Energy Metering Library Specifications

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MSP E-Metering Applications

1 Introduction

Energy metering library is required to seamlessly implement Energy monitoring using multiple MSP430 devices in a common ecosystem. The energy library will implement several metrology functions to showcase best-in-class performance. This energy library will run on TI designed HW to meet WW requirements for utility and non-utility energy/power measurements.

2 System diagram

Figure 1 shows typical connections of electronic electricity (energy/e-) meters in real life applications. The AC voltages supported are 230V/120V, 50/60Hz and the associated currents. The labels Line (L) and Neutral (N) are indicative of low voltage AC coming from the utilities.

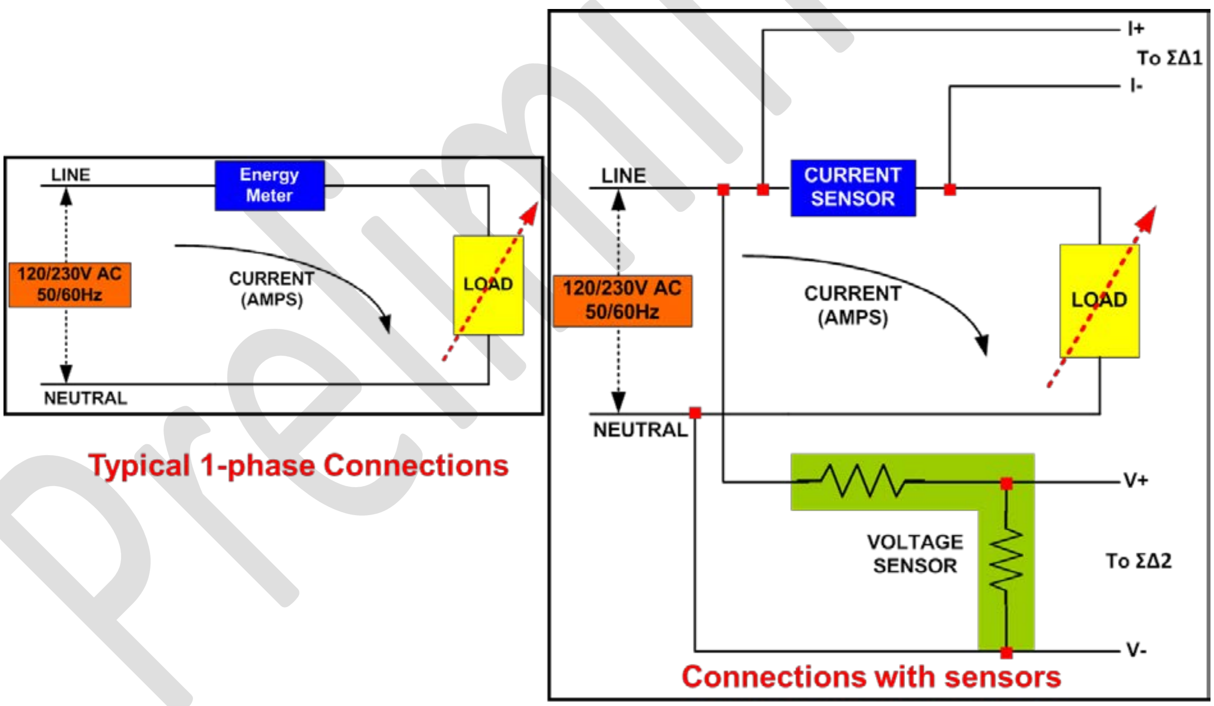


Figure 1: Typical connections inside an electronic meters

In succeeding sections more information on the current and voltage sensors, ADCs etc are discussed.

3 Functionality of Energy Meters

Energy meters measures amount of electrical energy consumed. Power is the product of instantaneous voltage and current. Energy is the power averaged over time measured in kilo-watt-hours (kWh). Single phase measurement is the most common in residential complexes. One voltage and one current to be measured and it supports low to medium load. Dual phase measurement is not common, but Japan uses this. In this case, two voltages and two currents to be measured with each phase is 180 degrees out of phase with the other and supports medium to large load. Three phase measurement is common in large office spaces and industries. Consists of 3 separate phases to distribute AC power and each phase is 120 degrees out of phase with the others. Three voltages and three currents to be measured and is designed for applications that service large loads

4 Metering parameters

Metering parameters are clearly defined by the simple power triangle

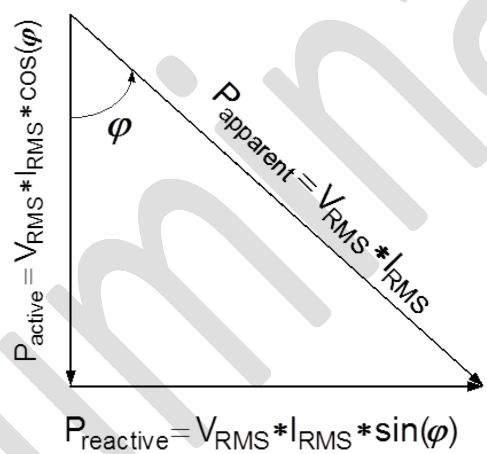


Figure 3: Power Triangle for 1-phase, independently extended to multiple phases

Metering parameters are all derived from the power triangle and repeated for each phase.

