ATC 2008

MSP430 Advanced Technical Conference

MSP430-based E-metering and AMR solutions

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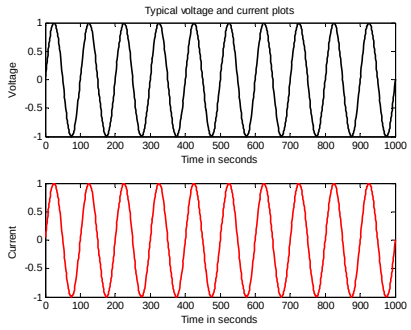
Agenda

- Introduction to Energy metering (E-metering)
- MSP430 for E-metering
- MSP430 System on Chip (SoC) and peripherals
- MSP430 Metrology and Calibration
- AMR and PLC solutions
- MSP430 E-metering solutions
- Demos

What Does an Energy Meter do?

- An energy meter is a device that measures amount of electrical energy consumed
- The energy is measured in kilo-watt-hours (kWh)
- Energy is the product of instantaneous voltage and current averaged over time



Types of E-meters

- Electromechanical meters
  - Most commonly used meters today
  - Operates by counting number of revolutions of an aluminium disc
  - The aluminium disc rotates at a speed proportional to the power usage
  - Reading of meter is done manually
  - Limited accuracy
- Electronic meters
  - Extremely favorable metrology with absolutely no moving parts
  - Uses microcontrollers, DSP processors or ASIC for the metrology
  - Extremely accurate measurements with digital display
  - Robust tamper protection
  - Self-energy consumption is negligible
  - Some of the latest meters have automatic meter reading (AMR)

Types of measurements

- Single phase measurement
  - Common in most residential complexes
  - One voltage and one current
  - Supports low to medium load
- Dual phase measurement
  - Not common
  - Two voltage separated by 180 degrees
  - Supports medium to large load
- Three phase measurement
  - Consists of 3 separate phases or wires to distribute AC current
  - Each phase is 120 degrees out of phase with the others
  - It is more efficient to transmit current via 3-phases that are out of phase than a single phase system
  - Especially designed for applications that service large loads

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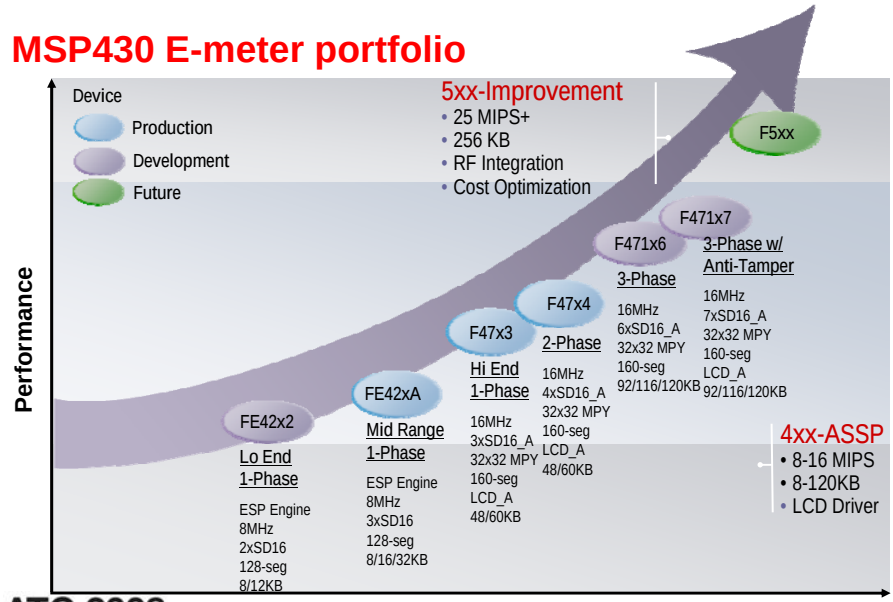
Why choose MSP430?

- Low-power + High performance
- Modern 16-bit RISC CPU
- Up to 192KB Flash and up to 16KB RAM
- Up to 25MHz powerful clock system w/ <6µs clock start-up
- Powerful analog front-end to form a System-on-Chip (SoC)
- Intelligent peripherals that boost performance
- 0.1µA power down/ 0.8µA standby mode
- Integrated LCD driver with charge pump to support up to 160 segments
- Embedded emulation

MSP430 for E-metering?

- Powerful 16-bit A/D converter (SD16, SD16_A) with programmable gain amplifier
- SD16/SD16_A supports differential input
- Multiple SD16/SD16_A for simultaneous sampling of voltage and current channels
- Hardware multiplier to support up to 32-bit x 32-bit multiply for better accuracy
- Multiple communication peripherals that support a variety of wired and wireless protocols
- Support for anti-tampering
- Calculates a comprehensive set of parameters with the use of a CPU independent metrology engine

MSP430 E-meter portfolio



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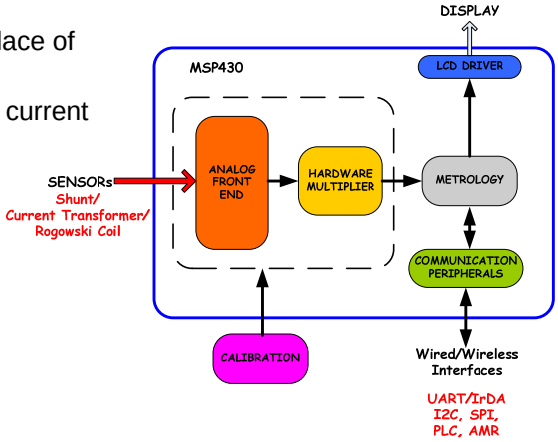
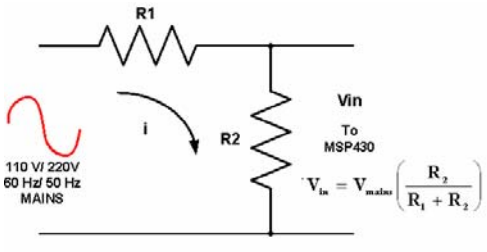
System-on-Chip (SoC) E-meter solution

