MCP6L2 and PIC18F66J93 Energy Meter Reference Design

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ISBN: 978-1-62076-090-4

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Derek Carlson
VP Development Tools

02-MAY-12
Date

NOTES:

MCP6L2 AND PIC18F66J93 ENERGY METER REFERENCE DESIGN

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Preface

NOTICE TO CUSTOMERS

All documentation becomes dated, and this manual is no exception. Microchip tools and documentation are constantly evolving to meet customer needs, so some actual dialogs and/or tool descriptions may differ from those in this document. Please refer to our web site (www.microchip.com) to obtain the latest documentation available.

Documents are identified with a "DS" number. This number is located on the bottom of each page, in front of the page number. The numbering convention for the DS number is "DSXXXXXA", where "XXXXX" is the document number and "A" is the revision level of the document.

For the most up-to-date information on development tools, see the MPLAB® IDE online help. Select the Help menu, and then Topics to open a list of available online help files.

INTRODUCTION

This chapter contains general information that will be useful to know before using the MCP6L2 and PIC18F66J93 Energy Meter Reference Design. Items discussed in this chapter include:

- Document Layout
- Conventions Used in this Guide
- Recommended Reading
- The Microchip Web Site
- Customer Support
- Document Revision History

DOCUMENT LAYOUT

This document describes how to use the MCP6L2 and PIC18F66J93 Energy Meter as a development tool to emulate and debug firmware on a target board. The manual layout is as follows:

- **Chapter 1. "Product Overview"** – Important information on using the MCP6L2 and PIC18F66J93 Energy Meter including a Getting Started section that describes wiring the line and load connections.
- **Chapter 2. "Hardware"** – Includes details about the function blocks of the meter including the analog front-end and power supply design.
- **Chapter 3. "Calculation Engine and Register Description"** – This section describes the digital signal flow for all power output quantities such as RMS current, RMS voltage, active power, reactive power and apparent power. This section also includes the registers' detail.
- **Chapter 4. "Communication Protocol"**– The protocol used for accessing the registers is described. It includes commands that are used to interface to the meter.
- **Chapter 5. "Microchip Energy Meter Software"**– Describes the functionality of the Graphical User Interface (GUI) that runs on the PC.
- **Chapter 6. "Energy Meter Calibration"**– Information on calibration of the energy meter using the GUI.
- **Appendix A. "Schematic and Layouts"** – Shows the schematic and layout diagrams
- **Appendix B. "Bill of Materials (BOM)"** – Lists the parts used to build the MCP6L2 and PIC18F66J93 Energy Meter.

CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

DOCUMENTATION CONVENTIONS

Description	Represents	Examples
Arial font:		
Italic characters	Referenced books	*MPLAB® IDE User's Guide*
	Emphasized text	...is the *only* compiler...
Initial caps	A window	the Output window
	A dialog	the Settings dialog
	A menu selection	select Enable Programmer
Quotes	A field name in a window or dialog	"Save project before build"
Underlined, italic text with right angle bracket	A menu path	<u>*File>Save*</u>
Bold characters	A dialog button	Click **OK**
	A tab	Click the **Power** tab
N'Rnnnn	A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.	4'b0010, 2'hF1
Text in angle brackets < >	A key on the keyboard	Press <Enter>, <F1>
Courier New font:		
Plain Courier New	Sample source code	`#define START`
	Filenames	`autoexec.bat`
	File paths	`c:\mcc18\h`
	Keywords	`_asm, _endasm, static`
	Command-line options	`-Opa+, -Opa-`
	Bit values	`0, 1`
	Constants	`0xFF, 'A'`
Italic Courier New	A variable argument	*`file`*`.o`, where *`file`* can be any valid filename
Square brackets [ ]	Optional arguments	`mcc18 [options]` *`file`* `[options]`
Curly brackets and pipe character: { | }	Choice of mutually exclusive arguments; an OR selection	`errorlevel {0|1}`
Ellipses...	Replaces repeated text	`var_name [, var_name...]`

	Represents code supplied by user	`void main (void)`
		`{ ...`
		`}`

RECOMMENDED READING

This user's guide describes how to use the MCP6L2 and PIC18F66J93 Energy Meter. Other useful documents are listed below. The following Microchip documents are available and recommended as supplemental reference resources.

- **MCP6L2 Data Sheet – *"2.8 MHz, 200 µA Op Amps"* (DS22135)**

This data sheet provides detailed information regarding the MCP6L2 device.

- **PIC18F66J93 Data Sheet – *"64/80-Pin, High-Performance Microcontrollers with LCD Driver, 12-Bit A/D and nanoWatt Technology"* (DS39948)**

This data sheet provides detailed information regarding the PIC18F66J93 device.

- **PIC18F87J72 Single-Phase Energy Meter Calibration User's Guide (DS51964)**

This User's Guide describes the calibration registers and Universal Asynchronous Receiver/Transmitter (UART) communication protocol used on the PIC18F87J72 Single-Phase Energy Meter Reference Design. Only some of the information applies to the MCP6L2 and PIC18F66J93 Energy Meter Reference Design. The chapters recommended for reading will be specified later in this document.

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- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user's guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQs), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives

CUSTOMER SUPPORT

Users of Microchip products can receive assistance through several channels:

- Distributor or Representative
- Local Sales Office
- Field Application Engineer (FAE)
- Technical Support

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Technical support is available through the web site at: http://www.microchip.com/support.

DOCUMENT REVISION HISTORY

Revision B (February 2013)

- Updated Figure 1-2.

Revision A (August 2012)

- Initial Release of this Document.

MCP6L2 AND PIC18F66J93 ENERGY METER REFERENCE DESIGN

Chapter 1. Product Overview

1.1 INTRODUCTION

The MCP6L2 and PIC18F66J93 Energy Meter is a fully functional single-phase meter that uses the 12-bit successive approximation analog-to-digital converter (SAR ADC) integrated in the microcontroller. This low-cost design has a shunt as the current sensor. The signal from the shunt is amplified by two external operational amplifiers and applied to the input of the ADC. The PIC18F66J93 directly drives the LCD and communicates via UART with the MCP2200, offering an isolated USB connection for meter calibration and access to the device power calculations. The system calculates active and reactive energy; active, reactive and apparent power; power factor; RMS current; RMS voltage, and line frequency.

The Microchip energy meter software is used to calibrate and monitor the system. The calibration can be done in closed loop or open loop. When connected to a stable source of voltage and current, the meter can do an auto-calibration by including the open loop calibration routine and formulas in the firmware.