Basic parameters include

1. Active/Reactive and Apparent Power
2. Active/Reactive and Apparent Energy
3. Voltage RMS and Voltage Peak
4. Current RMS and Current Peak
5. Frequency
6. Power Factor and phase angle between Voltage and Current

Advanced parameters include

1. Total Harmonic Distortion
2. Harmonic Content (some cases upto 51^{st} harmonics)
3. Phase-Phase angles (for multi-phase)
4. Zero Crossing Detector
5. Fundamental values for voltage and current

5 Metering parameters formulae

All metering parameters can be obtained using just the voltage and current samples. However, for the measurements to be accurate, the voltage and current need to be sampled simultaneously in time. These conditions are a must for a particular phase, and if advanced metering parameters are required, and then this condition needs to be satisfied for all phases together. If the voltage and current samples are denoted as v_{ph} and i_{ph} then the formulae is defined as follows

5.1 RMS Voltage

RMS voltage is the root mean squared value of the voltage samples v_{ph}. It is a positive integer and is basically the square root of sum of squares of "N" samples of v_{ph}. v_{ph} is the digitized version of the analog AC voltage signal available in the result register of the ΣΔ ADC corresponding to the AC voltage.

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

In this equation, "Sample count" is an integer, which is typically 1-sec worth of data. For example, if v_{ph} sample rate is 4096Hz, then "Sample count" will be equal to 4096. $V_{RMS,ph}$ is the final RMS value for the voltage and $K_{v,ph}$ is an integer scaling factor applied for the results to correspond to the true values of AC voltage applied. Units is Volts (V)

5.2 RMS Current

RMS current is the root mean squared value of the current samples. It is a positive integer and is basically the square root of sum of squares of "N" samples of i_{ph}. i_{ph} is the digitized version of the analog AC current signal available in the result register of the ΣΔ ADC corresponding to the AC current.

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

In this equation, “Sample count” is an integer, which is typically 1-sec worth of data. For example, if i_{ph} sample rate is 4096Hz, then “Sample count” will be equal to 4096. $I_{RMS, ph}$ is the final RMS value for the current and $K_{i, ph}$ is an integer scaling factor applied for the results to correspond to the true values of AC current applied. Units is Amperes (A)

5.3 Peak voltage

Peak voltage denoted by $V_{PEAK, ph}$ is simply the peak value of the AC voltage applied. It is the product of the $V_{RMS, ph}$ and $\sqrt{2}$ (~1.414). Units is Volts (V)

$$V_{PEAK, ph} = V_{RMS, ph} \times \sqrt{2}$$

5.4 Peak current

Peak current denoted by $I_{PEAK, ph}$ is simply the peak value of the AC voltage applied. It is the product of the $I_{RMS, ph}$ and $\sqrt{2}$ (~1.414). Units is Amperes (A)

$$I_{PEAK, ph} = I_{RMS, ph} \times \sqrt{2}$$

5.5 Active Power and Energy

Active Power is the averaged sum of squares of the voltage and current sample. Active energy is the product of active power and time. Active Power can be either positive or negative and this depends on the type of load connected. Active power is also the most important parameter since it is the parameter that truly determines the power consumed by the load, and is used to bill the end user. For example, active energy (variant of power) is a the billable quantity. Typical units used for active power is Watts or Kilo-watts (KW) and the units for active energy is Watt-Hour (Whr) or Kilo-watt-hour (KWhr).

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

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

$K_{ACT, ph}$ is the scaling factor used integer scaling factor applied for the results to correspond to the true values of AC current and voltage applied

5.6 Reactive Power and Energy

Reactive Power is the averaged sum of squares of the current sample and 90º phase shifted voltage samples. Reactive energy is the product of reactive power and time. Reactive Power can be either positive or negative and this depends on the type of load connected. Reactive power represents the losses due to the type of load, and is used to bill the end user by the utilities if the losses are high. Units used for reactive power is Vars or Kilo-vars (Kvar) and the units for active energy is Var-Hour (Varhr) or Kilo-var-hour (KVarhr).

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

and $E_{REACT,\,ph} = P_{REACT,\,ph} \times SampleCount$

v90,ph (n) = Voltage sample at a sample instant n shifted by 90 degrees, and $K_{REACT,\,ph}$ is the scaling factor used integer scaling factor applied for the results to correspond to the true values of AC current and voltage applied.

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

1. It allows accurate measurement of the reactive power for very small currents.

2. It conforms to the international specified measurement method.

The calculated mains frequency is used to calculate the 90 degrees-shifted voltage sample. Because the frequency of the mains varies, it is important to first measure the mains frequency accurately to phase shift the voltage samples. To get an exact 90° phase shift, interpolation is used between two samples. For these two samples, a voltage sample slightly more than 90 degrees before the current sample and a voltage sample slightly less than 90 degrees before the current sample are used. The application's phase shift implementation consists of an integer part and a fractional part. The integer part is realized by providing an N samples delay. The fractional part is realized by a one-tap FIR filter. In the software, a lookup table provides the filter coefficients that are used to create the fractional delays. After calculating the active and reactive power, each phase's apparent power is calculated

5.7 Apparent Power and Energy

Apparent power is the total power supplied by the source to service a load. This is the amount of power that is the sum of squares of the active and reactive power. The formula used for apparent power is

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

Once all the energies are calculated, the cumulative powers and energies are simply the algebraic sum of these values for the individual phases. Thus the formulae for total 3-phase power and energy are