- Single-chip solution in place of multi-chip
- Interfaces to a variety of current sensors
- Support for various wired/wireless protocols
- Metrology engine in Hardware/Software

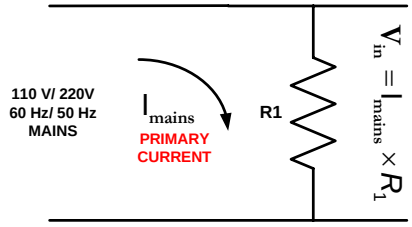


Voltage Sensor- Resistor



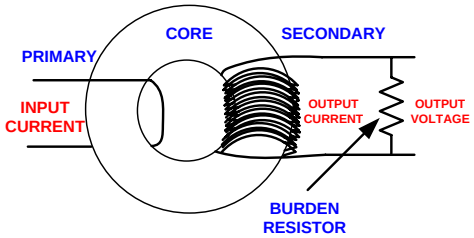
- Always used for voltage
- Simple and extremely cheap
- Values of R_1 and R_2 chosen depending on V_{mains} and desired range for V_{in} to A/D
- No level shifter necessary for differential inputs
- Gain amplifier stage not required

Current sensor-Shunt



- Commonly used current sensor
- Simple to design, based on Ohm's law
- Inexpensive
- Always in micro-ohms range to support a wide dynamic range of currents
- No magnetic effects
- Absolutely no inherent phase shifts
- Can be used only with single-phase measurement systems
- In almost all cases, resistance is not constant, stable or perfectly linear over temperature
- Limited accuracy, resistor tolerances a concern for high precision meters
- No electrical isolation provided
- Self-heating due to power dissipation is a concern, posing limitations

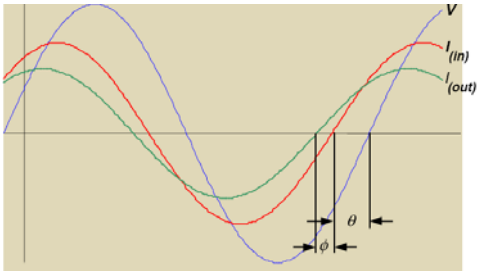
Current sensor-Current transformer



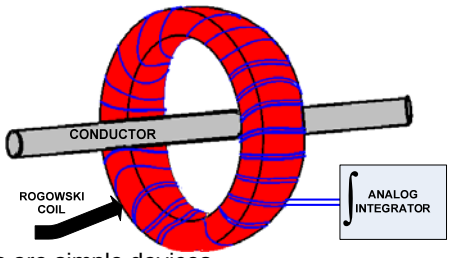
- Provides electrical isolation protecting the measuring device
- Current in secondary is proportional to in current in primary.
- With zero losses, the secondary current is the primary current divided by N (number of turns on the core)
- Provides best accuracy
- Subject to internal phase shift that needs to be compensated
- Burden resistor (load) control the maximum input current to CT
- Load must never be disconnected from secondary when current is flowing at the primary

Phase error due to CT

- CT introduces additional phase shift between V and I
- Phase compensation needed is measured during calibration time
- A simple FIR filter is used to provide this compensation



Current sensor-Rogowski Coil



- Rogowski coils are simple devices for measuring currents
- Based on Ampere's law
- Magnetic field produced by the current induces a voltage in the coil
- Output voltage proportional to the rate of change of current
- To get final voltage integration has to be performed

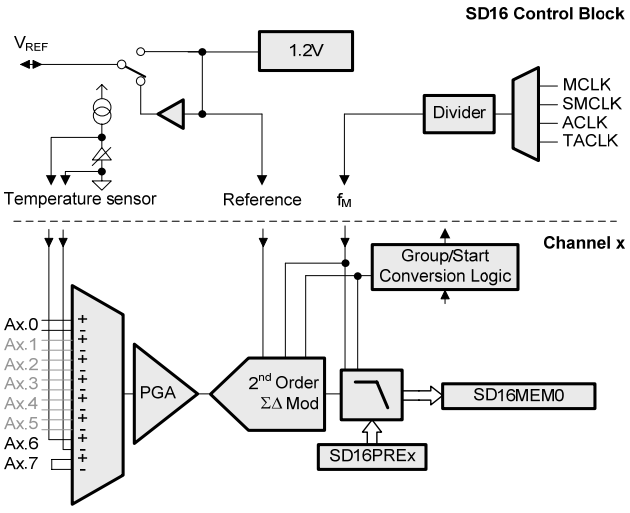
- Integration adds to extra circuitry and delay that would have be compensated
- Limited accuracy
- Position sensitive
- Not very common for E-metering, hard to find best match

MSP430 Analog front-end

- Second order 16-bit Sigma-Delta architecture
- Differential inputs
- Up to 4096 samples per second
- Over sampling ratio of up to 1024
- Independent converters for simultaneous sampling of instantaneous voltage and current
- Integrated gain amplifier to support a wide range of current measurements
- Software selectable internal/external reference
- Integrated temperature and/or battery voltage sensor
- Converters can be grouped together