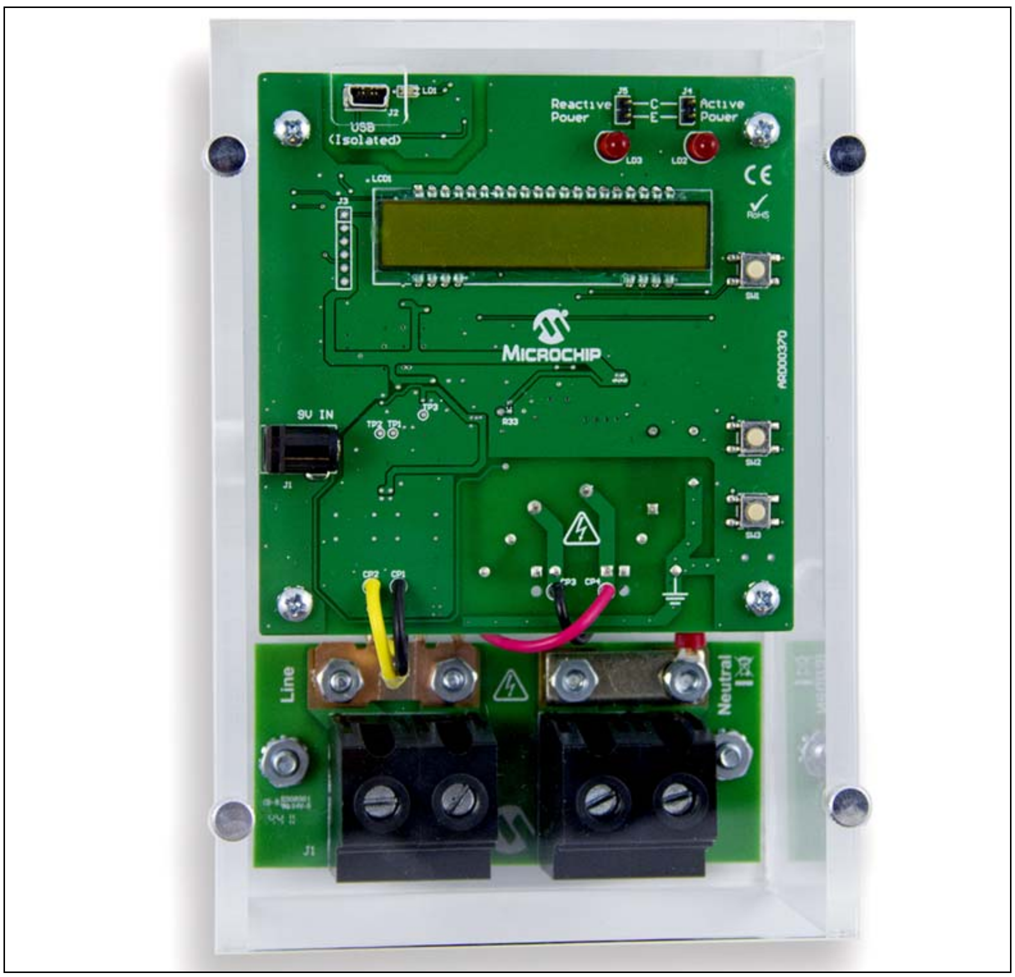


FIGURE 1-1: *MCP6L2 and PIC18F66J93 Energy Meter Reference Design.*

1.2 WHAT DOES THE MCP6L2 AND PIC18F66J93 ENERGY METER KIT INCLUDE?

This MCP6L2 and PIC18F66J93 Energy Meter kit includes:

- MCP6L2 and PIC18F66J93 Energy Meter (ARD00370)
- Important Information Sheet

1.3 GETTING STARTED

To illustrate how to use the MCP6L2 and PIC18F66J93 Energy Meter, the following example is shown using a two-wire 1-phase, 220 VAC line voltage and connections using energy meter calibrator equipment, or other programmable load source. The nominal current (I_N) is 5A, and the maximum current (I_{MAX}) is 60A. The energy meter was designed for 50 Hz line systems.

All connections described in this section are dependent upon the choice of the current sensing element. A secondary external transformer may be required in higher current meter designs. To test a calibrated meter, the following connections apply for a two-wire connection.

1.3.1 Step 1: Wiring Connections

Figure 1-2 is identifying the line and load connections of the MCP6L2 and PIC18F66J93 Energy Meter.

