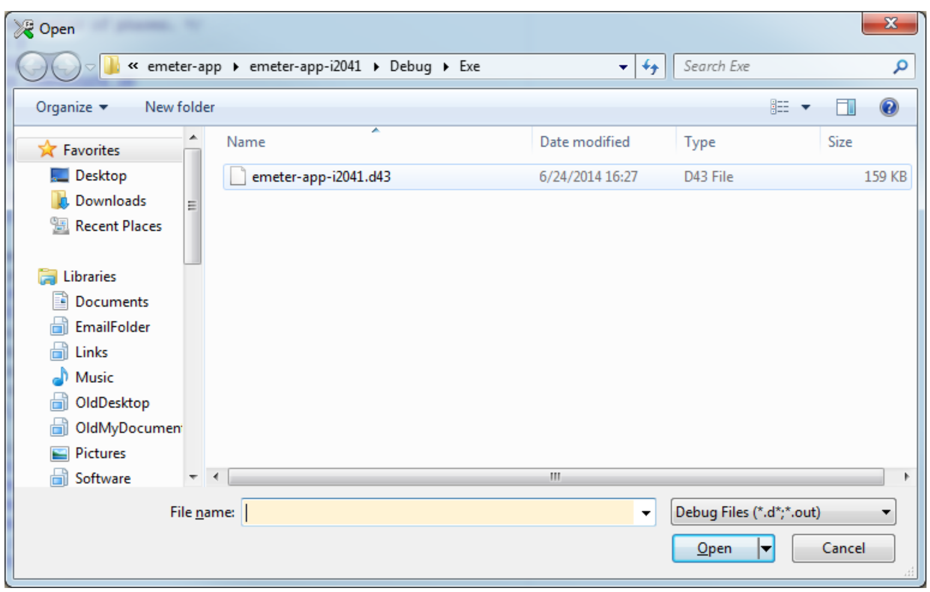


Figure 48. Select File to Download

Appendix B EVM Operation

B.1 *Download Application Code*

Download application to the board by using the IAR compiler as described in Appendix A.

B.2 *Setup the EVM Hardware*

CAUTION

Do not supply power to the EVM until the hardware and software setup is completed.

Install jumper to J5 as shown in Figure 49.

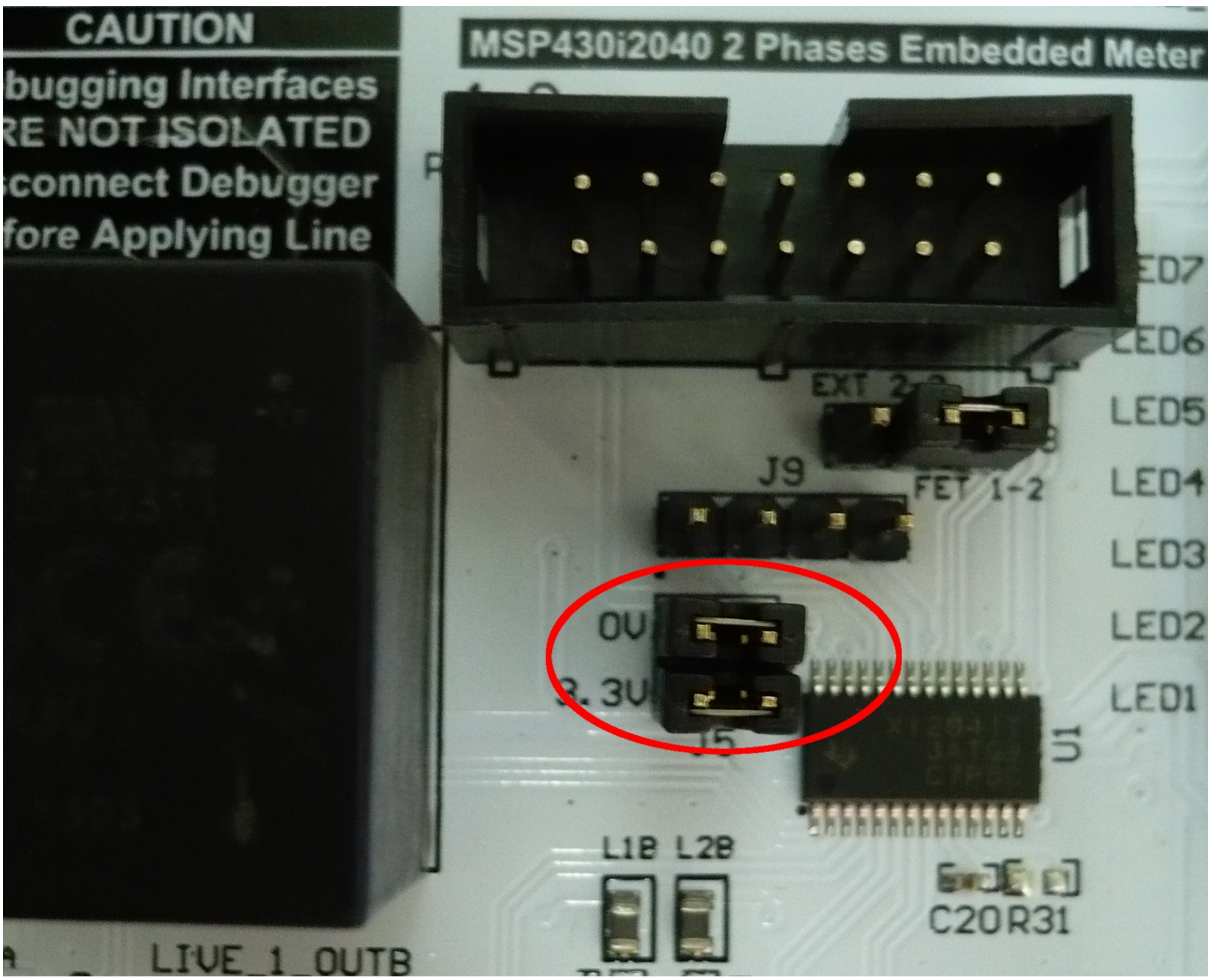


Figure 49. EVM J5 Jumper Setting

Install the isolated serial communication module as shown in Figure B 3 and connect EVM to a serial port on the PC.