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

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

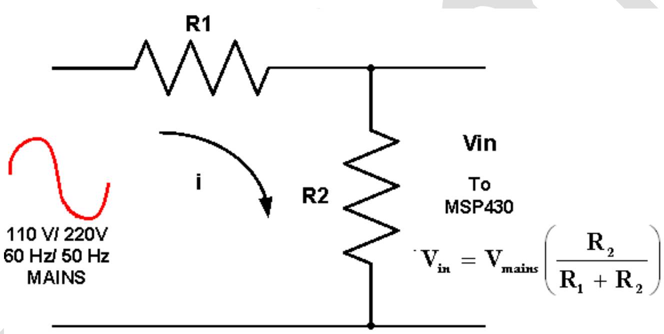
$$E_{ACT,Cumulative} = \sum_{ph=1}^{3} E_{ACT,ph}$$

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

6 Voltage and Current sensors

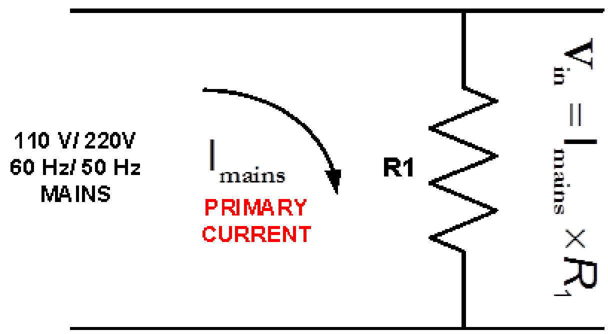
Voltage and current sensors vary for single and three phase energy meters, however, a lot of the sensor choices are made for the same reasons. The voltage sensor widely used will be the voltage divider and the current sensors can be either a shunt, current transformer (CT) or a Rogowski coil (RC) or a combination of these.

Voltage Sensor



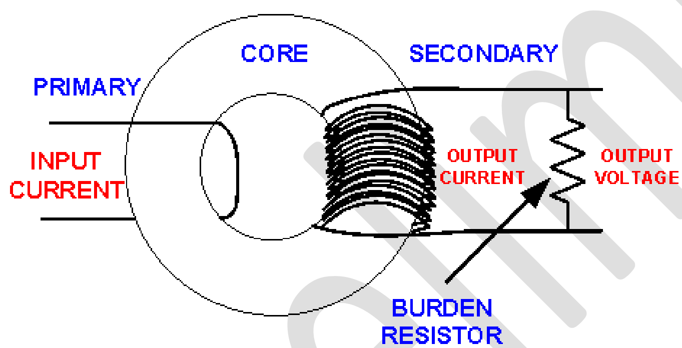
1. Always used for AC voltage measurement
2. Simple and extremely cheap
3. Values of R_1 and R_2 chosen depending on AC Mains voltage and desired range for V_{in} to A/D
4. No level shifter necessary for differential inputs
5. Gain amplifier stage not required

Current sensors: Shunt resistor



- Commonly used current sensor
- Simple to design, based on Ohm's law and is inexpensive
- Always micro-ohms (μΩ) range to support a wide dynamic range of currents
- No magnetic effects and absolutely no inherent phase shifts

Current sensors: Current Transformer



$$R_B = \frac{V_{sense,\max} * CT_{ratio}}{I_{prim,\max}}$$

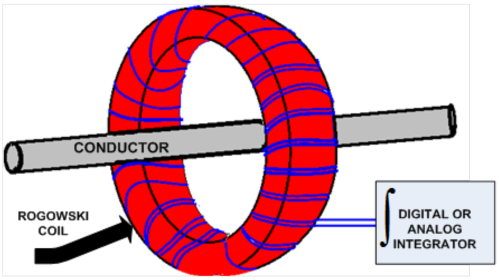
1. Provides electrical isolation protecting the measuring device
2. Current in secondary is proportional to in current in primary.
3. With zero losses, the secondary current is the primary current divided by N (number of turns in the core)
4. Provides best accuracy for utility grade energy meters.

However, CTs are

1. Subject to internal phase shift that needs to be compensated
2. Choice of burden (load) resistor (R_B) controls the maximum input current to CT if output voltage needs to be within the limits of the MSP430 A/D
3. Load must never be disconnected from secondary when current is flowing at the primary

4. Susceptible to external magnetic effects that will lead to tampering, that leads to saturation of the CT

<u>Current sensors: Rogowski Coil</u>



1. Rogowski coils are simple devices for measuring currents and provides isolation
2. Based on Ampere's law
3. Magnetic field produced by the current induces a voltage in the coil
4. Output voltage proportional to the rate of change of current
5. To get final voltage integration has to be performed either in the analog domain or digital domain
6. Wide dynamic range for high current applications ranging from small currents to large currents.
7. Cheaper Alternative to CTs and doesn't have a core, thereby immune to tampering.

7 MSP430 Devices that need to be supported

Metering devices from MSP430 that needs to be supported represent the most important devices for the market and will not include any old family of devices that are categorized as NRND.