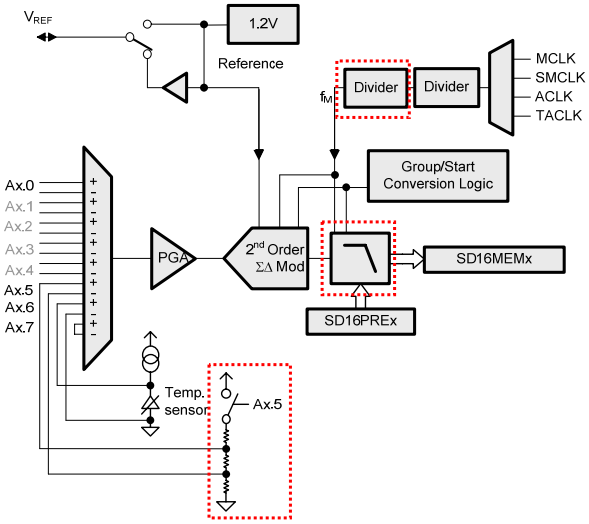
SD16 Overview

- MSP430FE42x & MSP430FE42xA
- Multiple channels
- Single external input per channel
- Up to 256 OSR
- 1MHz modulation frequency



SD16_A Overview

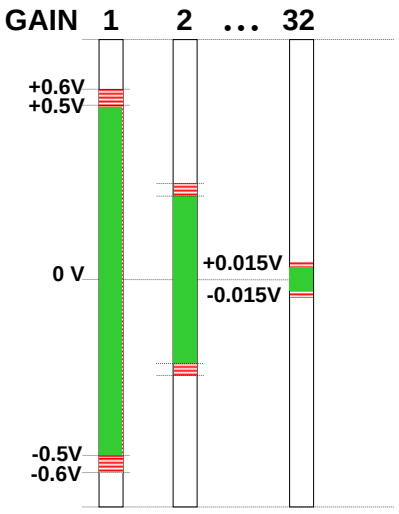
- MSP430F47x4
- Multiple channels
- 30kHz to 1.1MHz modulation frequency
- Modulation frequency divider
- Up to 1024 OSR
- Temperature sensor
- AVCC measure



Analog Input range

- What is V_{REF}?
- What is the PGA setting?
- Applies to all inputs & modes

$$V_{FSR} = \frac{V_{ref}/2}{GAIN_{PGA}}$$



Note: Diagram shows the differential input voltage V_{IN}

Hardware multiplier

- Ideal for energy calculation to multiply voltage and current readings
- Signed and unsigned multiply
- Signed and unsigned multiply and accumulate (MAC)
- 16-bit HW multiplier
  - supports 16×16 bits, 16×8 bits, 8×16 bits, 8×8 bits
- 32-bit HW multiplier
  - supports in addition all combinations with 24-bit and 32-bit data
  - supports fractional mode for operands
- DMA trigger available on devices with DMA module
- Available for all devices on MSP430 E-metering portfolio

MSP430 Communication peripherals

- Flexible on-chip synchronous and asynchronous interfaces
  - Asynchronous → UART, IrDA
  - Synchronous → SPI, I^2C
- High speed protocols possible
  - Up to 16 MHz frequency available
- Support for Smart metering
  - Automatic Meter Reading (AMR)
  - Advanced Metering Infrastructure (AMI)
  - Power line communication (PLC)
  - Radio Frequency communication
- Easy interface to wired and wireless devices

MSP430 Communication Module summary

USART	USCI	USI
UART: - **Only one modulator** - **n/a** - **n/a** - **n/a**	UART: - **Two modulators support n/16 timings** - **Auto baud rate detection** - **IrDA encoder & decoder** - **Simultaneous USCI_A and USCI_B (2 channels)**	- - -
SPI: - **Only one SPI available** - **Master and Slave Modes** - **3 and 4 Wire Modes**	SPI: - **Two SPI (one on each USCI_A and USCI_B)** - **Master and Slave Modes** - **3 and 4 Wire Modes**	SPI: - **Only one SPI available** - **Master and Slave Modes**
I2C: (n/a for FE42xx) - **Master and Slave Modes** - **up to 400kbps**	I2C: - **Simplified interrupt usage** - **Master and Slave Modes** - **up to 400kbps**	I2C: - **SW state machine needed** - **Master and Slave Modes**

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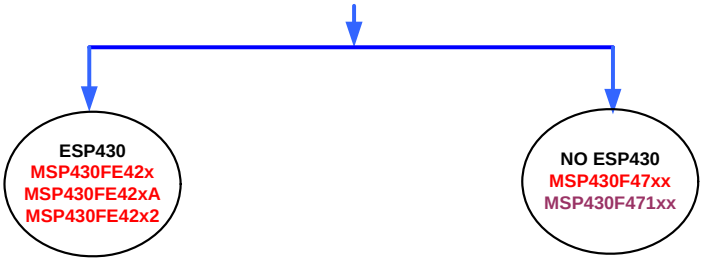
MSP430 E-meter Metrology Portfolio



Merits
1. Ease of use
2. Faster time to market
3. Comprehensive sets of results

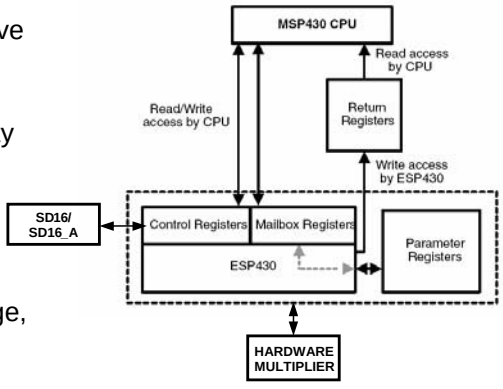
De-merits
1. Limited flexibility
2. Limited set of communication peripherals
3. 8 MHz maximum CPU frequency