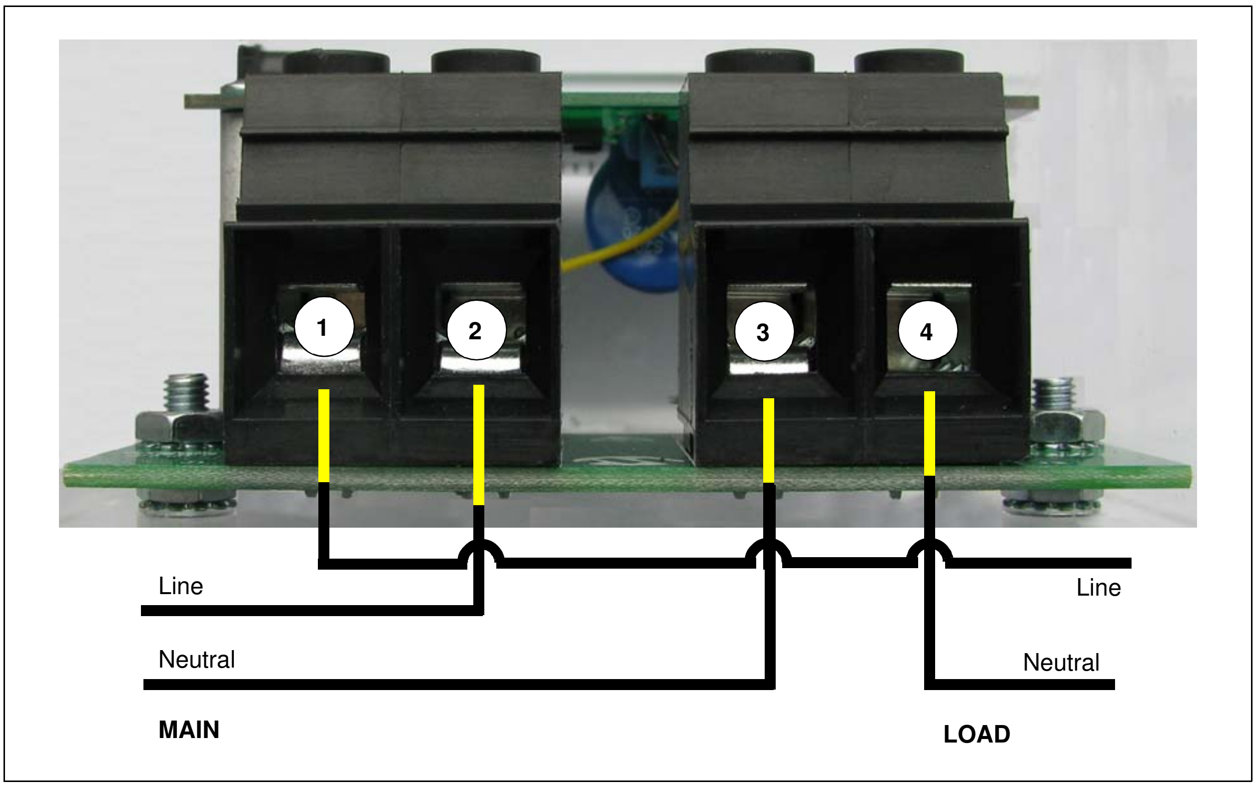


FIGURE 1-2: *Example Connections using a Two-Wire System.*

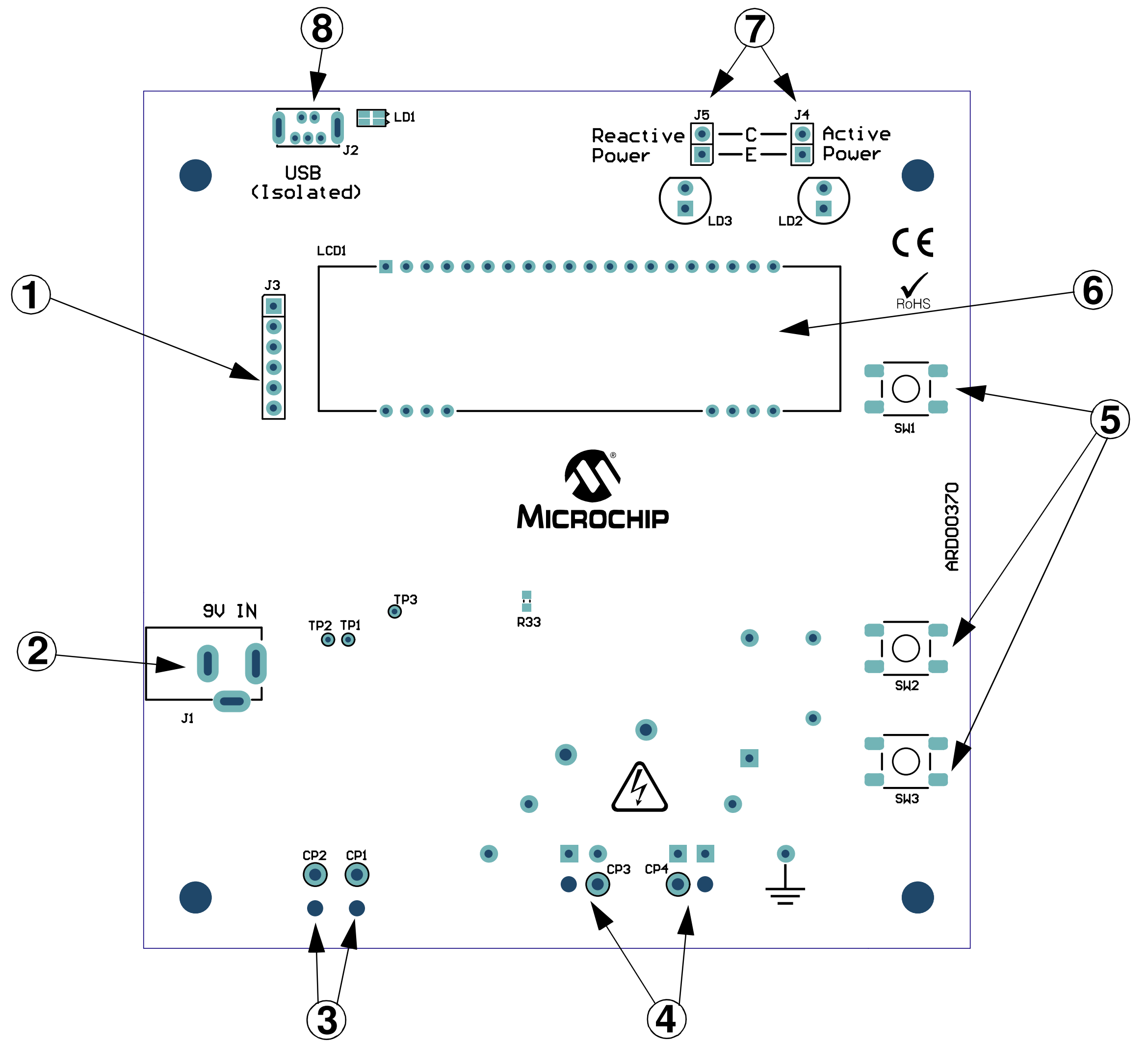
1.3.2 Step 2: Turn On Line/Load Power to the Meter (Power the Meter)

The meter will turn on when the line connection has 220V connected. The LCD display will show the total energy accumulated.

Chapter 2. Hardware

2.1 OVERVIEW

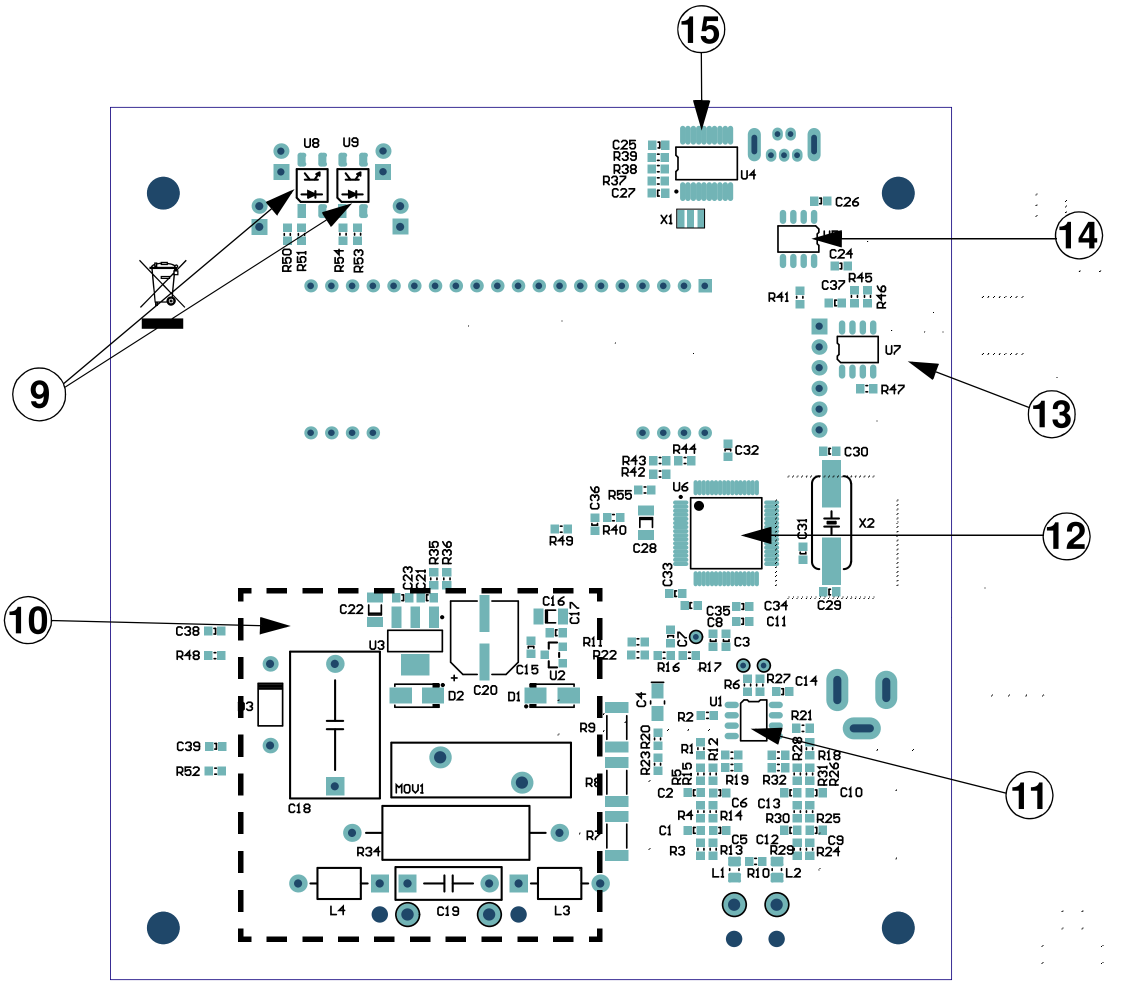
Figures 2-1 and 2-2 show the MCP6L2 and PIC18F66J93 Energy Meter:



