11063 EMS

Single and Polyphase Energy Metering Solutions from Microchip

Class Goals

1. *Design Digitally* … Use Microchip energy meter ICs and microcontrollers to design the mixed signal and digital side of an energy meter performing to IEC accuracy specifications
2. *Design Analog* … Have handful of analog design tips for a robust energy meter PCB design for IEC compliance
3. *Calibrate and Test …* Understand how to calibrate, test, and assign your energy meter design to a specific IEC accuracy class

Become a better energy meter designer and keep your energy meter design more competitive!

Agenda

- **Design Goals**
  - Power Measurement
  - Distortion, Power Factor, Why do we care?
    - Appliances and power consumption intelligence
- **Microchip's Energy Meter Solutions**
  1. MCP390X Energy Meter IC Overview & Single Phase Designs
  2. PIC18F2520 / MCP3909 Energy Meter Reference Design
     - Meter Accuracy Limits (IEC)
     - Testing Results
     - Calibration
  3. dsPIC33F / MCP3909 Energy Meter Reference Design
- **Analog Robustness**
  - EMC Immunity
  - Miscellaneous IEC Requirements

Design Goals

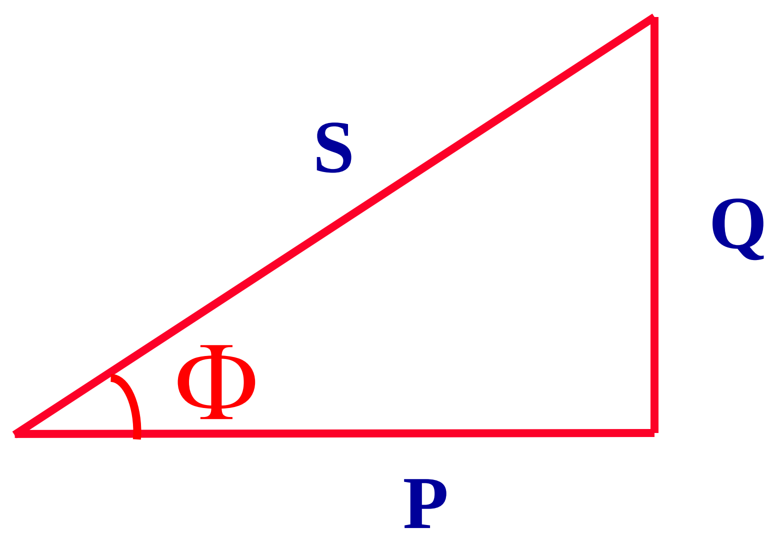
Power Triangle

- For sinusoidal inputs without distortion, apparent power, active power and reactive power form a triangle, which is referred to as the power triangle

$$P = S \cdot \cos \Phi$$ **(ACTIVE)**

$$Q = S \cdot \sin \Phi$$ **(REACTIVE)**

$$S = \sqrt{P^2 + Q^2}$$ **(APPARENT)**



Apparent Power

- **Apparent power (S) is defined as the product of the total RMS voltage and RMS current in a circuit**

Unit: VA

$$S = V_{RMS} \times I_{RMS}$$

$$S = \sqrt{P^2 + Q^2}$$

$$S \neq P + Q$$

Single-phase Active Power

- From principles of Electrical Engineering, the active power is defined as:

$$P = V_{RMS} I_{RMS} \cos\Phi$$

Unit: W

Angle between V & I

- Active power is the average power of a given phase
- Active power of non-sinusoidal periodic signals is defined as:

$$P = \frac{1}{T}\int_0^T v(t)i(t)dt$$

where T is the time period, v(t) and i(t) are instantaneous voltage and current at a given point

Single-phase Reactive Power

- From principles of Electrical Engineering, reactive power is defined as:

$$Q = V_{RMS} I_{RMS} \sin\Phi$$

unit: VAR

(Φ is the phase difference between voltage and current)

- Used to measure the scale of energy exchange in inductive circuits. In a circuit, inductors and capacitors have no energy loss, they only exchange energy with the power supply.
- The equation above can also be written as:

$$Q = V_{RMS} I_{RMS} \cos(90^\circ - \Phi)$$

Energy

- **Active energy is the integral of active power over a period of time. An equation that defines it is:**

$$W = \int_0^T P(t)dt$$

unit: kWh or kilo-watt hour

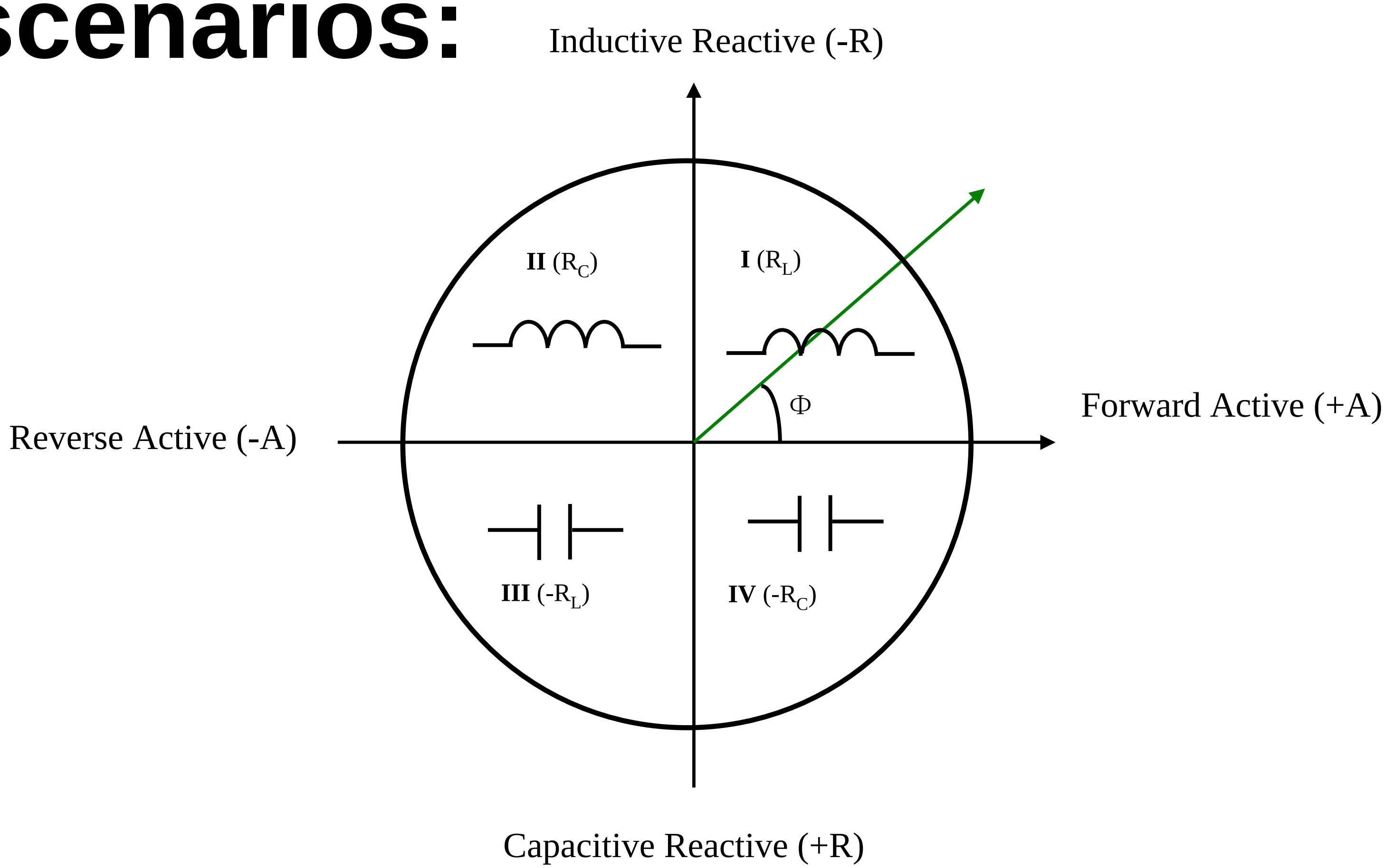
- **Reactive energy is the integral of reactive power over a period of time, and can be defined as:**

$$VAR = \int_0^T Q(t)dt$$

- **For a 3-phase circuit, the total energy is the sum of each phase energy**

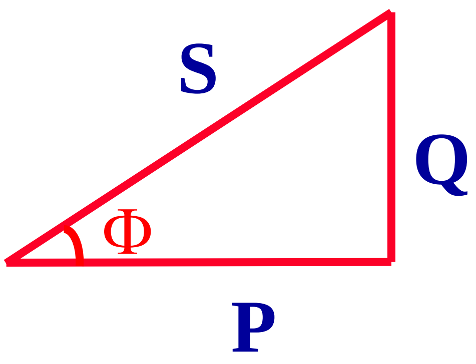
Energy Exchange

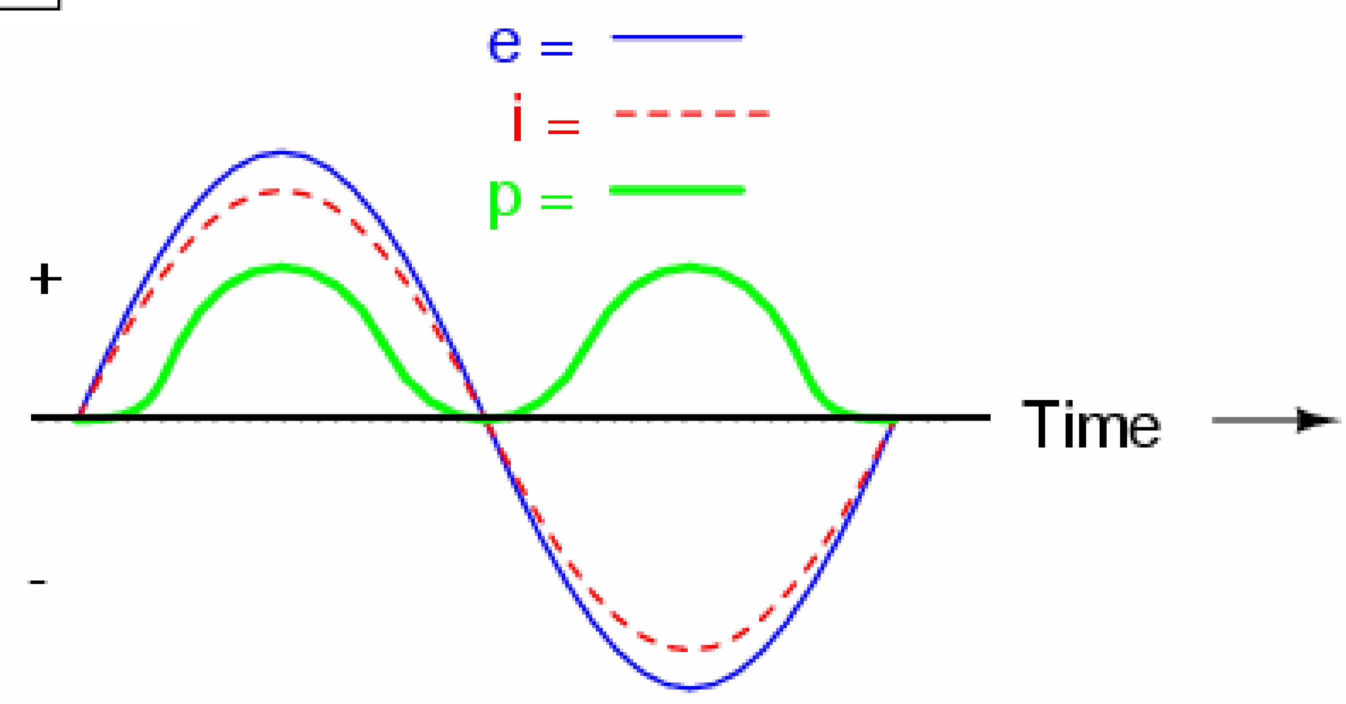
- **Energy exchange has 4 scenarios:**



Purely Resistive Load

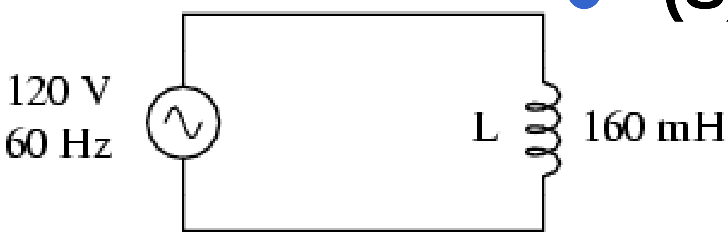
- (P) Active Power = 240W
- (Q) Reactive Power = 0 VAR
- (S) Apparent Power = 240 VA

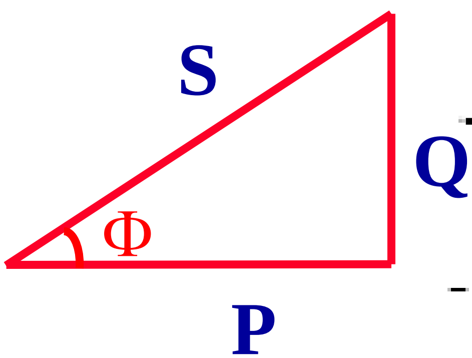


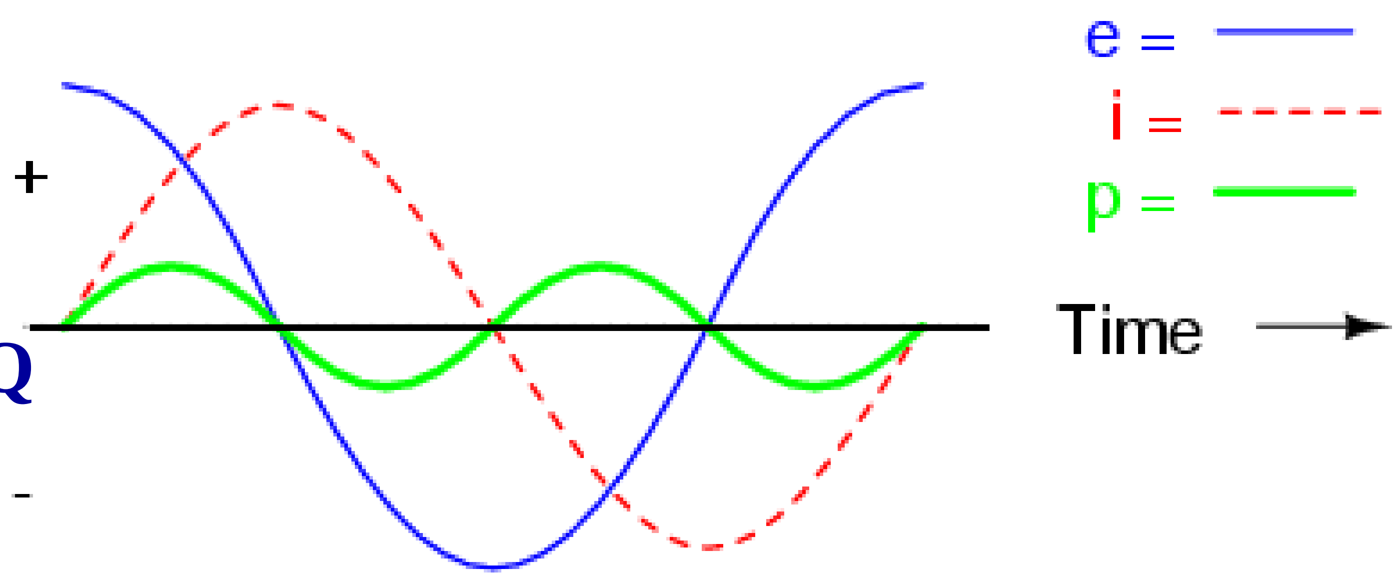


Purely Inductive Load

- **(P) Active Power = 0**
- **(Q) Reactive Power = 238.68 VAR**
- **(S) Apparent Power = 238.68 VA**