Merits
1. Flexible metrology
2. Better control of accuracy
3. 16 MHz CPU
4. Variety of communication peripherals

De-merits
1. Effort of implementation

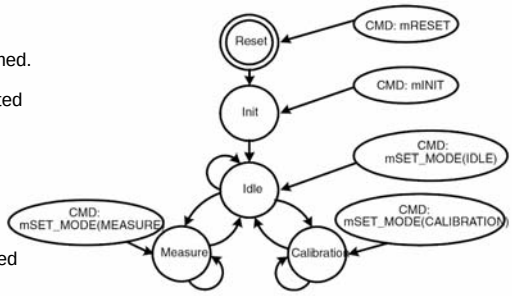
MSP430 E-metering metrology engine ESP430

- Embedded signal processor present on all devices that have an “E” in its nomenclature
- Energy metrology engine running parallel to CPU activity
- Dedicated use of SD16s and Hardware multiplier
- Combines analog and digital signal processing
- Returns energy, power, voltage, current and power factor measurements



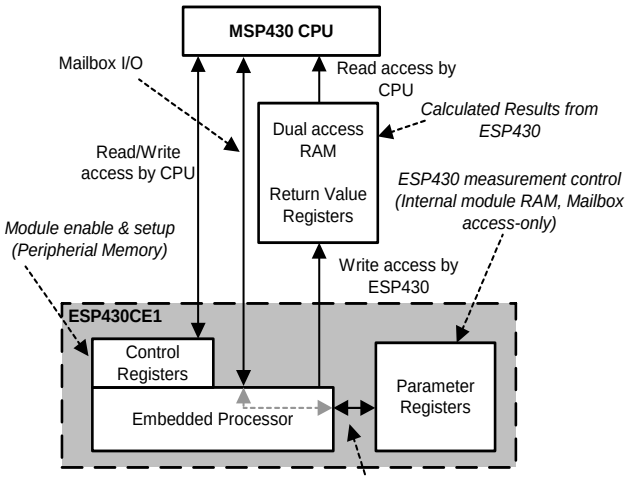
ESP430 Modes of Operation

- Reset mode
  - ESP430 module is reset
  - Parameter registers are initialized
  - Return registers are cleared
- Initialization mode
  - Internal offset calibration of is performed.
  - Offset of each SD16 channel is measured and stored using the shunted ADC input
- Idle mode
  - ESP430 is halted
  - All conversions are stopped
  - All return registers are cleared
- Measurement mode
  - All metering calculations are performed continuously and written to return registers
- Calibration mode
  - Calibration of analog front-end and all meter parameters active.
  - Done during production for the purpose of calibrating meter-specific performance and constants.



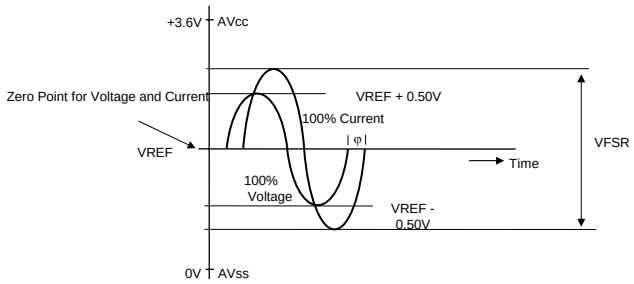
ESP430 Data Exchange Concept

- ESP430 continuously and independently performs energy calculation
- The MSP430 CPU can request information at any time using In and Out mailboxes



ESP430 Specifics

- All ESP430 are performed using fixed-point arithmetic



Energy $W = \int_{t=0}^{t=\infty} v \times i \times dt$ *is calculated for 4096 samples per second*

- With all functions enabled @ 8MHz MCLK, 4096 I&V samples are calculated in 1s

ESP430 Calculated Results

- Active, Reactive, Apparent Power
- Software programmable metering start current
- Status
- Waveform samples
- Power Factor
- DC removal
- Mains Period
- RMS, Peak Values (Current/Voltage)
- Temperature
- Line Cycle Counter
- Automatic voltage drop detection - level select by software
- Tamper detection for single phase, 2-wire metering

Non-ESP430 devices

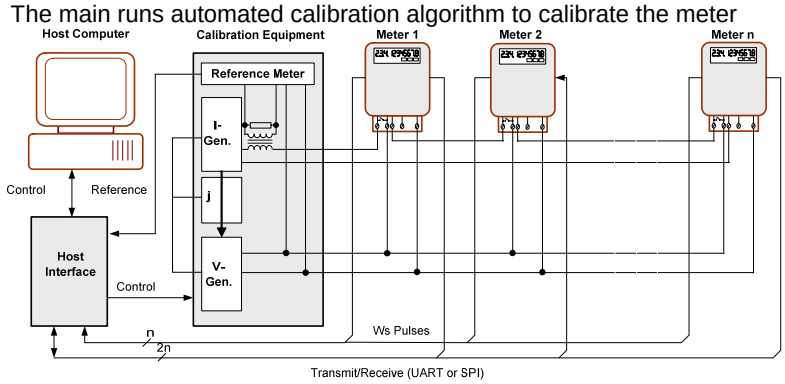
- Code flexibility provides the choice of some/all computation results in comparison to ESP430
- Use of 32-bit x 32-bit HW multiplier aims towards better accuracy at lower CPU overhead
- Higher clock speed increases efficiency and add to capabilities
- More memory means more features
- Support for dual and three-phase measurements
- Support for increased LCD segments
- Better features in flash
- Support for faster communication protocols