1. MSP430F673x family of devices
2. MSP430F677x family of devices
3. MSP430i20xx family of devices.

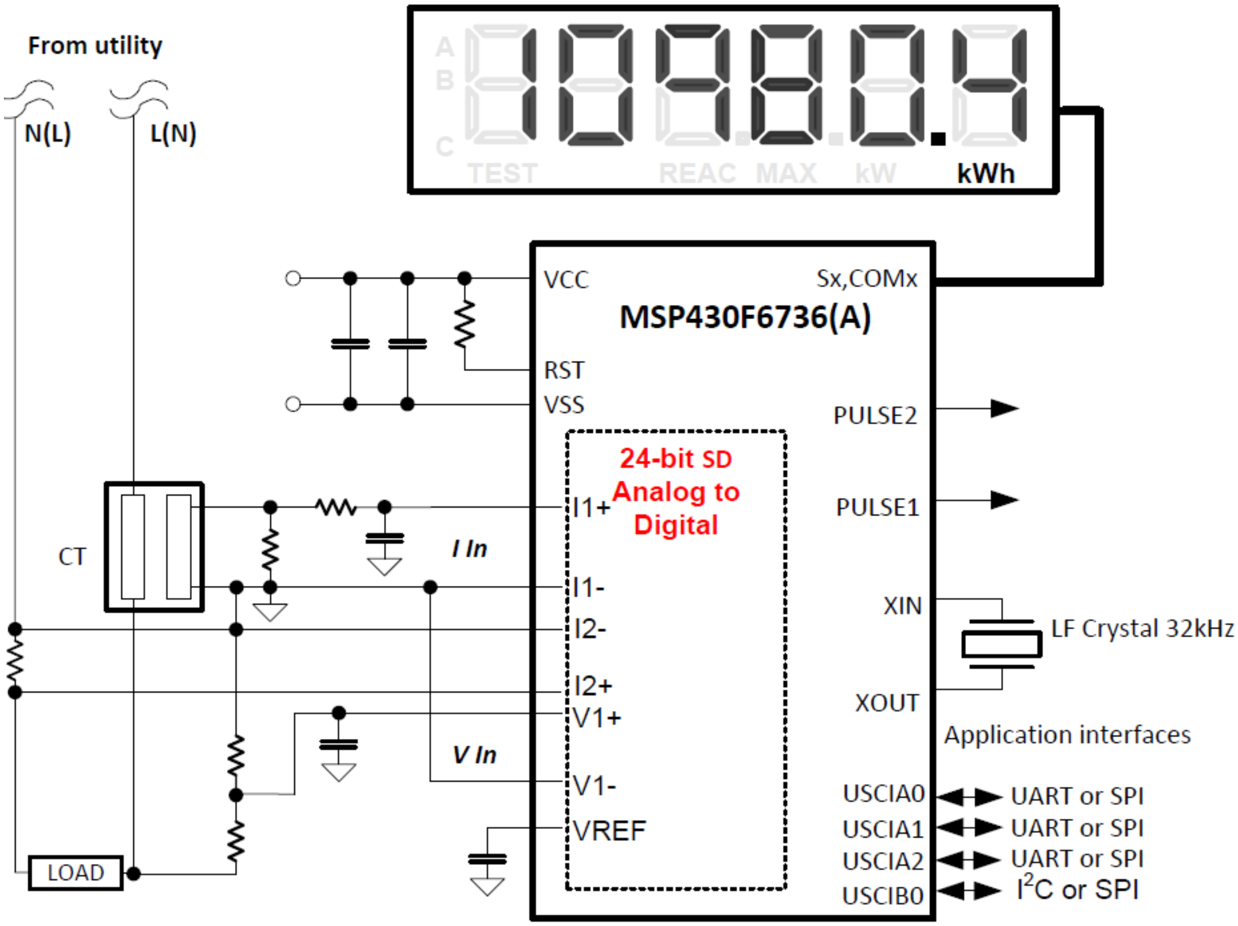
The following are the valid use cases based on the device family.