Legend:

1	=	ICSP Programming header (non-isolated)	5	=	Push-button switches
2	=	+9V DC input (non-isolated)	6	=	9-digit LCD Display with icons for kWh and kVARh
3	=	Connections to shunt current sensing resistor	7	=	Pulse Output for active and reactive energy (isolated)
4	=	Connections to Line and Neutral	8	=	USB connection (isolated)

FIGURE 2-1: *Top View – Hardware Components.*



Legend:

9	=	Opto-isolators for pulse outputs
10	=	Power supply
11	=	MCP6L2 and associated signal conditioning circuitry
12	=	PIC18F66J93
13	=	EEPROM for storing calibration constants and energy counters
14	=	Isolation IC
15	=	MCP2200 for USB connection

FIGURE 2-2: *Bottom View – Hardware Components.*

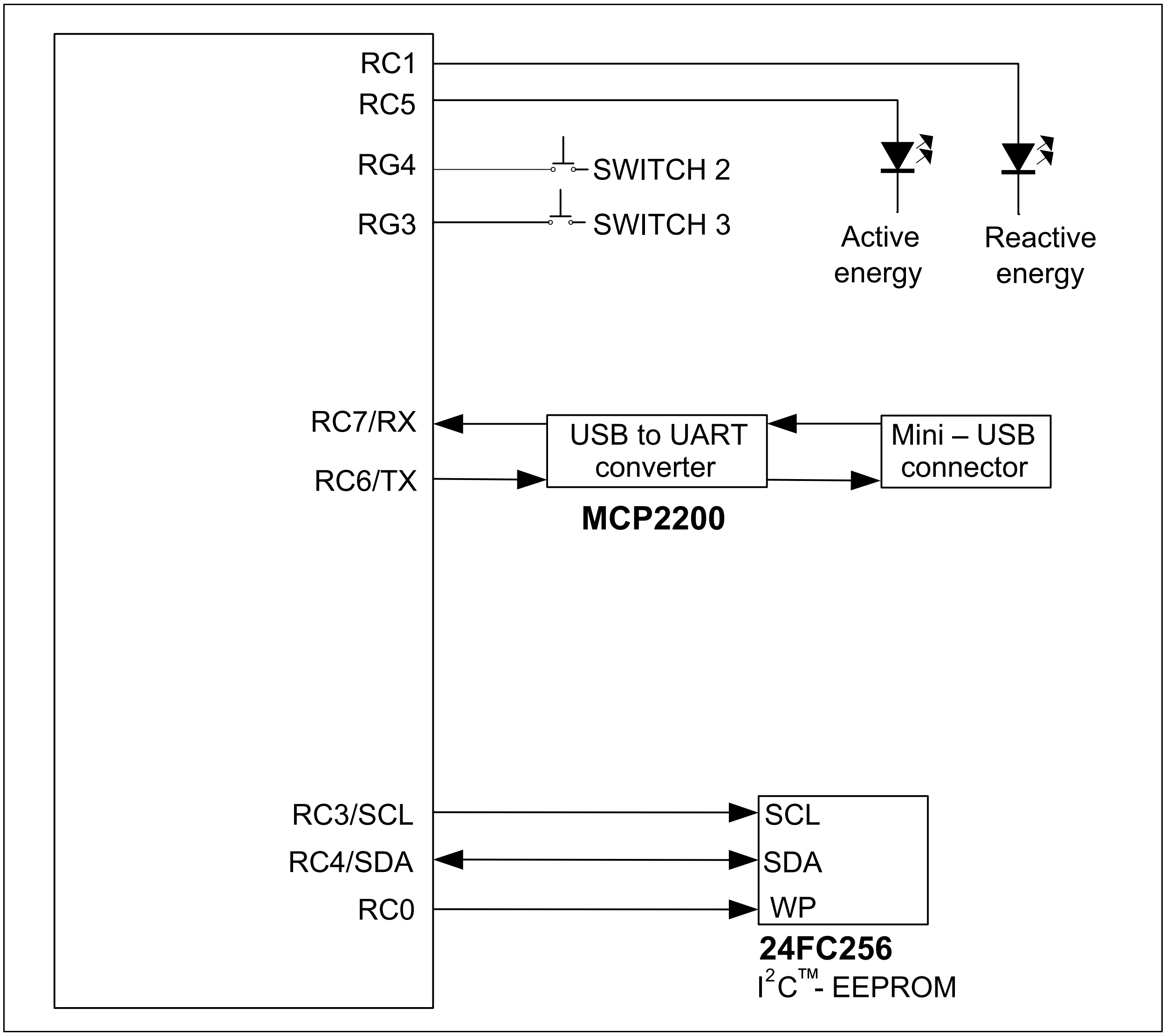


FIGURE 2-3: *Digital Connections.*

2.2 INPUT AND ANALOG FRONT END

The MCP6L2 and PIC18F66J93 Energy Meter comes populated with components designed for 220V line voltage. The high voltage line and neutral connections are at the bottom of the main board. The 200 μΩ shunt sits on the high or line side of a two-wire system, and the meter employs a hot or "live" ground.

The neutral side of the two-wire system goes into a resistor divider on the voltage channel input, along with a DC offset added from V_{DD}. Anti-aliasing low-pass filters are included. The voltage channel uses three 100 kΩ resistors and one 820Ω resistor to achieve a divider ratio of 366:1. For a line voltage of 220 V_{RMS} , the voltage channel input signal size will be 601 mV_{RMS} ,with a DC offset of 1.65V.