Calibration

- Mandatory for every meter
- Corrects inherent errors
  - Digital Phase Correction (Current channels)
  - Offset Correction (Current, Voltage)
  - Gain Correction (Current, Voltage)
  - Power Offset
- Single point and double point calibration
  - If the single point calibration is used, only the slope (Gain Correction) is calculated
  - If the double point calibration is used, the slope (Gain Correction) and the offset (Power Offset) are calculated
- Two calibration methods are possible
  - Measurement of energy for a defined number of periods of the mains (ESP430 Calibration Mode is used for example)
  - Continuous measurement mode: Energy accumulation for a single period of mains or fixed measurements (Ex: 4096) is compared using a calibration equipment

Calibration setup

- The main runs automated calibration algorithm to calibrate the meter



- Several meters can be calibrated simultaneously
- Calibration constants are programmed in-system to the Flash memory
- A host PC can completely automate a production calibration run

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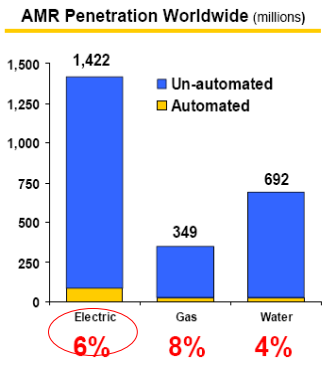
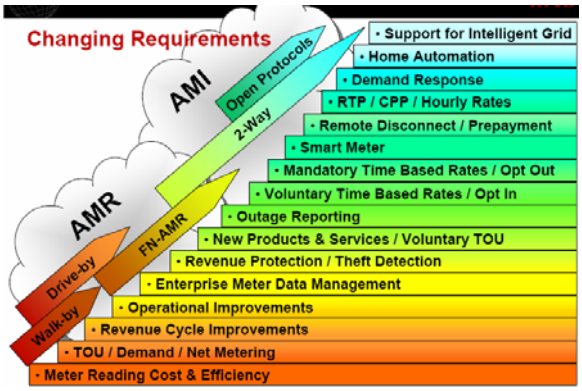
Smart Meters?

- Meters that have some sort of communication capability
- Communication channels for AMR could be PLC, RF GSM/GPRS or M-BUS
- Advantages for the consumer:
  - Clear and consumption-based invoicing
  - Failure information/handling
  - New tariff possibilities, load management included
- Advantages for the energy companies:
  - Network optimization
  - Automated metering and invoice processes
  - Bad payers process (pre-paid services)
  - Immediate detection of tampering

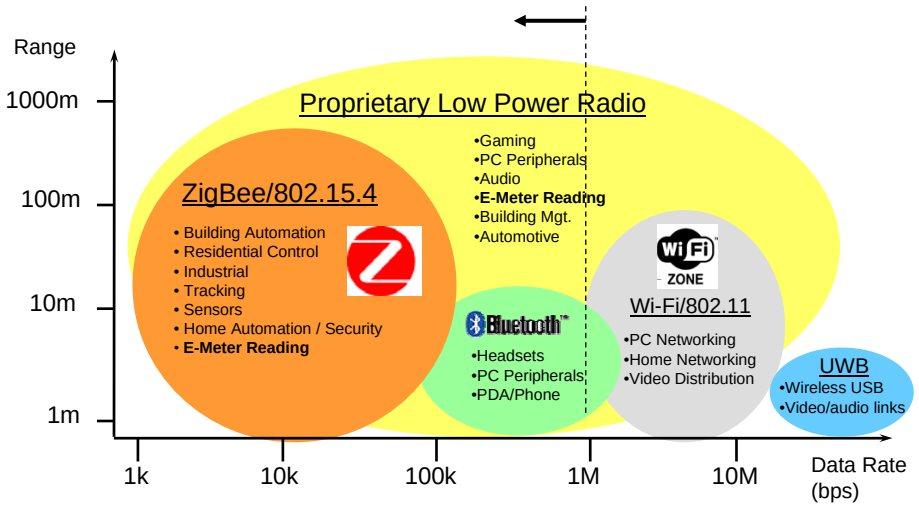
AMR Trend

- From Walk-by/Drive-by to Fixed Network
- From Automatic Meter Reading to Advance Metering Infrastructure



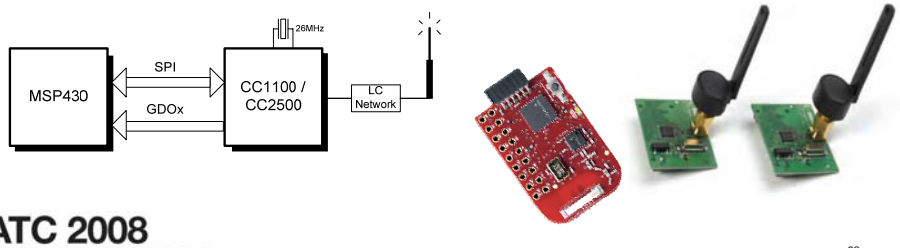


Wireless spaces



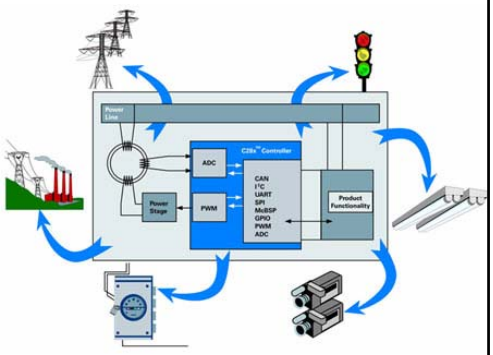
MSP430 and Wireless solutions

- Easy Interface to Chipcon's Transceivers
  - CC1100EMK, C2500EMK, CC2420EMK etc.
- Ideal for simple proprietary RF protocols
  - SimpliciTI
- Interfaced to the MSP430 via the SPI lines and some control lines
- Support for sub 1GHz and 2.4GHz frequency bands