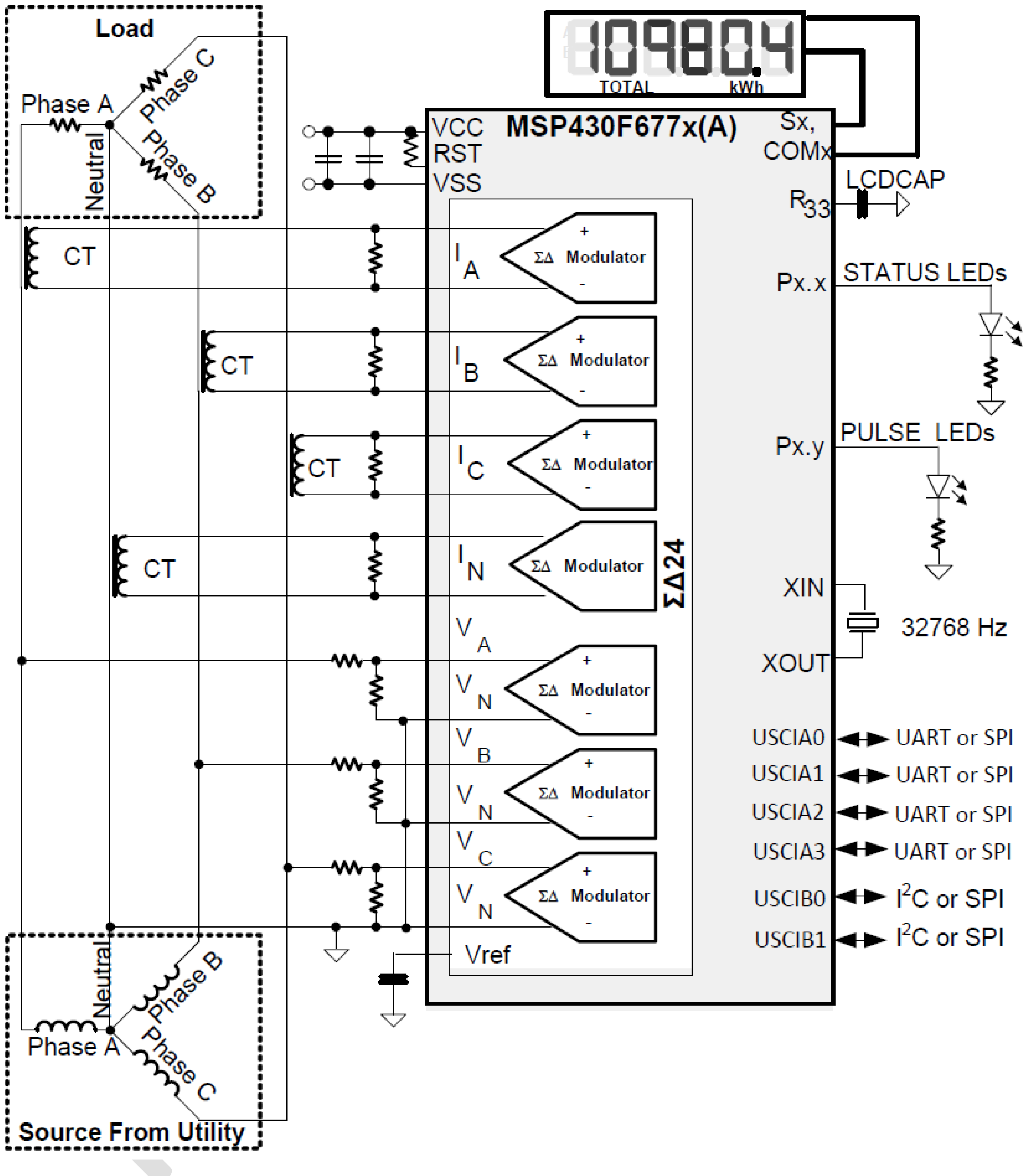
1. MSP430F673x → Single Phase (1V, 1C), Single Phase with tamper detect (1V, 2C)
2. MSP430F677x → Single Phase (1V, 1C), Dual Phase (2V, 2C), Three phase (3V, 3C), Three phase with tamper detect (3V, 4C)
3. MSP430i20xx → Single Phase (1V, 1C), Single Phase with tamper detect (1V, 2C), Single Phase with multiple currents (1V, 3C), Dual Phase (2V, 2C)

It is important that all devices in the respective families will need to be tested for code compilation and build. For eg: F673x includes F672x, F677x includes F674x and i20xx includes i203x, i202x and i204x.

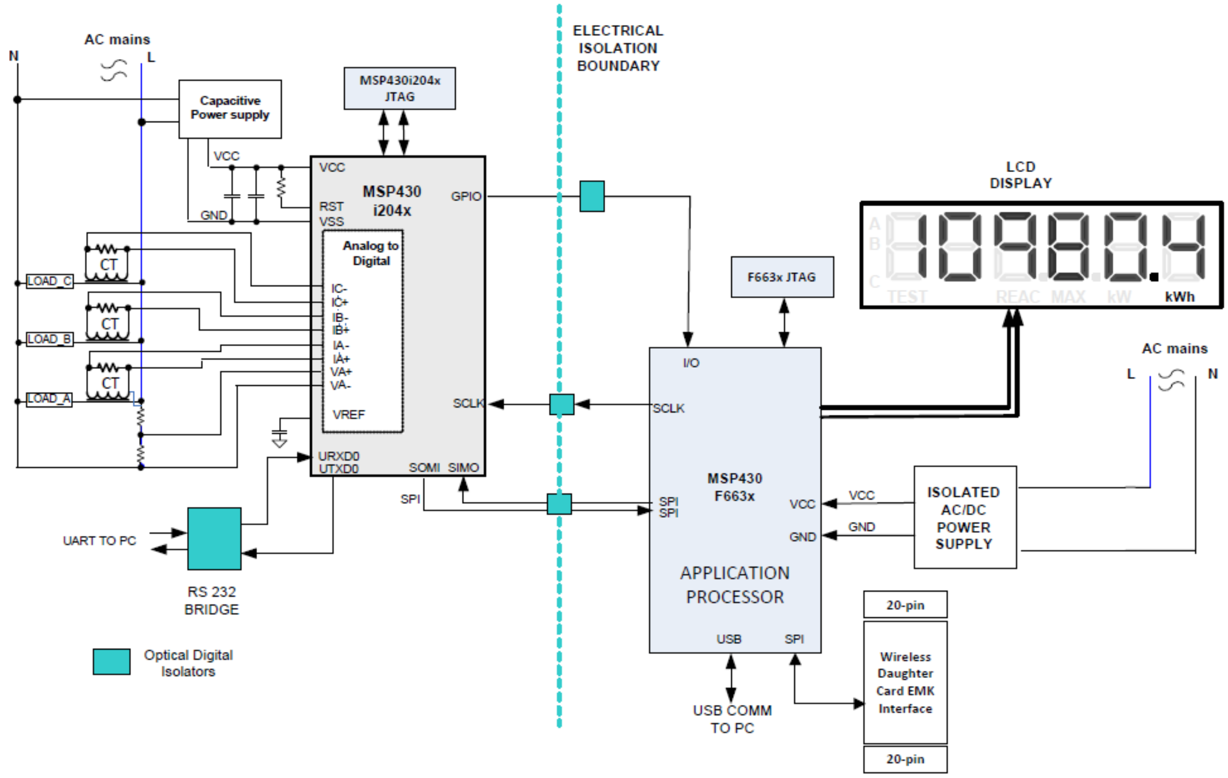
8 HW configurations and MSP430 block diagrams