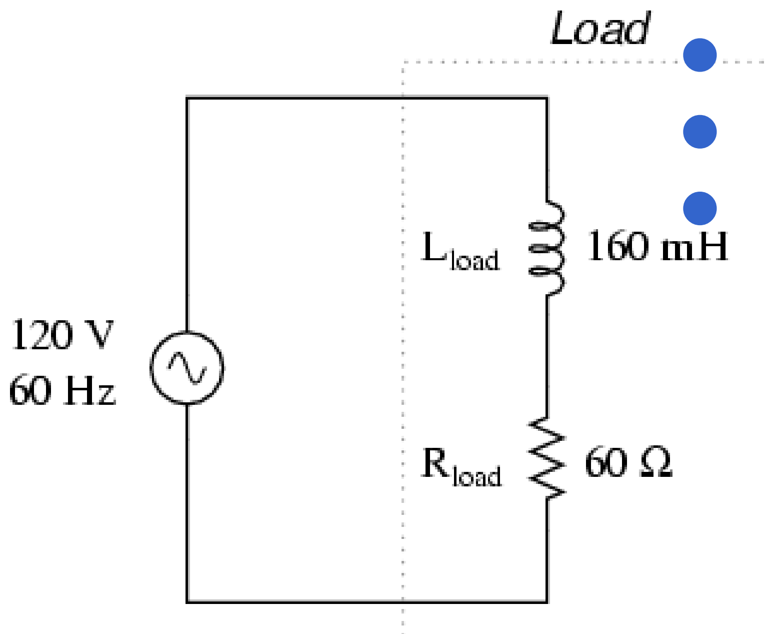


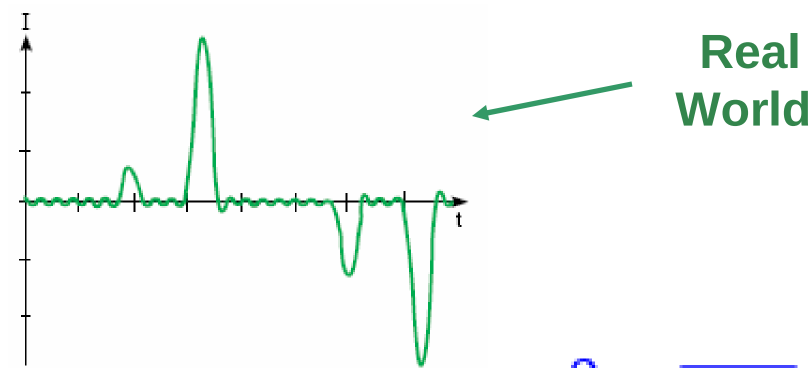


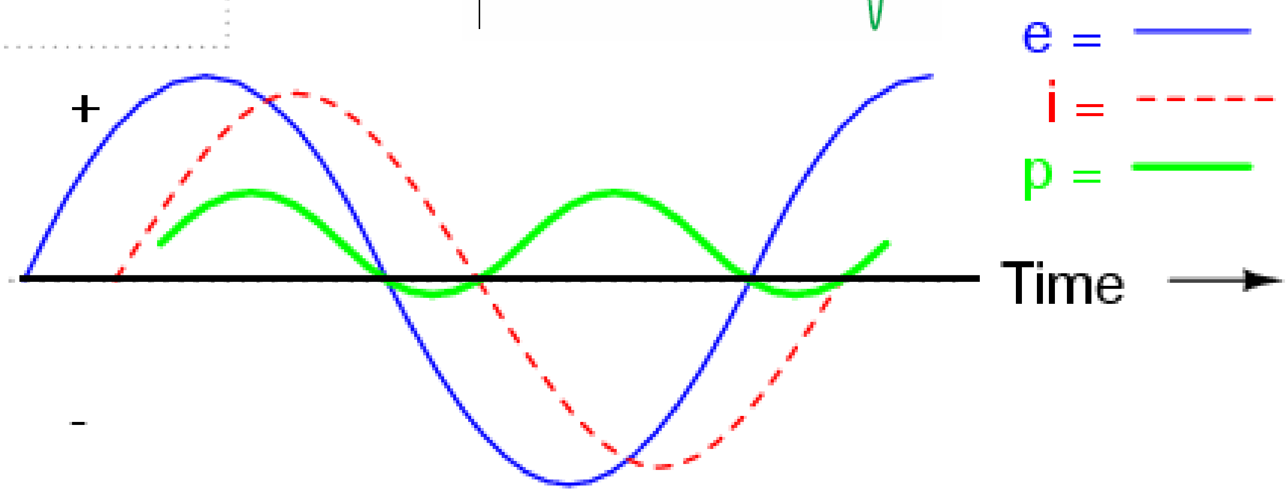


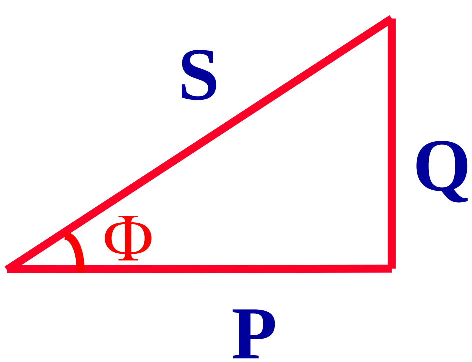
Combination Resistive & Inductive Load

- (P) Active Power = 119.365 W
- (Q) Reactive Power = 119.998 VAR
- (S) Apparent Power = 169.256 VA







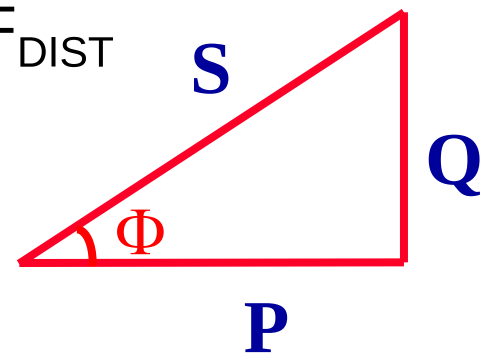


Power Factor

- **The true power factor is defined as the ratio of active power to apparent power**

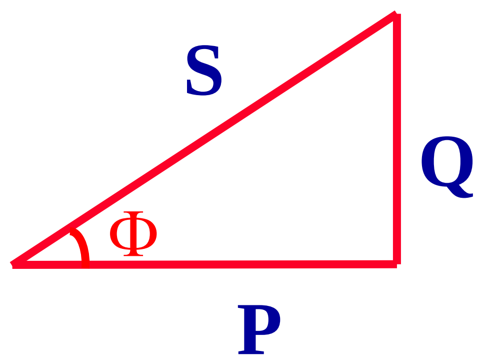
$$PF_{TRUE} = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = PF_{DISPLACEMENT} \bullet PF_{DISTORTION}$$

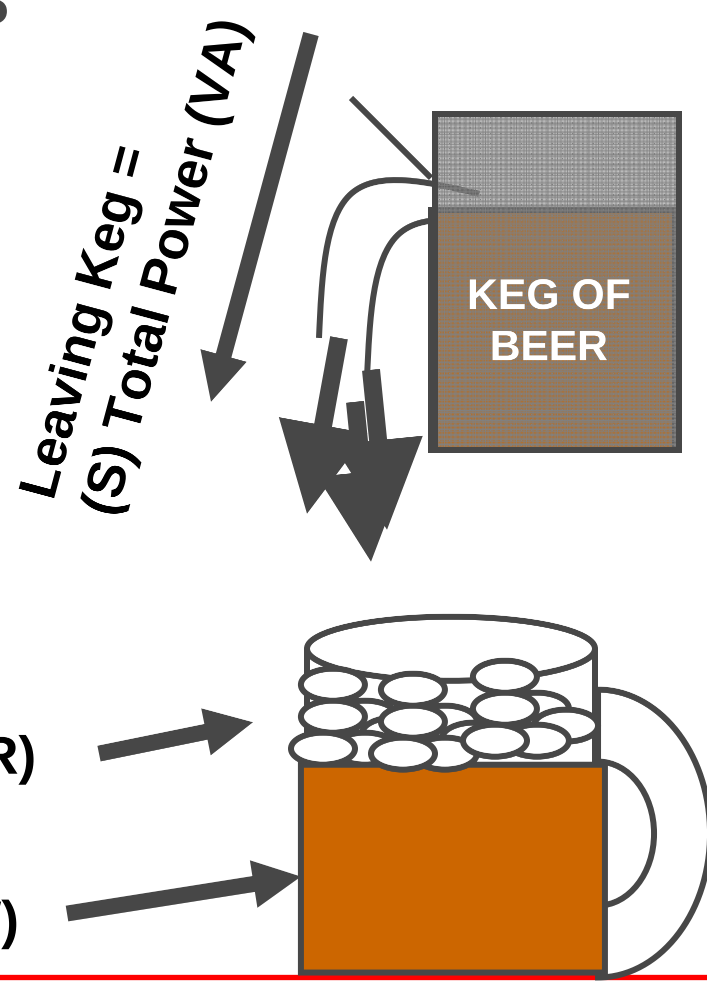
- **Relationship not easily generalized**
  - Component due to fundamental = PF_{DISP}
  - Component due to harmonics = PF_{DIST}



S, P & Q – Why do we care?

- **Utility companies supply customers with VOLT-AMPERES but bill them for WATTS**

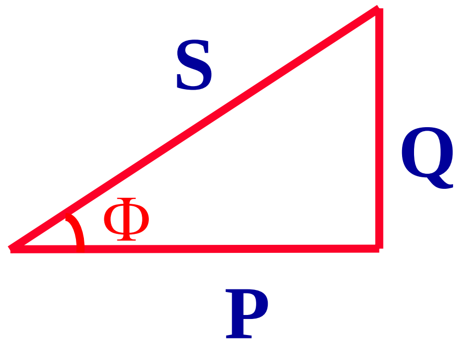




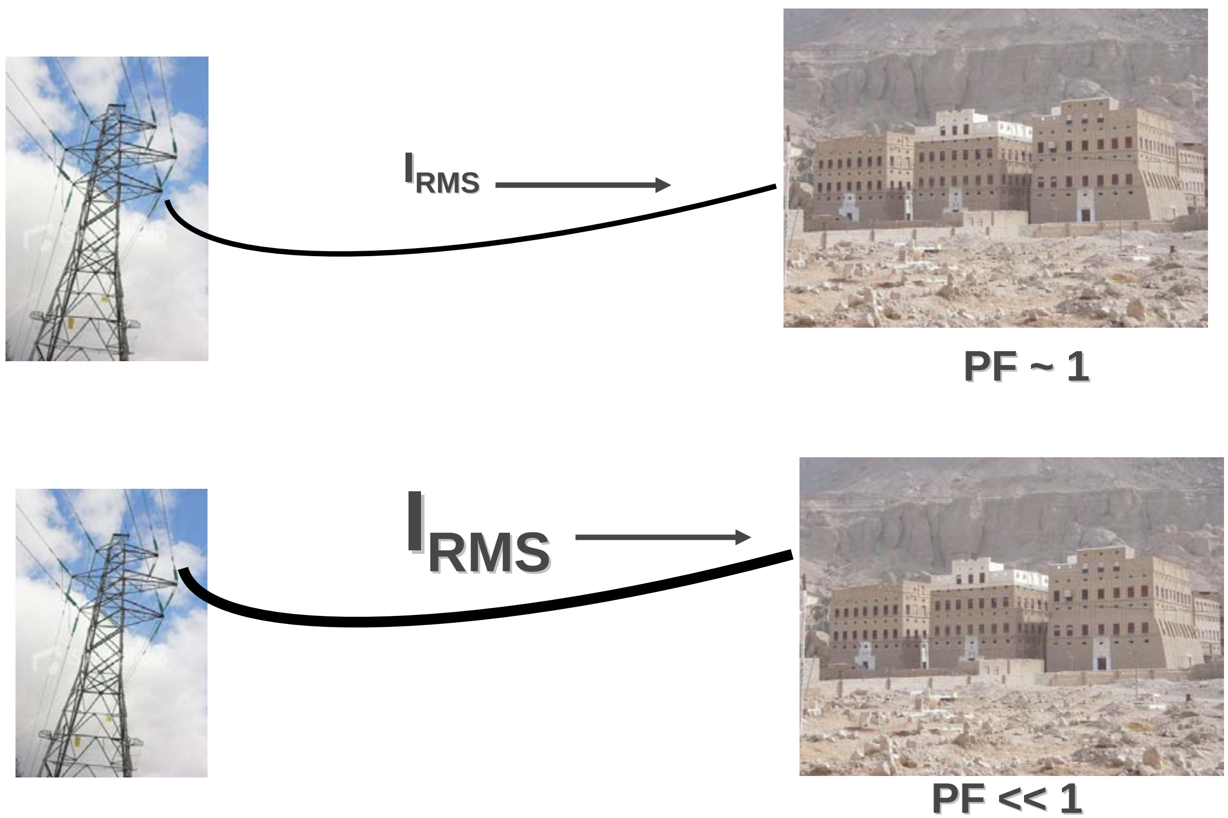
FOAM = (Q) Reactive Power (VAR)

BEER = (P) Active Power (W)

S, P & Q – Why do we care ?