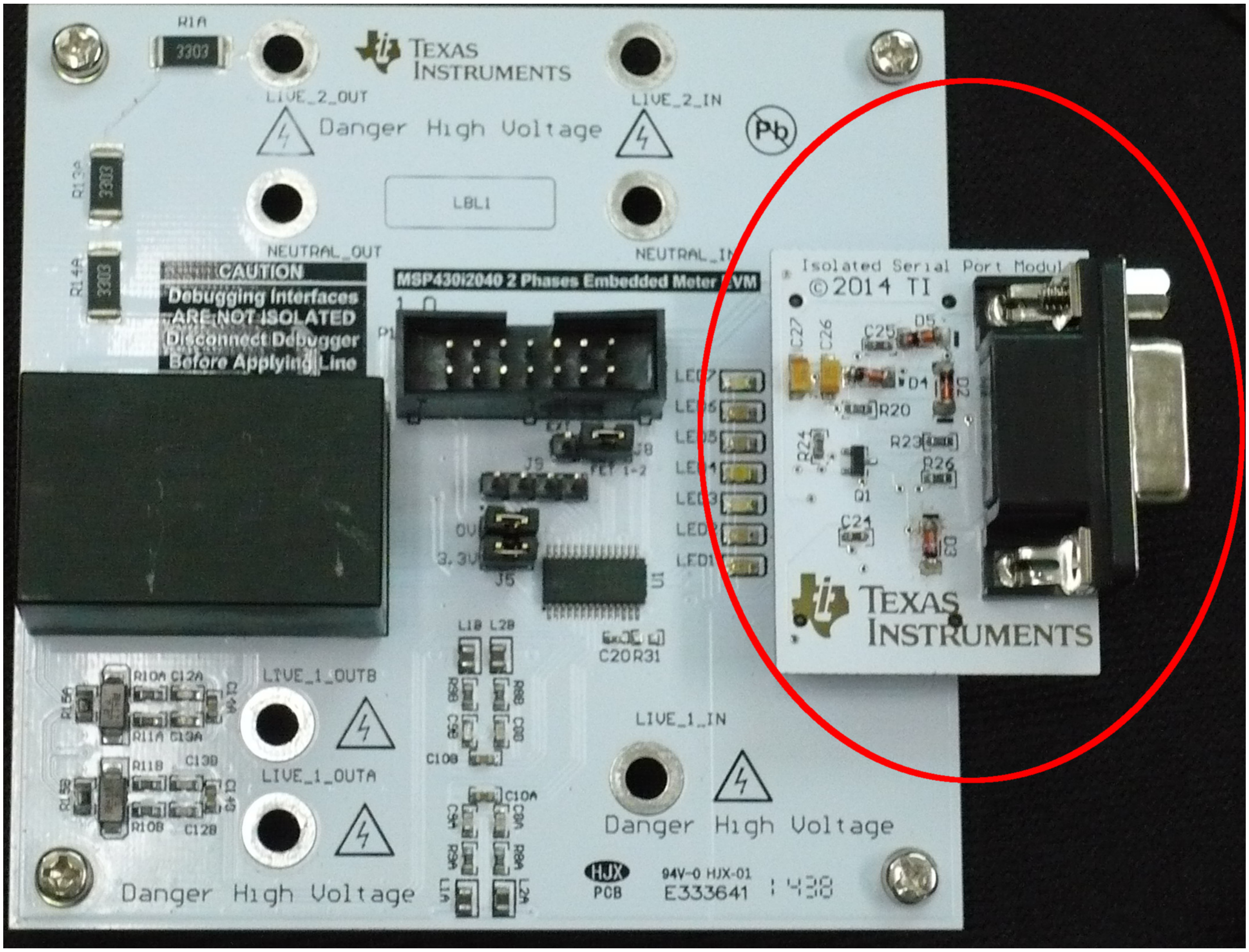


Figure 50. Serial Communication Module Installation

B.2.1 Install and Run PC Software

B.2.1.1 Installing PC Software

Unzip the file named "calibrator-runtime.zip" into any folder. A folder named *calibrator-runtime* containing the necessary files to run the software tool will be in that folder. The file named "calibrator-20121120.exe" is the executable file of the software tool. The file named "calibrator-config.xml" contains the setup information for the software tool. Users must make a few edits to this XML file before calibrator-20121120.exe can launch.

B.2.1.2 Configuring PC Software

Follow these steps to setup the XML to run calibrator-20121120.exe properly:

1. Right click the *My Computer* icon and select *Properties* in the pop-up menu.
2. Select *Device Manager* to go to the *Device Manager* window and check the COM port number of the serial port that connecting the PC and the EVM (see Figure 51).

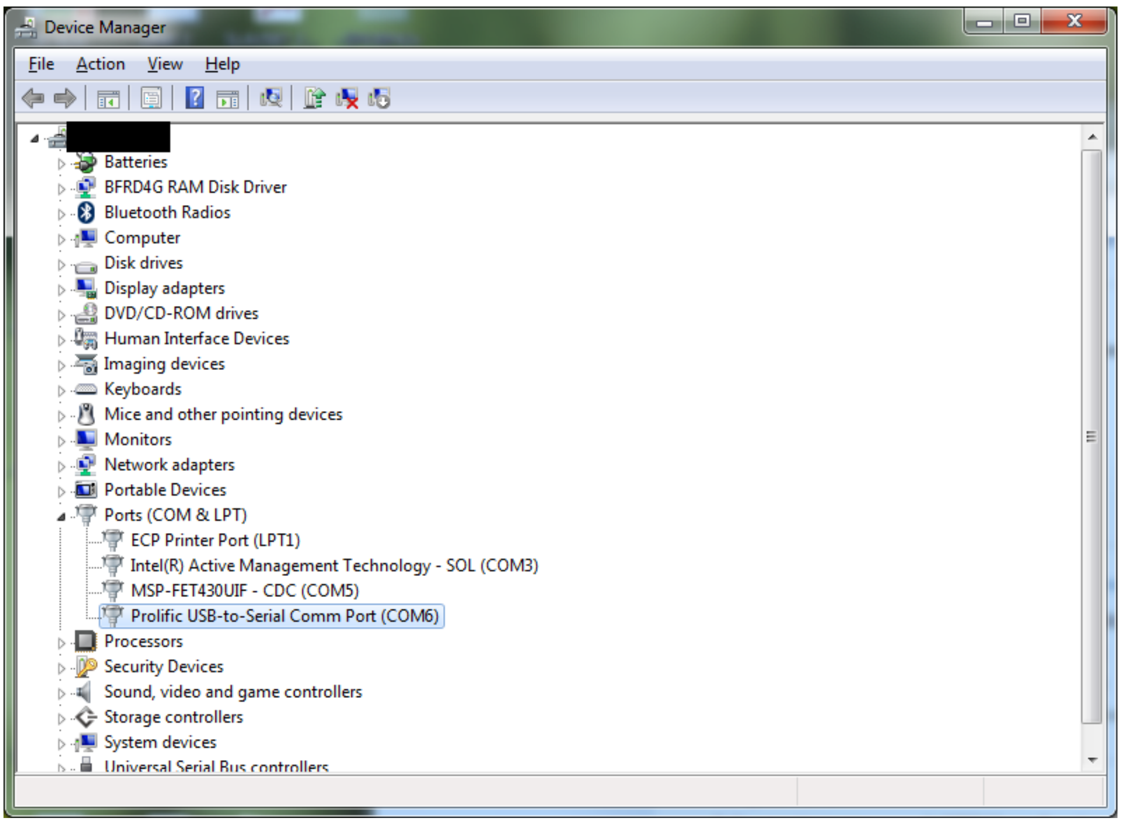


Figure 51. Device Manager Window

3. Open “calibration-config.xml” in the folder *calibrator-runtime* with a text or XML editor. Go to the line highlighted in Figure 52, put in the COM port number in, and save the file.

