MCP3901 Low-Cost Power Monitor Reference Design User's Guide

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ISBN: 978-1-60932-483-4

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MCP3901 LOW-COST POWER MONITOR USER'S GUIDE

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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 on-line help. Select the Help menu, and then Topics to open a list of available on-line help files.

INTRODUCTION

This chapter contains general information that will be useful to know before using the MCP3901 Low-Cost Power Monitor. 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 MCP3901 Low-Cost Power Monitor as a development tool to emulate and debug firmware on a target board. The manual layout is as follows:

- **Chapter 1. "Product Overview"**– Provides important information about the MCP3901 Low-Cost Power Monitor hardware.
- **Chapter 2. "Installation and Operation"**– Describes the MCP3901 Low-Cost Power Monitor firmware.
- **Appendix A. "Schematics and Layouts"**– Shows the schematic and board layouts for the MCP3901 Low-Cost Power Monitor Reference Design.
- **Appendix B. "Bill of Materials"** – Lists the parts used to build the MCP3901 Low-Cost Power Monitor.

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 MCP3901 Low-Cost Power Monitor Reference Design. Other useful documents are listed below. The following Microchip documents are available and recommended as supplemental reference resources.

- **MCP3901 Data Sheet - *"Energy Metering IC with SPI Interface and Active Power Pulse Output"* (DS22192)**
- **AN1291 - *"Low-Cost Shunt Power Meter using MCP3909 and PIC18F25K20"* (DS01291)**

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- **General Technical Support** – frequently asked questions (FAQs), technical support requests, online discussion groups, and 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

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

Customers should contact their distributor, representative or field application engineer (FAE) for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

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

DOCUMENT REVISION HISTORY

Revision A (November 2010)

Initial release of this document.

NOTES:

Chapter 1. Product Overview

1.1 OVERVIEW

The MCP3901 Low-Cost Power Monitor Reference Design is used to evaluate the performance of the MCP3901 dual channel ADC, as well as a development platform for PIC18F-based applications. A programmed PIC18F25K20 device in the power monitor processes samples acquired by the MCP3901 to obtain Root Mean Square Voltage (U_{RMS}), Root Mean Square Current (I_{RMS}), Active Power, Apparent Power, and Power Factor values.

1.1.1 Feature Highlights

- Dual ADC MCP3901 output display using serial communication to the PC software interface
- MCP3901 ADC ability to do simultaneous sampling; with sampling speed up to 64 ksps, and 91 dB SINAD
- Computation of U_{RMS}, I_{RMS}, Active Power, Apparent Power, and Power Factor

FIGURE 1-1: MCP3901 Low-Cost Power Monitor Reference Design

1.2 ANALOG INPUT CIRCUIT

The MCP3901 Low-Cost Power Monitor Reference Design uses an MCP3901 dual ADC to acquire current and voltage samples. For best performance, the power supply and ground must be noise free. To ensure low noise, large capacitors are located on the lines that power the MCP3901 device, i.e., C4 and C5. Additionally, multi-layer ceramic capacitors are located near the ADC, on the C13 and C14 pins, to ensure that high-frequency noise is also eliminated.

The V_{REF} is potentially another source of noise. Accordingly, it is mandatory to place at least one 100 nF multi-layer capacitor on the V_{REF} pin. For better noise rejection on V_{REF}, a larger capacitor has been added (C77).

The MCP3901 Low-Cost Power Monitor is provided with a 200 μΩ shunt as a current sensor. The user has the option to use the two current transformer footprints U1 and U10 that are available on the printed circuit board (PCB). Refer to the board schematic in the appendix, **A.1 “Board Schematic – Analog and Power”**.

The MCP3901 Power Monitor Reference Design does not contain a crystal – it uses the clock signal from the output compare pin RC2/CCP1 of the PIC18F25K20 microcontroller (MCU).

1.3 POWER CIRCUIT

Two voltages are required for the power monitor reference design:

- 3.3V for the MCU
- 5V for the ADC

For this reason, two MCP1703 Low Dropout Voltage Regulators (LDOs) are placed after the C51 capacitor, with the required voltages at the outputs.