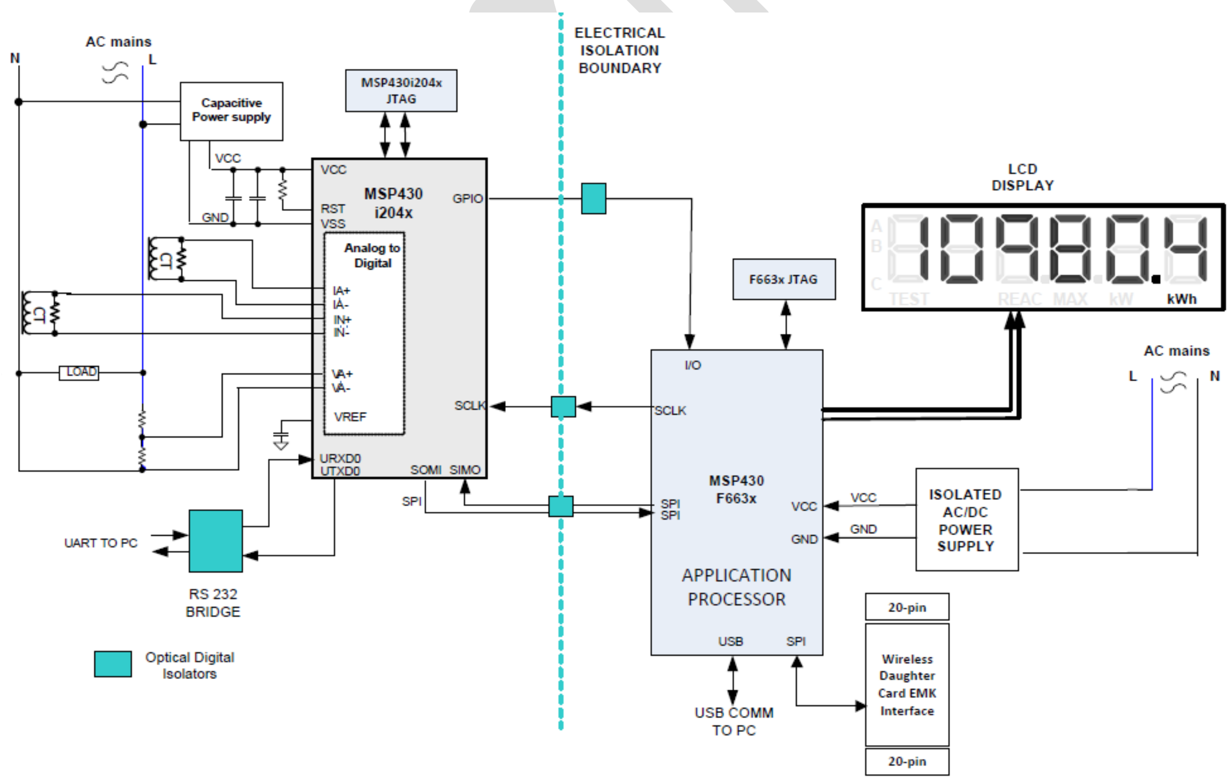
The HW configurations are to indicate the typical use case. This is not necessarily the only way to connect up the MSP430 in the applications.





Load
Phase A
Phase C
Phase B
Neutral
109804
TOTAL
kWh
VCC
RST
VSS
MSP430F677x(A)
Sx,
COMx
LCDCAP
R33
CT
IA
IB
IC
IN
ΣΔ Modulator
ΣΔ24
Px.x
STATUS LEDs
Px.y
PULSE LEDs
XIN
XOUT
32768 Hz
VA
VN
VB
VC
Vref
USCIA0
USCIA1
USCIA2
USCIA3
USCIB0
USCIB1
UART or SPI
I2C or SPI
Source From Utility


AC mains
N
L
Capacitive Power supply
MSP430i204x JTAG
ELECTRICAL ISOLATION BOUNDARY
VCC
GND
MSP430 i204x
RST
VSS
GPIO
Analog to Digital
IC-
IC+
IB-
IB+
IA-
IA+
VA+
VA-
VREF
SCLK
URXD0
UTXD0
SOMI
SIMO
SPI
LOAD_C
LOAD_B
LOAD_A
CT
LCD DISPLAY
F663x JTAG
I/O
SCLK
MSP430 F663x
SPI
VCC
GND
APPLICATION PROCESSOR
USB
AC mains
L
N
ISOLATED AC/DC POWER SUPPLY
20-pin
Wireless Daughter Card EMK Interface
UART TO PC
RS 232 BRIDGE
Optical Digital Isolators
USB COMM TO PC