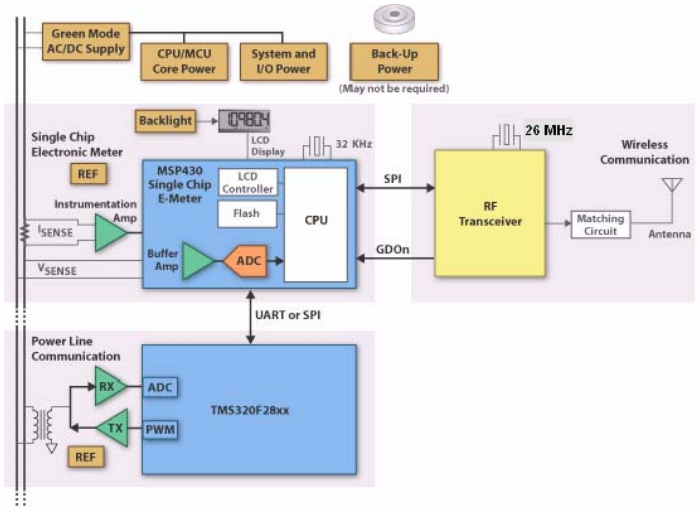


Power Line Communication (PLC) with C2000

- C2000 Digital Signal Controllers
  - Up to 150 MIPS to support real-time modulation/demodulation and filtering
  - Flexibility to support newer/propriety technologies
  - Perfect support for an E-metering chip such as MSP430
  - Reliable power line modem software with easy periodic updates to flash
  - Advanced communication peripherals to support SPI, I^2C and CAN
  - Speeds up to 4.5Kbps on one side of a transformer
  - Higher speeds up to 51Kbps available with 3rd party software
  - Entire system runs on a single F28x controller plus line drivers



Multi-chip MSP430 Metrology + C2000 PLC



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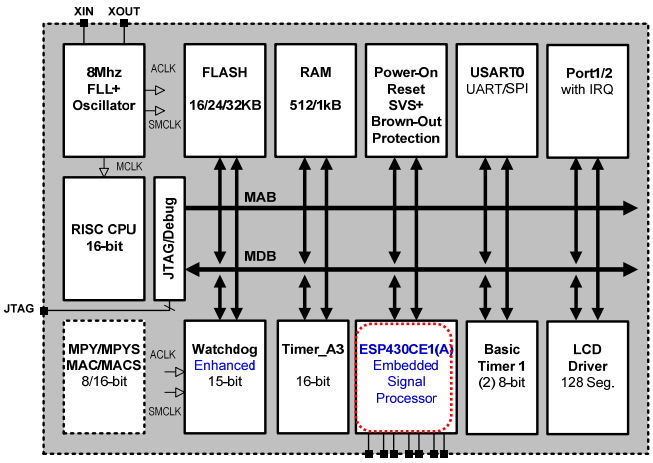
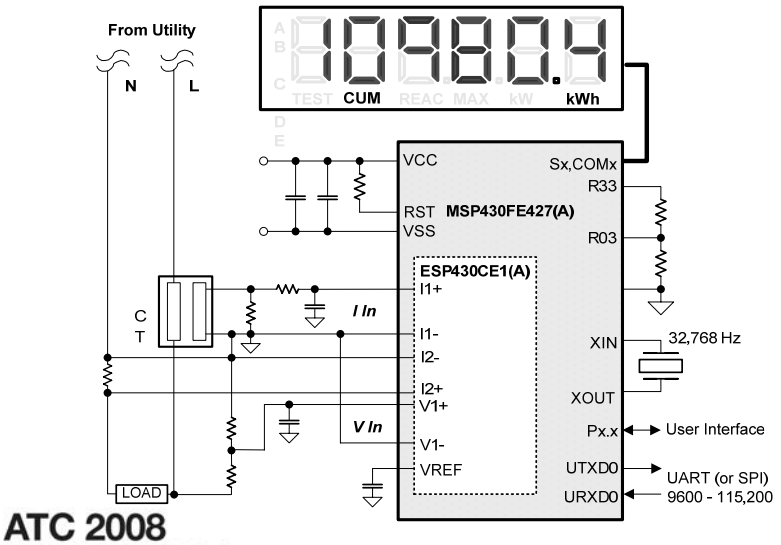
1-phase MSP430 E-meter solutions