- Reactive and distortion power produces extra RMS currents leading to larger copper requirements (WIRE)
- Overheated transformers



Design Goals Summary

- **Active Power, Apparent Power, and Reactive Power**
  - I_{RMS}, V_{RMS}, Harmonic Distortion
  - 50 or 60 Hz is not upper limit of conversion and calculation
- **Proper calculation of power, energy, THD, or other <u>power</u> quantities has *Analog to Digital Conversion (ADC)* accuracy and bandwidth requirements**
  - 16-bit MCP390x Energy Meter IC with 14ksps sample rate and 82 dB SINAD (Signal-to-Noise And Distortion) will meet requirements as we will show
  - PIC® MCU calculations follow

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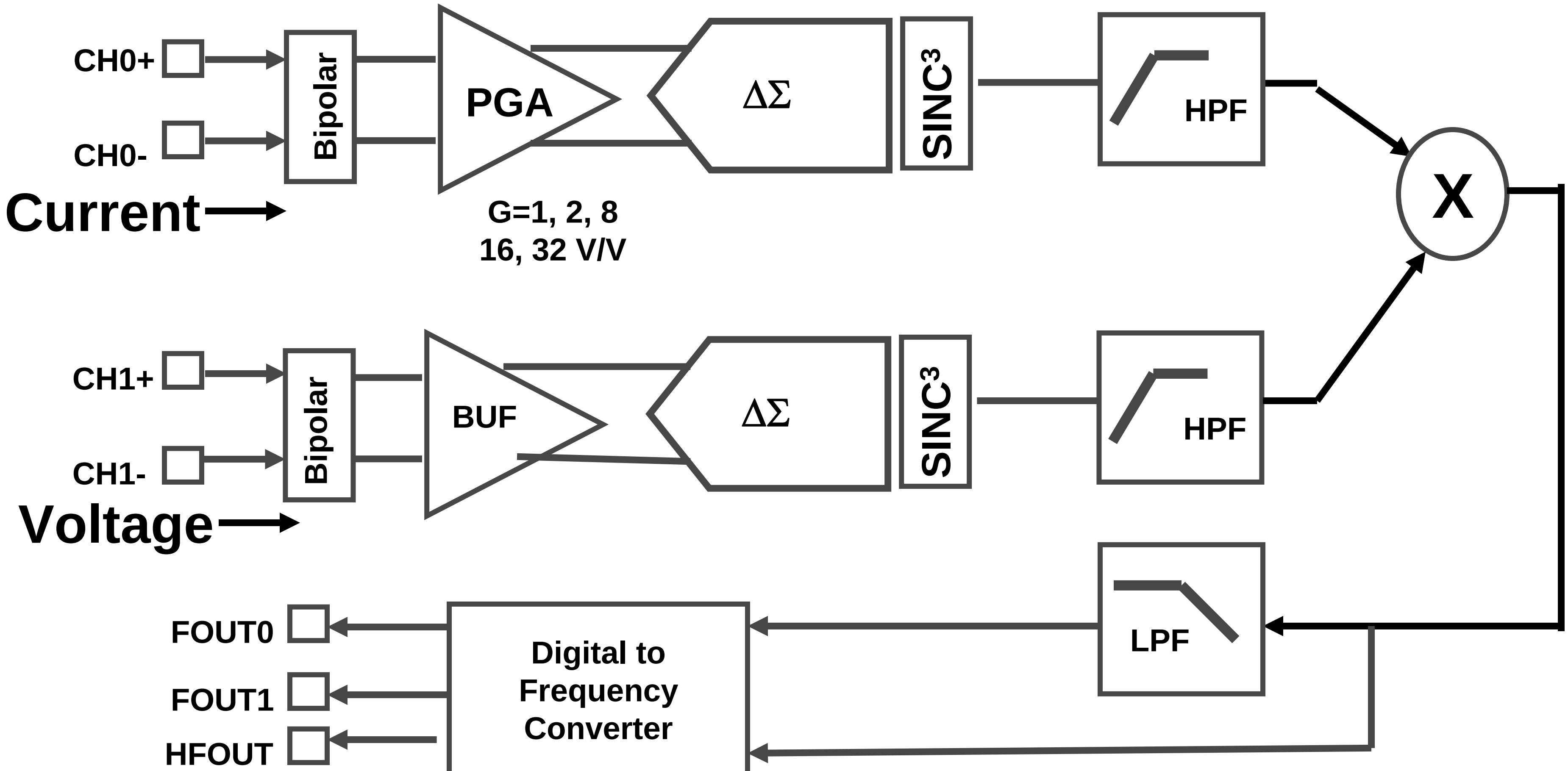
Microchip's Energy Metering Solutions

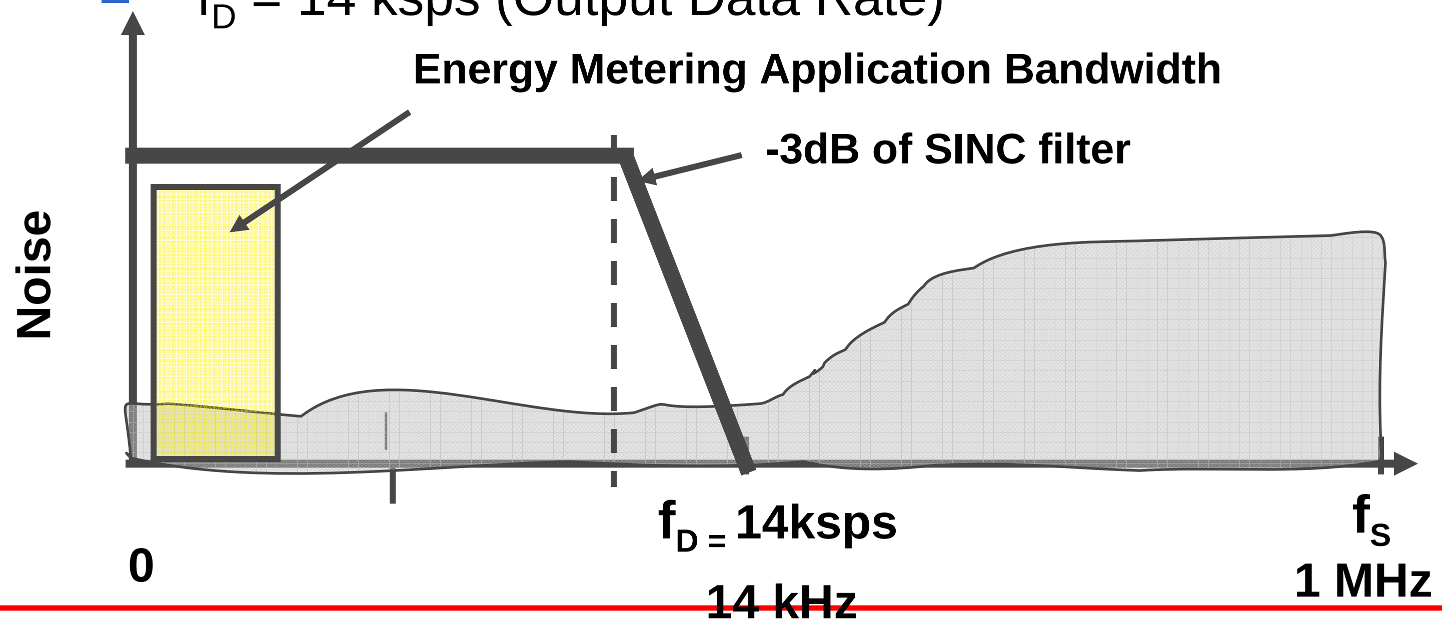
MCP390X Energy Meter ICs

- **MCP3905A/05L/06A/09**
- **0.1% typical measurement error across 500:1 or 1000:1 dynamic range**
- **Accuracy is compliant to all classes of IEC62053 Energy meters**
  - Class 2, Class 1, Class 0.5, Class 0.2



MCP390X Energy Metering ICs

- **Entire family of devices contain two 16-bit Delta Sigma A/D converters**
  - 0.1% Measurement Error
    - **500:1 Dynamic Range (MCP3905A/05L)**
    - **1000:1 Dynamic Range (MCP3906A/09)**
  - Over-samples at 1 MHz (with 4 MHz external crystal)
  - f_S = 1 MHz (Sample Rate)
  - f_D = 14 ksps (Output Data Rate)



IEC 62053 Accuracy in the Presence Of Harmonics (Parts -21, -22, -23)

- **IEC Test Conditions**
  - Fundamental frequency current: $I1 = 0,5\ I\text{max}$
  - Fundamental frequency voltage: $U1 = U\text{n}$
  - Fundamental frequency power factor: 1
  - Content of 5th harmonic voltage: $U5$ = 10 % of $U\text{n}$
  - Content of 5th harmonic current: $I5$ = 40 % of fundamental current
  - Harmonic power factor: 1
  - Fundamental and harmonic voltages are in phase, at positive zero crossing

Resulting harmonic power due to the 5th harmonic is $P5 = 0,1\ U1 \times 0,4\ I1 = 0,04\ P1$ or total

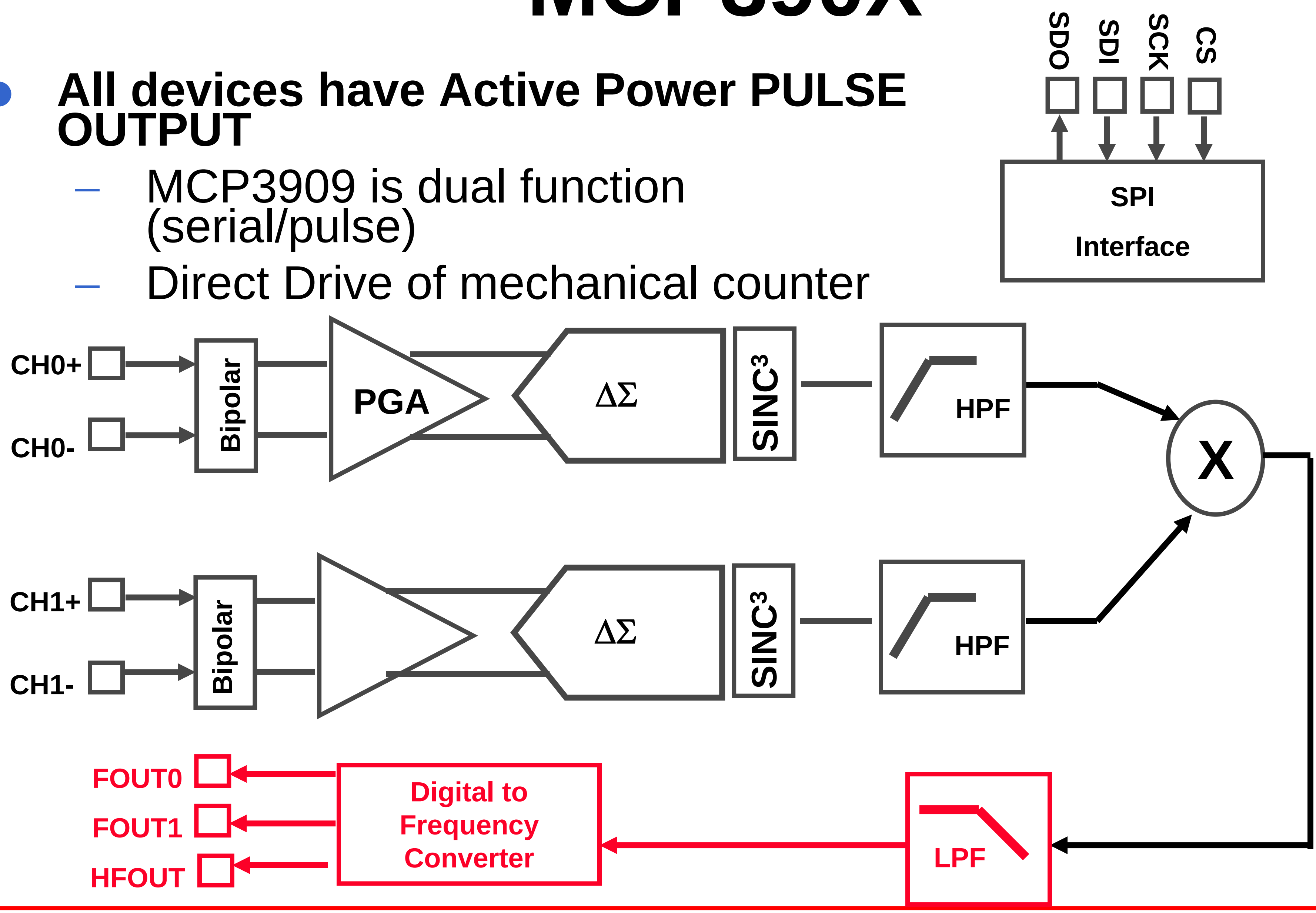
Active power = 1,04 $P1$ (fundamental + harmonics).

What kind of currents and Waveforms?

- **Basic test of harmonic components in current and voltage**
  - PF=1
  - 5TH HARMONIC IS 10% (voltage)
  - 5TH HARMONIC IS 40% (current)
- **DC Components and even harmonics in AC current circuit only**
  - Half-wave rectified circuit
  - IEC62053-21 and -23 only
- **Odd harmonics and sub Harmonics in the AC current circuit**
  - Burst and Phase Fired waveforms

MCP390X

- **All devices have Active Power PULSE OUTPUT**
  - MCP3909 is dual function (serial/pulse)
  - Direct Drive of mechanical counter