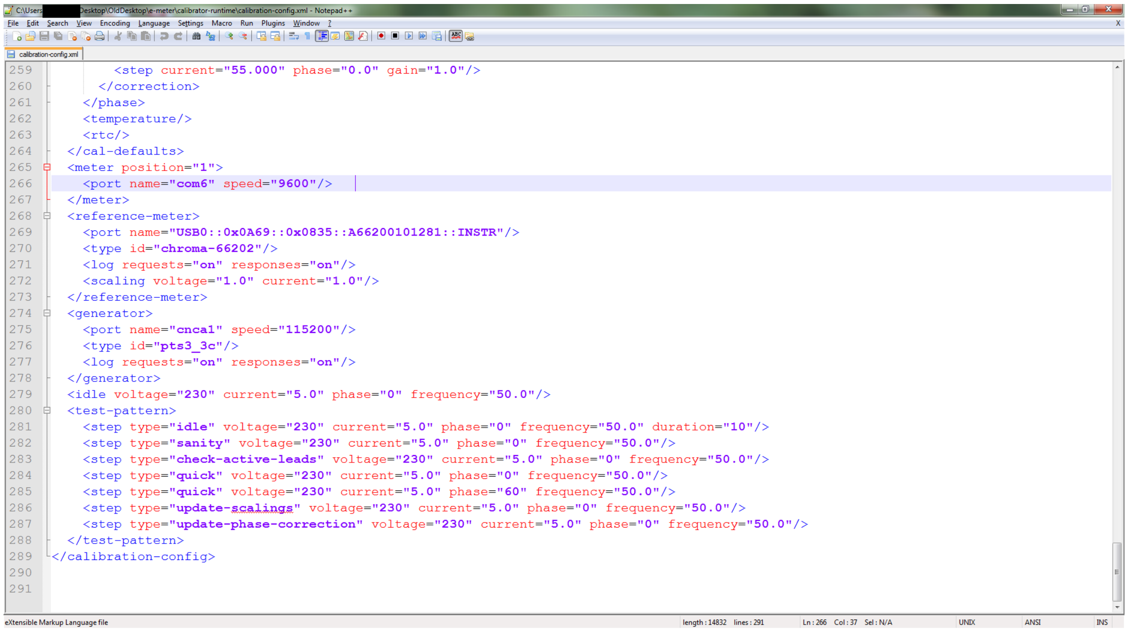


Figure 52. Editing “calibration-config.xml”

B.3 Start Using the EVM

To run the readied EVM, connect the correct AC wiring to labeled input and apply AC power. Then launch the software "calibrator-20121120.exe" in the folder *calibration-runtime* to start communicating with the EVM. A window as shown in Figure 53 appears. As defined in the XML file "calibration-config.xml", meter position 1 is assigned the serial port to communicate with the EVM. The *Comms* indicator will turn green if communication to EVM from PC is established, and it will flash between red and green when the communication takes place.

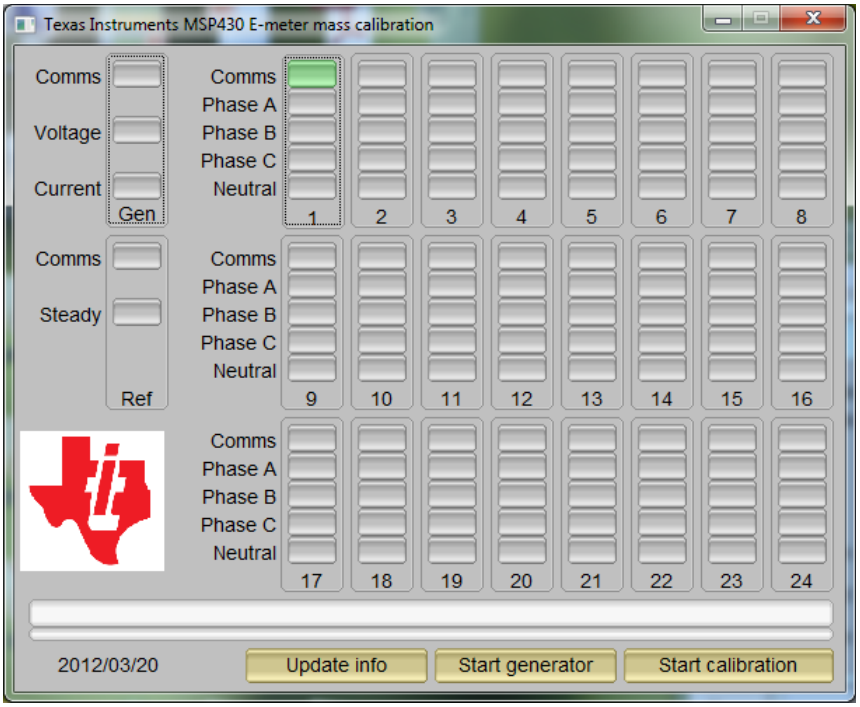


Figure 53. Calibrator Software Startup Window

Click on the *Comms* indicator to show the *Meter status* window as shown in Figure 54.

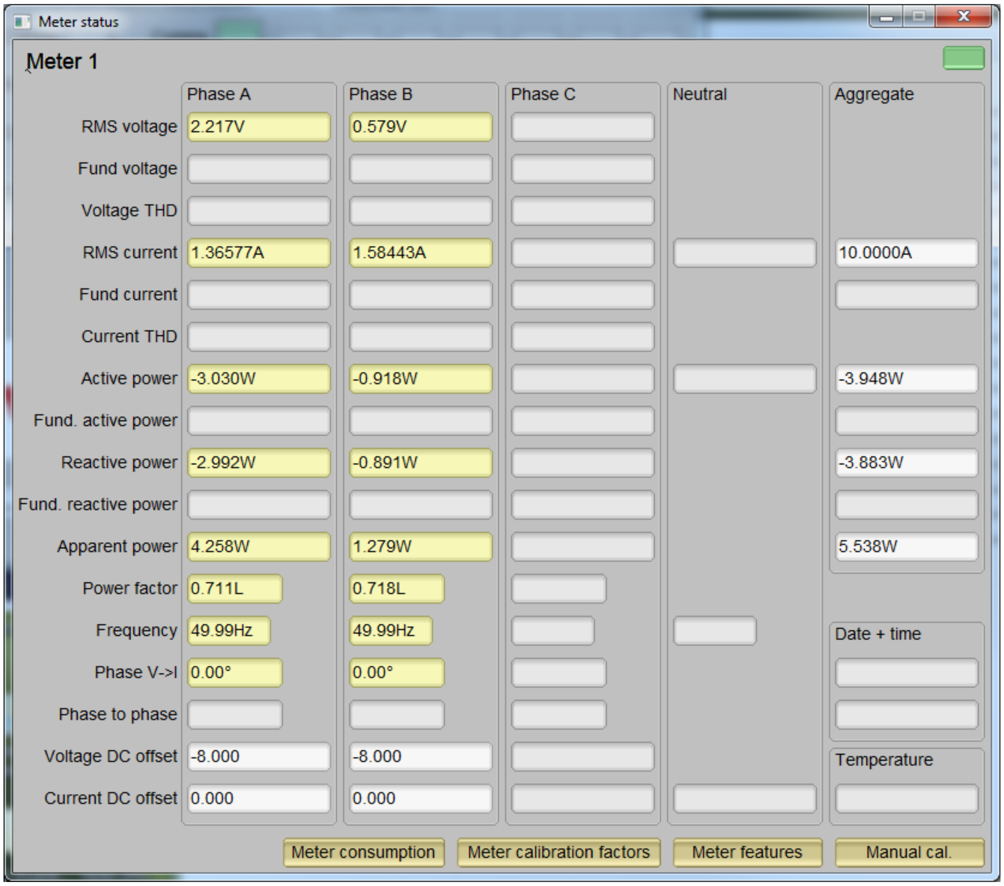


Figure 54. Meter Status Window

This window shows the current reading of the meter. The background of a reading box is gray if the EVM does not support that particular reading. The box turns red if the reading from EVM to that box has a large variance, yellow if the reading from EVM has a fairly low variance, and green if the reading has a low variance.

NOTE: The software on PC reads the EVM every second and averages the data read, meaning the update rate is slower than the update rate of the EVM.