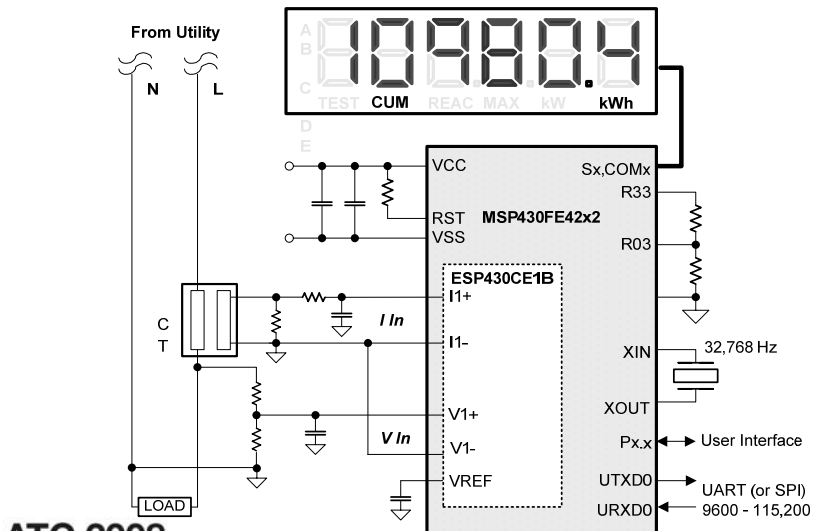


MSP430FE427, MSP430FE427A Block Diagram

MSP430FE42x(A) E-meter solution



MSP430FE42x2 Low-cost E-meter

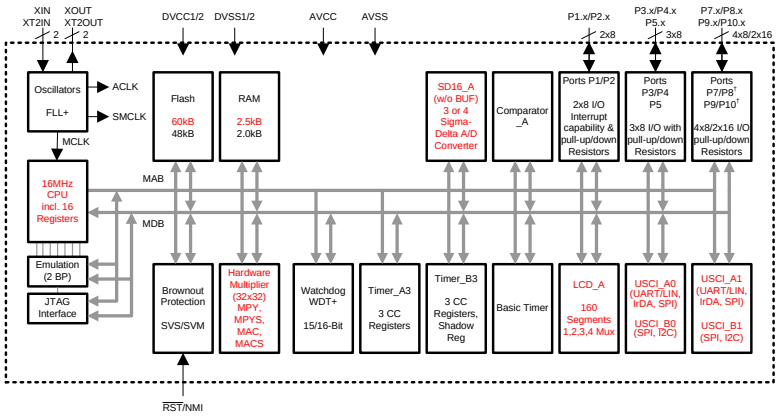


MSP430FE427(A), MSP430FE42x2 EVM

- Class 1 Single-phase E-meter
- Support for FE427, FE427(A) and FE42x2 devices

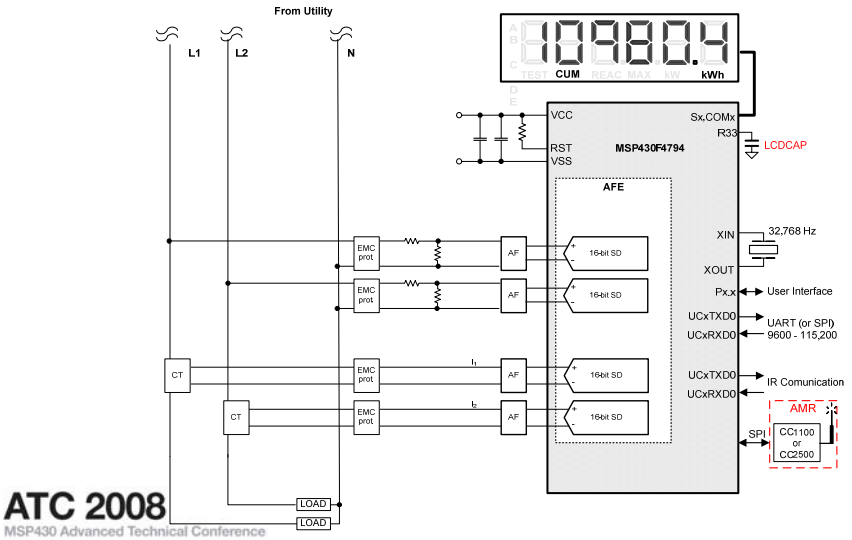
Demo-S/W "ready to use" is included in the FE427(A) 1-Phase application report (SLAA203B)

2-phase MSP430 E-meter solution



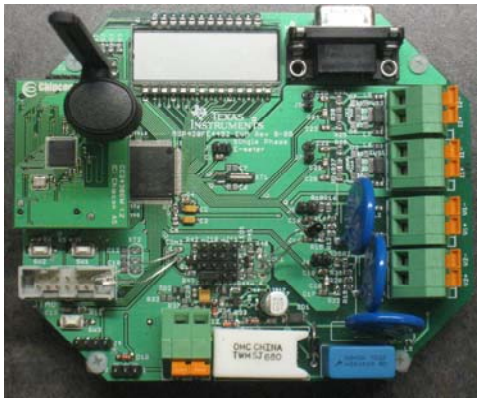
MSP430F47xx Block Diagram

MSP430F47x4 E-meter solution



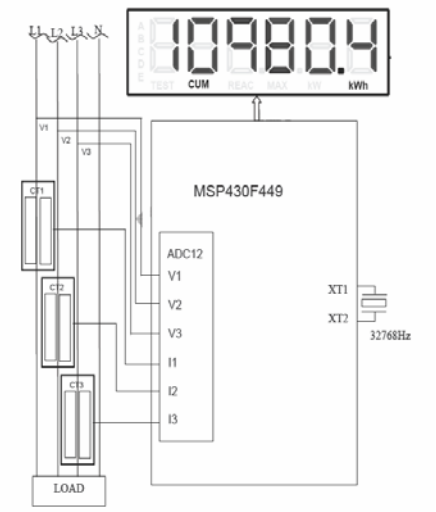
MSP430F4794 EVM

- Class 1 single-phase E-meter
- Comprehensive easy tool for energy measurement
- RS-232 based GUI for metrics and calibration
- Complete HW and SW available for customers 2H of 08



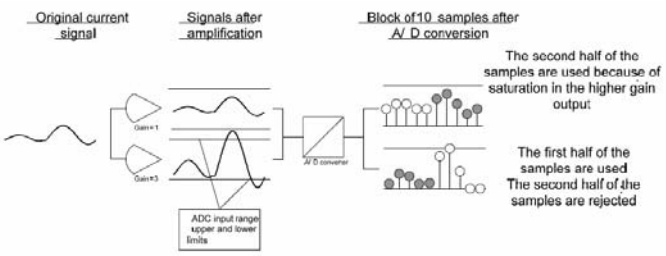
3-phase MSP430 E-meter solution

- L1, L2, L3 and N form the three phases and the Neutral respectively
- All voltages and currents hooked to individual channels of the ADC12
- Separate current transformers used for each line
- 160 segment LCD display
- 32kHz watch crystal to support RTC