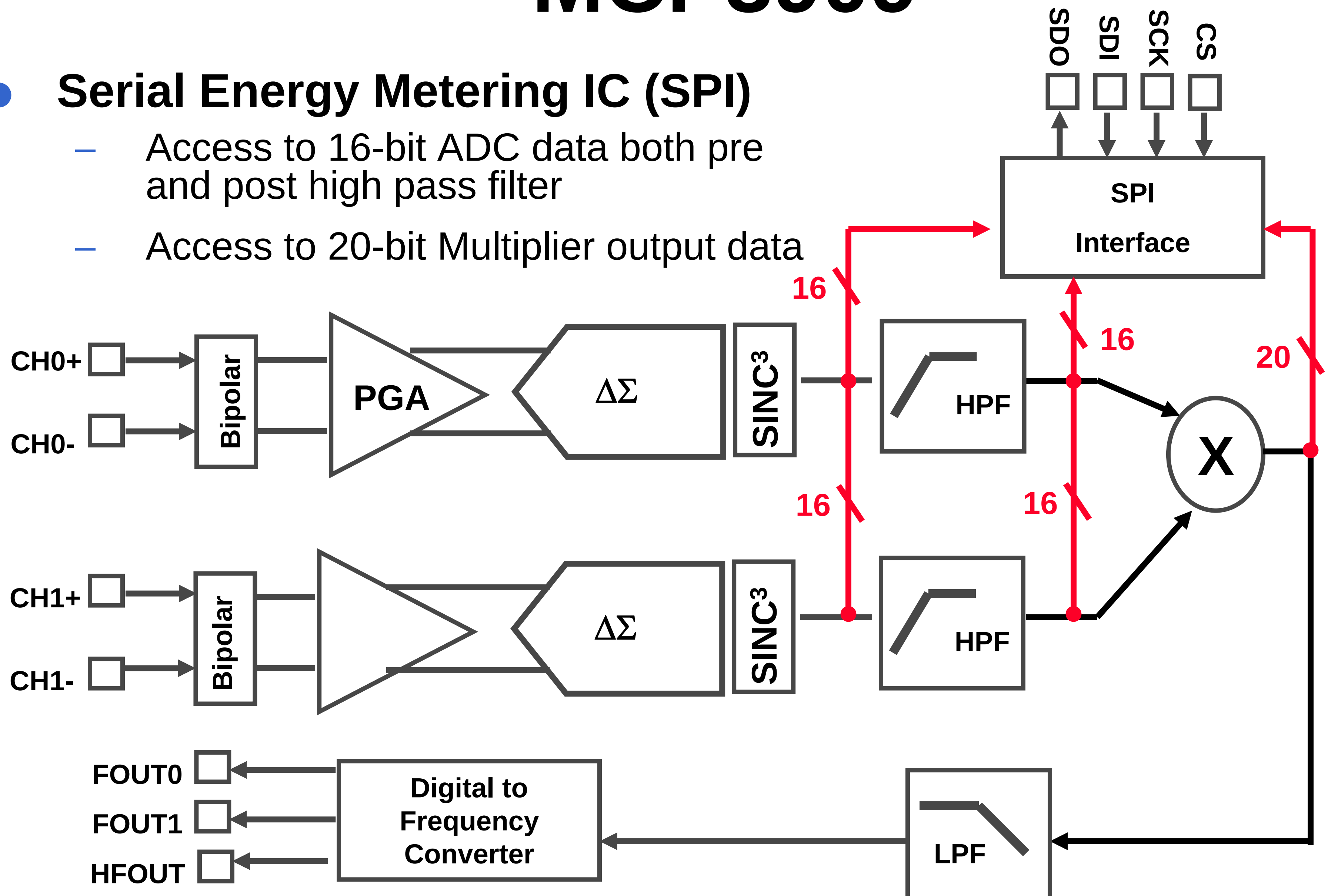


MCP3905A/06A Energy Meter Reference Design

- Direct connection to line for energy meter, no transformers required
- On-board power supply circuitry
- Resistive network and Output LED for meter calibration
- Resistor shorts for gain and frequency selection

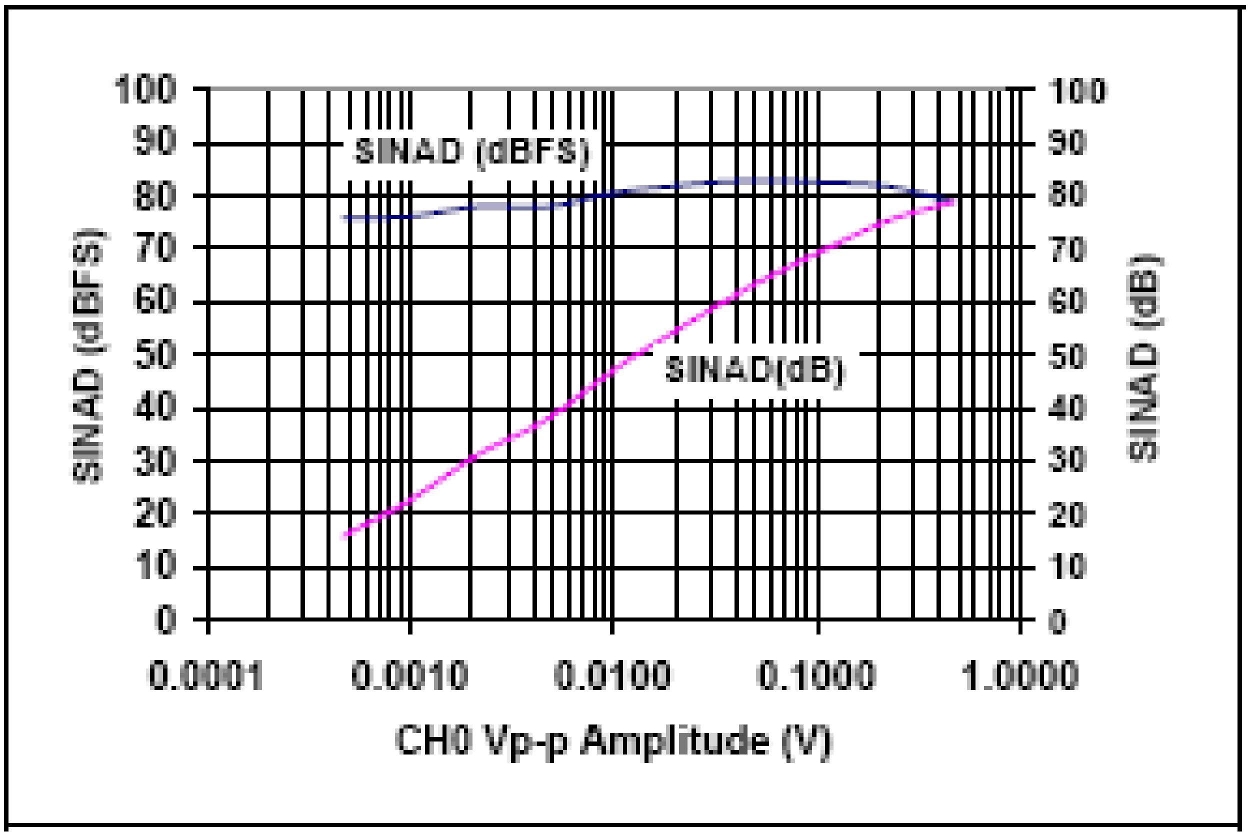
MCP3909

- **Serial Energy Metering IC (SPI)**
  - Access to 16-bit ADC data both pre and post high pass filter
  - Access to 20-bit Multiplier output data

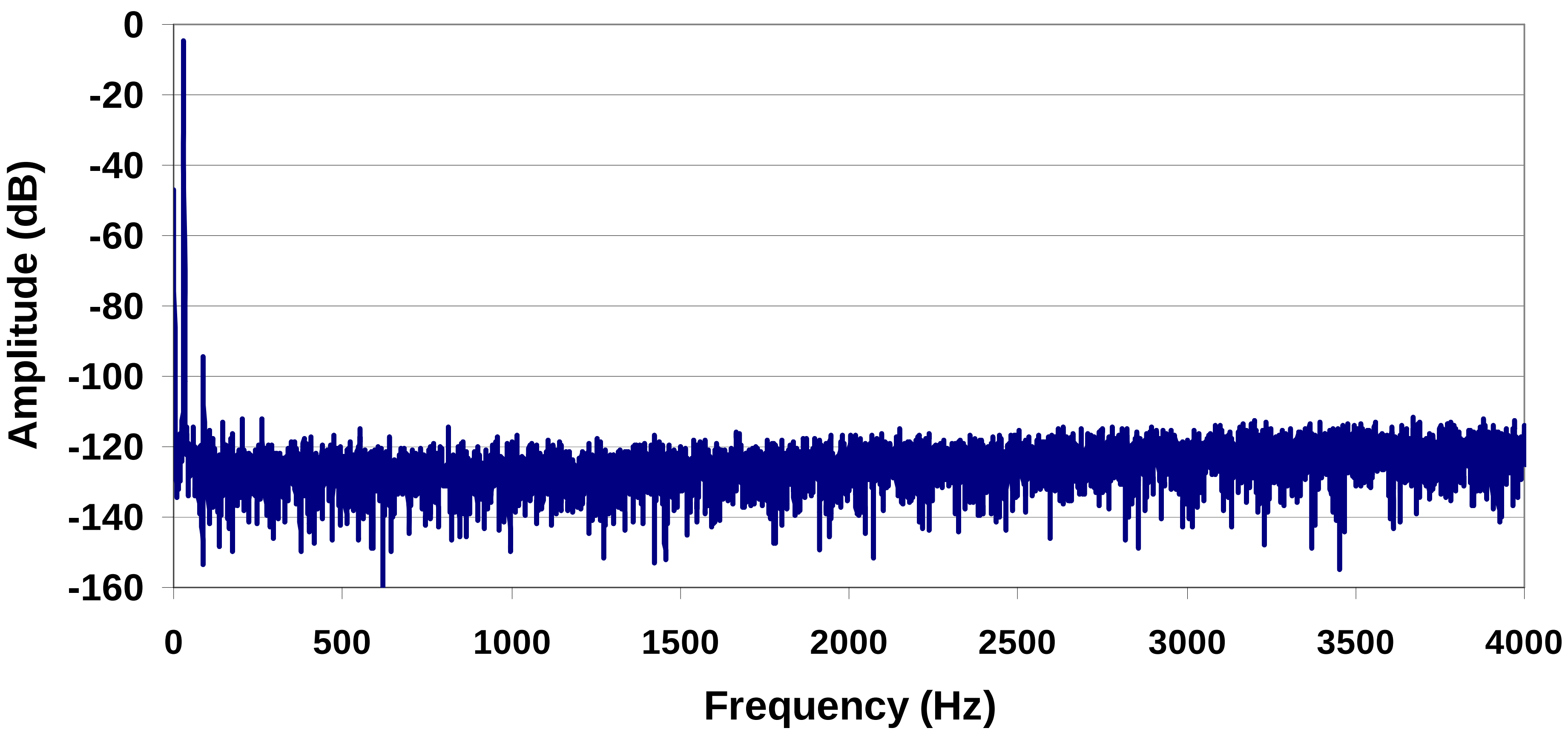


MCP3909 ADC Performance

- **SINAD = Signal to Noise Plus Distortion**



MCP3909 ADC Performance



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MCP3909 / PIC18F Meter Solution

PIC18F2520 / MCP3909 Meter Overview

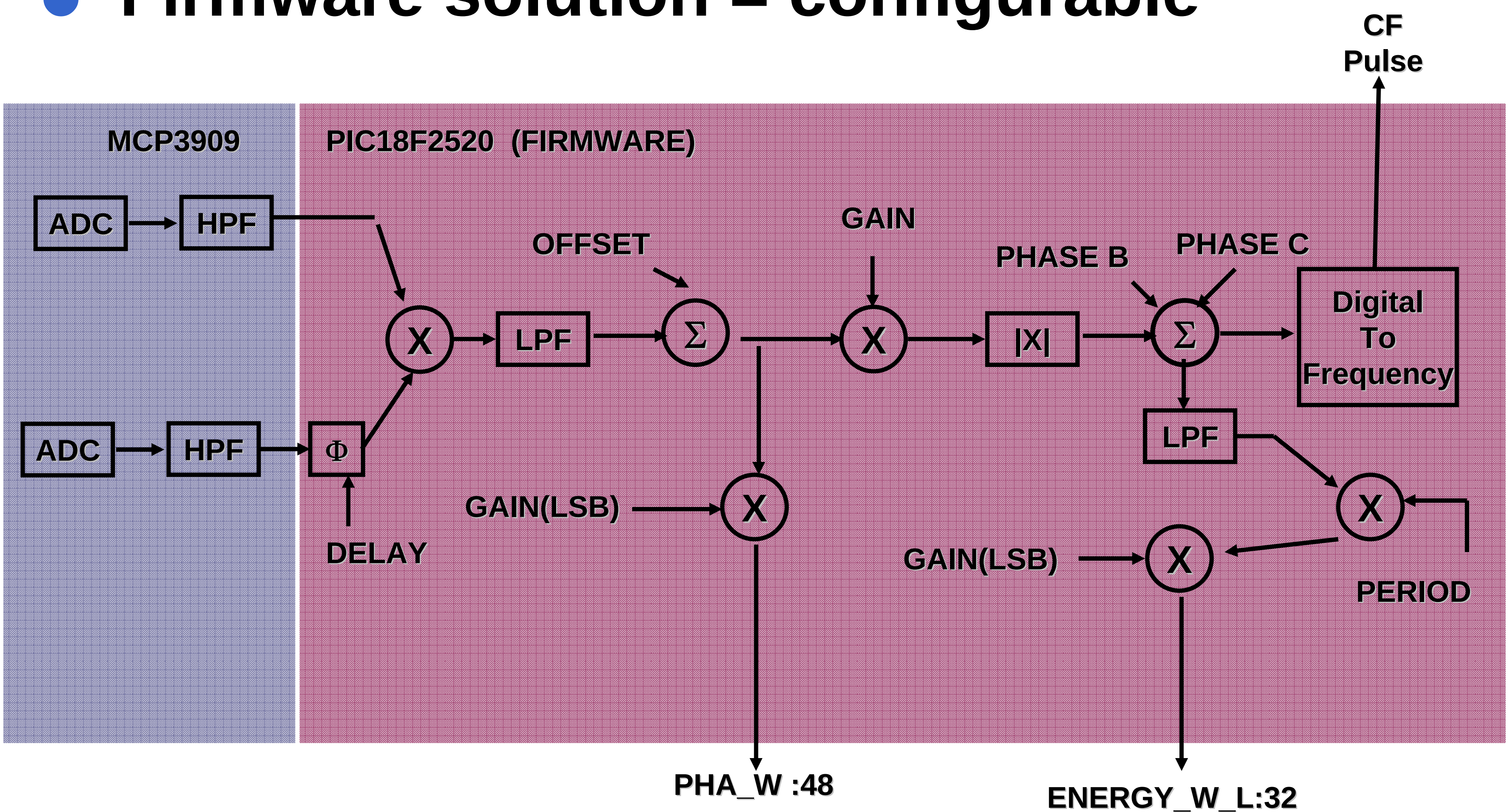
- **Industry & commercial mid-range 3-phase power meters**
- **Distribution transformers and transformer substations**
- **Equipments for monitoring grid power quality**
- **Measurement instruments**
- **Power Measurement Circuits for non-energy designs**
- **Connectivity**
  - USB and RS/232
- **PC Software**
  - USB Calibration and Meter Reading of all measurement quantities

PIC18F2520 / MCP3909 Meter Features

- Fully functional 3-phase energy meter using MCP3909 and 7K of PIC18F2520 program memory
- Active Energy Pulse Output, Active Power, Apparent Power, RMS current and RMS voltage calculation
- 62 serially accessible output registers containing power quantities, in Flash
- 54 serially accessible calibration registers, including offset, gain, phase, and LSB correction for all power and energy quantities, in Flash
- Easy to use 'Store' command pushes calibration registers to EEPROM for user configurable write cycles
- High accuracy 16-bit ADCs MCP3909, sampled at 128 times per line cycle
- 'Zero-Blind' measurements for all power quantities per line cycle
- Phase Lock Loop circuit for line cycle sample lock