The meter is powered from the capacitive divider, mainly C6 and U53. A parametric regulator circuit, using Zener diode D5, limits the input voltage of the LDOs to 12V.

Rectifier diode D2 restricts the current flow to a single direction, while ripple is reduced by C51 and the LDOs.

1.4 PIC18F25K20 MICROCONTROLLER AND LIQUID CRYSTAL DISPLAY (LCD)

A PIC18F25K20 MCU is used in this application for its high speed (16 MIPS) and low power (nanoWatt XLP technology). It also has an internal EEPROM, where the calibration constants are saved.

Because the MCU does not include an LCD driver, the LCD used in this reference design has the driver built in. The connection between the LCD and the MCU carries four lines of data and three lines of control.

Chapter 2. Installation and Operation

2.1 POWER MONITOR FIRMWARE DESCRIPTION

2.1.1 Samples Acquisition

Using the external ADC, the current and voltage samples must be acquired before the correct values of the desired parameters can be computed. The MCU reads the values of the samples from the ADC through the SPI bus.

The sampling speed of the ADC is controlled by the clock frequency of the MCP3901. The MCU uses the Output Compare 1 module to generate a 50% pulse-width modulation (PWM) signal that has a frequency of 901.120 kHz. This frequency can be easily changed by modifying values in the Timer2 Period Register (PR2) and the Compare Register 1 (CCPR1).

The sampling speed of the ADC is 1024 times lower than the master clock in the MCP3901, meaning 880 sps at an Over Sampling Rate (OSR) of 256.

2.1.2 Signal Processing

In order to obtain the desired parameter values out of the acquired samples, a signal processing technique must be assumed. Since this design uses an 8-bit MCU, the signal processing technique that is implemented must be fast enough to avoid limiting the sampling speed, so that a time-domain analysis can be performed. The signal processing technique is graphically described in Figure 2-1.

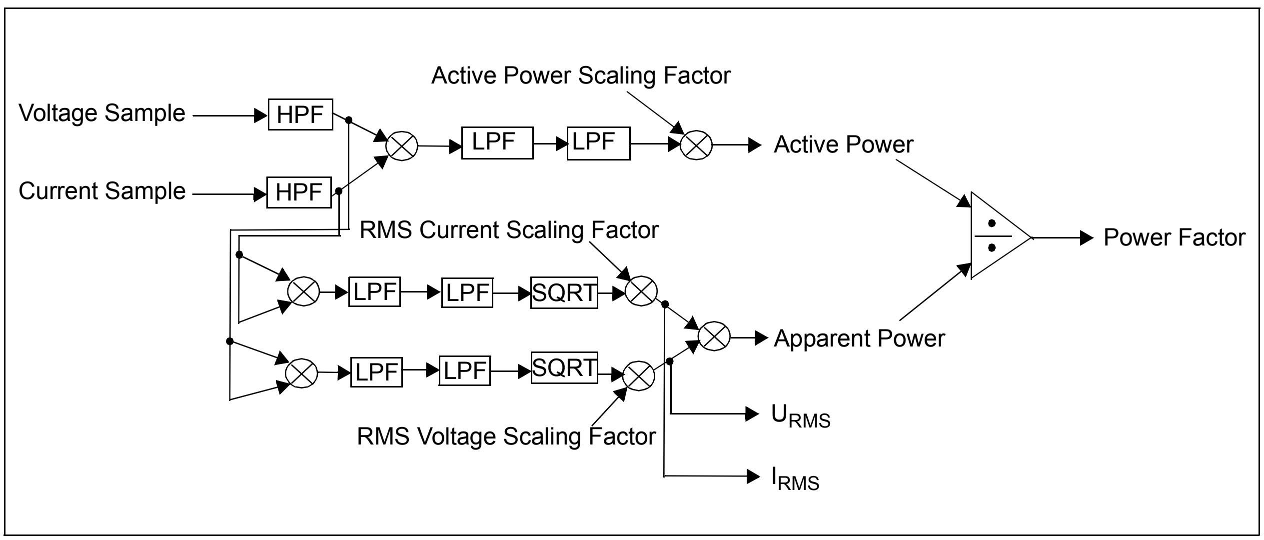

FIGURE 2-1: *Block Diagram of the Signal Processing Algorithm.*

Initially, the acquired samples go through a first-order Infinite Impulse Response high-pass filter (IIR HPF), which has the following roles:

1. Removes the offset of the ADC
2. Compensates for the Sinc filters transfer function

Because the offset is removed and the rest of the system has a linear response, a single point calibration method is sufficient to obtain accurate readings.