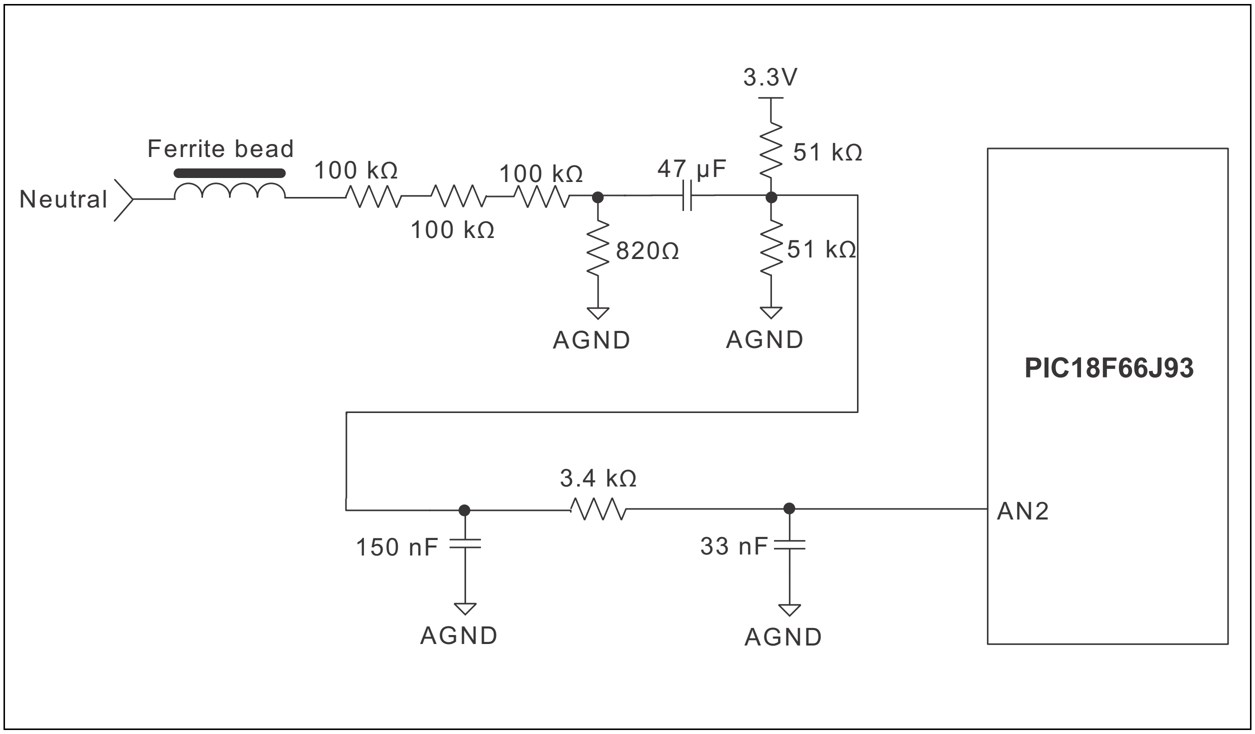


FIGURE 2-4: *Analog Front End -Voltage Measurement.*

To amplify the signal from the shunt, this energy meter design uses the two operational amplifiers from the MCP6L2 device to create two signal paths, with different gains: one for the low-current's range and one for the high-current's range, as shown in Figures 2-5 and 2-6:

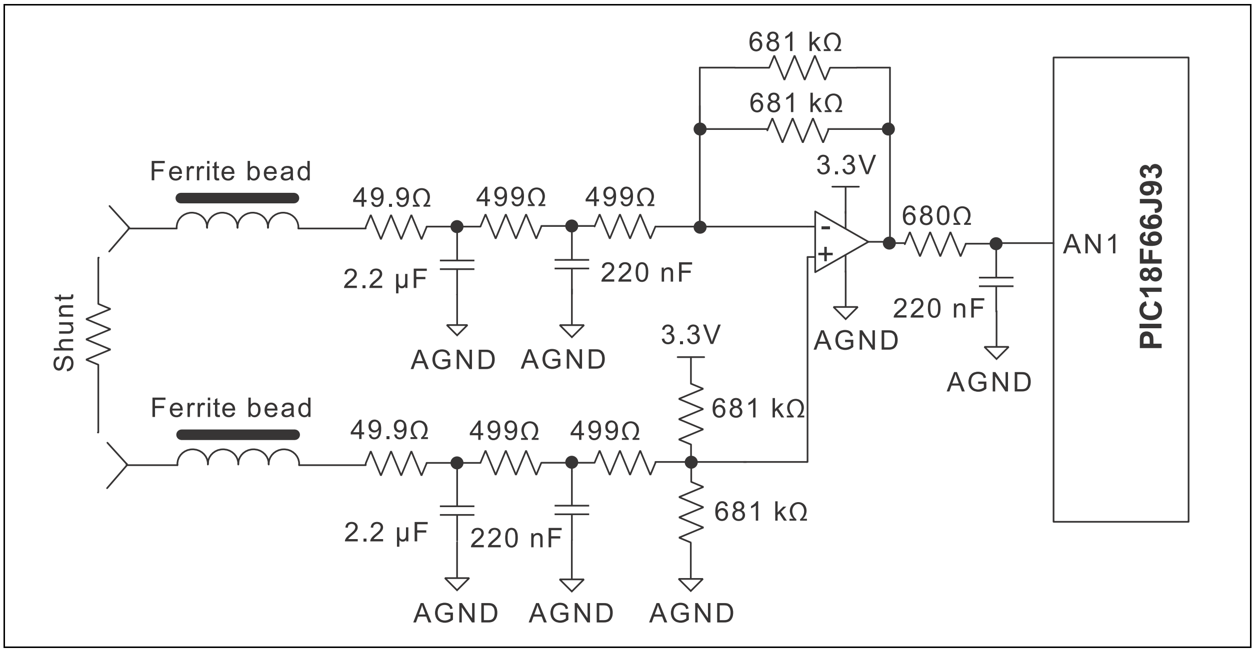


FIGURE 2-5: *Analog Input Circuitry for Current Measurement, LOW-Current's Range.*