Digital Signal Processing Flow For Active Power

- Firmware solution = configurable

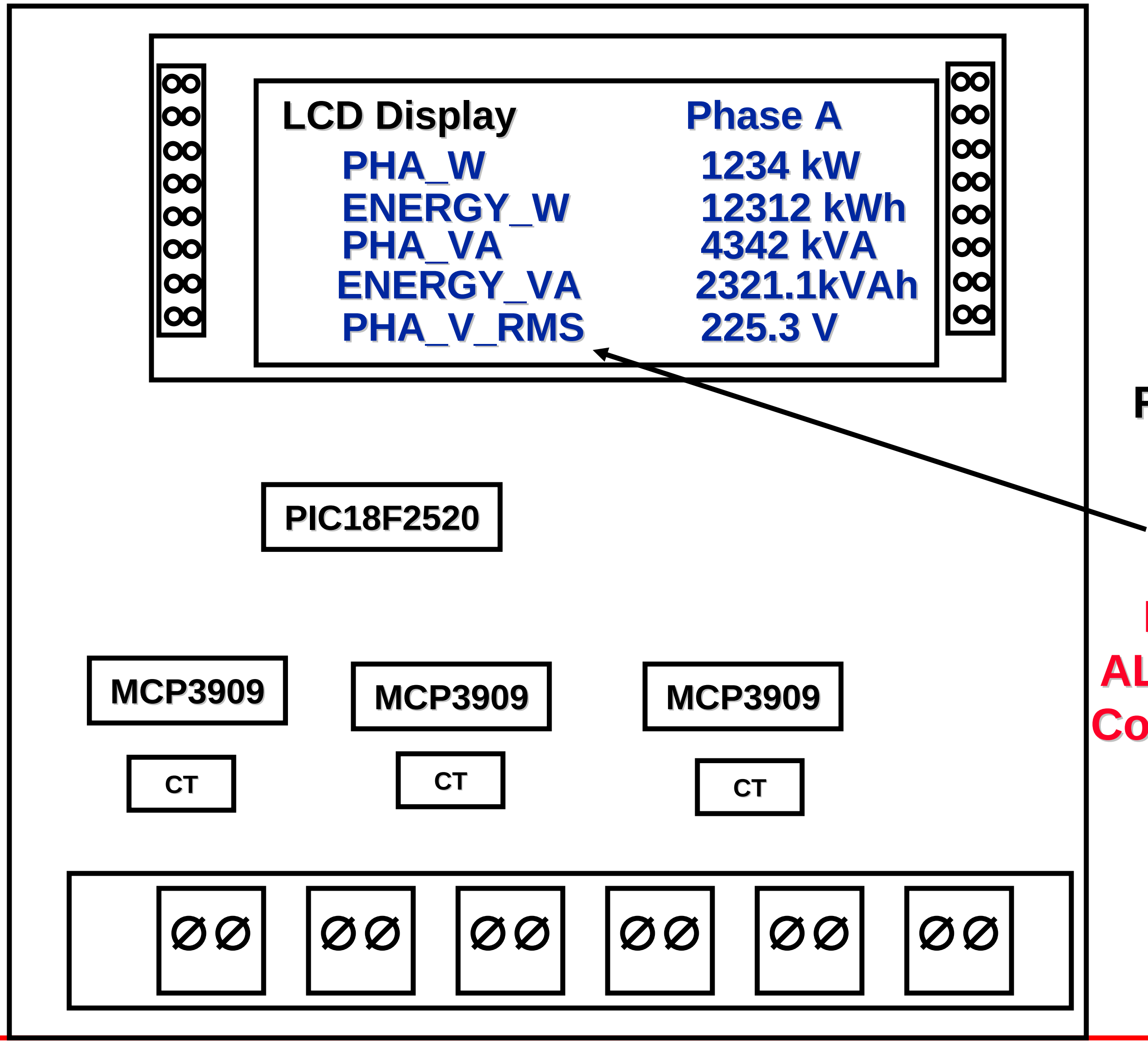


PIC18F2520
The "Power Calculation Engine"

- Measurement (PIC18F2520 REGISTER)
  - Instantaneous Active Power (PHy_W)
  - Instantaneous Apparent Power (PHy_VA)
  - Active Energy (ENERGY_W)
  - Apparent Energy (ENERGY_VA)
  - RMS Current (PHy_I_RMS)
  - RMS Voltage (PHy_I_RMS)
  - Calibration Pulse Output (CF)
  - Import/Export Energy

'y' replaced by A,B, or C

Solution Advantage Storing Calibration & Correction In Flash



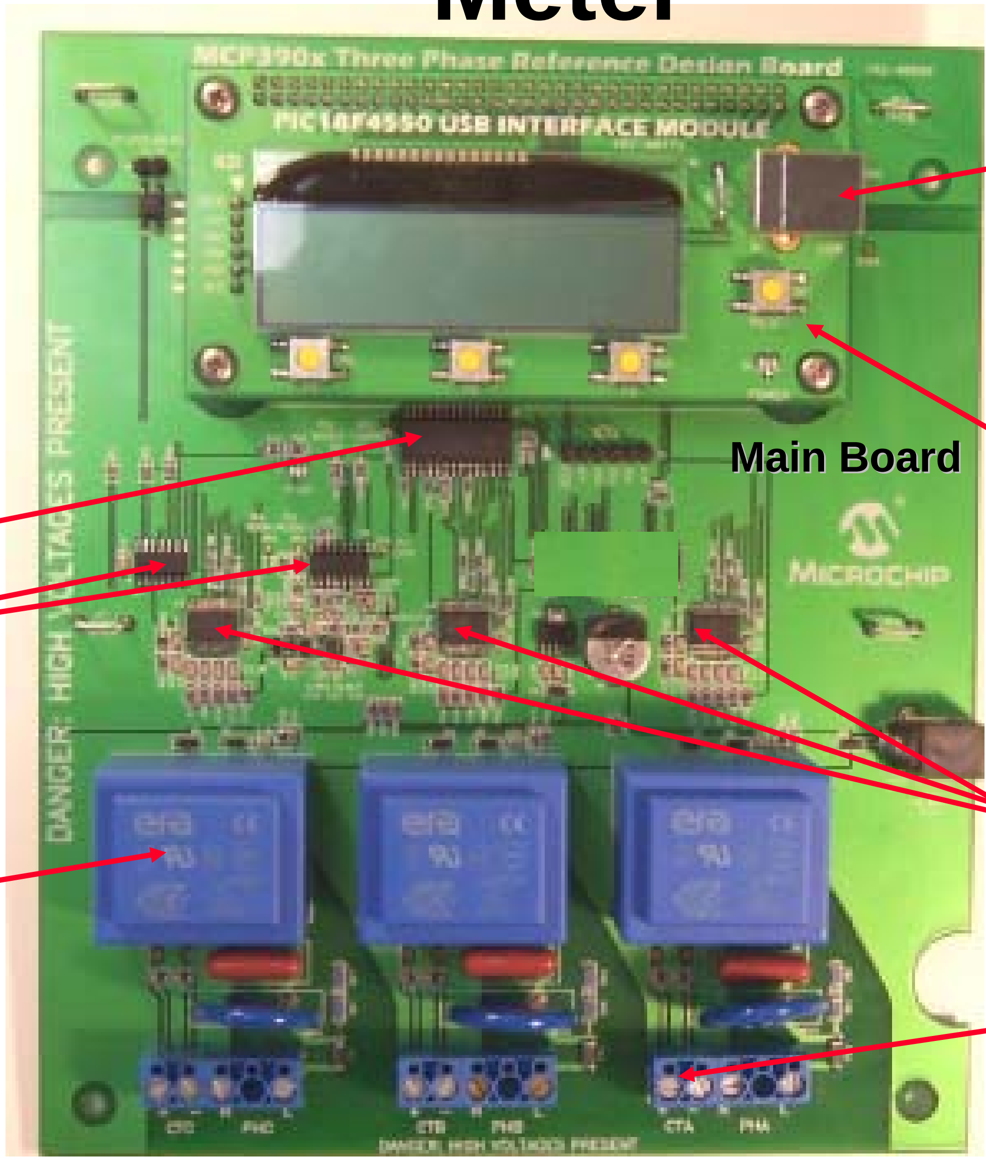
Register Values Are ready to display

PIC18F holds ALL calibration & Correction factors In FLASH

PIC18F2520 / MCP3909 Meter Specifications

- **Input: 3-phase, 4-wire at 50 OR 60 Hz**
- **Frequency Range: 45-65 Hz**
- **128 samples / line cycle (50 or 60 Hz System)**
- **Voltage Input Range: 176-300V**
- **Rate Current (I_b): 3 X 5(10)A**
  - Easily configured to different current ratings through PC Calibration Software
- **Start-up Current: 0.001 I_b**
- **Active Power：0-13200W**
- **Pulse Constant: 3200**
  - Easily configured to different current ratings through PC Calibration Software

PIC18F2520 / MCP3909 Energy Meter



Calibration Software PC USB Connection

Main Board

USB Interface Module

PIC18F2520

PLL (optional)

MCP3909

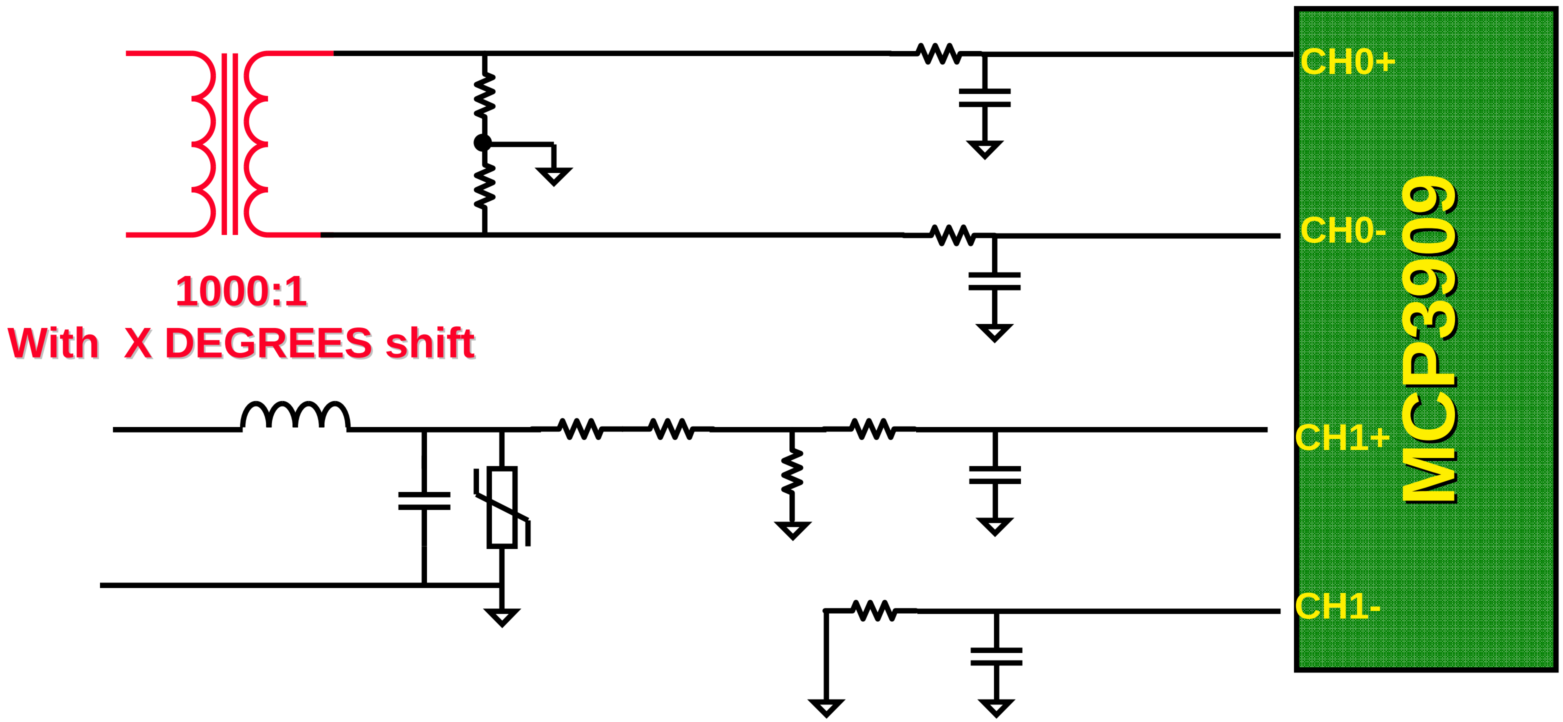
Power Transformers (PT)

Current Transformers (CT) *(NOT SHOWN)*

Phase Error Added from CT

- **Active Power = S * COS (Φ)**
- **AT PF = 1 (0 DEGREES), 0.2 degree error no big deal (<00.00001%))**
- **AT PF = -0.5 (60 DEGREES LAG), 0.61% error in P_A**

$$\%Error = \left(\frac{\cos(\phi) - \cos(\phi + \phi_e)}{\cos(\phi)} \right) \bullet 100\%$$



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CT Selection and Accuracy Specifications

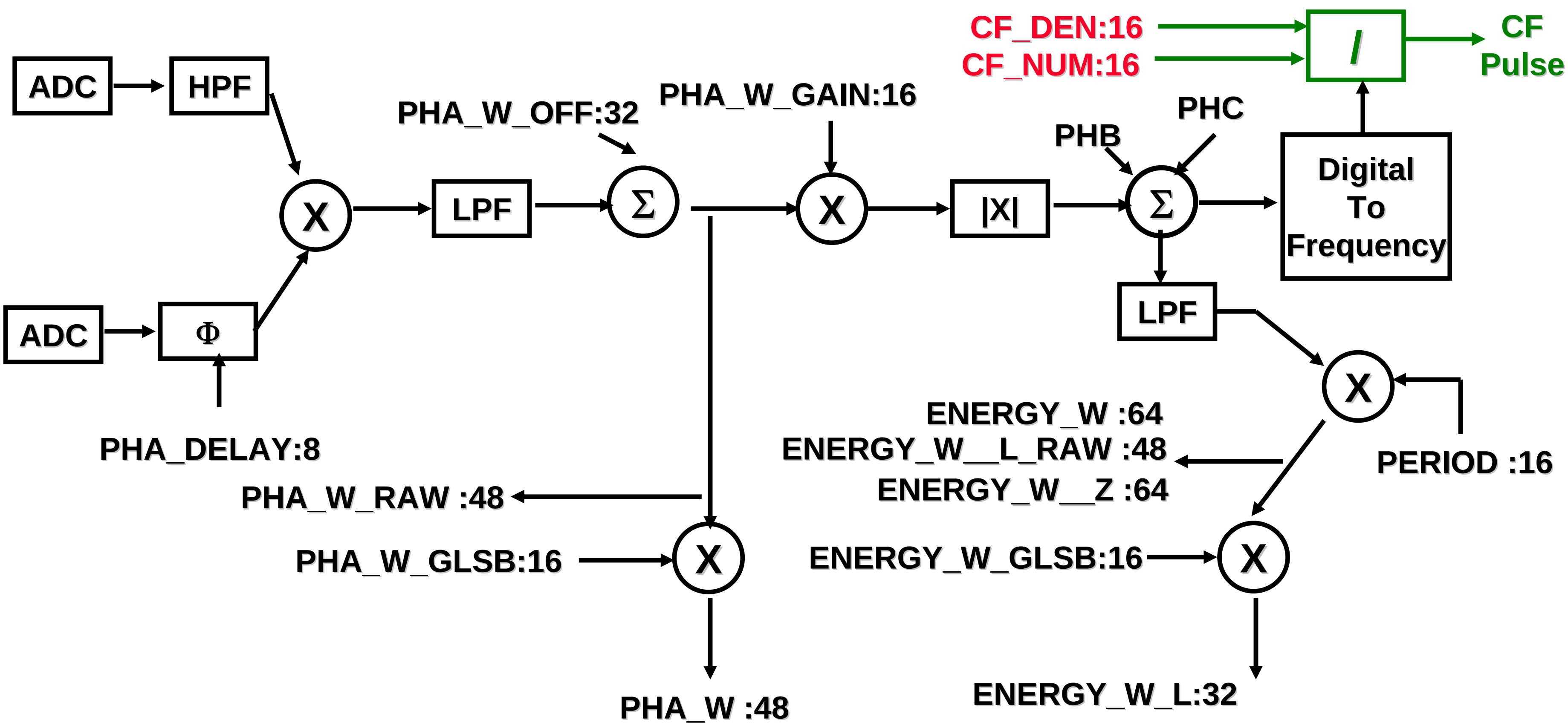
- **PIC18F Reference design**
  - TBD
- **dsPIC33F Reference design**
  - SY070401
  - SCT254GB
  - SCT254FK