AC mains
N
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MSP430i204x JTAG
ELECTRICAL ISOLATION BOUNDARY
VCC
GND
MSP430 i204x
RST
VSS
GPIO
Analog to Digital
IA+
IA-
IN+
IN-
VA+
VA-
VREF
SCLK
URXD0
UTXD0
SOMI
SIMO
SPI
LOAD
CT
LCD DISPLAY
F663x JTAG
I/O
SCLK
MSP430 F663x
SPI
VCC
GND
APPLICATION PROCESSOR
USB
AC mains
L
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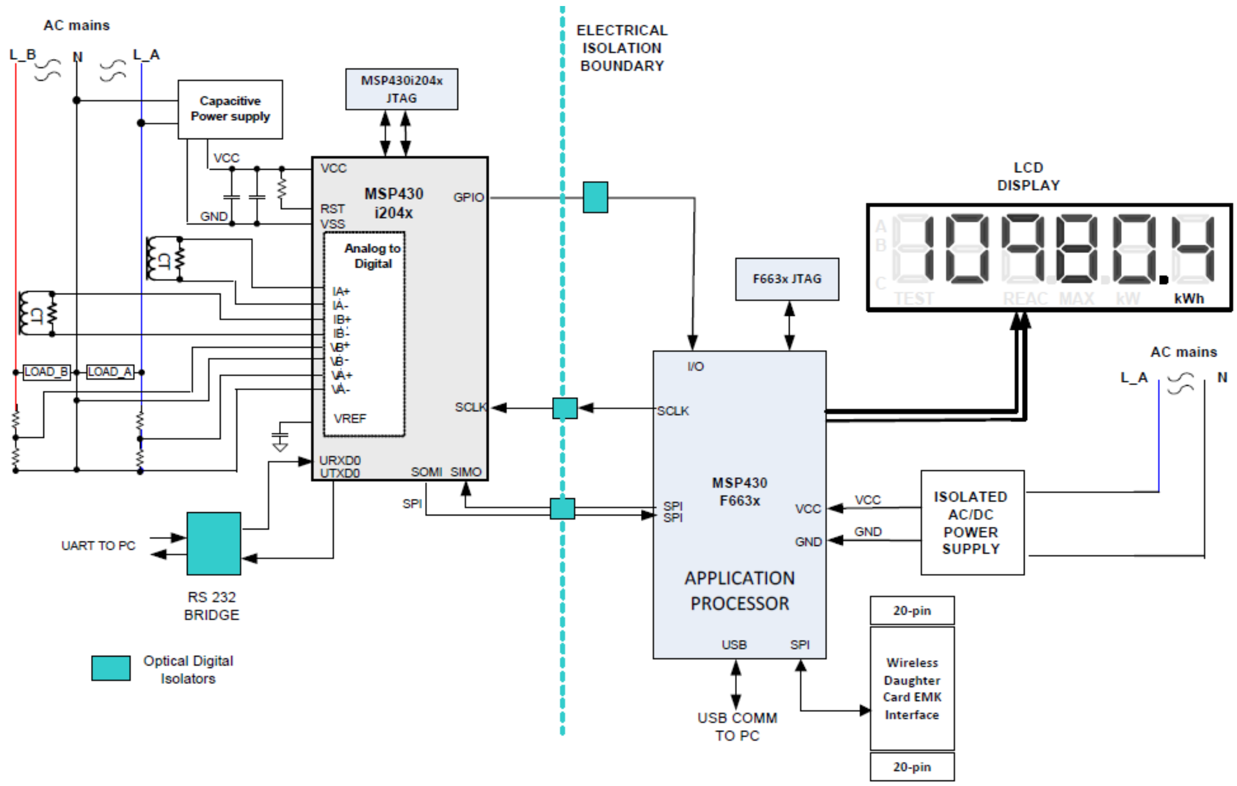
20-pin
Wireless Daughter Card EMK Interface
UART TO PC
RS 232 BRIDGE
Optical Digital Isolators
USB COMM TO PC



9 Integer width definitions for metering parameters

Integer width is important for all types of calculations

Parameter	Representation Type	Representation Resolution (Minimum)	Comments
Voltage Sample	Integer	16-bit	Good enough
Current Sample	Integer	24-bit	To accommodate the 24-bit mode of ΣΔ
V_{RMS}	Integer	48-bit	16-bit x 16-bit averaged over up to 8k Samples
I_{RMS}	Integer	64-bit	24-bit x 24-bit averaged up to 8k Samples
P_{ACT} , P_{REACT} , P_{APP}	Integer	64-bit	24-bit x 16-bit averaged up to 8k samples
E_{ACT} , E_{ACT} , E_{APP}	Integer	64-bit	Power x time

Power Factor	Float	N/A	Result of integer/integer division
Frequency	Float	N/A	Result of interpolation and zero crossings
Phase Angle	Float	N/A	Result of acos function

10 Validation Plan

Validation of the energy library has to be done in a phased manner and this will include testing independent of HW and with HW.