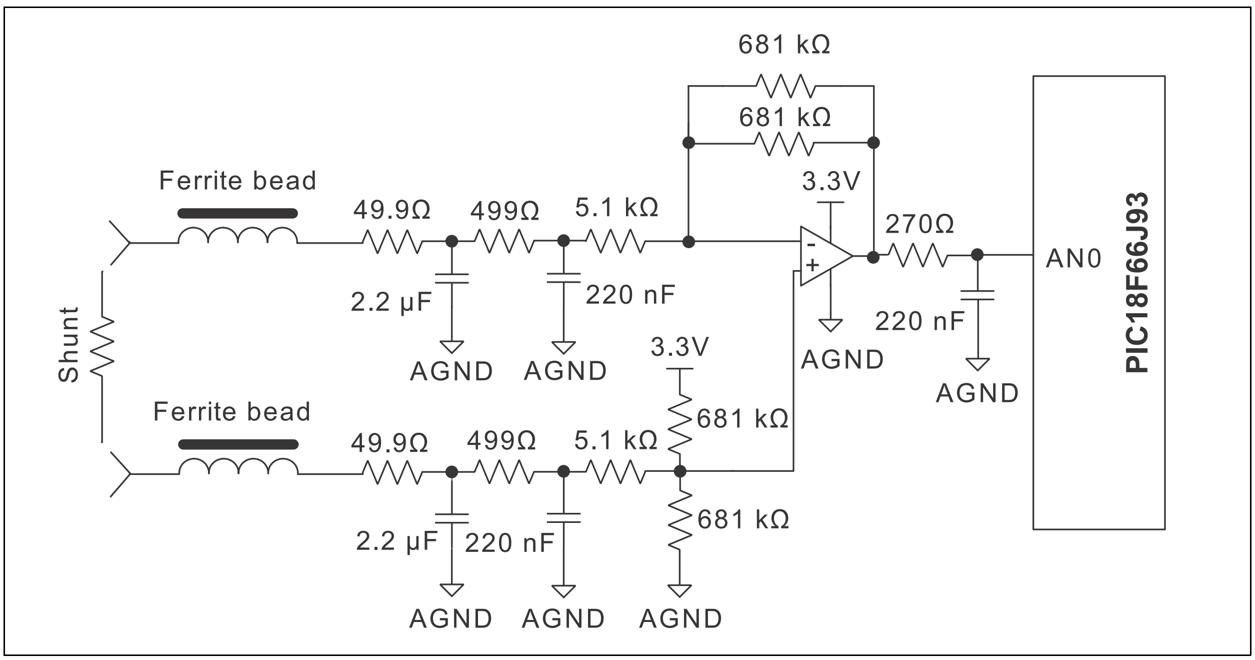


FIGURE 2-6: *Analog Input Circuitry for Current Measurement, HIGH-Current's Range.*

The low-current's range circuit (Figure 2-5) has a gain of 325 V/V. The high-current's range circuit (Figure 2-6) has a gain of 60 V/V. The firmware switches between the two gains with hysteresis between 4 and 5 A_{RMS}.

Note that all of the circuitry associated with the analog front-end is connected to the analog ground plane, AGND.

2.3 POWER SUPPLY CIRCUIT

The capacitive power supply circuit for the MCP6L2 and PIC18F66J93 Energy Meter uses a half-wave rectified signal and two +3.3V voltage regulators. One Low-dropout (LDO) supplies the analog side, and the other supplies the digital circuitry of the meter. There is an option to use only one LDO, by populating the R33 resistor and removing the U2 LDO. This will result in a lower cost meter, at the price of a decrease in accuracy.

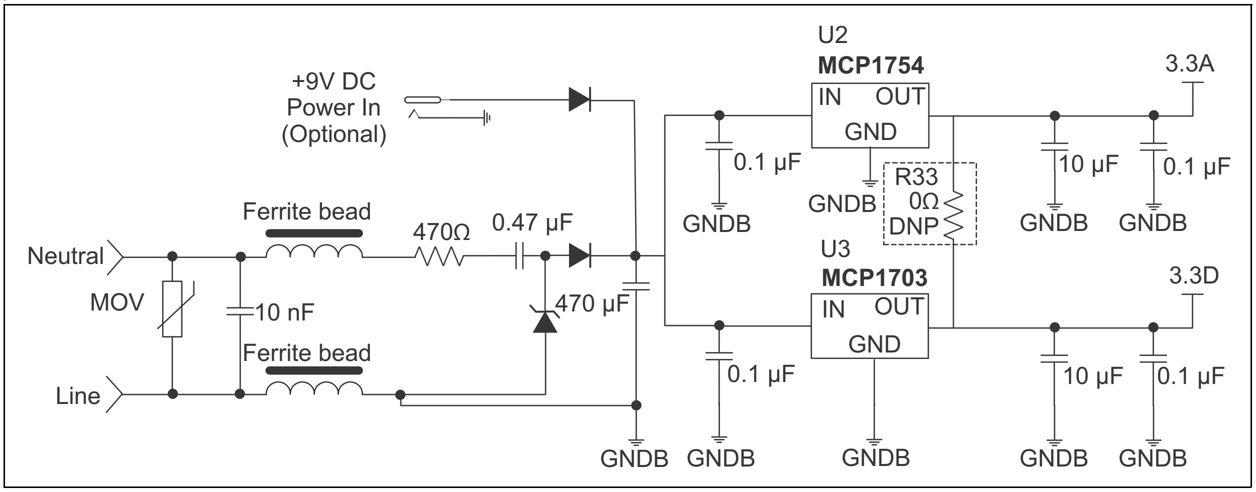


FIGURE 2-7: *Power Supply Circuit.*

Chapter 3. Calculation Engine and Register Description

3.1 COHERENT SAMPLING ALGORITHM

3.1.1 The Advantages of the Coherent Sampling in this Energy Metering Design

The outputs of an energy meter, power and RMS values are obtained by multiplying two AC signals, computing the average value and then multiplying it with a calibration gain. Ideally, these signals are sinusoids, with the frequency equal to the line frequency:

EQUATION 3-1:

$$S_1(t) = A_1 cos(\omega t)$$
$$S_2(t) = A_2 cos(\omega t + \phi)$$

The two signals (S_1 and S_2) can be the voltage and/or the current waveforms. The instantaneous power value is obtained by multiplication:

EQUATION 3-2:

$$P(t) = S_1(t) \times S_2(t) = \frac{A_1 \times A_2}{2} \times cos(\phi) + \frac{A_1 \times A_2}{2} \times cos(2\omega t + \phi)$$

The resultant signal has a continuous component and a sinusoidal component with a frequency equal to double the line frequency. Because the energy meter is computing the average power, only the continuous component is of interest, with the other requiring attenuation. If it is not properly attenuated, the indication of the energy meter will fluctuate in time. There are two methods to obtain efficient attenuation of the unwanted component: low-pass filtering and coherent sampling.

The instantaneous power signal can be applied to a low-pass filter with the cutoff frequency much lower than the double of the line frequency. If the energy meter must compute Active Power, Reactive Power, RMS Voltage, RMS Current (four instantaneous power computations, in total), it means that four low-pass filters must be applied.

In this particular energy meter design, with two current paths and gain switching controlled by the firmware, the problem is more complex with the low-pass filtering approach. This is because the low-pass filters have low-cutoff frequency, and consequently, high settling time. This affects the response of the meter outputs when the current gain is switched. In order to avoid this, the signals from the two current paths must be processed simultaneously, and low-pass filters must be applied on the instantaneous powers resulting from both paths. Therefore, three additional low-pass filters are required (for the instantaneous Active Power, Reactive Power and RMS Current on the other current channel). This means a total of seven low-pass filters are required for this energy meter design. Considering that the low-pass filter routines must be executed for each sample, the resulting processing time can be too long.