At the bottom of this window, there are four buttons.

- The *Meter consumption* button brings up the *Meter consumption* window. This window gives no useful information because the EVM does not support this feature.
- The *Meter calibration factors* button brings up the *Meter calibration factors* window, which shows the current calibration factor values (see Figure 55).

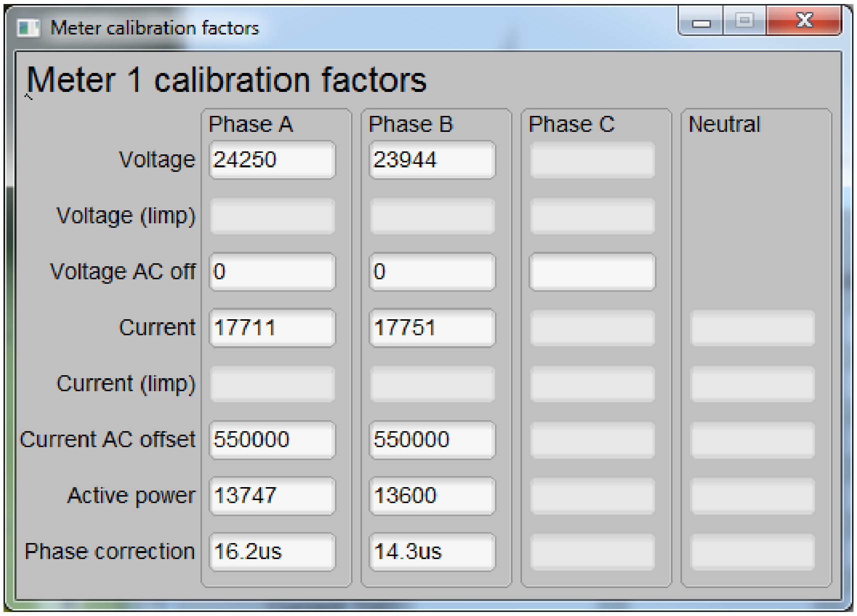


Figure 55. Meter Calibration Factors Window

- The *Meter features* button brings up the *Meter features* window. This window reports the support feature of the EVM (see Figure 56).

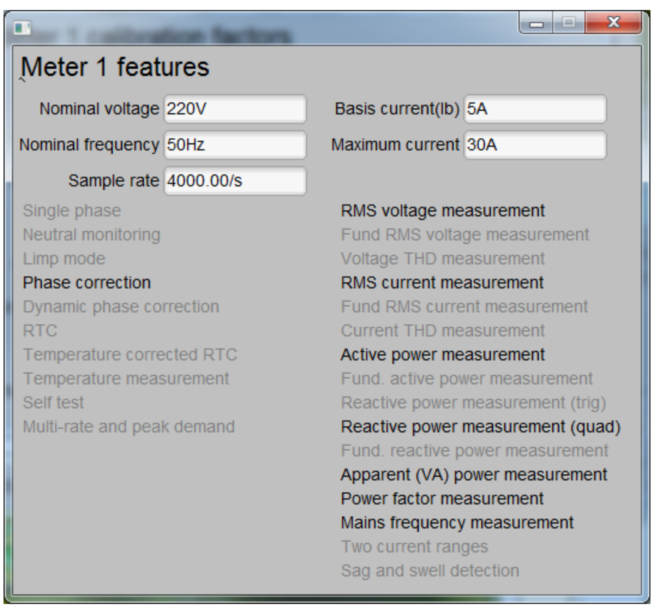


Figure 56. Meter Features Window

- Click on the *Manual cal* button to bring up the *Manual cal* window (Figure 57). In this window, adjust the calibration factor values by entering the percentage error of the reading from the EVM and compare to the reading from the reference meter. The technique and procedure of performing calibration will be discussed in further detail in Appendix C.

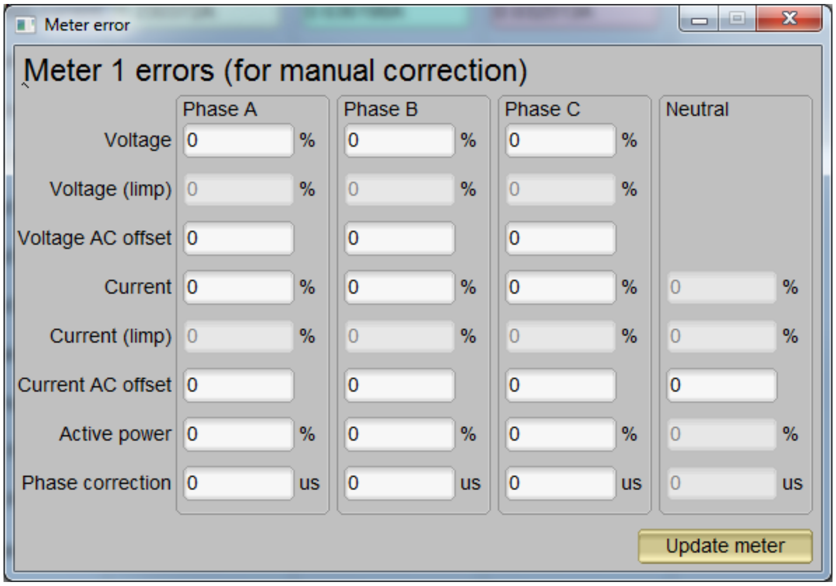


Figure 57. Meter Error Window

To modify the calibration factor, enter the correction in the percentage error. The percentage error is calculated as follows:

$$\%Error = \frac{EVM\ Reading - ReferenceMeterReading}{ReferenceMeterReading} \times 100\% \quad (8)$$

Put the percentage error into its corresponding box in the *Meter calibration* window. Click *Update meter* to calculate and write the updated calibration values to the EVM. The corresponding values will be reflected on the *Meter calibration factor* window (Figure 55).

B.4 Known Issues

The calibrator software is legacy software that operates with utility meters that have not been customized completely for embedded metering. The following is a list of known issues with the existing software that will be fixed in the next version of calibrator software customized for embedded metering.

- Voltage AC offset values cannot be written with the calibrator software. The value put into the voltage AC offset box is written to the current AC offset instead. The value put into the current AC offset box has no effect.
- The aggregate current in *Meter status* windows always shows 10.0000 A.

Appendix C EVM Calibration

C.1 Introduction

The EVM is programmed with calibration values that allow the EVM to give roughly accurate readings; however, the EVM has not been calibrated while shipped. To maximize accuracy and to compensate component and manufacturing tolerance, the EVM must go through a calibration process. This chapter will discuss the techniques, procedures, and steps of calibration.

C.2 Calibration Techniques

To calibrate, use the instruments listed in Section 6.1 and connected properly as in Section 6.2. Calibrate each phase.

This design requires a two-point calibration. VGAIN, IGAIN, PGAIN, VDC_OFFSET, and IDC_OFFSET are parameters that will be calibrated during the process; an estimated value is put into the memory during the design and characterization to help to speed up calibration.

VAC_OFFSET, IAC_OFFSET, and PHASE_CORRECT are parameters that may not need calibration but a characterization would be sufficient for embedded metering application except for a high accuracy of <0.1%.

NOTE: The calibration values are written in one flash page in the EVM, so when a new value needs to be written the whole page is erased. The provided GUI will do the read, modify, and write operations automatically. When using a user calibration facility, read the complete set of calibration values, back them up, update the modified field, and write the complete set back to the EVM.