10.1 Validation of SW in the absence of HW, done by the SW team

Validation can be easily done for several functions of the library in the absence of HW. This can be done using a Matlab script, which will bypass the ΣΔ peripheral, sensors and passives from the validation. If this is not ideal, we can generate the samples from the EVM HW, which then will be true samples to include the sensor, passives and ΣΔ peripheral. The input vectors will include voltage and current samples recorded from the accurate test setup (Matlab or MTE AC setup) and digitized using the HW. The SW team will be provided this data for voltage and current simultaneously sampled at various sampling frequencies 2kHz, 4kHz and 8kHz and 50/60Hz. There will be a separate vector for voltage and current for the above conditions. In total, there will be at least 1-sec of information with 24-bit resolution for current and 16-bit resolution for voltage. The voltage vectors will be one set for 120VAC and 230VAC. The current will have 3 sets with a current of 100mA, 10A and 60A. We should also have the ability to add a DC component to the test vectors (valid for Matlab only)

This level of testing will be independent of the device selection.

Vectors that will be provided

1. Voltage samples at 60Hz sampled at 2ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 0° phase shift between them. 120VAC and 230VAC
2. Voltage samples at 60Hz, 120VAC sampled at 2ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 60° phase shift between them. 120VAC and 230VAC
3. Voltage samples at 60Hz sampled at 4ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 0° phase shift between them. 120VAC and 230VAC

4. Voltage samples at 60Hz sampled at 4ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 60° phase shift between them. 120VAC and 230VAC
5. Voltage samples at 60Hz sampled at 8ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 0° phase shift between them. 120VAC and 230VAC
6. Voltage samples at 60Hz sampled at 8ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 60Hz with 60° phase shift between them. 120VAC and 230VAC
7. Voltage samples at 50Hz sampled at 2ksps and simultaneously sampled current samples at 50Hz (100mA, 10A and 60A) with 0° phase shift between them. 120VAC and 230VAC
8. Voltage samples at 50Hz sampled at 2ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 50Hz with 60° phase shift between them. 120VAC and 230VAC
9. Voltage samples at 50Hz sampled at 4ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 50Hz with 0° phase shift between them. 120VAC and 230VAC
10. Voltage samples at 50Hz sampled at 4ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 50Hz with 60° phase shift between them. 120VAC and 230VAC
11. Voltage samples at 50Hz sampled at 8ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 50Hz with 0° phase shift between them. 120VAC and 230VAC
12. Voltage samples at 50Hz sampled at 8ksps and simultaneously sampled current samples (100mA, 10A and 60A) at 50Hz with 60° phase shift between them. 120VAC and 230VAC

Collection of data will approximately take 2 man-weeks from the start date. Start date will be provided by the SW team.

10.2 Validation of SW on HW will be done by MSP Sys Apps/ MPS430 Apps

The validation of SW on HW will be done on the respective EVM for the devices. For example, the EVMs that constitute as HW are EVM430-F6736, EVM430-F6779 and EVM430-i2040. For this exercise, the library will be flashed into the HW and real AC high voltage and current signals will be fed to the EVM, through the sensor, passives and to the inputs of the ΣΔ peripherals. Test points will be the same as the test conditions as mentioned in the application notes below.

Validation on HW must include the following tests on each HW platform independently for CT, Rogowski coil and shunts. Essentially the table below must be completed for all 3 sensors

Voltage	Current	Phase shift	Comments
120VAC @ 60Hz	50mA to 100A	0°, +60°, -60°, +45°, -45°, +30°, -30°	Measurement error for Active Energy, Reactive Energy
230VAC @ 60Hz	50mA to 100A	0°, +60°, -60°, +45°, -45°, +30°, -30°	Measurement error for Active Energy, Reactive Energy
120VAC @ 50Hz	50mA to 100A	0°, +60°, -60°, +45°, -45°, +30°, -30°	Measurement error for Active Energy, Reactive Energy
230VAC @ 50Hz	50mA to 100A	0°, +60°, -60°, +45°, -45°, +30°, -30°	Measurement error for Active Energy, Reactive Energy

In addition the all basic parameters discussed in Section 4 must be made available in the GUI and/or LCD and to the application SW. It is understood that calibration SW is completed for this test and it works. Test coverage must include all accuracy tests (not environmental or temperature) included in the ANSI 12.20, IEC62053 specifications and/or CEPRI results.

Results need to be done for all valid use cases indicated in Section 7. Typically, this task without any bugs in SW is about 6 man-weeks. However, we can have certain check-points on a day-day basis and can give the GREEN light to the SW team.

11 Acceptance criteria

The code library functionality is said to be complete when the above results are completed. However, the accuracy of the results must conform to the following. These criteria will apply to both validation steps viz. with and without HW in Section 10 (minus the dependence of HW).

1. MSP430F6736 → Results should be the same or better than what is published in the application note SLAA517
2. MSP430F6779 → Results should be the same or better than what is published in the application note SLAA577
3. MSP430i2040 → Results should be the same or better than what is published in the application note SLAA637 and SLAA638
4. In addition, it is important that the energy accuracy in the table in Section 10, must not exceed ±0.2% and closer ±0.1% to for the entire dynamic range (see table above).
5. All results discussed in Section 4 made available in the GUI
6. Calibration should work for all 3 phases independently using the GUI. Calibrated meter should remain stable over a period of 10 minutes and following a POR to ensure calibration works as expected
7. Results signed off by James Evans, Mekre Mesganaw and Kripa Venkat
8. Library made available in IAR and CCS
9. It would be important to have the Flash and RAM size comparable to the existing energy library in IAR. To be provided by Sys Apps. There is a possibility that the new library would be slightly larger due to SW abstraction

10. It would be important to have the same CPU BW usage comparable to the existing energy library in IAR. To be provided by Sys Apps. There is a possibility that the new library takes a slightly larger CPU BW due to SW abstraction