TABLE 2-1: ACCURACY CLASSES AND ERROR LIMITS FOR CURRENT TRANSFORMERS

Accurate Class	Ratio Error ±(%)					Phase Error									
	Rated Current (%)					±(%)					±(Grad)				
						Rated Current (%)					Rated Current (%)				
	1	5	20	100	120	1	5	20	100	120	1	5	20	100	120
0.1	—	0.4	0.2	0.1	0.1	—	15	8	5	5	—	0.45	0.24	0.15	0.15
0.2	—	0.75	0.35	0.2	0.2	—	30	15	10	10	—	0.9	0.45	0.3	0.3
0.5	—	1.5	0.75	0.5	0.5	—	90	45	30	30	—	2.7	1.35	0.9	0.9
1	—	3	1.5	1.0	1.0	—	180	90	60	60	—	5.4	2.7	1.8	1.8
	Rated Current (%)					Phase Error									
	50		120												
3	3		3			Phase errors of class 3 and class 5 are not specified.									
5	5		5												

Output Pulse (CF) Generation

- CF pulse frequency is proportional to active power or Watts
- Same in functionality as MCP3905A/06A/09 CF output



Configuration Of CF Output Pulse

- **Frequency is proportional to the total active power measurement (All 3 Phases)**
- **Meter Constant is in units of imp/kWh**
- **Registers CFNUM and CFDEN**

Meter Constant

EXPECTED

$$CF(Hz) = \left(\frac{V_{CAL}(V) \times I_{CAL}(A)}{3600(\sec) \times 1000(kilo)} \right) \times \left(\frac{1000imp}{kWh} \right)$$

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Accuracy Limits Demonstration & Testing Results

Metering Specification Overview

- **From IEC the main specifications for energy metering**
  - IEC62053-21, Active Energy Meters
    - **Class 1 and Class 2**
  - IEC62053-22, Active Energy Meters
    - **Class 0.5 and Class 0.2**
    - **Transformer Only**
  - IEC62053-23, Reactive Energy Meters
    - **Class 2 and 3**

IEC Accuracy Limits and Example Meter Specifications
(not Microchip reference design)

- **Class 2**
  - 2.5% to 2%
- **Class 1**
  - 1.5% to 1%
- **Class 0.5**
  - 1% to 0.5%
- **Class 0.2**
  - 0.5% to 0.2%

**

Technical data **

Modifications or deviations are reserved R 1.3

Nominal voltage	2-wire, 1 system	220 .. 240V (-20% .. 15%)
Nominal frequency		50 / 60Hz, +/-5%
Nominal / maximum current	Continuous current Short duration	DC: 5(60)A, 5(80)A, 5(100)A DC: 7000A for 2 cycles
Starting current		DC: < 16mA
Accuracy	EN 62053-21 (former EN 61036)	Class 2 or 1
Power supply	Nominal voltage	220 … 240V (-20%..+15%)

**** Note this meter and technical data is not from a Microchip reference design but rather a meter manufacturer to demonstrate typical meter specifications**

Testing Results – Excel file

- **Results using CT#1**
  - See file
- **Results using CT#2**
  - See file
- **CF Accuracy**
  - See file
- **Presence of Harmonics Accuracy**
  - See file
- **Accuracy with PF <> 1**
  - See file
- **Bandwidth Limits of Meter – Results**
  - See file

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Calibration

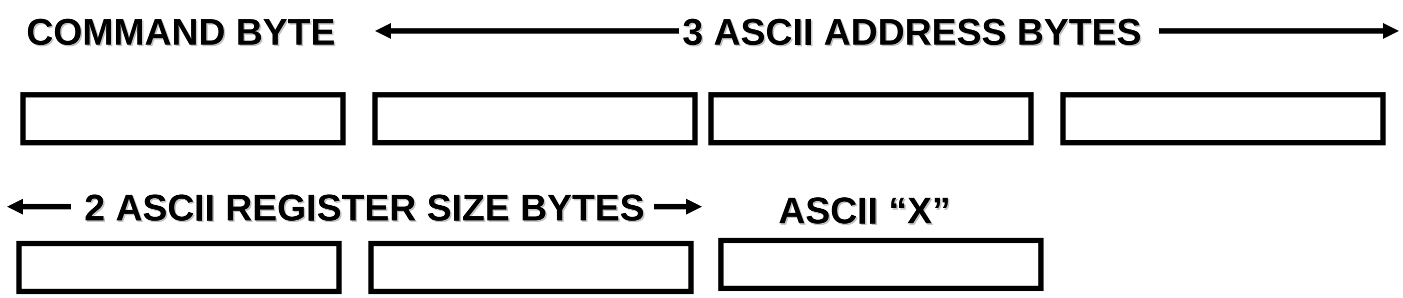
Calibration Overview & Demonstration

- **Example 5(10)A 220V Meter**
  - I_{CAL} = 5A, V_{CAL} = 220V, I_{MAX} = 10A
- **For complete calibration, 4 Calibration States for each phase**

1. **I_{CAL} & V_{CAL} at power factor = 1**
   - Registers affected are CFNUM, CFDEN, PHy_W_GAIN, PHy_I_RMS_GLSB, PHy_V_RMS_GLSB, PHy_W_GLSB, PHy_VA_GAIN, and PHy_VA_GLSB registers
2. **I_{CAL} & V_{CAL} at power factor = 0.5**
   - Registers affected are PHy_DELAY register
3. **1/100 I_{CAL} & V_{CAL}**
   - Active Power Offset register PHy_W_OFF
4. **1/10 I_{CAL} & 1/10 V_{CAL}**
   - RMS Offset register PHy_I_RMS_OFF, PHy_V_RMS_OFF

PIC18F2520 Read Communication Protocol

- **Read Command “R”**
- **Example: Read of ENERGY_W_L register**
  - “R 03C 08 X” (ASCII)
  - 52 30 33 43 30 38 58 (HEX)



Line Accumulation & Calibration Mode

- **LINE_CYC register holds the integer number of full line cycles that measurements will accumulate over (power of 2)**
- **CAL_CONTROL register**
  - Bit 0 (CALMODE) Enables Calibration Mode
  - Bit 1 (CALUPDATE) Starts/stops this accumulation for calibration purposes

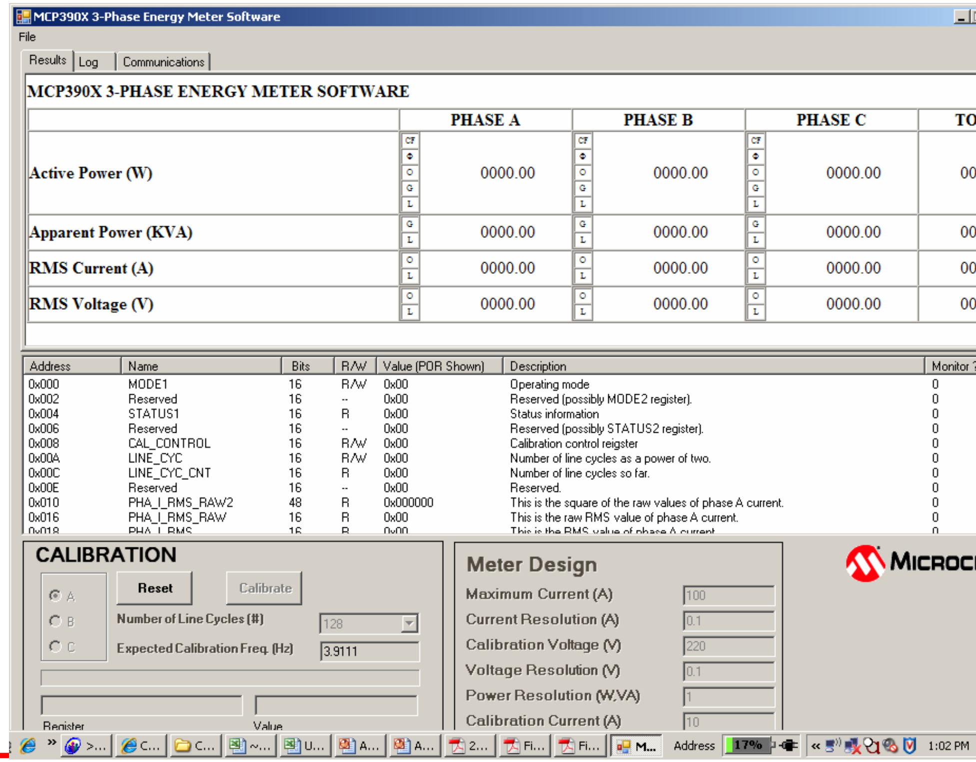
- **1) Set Meter Voltages 2) Set Bit 0 3) Clear Registers 4) Set Bit 1 5) Wait for Bit 1 to be Cleared**

Key Advantage: Faster Design Cycle

- **LSB adjustment register values calculated by software, allowing exact power quantities such as active power, energy, RMS current to be represented exactly by the contents of their registers**
  - Example
    - PHA_POWER (active power register for Phase A) = 255d or 0xFF
    - PHA_POWER = 25.5 WATTS

Having registers that represent the exact power quantity numerically is not possible with ROM energy meter ICs from competition.

This Approach Greatly Eases Meter Design Cycle time and Meter Calibration during Meter Production



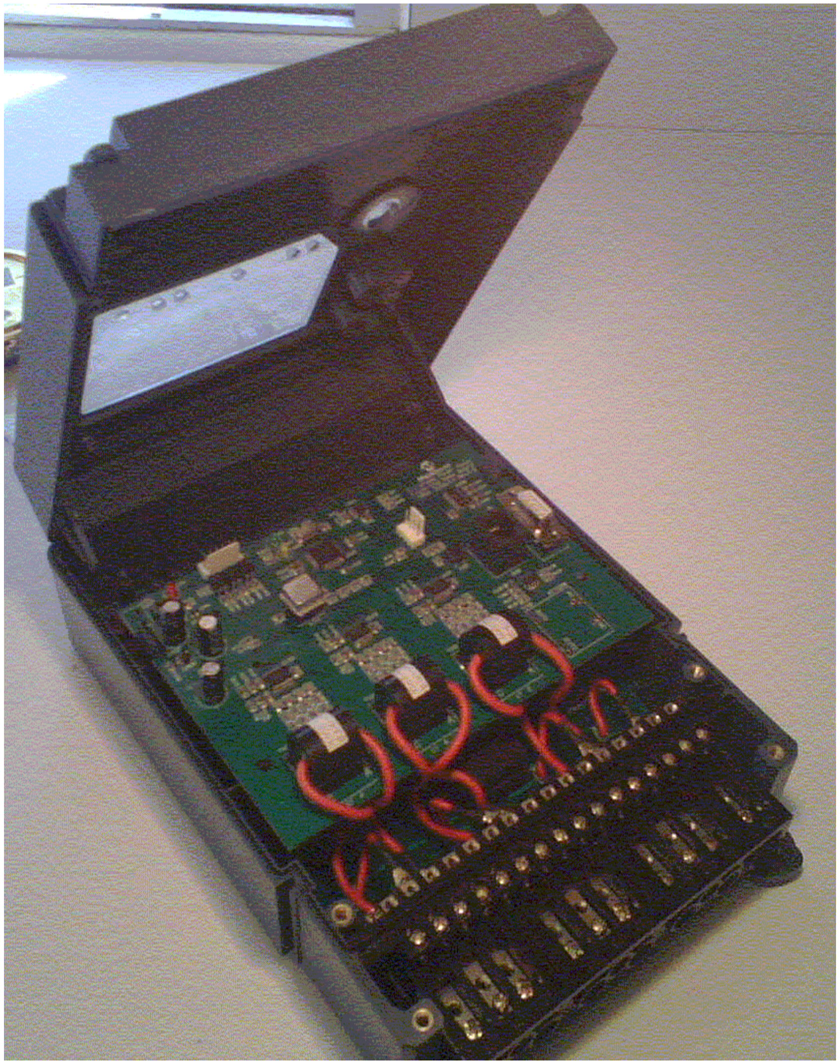
Agenda

- **Design Goals**
  - Power Measurement
  - Distortion, Power Factor, Why do we care?
    - Appliances and power consumption intelligence
- **Microchip's Energy Meter Solutions**
  1. MCP390X Energy Meter IC Overview & Single Phase Designs
  2. PIC18F2520 / MCP3909 Energy Meter Reference Design
     - Meter Accuracy Limits (IEC)
     - Testing Results
     - Calibration
  3. dsPIC33F / MCP3909 Energy Meter Reference Design
- **Analog Robustness**
  - EMC Immunity
  - Miscellaneous IEC Requirements