The coherent sampling approach solves this issue by eliminating the low-pass filters. Coherent sampling refers to the situation when the sampling frequency is a fixed integer multiple of the line frequency. The unwanted sinusoidal component from the instantaneous power signal is attenuated under coherent sampling conditions, if the averaging is computed over a number of samples corresponding to an integer number of line cycles.

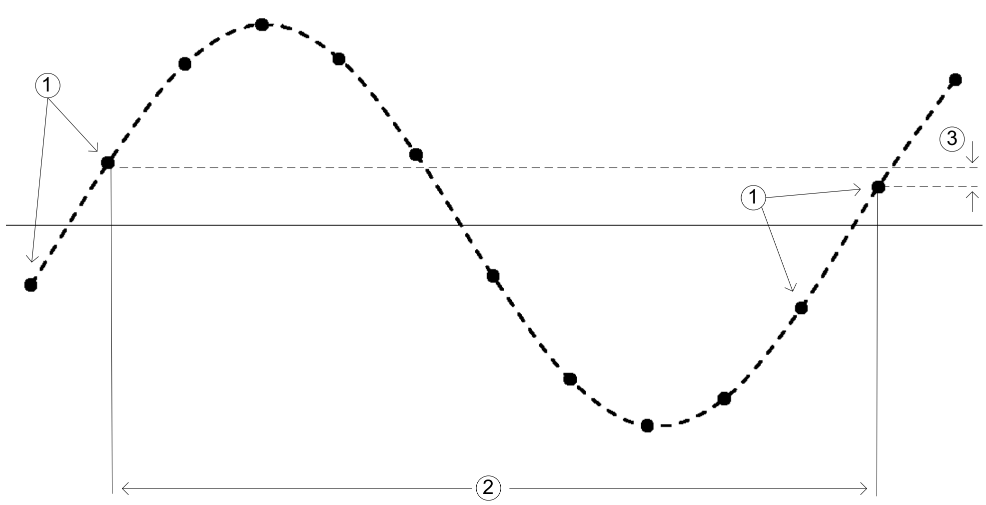
3.1.2 Coherent Sampling Algorithm

Coherent sampling implies a dependency between the sampling frequency and the line frequency. Because the line frequency is not fixed, the sampling frequency needs to be adjustable. In the MCP6L2 and PIC18F66J93 Energy Meter design, based on the microcontroller's internal successive approximation ADC (SAR ADC), the sampling period is controlled by a timer. At the beginning of the Interrupt Service Routine, the new timer value is set, and then the ADC samples are acquired and processed. The new timer value is computed based on the value of the line signal period.

In order to save hardware resources (timers), the line signal period is not measured directly in this design. Based on the amplitude of the acquired signal samples, the firmware detects the zero crossings on rising edges and tries to achieve a fixed integer number of samples between successive crossings, by adjusting the sampling period. The conditions for obtaining coherent sampling implemented in the firmware are:

- The number of samples between zero crossings must have a certain value (64 samples per line cycle in this design)
- The difference between the first sample after zero crossing and the corresponding sample from the previous line period, must be within certain limits (for more accurate locking on the line frequency).

A graphical representation of these conditions is shown in Figure 3-1.



Legend:

1 = Zero-crossing detection on rising edge
2 = The number of samples between zero crossings must have a certain value
3 = The difference must be within certain limits

FIGURE 3-1: *Conditions for Obtaining Coherent Sampling Implemented in the Firmware.*

These conditions are checked after every zero crossing on rising edge. If they are not met, then the corrections are applied to the sampling period.

The zero-crossing detection is done on the voltage channel, because it has much lower dynamic range than the current channel. To increase immunity to noise and distortions (harmonics), the acquired voltage samples are passed through a low-pass filter with a cutoff frequency lower than the line frequency, before being processed for zero-crossing detection.

3.2 CALCULATION ENGINE SIGNAL FLOW SUMMARY

RMS voltage, RMS current, Active Power, Reactive Power, Apparent Power and calibration output pulses are calculated through the process described in Figure 3-2. The calibration registers for each calculation are shown as well as the output registers.