C.3 Calibration Procedures

C.3.1 Calibration of AC Parameters

Use the following steps to calibrate the AC parameters.

Calibrating VGAIN

1. Set *VIN* to line voltage.
2. Calculate the value for VGAIN with the formula

$$VGAIN_{n+1} = \frac{V_{REF}}{V_{UUT}} \times VGAIN_n$$

where

- $VGAIN_{n+1}$ is the new voltage calibration factor
- $VGAIN_n$ is the original voltage calibration factor
- V_{REF} is the reference meter voltage reading at the voltage set for VGAIN calibration
- V_{UUT} is the unit under test voltage reading at the voltage set for VGAIN calibration (9)

Or, if percentage error is used (as with the provided calibration software),

$$\%Error = \frac{V_{UUT} - V_{REF}}{V_{REF}} \times 100\% \quad (10)$$

3. Write and apply the calibrated VGAIN.

Calibrating IGAIN

1. Set to calibration current (for example, 5 A).
2. Calculate IGAIN value with the formula

$$IGAIN_{n+1} = \frac{I_{REF}}{I_{UUT}} \times IGAIN_n$$

where

- $IGAIN_{n+1}$ is the new current calibration factor
- $IGAIN_n$ is the original calibration factor
- I_{REF} is the reference meter current reading at the current set for IGAIN calibration
- I_{UUT} is the unit under test current reading at the current set for IGAIN calibration (11)

Or, if percentage error is used (as with the provided calibration software),

$$\%Error = \frac{I_{UUT} - I_{REF}}{I_{REF}} \times 100\% \quad (12)$$

3. Write and apply the calibrated IGAIN.

Calibrating PGAIN

1. Set to calibration current (for example, 5 A) and power factor of 1.
2. Calculate PGAIN gain with the formula

$$PGAIN_{n+1} = \frac{P_{REF}}{P_{UUT}} \times PGAIN_n$$

where

- $PGAIN_{n+1}$ is the new power calibration factor
- PGAIN is the original power calibration factor
- P_{REF} is the reference meter power reading at the power set for PGAIN calibration
- P_{UUT} is the unit under test power reading at the power set for PGAIN calibration (13)

Or, if percentage error is used (as with the provided calibration software),

$$\%Error = \frac{P_{UUT} - P_{REF}}{P_{REF}} \times 100\% \quad (14)$$

3. Write and apply the calibrated PGAIN.

C.3.2 Calibration of Current AC Offset

The current AC offset is the result of noise pickup, and the offset generated on the shunt resistor circuit causes an illusion of having a finite current flowing when there is actually not current flowing through the shunt. Although this noise current does not affect the power reading's accuracy, this illusion contributes to the current reading and its accuracy, especially when the current is small. To offset this miscalculation, the EVM firmware has the mechanism to remove this from the current reading. The steps to calibrate this current offset are as follows:

1. Apply nominal voltage to make sure the EVM operates.
2. Remove all loading from the EVM.
3. Take multiple current readings (for example, 100) and take an average as I_NOISE (in A).
4. Calculate the current AC offset value with the equation

$$I\_AC\_OFFSET = int\left[I\_NOISE\left(\frac{1024 \times 10^6}{IGAIN}\right)\right]^2 \quad (15)$$

NOTE: This is a big number even in the case of a few mA of noise.

5. Write and apply the calibrated I_AC_OFFSET.

C.3.3 Calibration of Voltage AC Offset

In most cases, the voltage AC offset rarely affects the voltage reading and does not require calibration.

C.3.4 Calibration of Phase Correction

1. Set the test set to generate rated voltage and set to calibration current (for example, 5 A).
2. Make sure calibrations are complete for PGAIN (at PF = 1).
3. Set the test set to output at power factor 0.5 (+ or – is not important at this point).
4. Note the power error.
5. Switch the test set to output at power factor 0.5 in the other direction to Step 3.
6. Note the power error.
7. At this point, both power errors should be approximately the same deviation but a different direction from the calibrated power error at PF = 1.
   - For example, at PF = 1, the calibrated error is 0.1%. If at PF = 0.5, the power error reads about 0.5%. Then at PF = –0.5, the power error should read about –0.3%.
8. Adjust the phase correction with time deviation from the current phase correction such that the power errors at PF = ±0.5 are minimized.
   - For example, if the current phase correction is 13 µs and 11 µs is desired, enter –2 into the phase correction box of the manual calibration window.
9. Repeat for both phases.

Appendix D EVM Specification

- Voltage operating range (with supplied power supply): 85 to 265-V AC
- Sample rate: 4000 Hz
- Sampling bit depth: 24 bits
- Polling report supported
- Update rate: Eight AC cycles
- UART communication data rate: 9600 bps
- Measurements: RMS voltage, RMS current, active power, reactive power, apparent power, power factor, and line frequency
- Measurement voltage range: 0 to 265 V_{RMS} AC (one phase), 0 to 125 V_{RMS} AC (two phases)
- Measurement current range: 0 to 30 A_{RMS} AC
- Voltage resolution: 1 mV
- Current resolution: 1 µA
- Active power resolution: 1 mW
- Reactive or apparent power resolution: 1 mW
- Power factor resolution: 0.001
- Frequency resolution: 0.01 Hz

Appendix E Running on MSP430i2040 and MSP430i2041

The example IAR project has been configured for MSP430i2041. To run on MSP430i2040, follow these steps once:

1. Open the workspace. After launching IAR 5.5, select *File→Open→Workspace.*

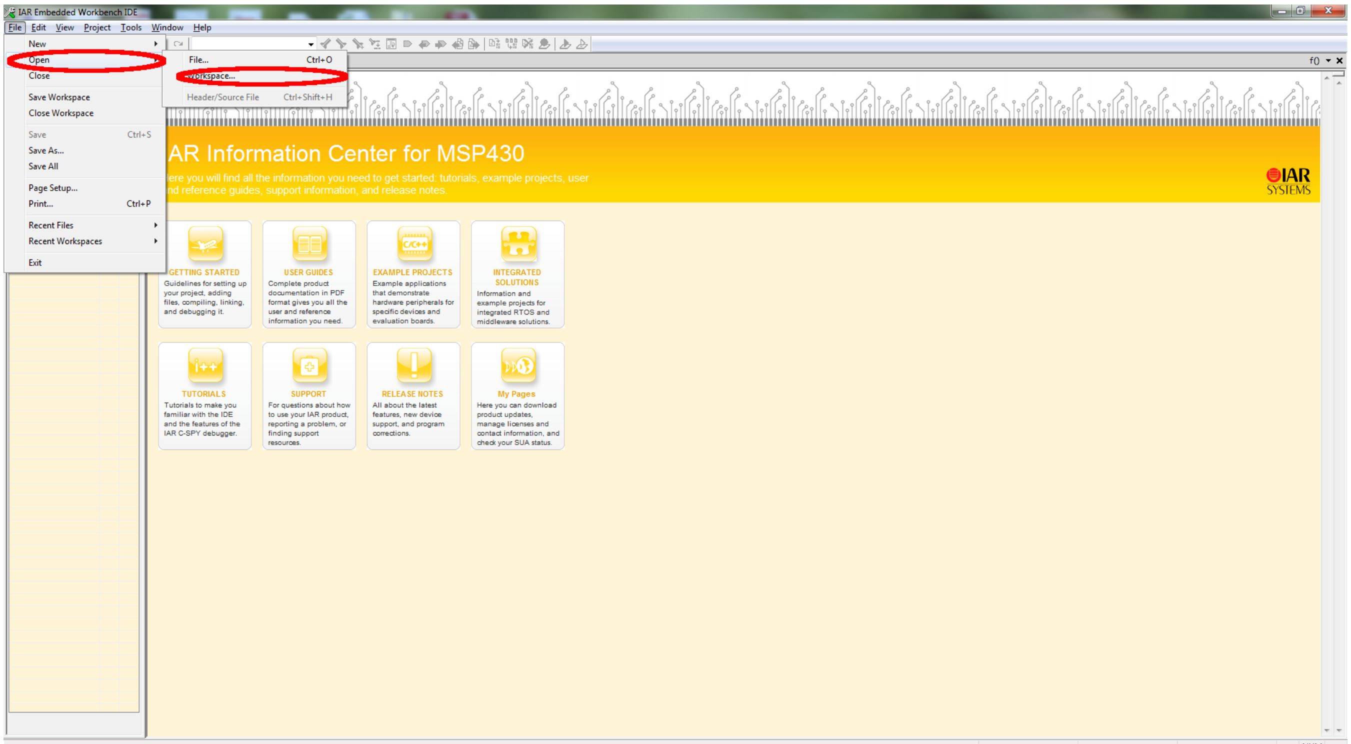


Figure 58. IAR 5.5 Launch Window

When prompted to open the project, select *emeters.eww* from the project directory of the example code.

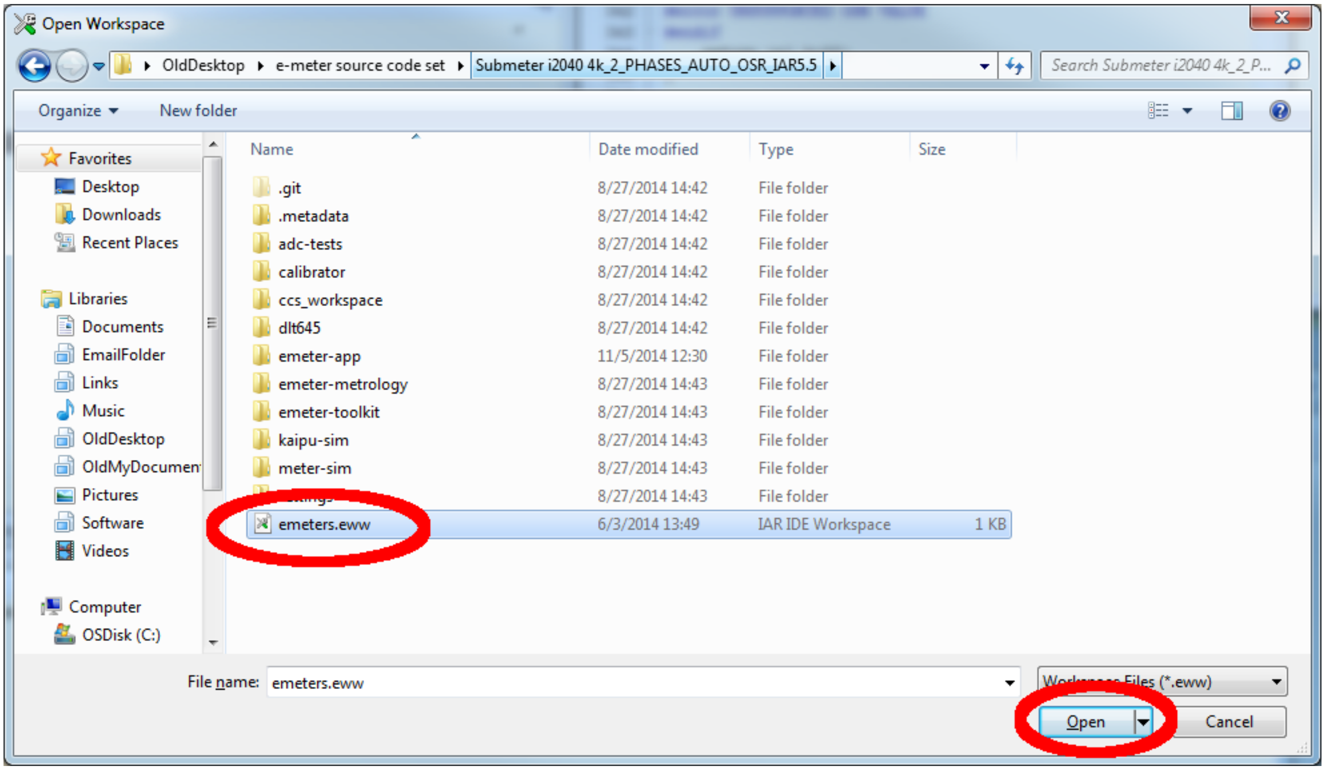


Figure 59. Open Workspace Window

2. Set the option. Right click on the project *emeter-app-i2041* and select *Options...*

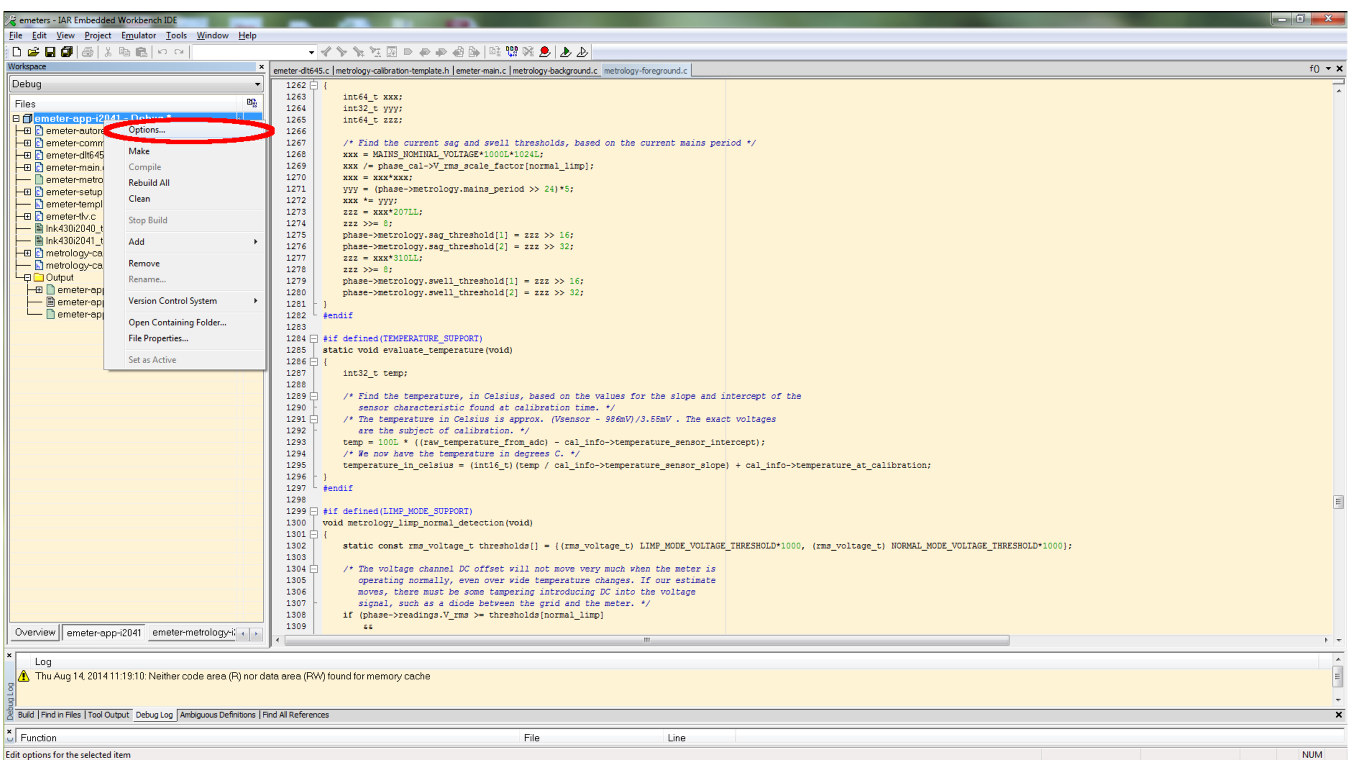


Figure 60. Workspace Options

In the *Options* window, click on *General Options* on the left-hand column and then select the *Target* tab. Then, in the *Device* section, click on the right-hand side button of the entry box and select *MSP430Ixxxx Family→MSP430I2040.*