MCP3909 / dsPIC33F Meter Solution

dsPIC33FJ128GP206 / MCP3909 Meter Overview

- **Industry & commercial high-end 3-phase energy meter**
- **Harmonic Analysis up to 32nd harmonic**
- **Per Phase Distortion Measurement**
- **Channel Waveform Data**
- **Distribution transformers and transformer substations**
- **Equipments for monitoring grid power quality**
- **Circuit breakers and other circuit protecting devices**
- **Connectivity**
  - RS/232
- **PC Software**
  - Calibration and Meter Reading of all power measurements and harmonic analysis for each phase



dsPIC33FJ128GP206 / MCP3909 Meter Overview

- Input: 3-phase, 4-wire at 50 Hz (60 Hz firmware available)
- Frequency Range: 47～53HZ (60 Hz firmware available)
- Data Sample Rate: 3.2 ksps (40 MIPS dsPIC® DSC)
- Voltage Input Range: 176-300V, 0.2 class
- Rate Current(I_b): 3 X 5(20)A, 0.2 class
- Start-up Current: 0.001 I_b
- Active Power: 0-13200W, 0.2 class
- Reactive Power: 0-13200Var, 0.5 class
- Pulse Constant: 3200
- Frequency Measurement: 0.5 class, Maximum error: 0.05HZ

Harmonic Analysis

- Distorted wave can be approximated by superposing a series of sinusoidal waves of different frequencies. Sin(ω t) is the fundamental, whose period is the same as that of the distorted wave. This is the period of power frequency in the power grid. The rest are called harmonics.
- **The *TOTAL* voltage and current with harmonic contents can be expressed as:**

$$u(t) = u_0 + \sum_{1}^{N} \sqrt{2} u_k * \sin(k\omega t + \alpha_k)$$

$$i(t) = i_0 + \sum_{1}^{N} \sqrt{2} i_k * \sin(k\omega t + \beta_k)$$

where u0 and i0 are the DC components of the voltage and current, respectively. k is the order of a harmonic, k= 1,2,3…

Harmonic Content

- **The deviation of a distorted wave from a sine wave is usually expressed in 3 terms: the harmonic content, the total distortion and harmonic ratio of k-th harmonic**

- **Harmonic content means the root mean square of the effective values for all harmonics, which is defined in the following equation:**

$$U_H = \sqrt{\sum_{k=2}^{k=N} U_k^2}$$

Harmonic Distortion (Ratio)

- **The total voltage distortion of a harmonic is the ratio (in percentage) of the harmonic content to the fundamental, which can be defined as:**

$$THD_U = \frac{U_H}{U_1} \times 100\%$$

- **The harmonic ratio of k-th harmonic voltage is the ratio (in percentage) of k-th harmonic to the fundamental, which can be defined as:**

$$HD_{U_k} = \frac{U_k}{U_1} \times 100\%$$

- **Likewise, the expressions for harmonic currents can also be written**

Agenda

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Analog Robustness

IEC Specification: Immunity to Electromagnetic Disturbances

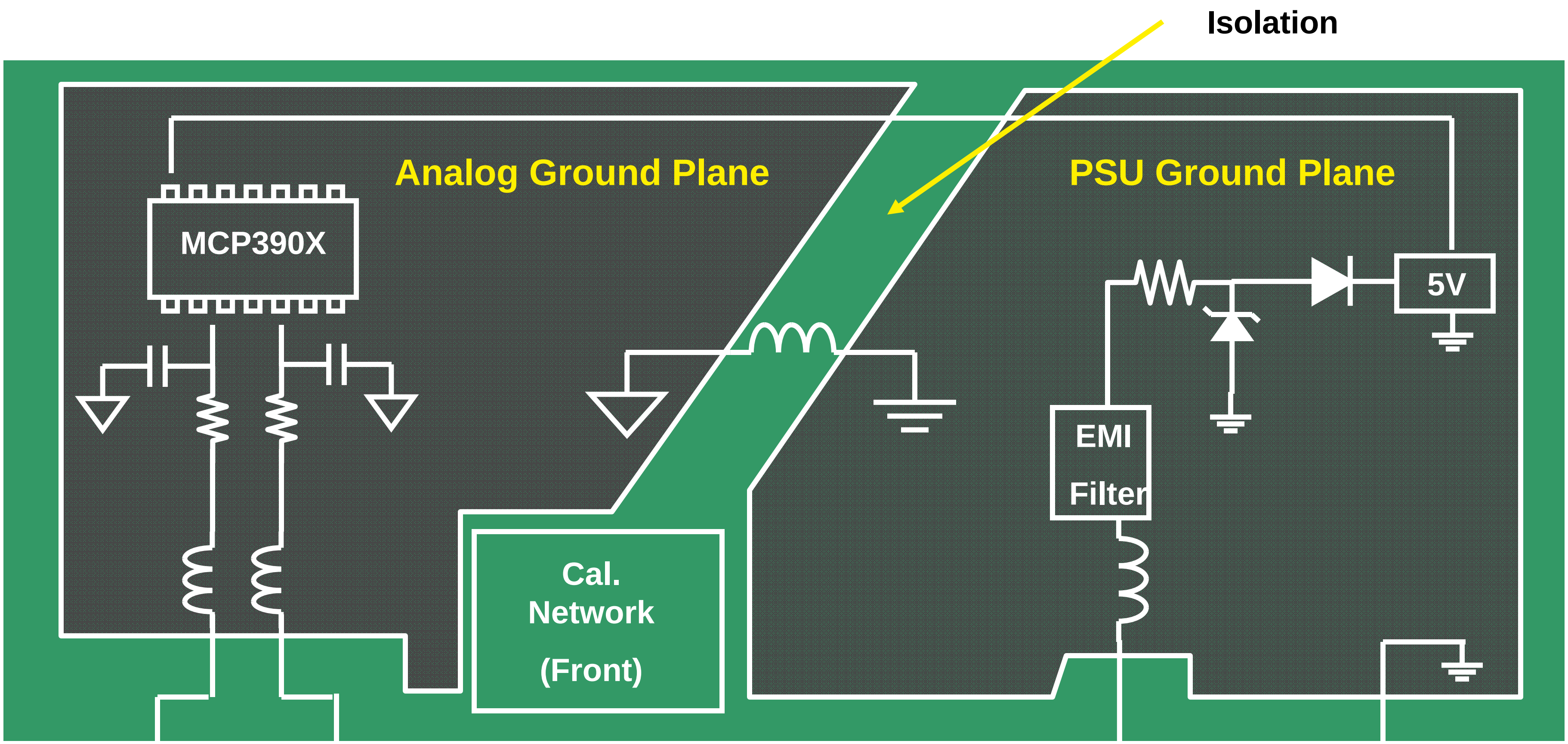
- **IEC62053 section states**
  - Conducted
  - Radiated Electromagnetic
  - Electrostatic Discharge

"do not damage or substantially influence" the meter

The Analog and Mixed Signal (A/D) Circuitry Must be Designed Properly

IEC Immunity Requirements: How to pass?

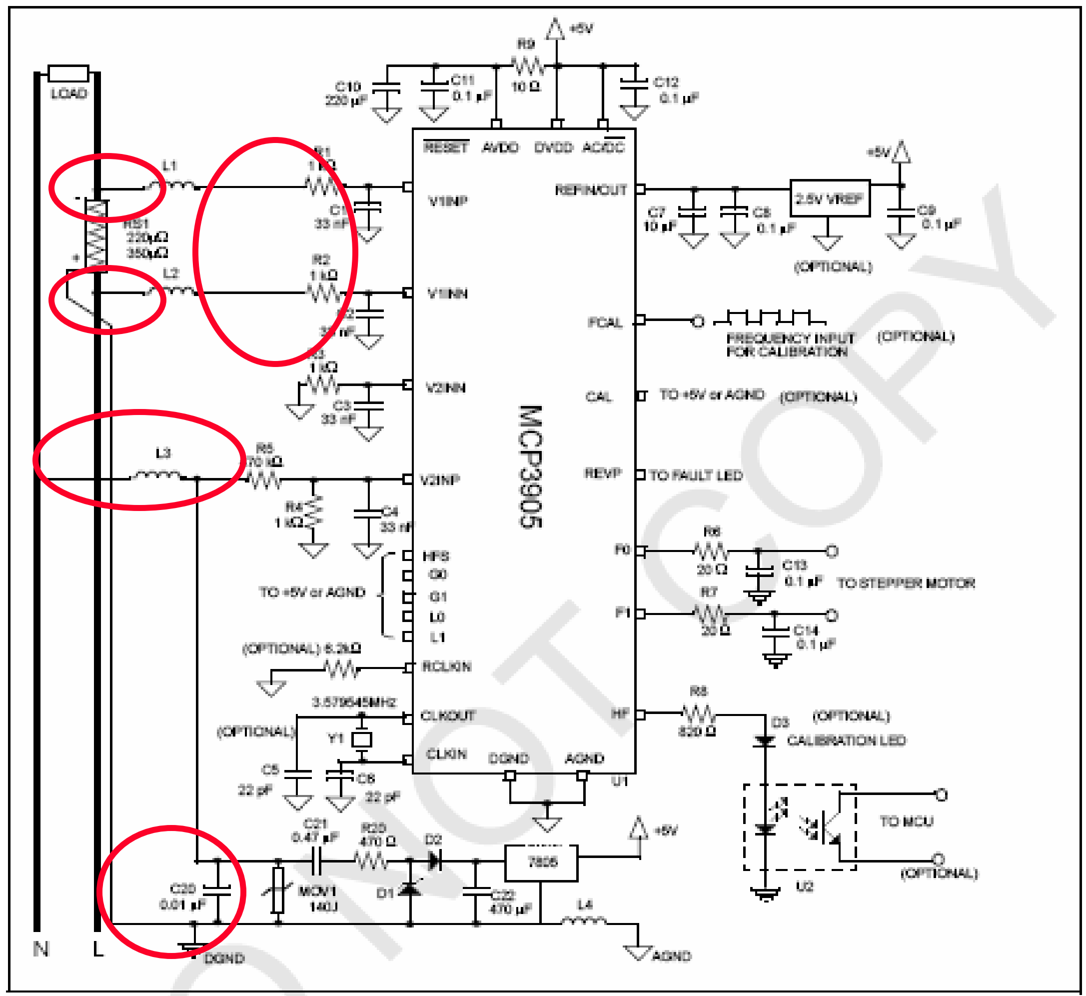
- Typical of any energy meter IC design



EMC (Immunity)

- **ESD**
  - 8kV Contact Discharge
  - 10 discharges (in each polarity)
- **HF**
  - 10 V/m in 80 MHz to 1 GHz bandwidth
- **EFT**
  - 2kV burst
    - **10 minute test**
    - **1 second bursts with 300ms pause**
  - 4kV burst
    - **60 second duration**

Analog Design Tip



EXAMPLE 11-1: SIMPLE WATT-HOUR METER USING MCP3905

Summary

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Summary

- **Proven Analog Performance**

  Our ADC performance is unmatched for energy metering ICs

  - **MCP3905A / 06A/ 09 devices use proven 16-bit ADCs with 82dB signal to noise performance**
    - Competing Energy Meter ICs are typically around 60dB
  - **Measurement Error of 0.1% typical exceeds IEC requirement for all classes of energy meter designs**
- **Industry Leading MCU supplier**

  Microchip's PIC® MCU and dsPIC® DSC portfolio brings limitless design options for energy metering

  - **Connectivity for energy meter reading and calibration such as USB, Ethernet, CAN, Infrared, Radio Frequency, MiWi™ Protocol**
  - **Range of memory technologies: Flash, OTP, ROM**
  - **Easy migration between MCU families**
- **Application Support and Energy Meter Reference Designs**
  - **Our energy meter demo boards are fully functional energy meters!**
  - **Competing energy meter solutions use ROM-based ICs, our Flash-based meters help reduce system cost and meter calibration time**

Reference Material

Voltage & Current Definition in 3-Phase Circuits

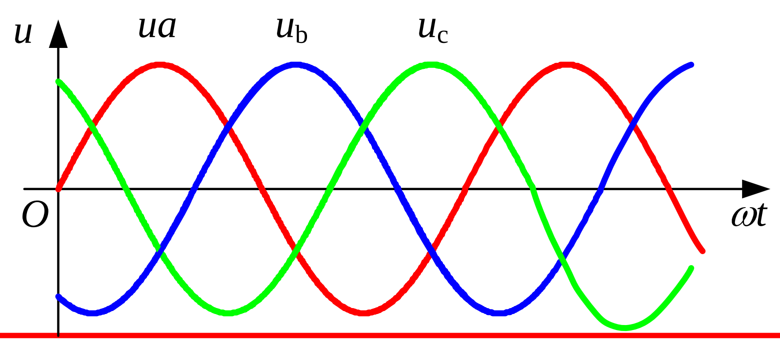
- **In a 3-phase power system, sinusoidal voltage and current signals are defined as:**

$$v_A = \sqrt{2}V_A \sin(\omega t) \qquad i_A = \sqrt{2}I_A \sin(\omega t)$$

$$v_B = \sqrt{2}V_B \sin(\omega t - 120) \qquad i_B = \sqrt{2}I_B \sin(\omega t - 120)$$

$$v_C = \sqrt{2}V_C \sin(\omega t + 120) \qquad i_C = \sqrt{2}I_C \sin(\omega t + 120)$$

- **Where v_A, v_B and v_C are instantaneous values, while U_A, U_B and U_C are the RMS values. The phase difference between 2 voltages or 2 currents is 120º**



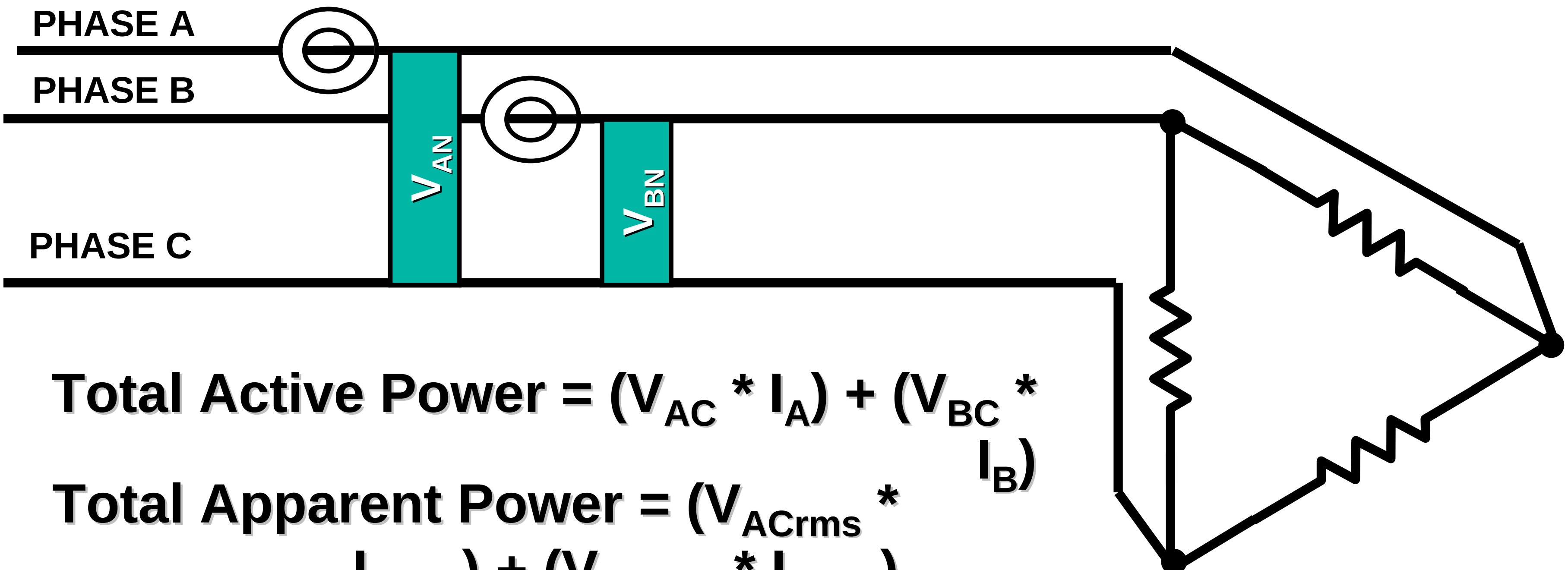
Voltage & Current Definition of Non-sinusoidal Periodic Signals