Improving ADC12 accuracy

- To maintain accuracy over the entire range the ADC resolution must be extended to 15-bits
- For each current channel two sets of samples are available at the ADC namely I1 low gain and I1 high gain
- Provide an extra gain of 16 and in software make the suitable selection and provide necessary phase compensation

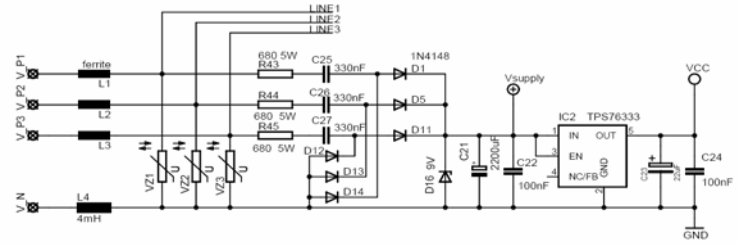


Software implementation-ADC12

- Analog inputs
  - ADC12MEM0 → I1 low gain
  - ADC12MEM1 → I1 high gain
  - ADC12MEM2 → V1
  - ADC12MEM3 → I2 low gain
  - ADC12MEM4 → I2 high gain
  - ADC12MEM5 → V2
  - ADC12MEM6 → I3 low gain
  - ADC12MEM7 → I3 high gain
  - ADC12MEM8 → V3
- All channels sequentially sampled with one trigger
- Sampling triggered at 3.2768 ksps with Timer_A using ACLK

Power-supply circuitry

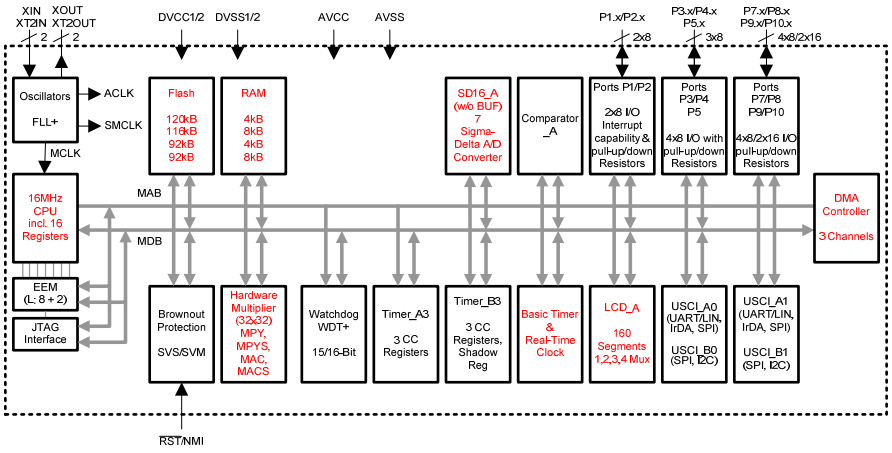
- Supply to the MSP430 is required from the AC mains
- Capacitive power supplies are used
  - No transformer required
  - Simple hardware
  - No isolation from AC
- Series capacitance must have a high voltage rating
- Series resistance acts as a protection and limits current spikes
- Zener diode is used for limiting the charging voltage to 9V



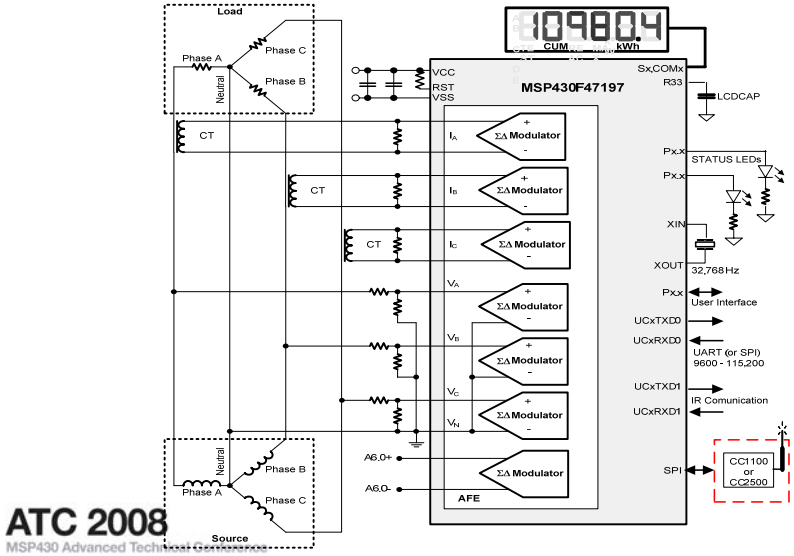
MSP430F449 EVM

- Easily meets Class 1 three-phase E-meter performance
- Comprehensive easy tool for energy measurement
- RS-232 based GUI for metrics and calibration
- Complete SW
- ***Three-Phase Electronic Watt-Hour Meter Design Using MSP430*** *(slaa391)*

MSP43F471xx future device



MSP430F47197 E-Meter



Conclusion

- MSP430 a perfect choice for E-metering
  - Simple low-power architecture
  - Powerful analog front-end with multiple converters
  - Enhanced peripherals for greater accuracy
  - Single-chip solution with minimum external circuitry
  - Comprehensive set of communication peripherals
  - Support for low-power RF and other transceivers
  - Metrology engine solution for single phase, faster time to market
  - Flexible single, dual and three phase solutions available today
  - Reference designs available for all types of phases

Thank you