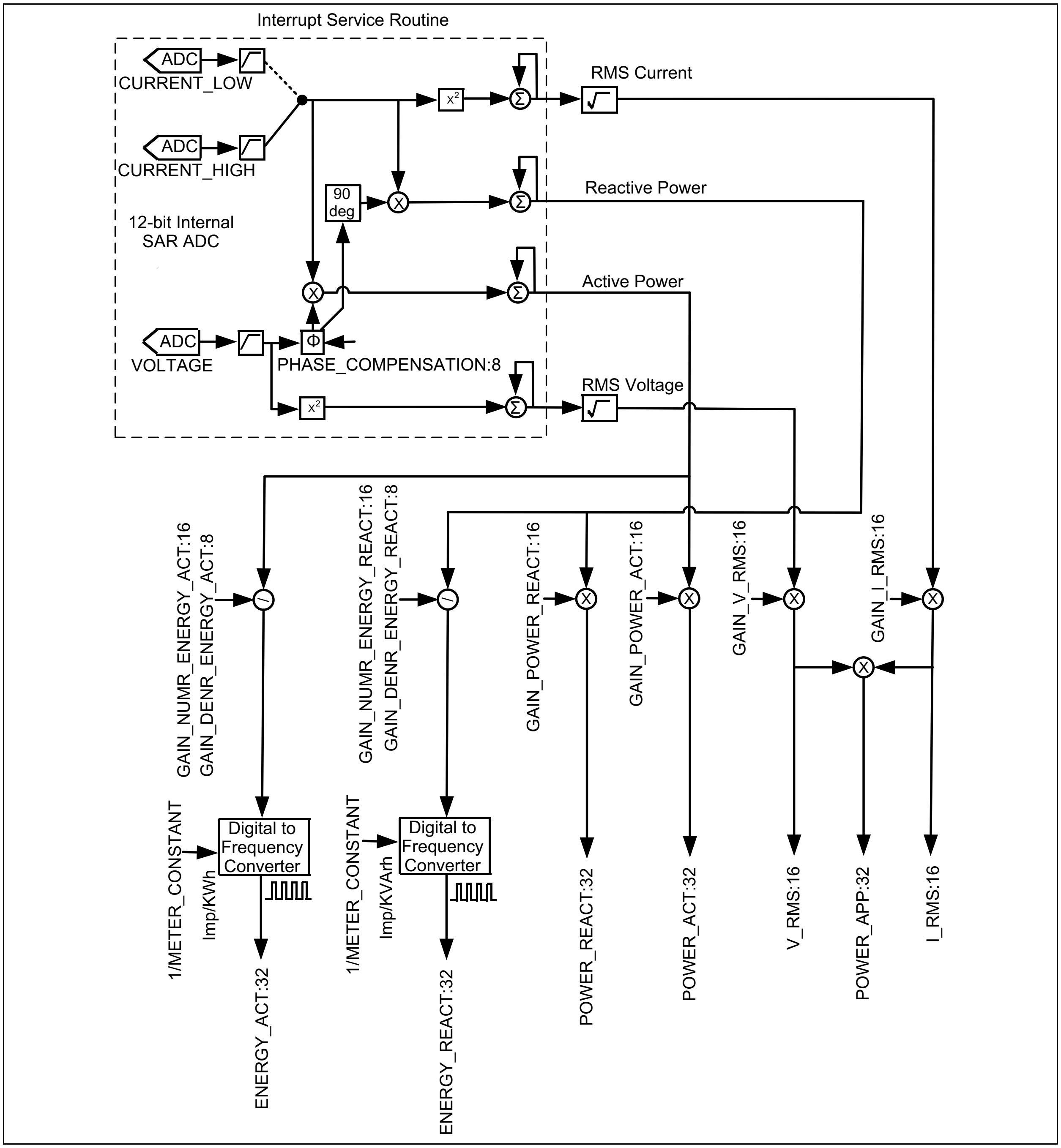


FIGURE 3-2: *MCP6L2 and PIC18F66J93 Calculation Engine Signal Flow.*

3.3 COMPLETE REGISTER LIST

TABLE 3-1: INTERNAL REGISTER SUMMARY

Address	Register Name	Bits	R/W	Description
0x000	METER_VERSION_ID	8	R	Hardware and firmware version identification register
0x001	METER_STATUS	8	R	Contains information regarding the operational status of the meter
0x002	CAL_CONTROL	8	R/W	Configuration register for calibration control
0x003	RAW_I_RMS	16	R	Raw RMS value of the current channel
0x005	I_RMS	16	R	RMS value of the current channel, post calibration
0x007	RAW_V_RMS	16	R	Raw RMS value of the voltage channel
0x009	V_RMS	16	R	RMS value of the voltage channel, post calibration
0x00B	FREQUENCY	16	R	Line frequency indication
0x00D	POWER_ACT	32	R	Active Power indication
0x011	POWER_REACT	32	R	Reactive Power indication
0x015	POWER_APP	32	R	Apparent Power indication
0x019	POWER_FACTOR	16	R	Power factor indication
0x01B	PHASE_COMPENSATION	8	R	Phase delay between voltage and current channels
0x01C	GAIN_I_RMS	16	R	Gain adjustment for current channel RMS
0x01E	GAIN_POWER_ACT	16	R	Active Power Gain adjust
0x020	GAIN_POWER_REACT	16	R	Reactive Power Gain adjust
0x022	GAIN_NUMR_ENERGY_ACT	16	R	Active Power Pulse Output correction factor
0x024	GAIN_DENR_ENERGY_ACT	8	R	Active Power Pulse Output correction factor
0x025	GAIN_NUMR_ENERGY_REACT	16	R	Reactive Power Pulse Output correction factor
0x027	GAIN_DENR_ENERGY_REACT	8	R	Reactive Power Pulse Output correction factor
0x028	PHASE_COMPENSATION_LOW	8	R/W	Phase-delay between voltage and low region current channels
0x029	PHASE_COMPENSATION_HIGH	8	R/W	Phase-delay between voltage and high region current channels
0x02A	GAIN_V_RMS	16	R/W	Gain adjustment for voltage RMS
0x02C	GAIN_I_RMS_LOW	16	R/W	Gain adjustment for low region current RMS
0x02E	GAIN_I_RMS_HIGH	16	R/W	Gain adjustment for high region current RMS
0x030	GAIN_POWER_ACT_LOW	16	R/W	Low-region Active Power gain adjust
0x032	GAIN_POWER_ACT_HIGH	16	R/W	High-region Active Power gain adjust
0x034	GAIN_NUMR_ENERGY_ACT_LOW	16	R/W	Low-region Active Power Pulse Output correction factor
0x036	GAIN_NUMR_ENERGY_ACT_HIGH	16	R/W	High-region Active Power Pulse Output correction factor
0x038	GAIN_DENR_ENERGY_ACT_LOW	8	R/W	Low-region Active Power Pulse Output correction factor
0x039	GAIN_DENR_ENERGY_ACT_HIGH	8	R/W	High-region Active Power Pulse Output correction factor
0x03A	GAIN_POWER_REACT_LOW	16	R/W	Low-region Reactive Power gain adjust
0x03C	GAIN_POWER_REACT_HIGH	16	R/W	High-region Reactive Power gain adjust
0x03E	GAIN_NUMR_ENERGY_REACT_LOW	16	R/W	Low-region Reactive Power Pulse Output correction factor

TABLE 3-1: INTERNAL REGISTER SUMMARY (CONTINUED)

Address	Register Name	Bits	R/W	Description
0x040	GAIN_NUMR_ENERGY_REACT_HIGH	16	R/W	High-region Reactive Power Pulse Output correction factor
0x042	GAIN_DENR_ENERGY_REACT_LOW	8	R/W	Low-region Reactive Power Pulse Output correction factor
0x043	GAIN_DENR_ENERGY_REACT_HIGH	8	R/W	High-region Reactive Power Pulse Output correction factor
0x044	METER_CONSTANT	16	R/W	Meter Constant in imp/kWh
0x046	PULSE_WIDTH	8	R/W	Defines CF pulse width in milliseconds
0x047	NO_LOAD_THRESHOLD_I_RMS	8	R/W	Bellow this Current RMS indication, energy accumulation is disabled
0x048	LINE_CYC	8	R/W	It is "n" from the formula: Computation cycle = 2^n number of line cycles
0x100	ENERGY_ACT	32	R/W	Active Energy Counter
0x104	ENERGY_REACT	32	R/W	Reactive Energy Counter

3.4 METER_VERSION_ID

Name	Bits	Address	Cof.
METER_VERSION_ID	8	0x000	R

This register contains a constant that is hard-coded in the firmware, giving information regarding the hardware and firmware version running on the energy meter.

3.5 METER_STATUS

Name	Bits	Address	Cof
METER_STATUS	8	0x001	R

The register contains information regarding the operational status of the energy meter.

REGISTER 3-1: METER_STATUS REGISTER

U-0	U-0	U-0	U-0	U-0	U-0	U-0	R
—	—	—	—	—	—	—	CURRENT_ REGION
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as ‘0’	
-n = Value at POR	‘1’ = Bit is set	‘0’ = Bit is cleared	x = Bit is unknown

bit 7-1 **Unimplemented:** Read as ‘0’

bit 0 **CURRENT_REGION:** Indicates the selected current region

1 = High Current Region
0 = Low Current Region