- **The non-sinusoidal periodic signals are present in a circuit due to the existence of nonlinear loads and components in a power grid**
- **AC voltage and current can be represented by sRMS, average and peak values. But in practice, esp. for non-sinusoidal signals, the RMS value is used more often.**
- **The RMS voltage/current values of a non-sinusoidal periodic signal are defined as:**

$$V = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} \qquad I = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt}$$

3-Phase 3-Wire Delta

- **4 Total Measuring Elements**

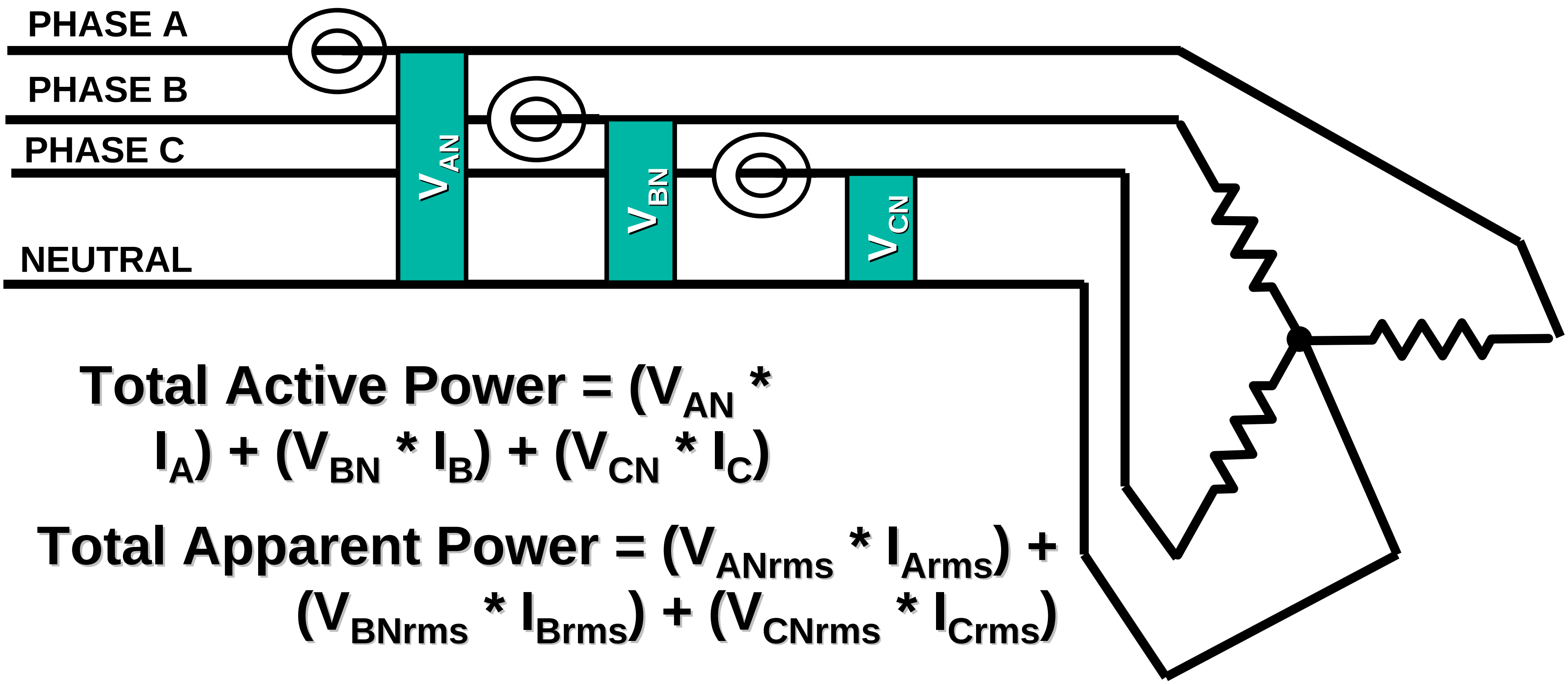


Total Active Power = $(V_{AC} * I_A) + (V_{BC} * I_B)$

Total Apparent Power = $(V_{ACrms} * I_{Arms}) + (V_{BCrms} * I_{Brms})$

3-Phase 4-Wire Wye

- **6 Total Measuring Elements**

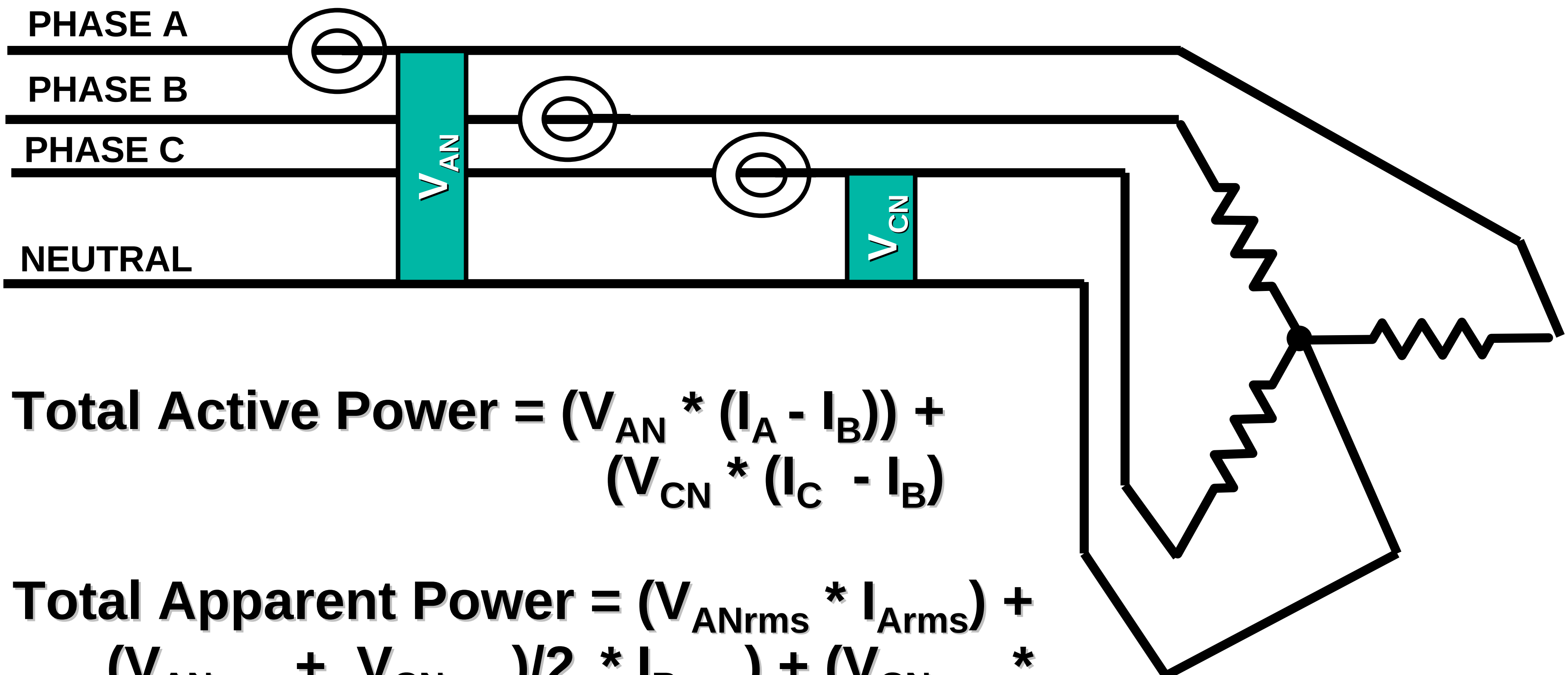


Total Active Power = $(V_{AN} * I_A) + (V_{BN} * I_B) + (V_{CN} * I_C)$

Total Apparent Power = $(V_{ANrms} * I_{Arms}) + (V_{BNrms} * I_{Brms}) + (V_{CNrms} * I_{Crms})$

3-Phase 4-Wire Wye
2 Voltage Sensors

- 5 Total Measuring Elements

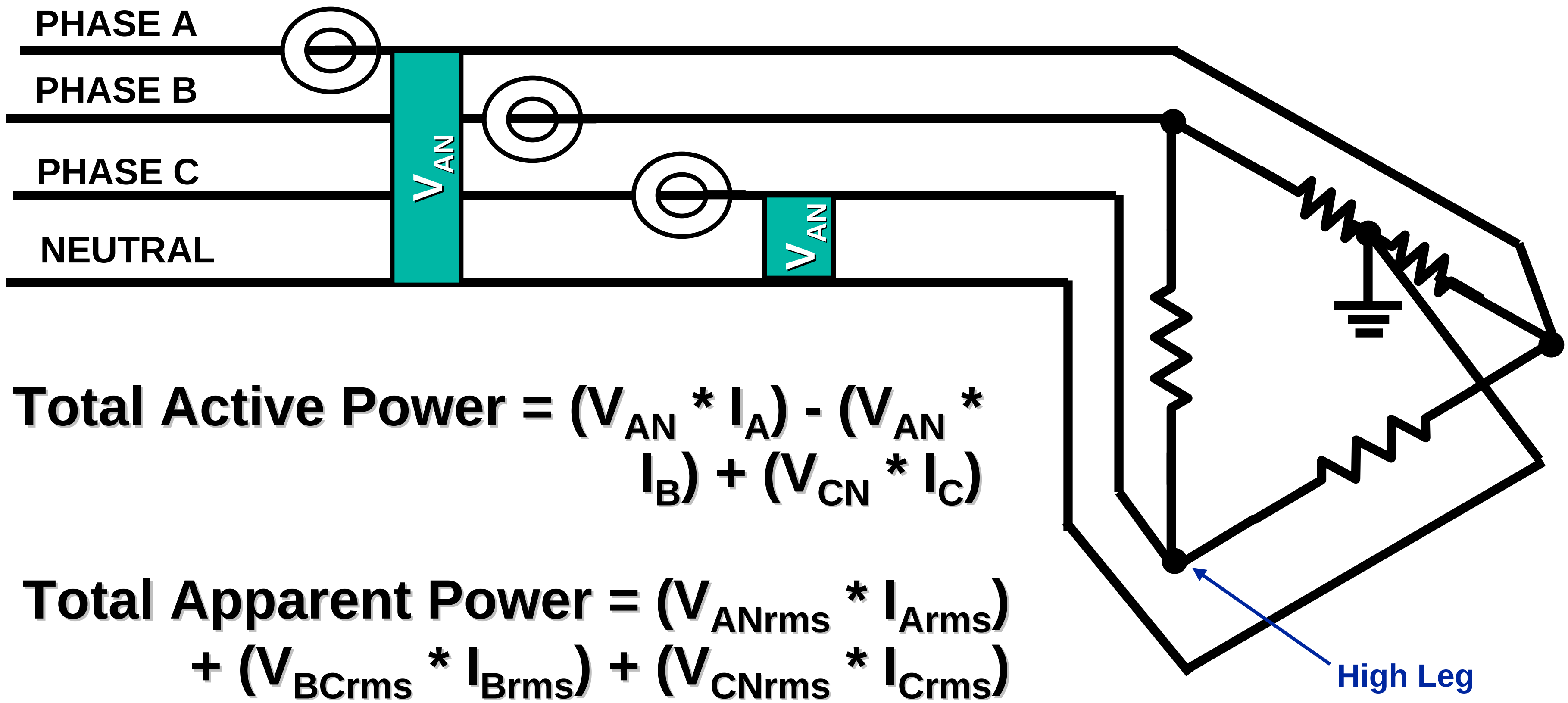


Total Active Power = $(V_{AN} * (I_A - I_B)) + (V_{CN} * (I_C - I_B))$

Total Apparent Power = $(V_{ANrms} * I_{Arms}) + (V_{ANrms} + V_{CNrms})/2 * I_{Brms}) + (V_{CNrms} * I_{Crms})$

3-Phase 4-Wire Delta
Center Tap on A-B

- **5 Total Measuring Elements**



Total Active Power = $(V_{AN} * I_A) - (V_{AN} * I_B) + (V_{CN} * I_C)$

Total Apparent Power = $(V_{ANrms} * I_{Arms}) + (V_{BCrms} * I_{Brms}) + (V_{CNrms} * I_{Crms})$

Miscellaneous IEC Requirements

- **No Load Threshold**
  - "… the meter shall not emit more than one pulse during minimum test period d_T"
  - Purpose: Meter should not continually register energy below a certain threshold, i.e. a very small signal can not integrate over a large period of time
- **Starting Current**
  - "…The meter shall start and continue to register at 0,001 *I* n and unity power factor … If the meter is designed for the measurement of energy in both directions, then this test shall be applied with energy flowing in each direction."

No Load Threshold

- **Example, for 220V Class 1 5(60) 3200 imp/kWh meter, Δt = 14 minutes or 1.2 mHz**
- **0.0015% F_{OUT} is minimum output frequency per MCP390X data sheet specification**
  - MCP390X contains a 40-bit internal counter that blocks F_{OUT} pulses below the output frequency selected by F2,F1,F0 output frequency pins

From IEC Specification

$$\Delta t \geq \frac{600\times10^6}{k\,m\,U_n\,I_{max}} \text{ [min] for meters of class 1}$$

$$\Delta t \geq \frac{480\times10^6}{k\,m\,U\quad I} \text{ [min] for meters of class 2}$$

k	is the number of pulses emitted by the output device of the meter per kilowatthour (imp/kW·h);
m	is the number of measuring elements;
U_n	is the reference voltage in volts;
I_{max}	is the maximum current in amperes.

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