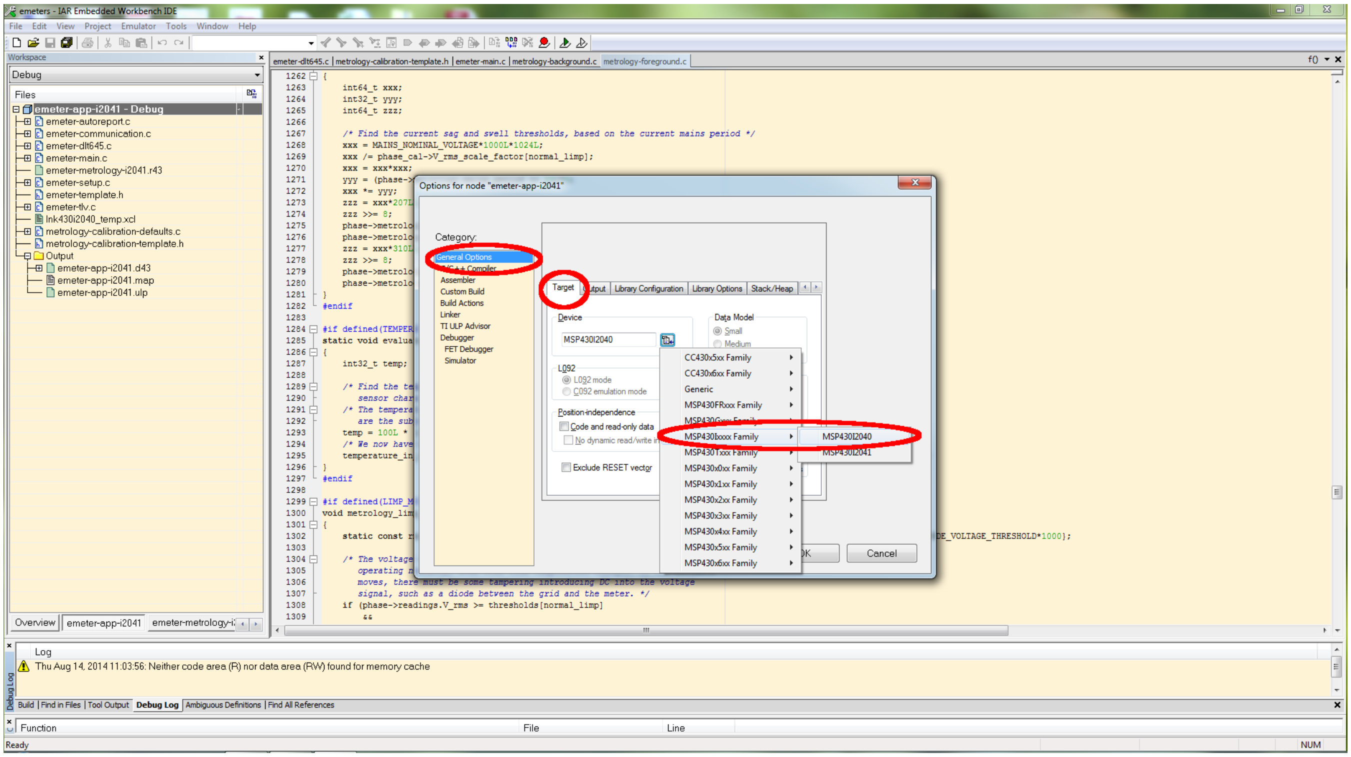


Figure 61. Options Window

Click on *Linker* in the left-hand column and select the *Config* tab. Then click on the right-hand button in the *Linker configuration file* box.

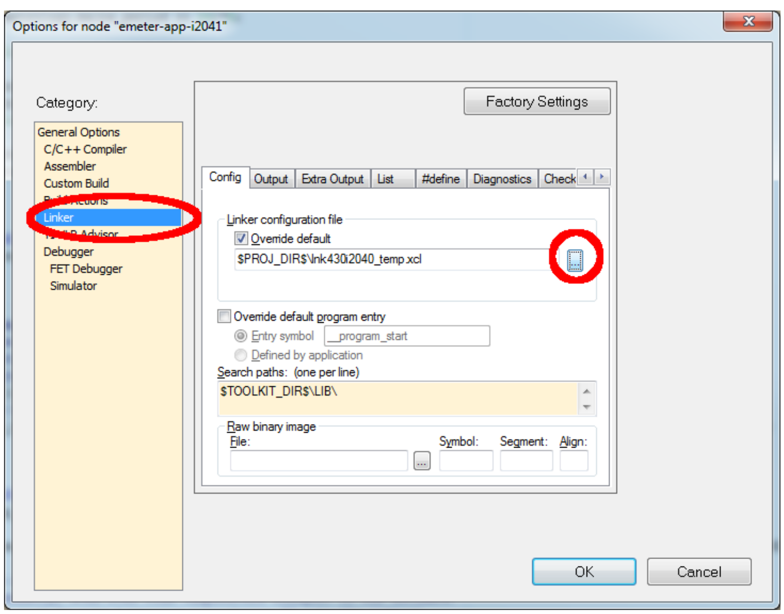


Figure 62. Config Tab

Select *lnk430i2040_temp.xcl* when prompted and click *Open.*

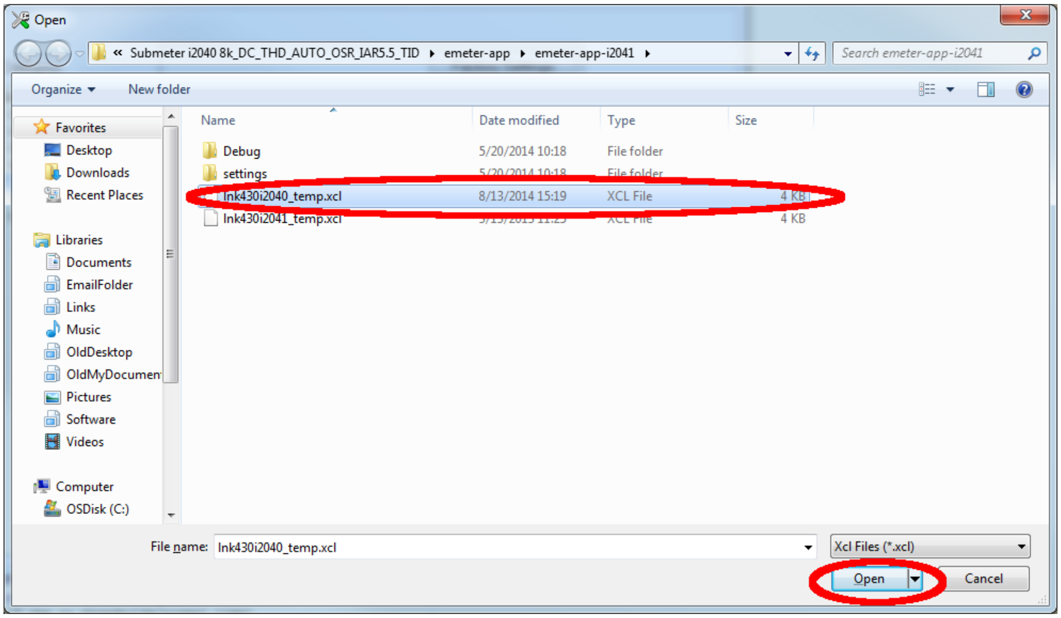


Figure 63. Selecting Default XCL File

When brought back to the *Options* window, click *OK.*

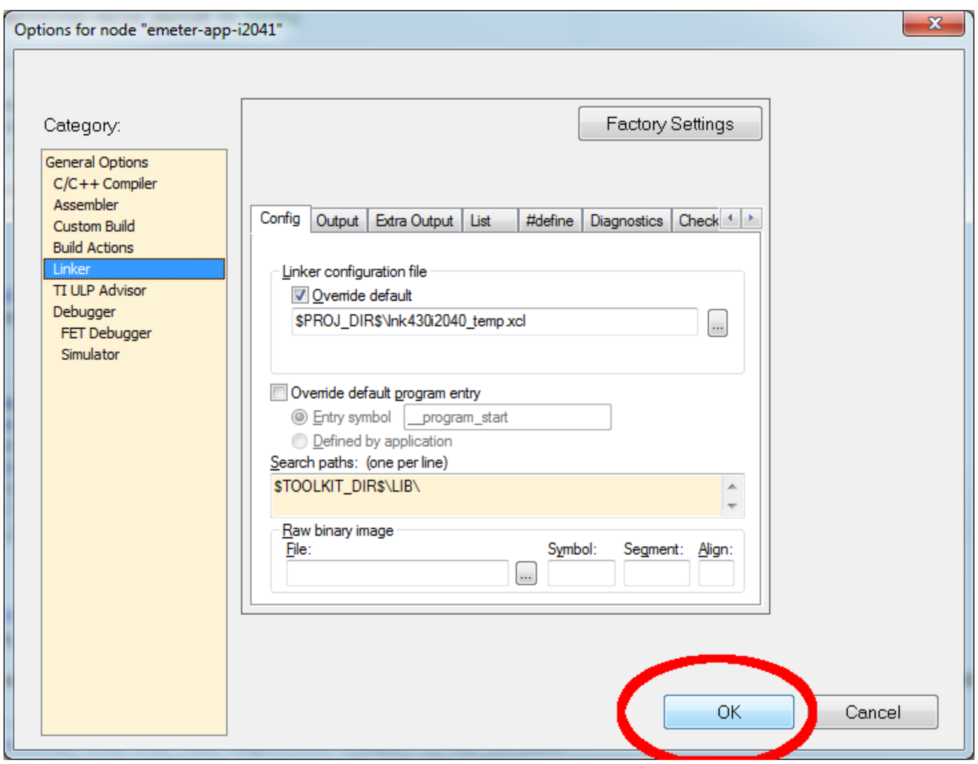


Figure 64. Finishing the Setting Changes

When brought back to the main screen, select *File→Save* to save the setting.

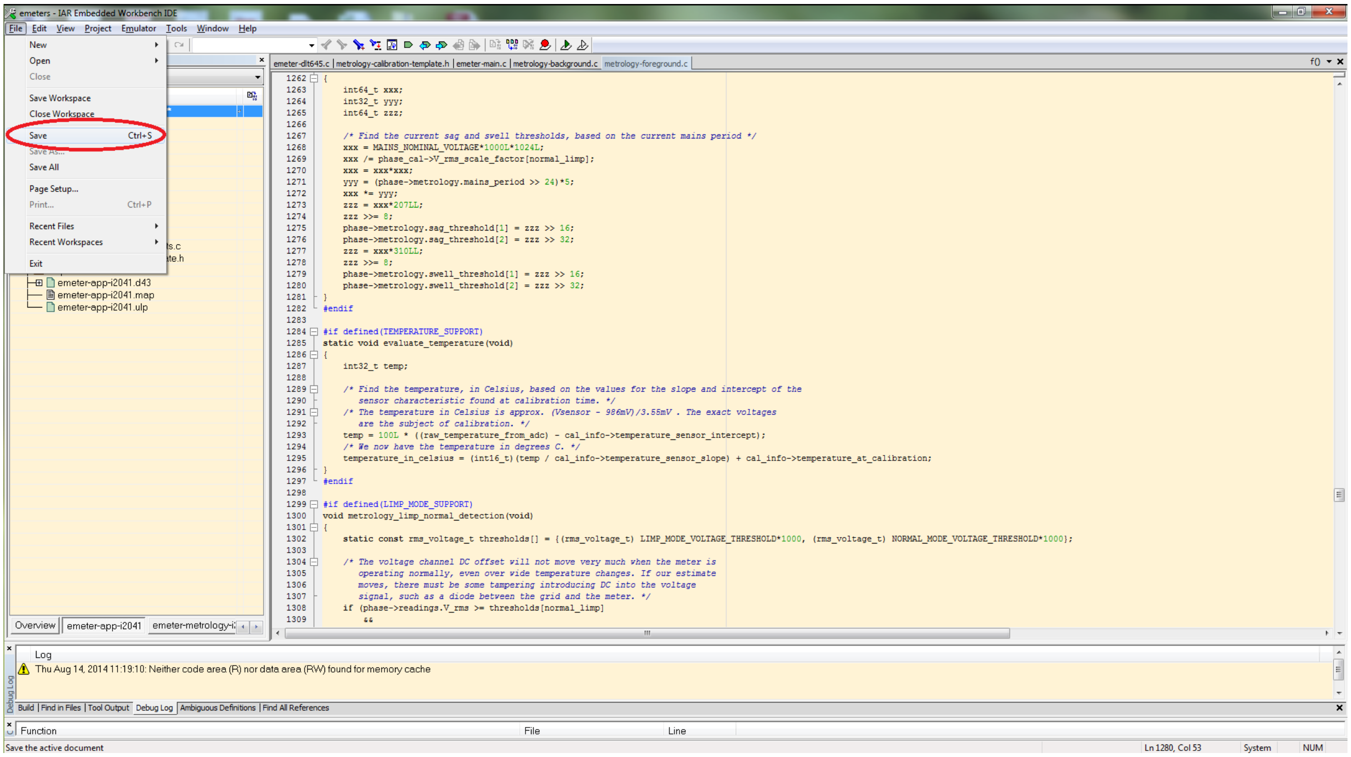


Figure 65. Saving the Setting Changes

The project is now set for run on MSP430i2040. To have the project to run back on MSP430i2041, follow the same steps except select *MSP430Ixxxx Family→MSP430I2041* in the *Options* window and select *lnk430i2041_temp.xcl* when prompted in the *Linker configuration file* box.

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Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265