To compute the instantaneous active power, samples of the current and voltage are multiplied. To extract the average active power, the instantaneous active power samples are filtered by two first-order Infinite Impulse Response low-pass filters (IIR LPF). To obtain the values for the U_{RMS} and I_{RMS}, the acquired samples are multiplied to extract the instantaneous U^2 and I^2. For the integrated values, the samples go through the second first-order IIR LPF. To obtain a value proportional with I_{RMS}, a square root operation (SQRT) is performed.

The structure of a first-order IIR filter is illustrated in Figure 2-2.

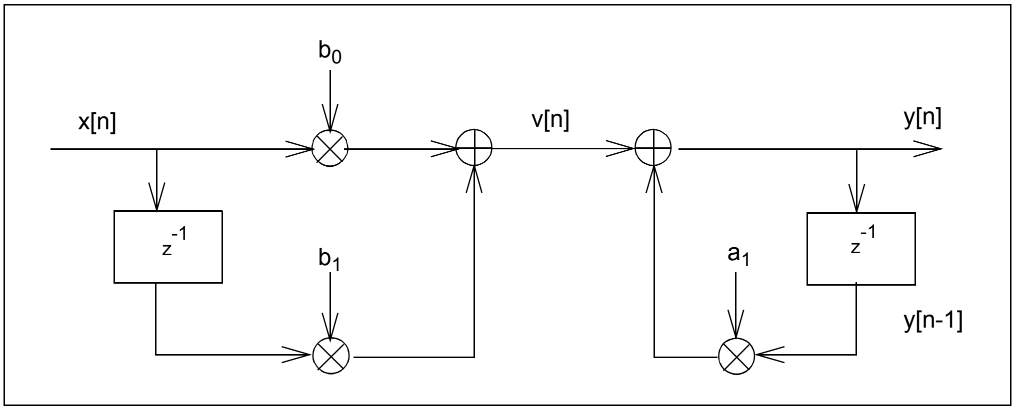

FIGURE 2-2: *First-Order IIR Filter Structure.*

The power monitor also has a pulse output for energy measurements and an extra circuit that is implemented to perform a power-to-frequency conversion. In addition, a 24-bit timer is included to supply accurate timings of the pulse output. Because the PIC18F25K20 MCU only has a 16-bit timer, a 8-bit Timer0 extended (`t0e`) register is included in the software to obtain the desired pulse period.

The power-to-frequency conversion is achieved through the Timer0 interrupt routine. For better accuracy in power measurement, the power is averaged for a period of time that is equal to the pulse output. The resulting averaged power value is converted into three bytes that are written to the `t0l`, `t0h`, and `t0e` global variables. These variables control the 24-bit timer.

The LCD displays the important parameters U_{RMS}, I_{RMS}, Power Factor, and Active Power (default). However, more parameters, such as Reactive Power and Apparent Power, can be displayed with minimum modifications of the firmware. The LCD display is controlled in the main loop, since it does not require an update at a definite period of time.

Measurement results are available via UART, as well – the MCU steadily sends U_{RMS}, I_{RMS} and Active Power values. The UART connection is configured with the following values: 19200 baud, 8-bit of data, 1-bit of stop, none of parity, and no flow control.

The connection between the MCP3901 power monitor reference design and a PC is simple and secure. The UART-USB converter is located on the upper-right corner of the PCB and implemented via U4 (PIC18F14K50). And, to prevent exposing the PC to high-risk voltage, the circuit is galvanically isolated by the rest of the meter through an optocoupler.

2.1.3 Power Factor Compensation

One of the major tasks in energy meter design is to minimize the effect of the power factor variations on measurement accuracy. In order to have accurate measurements over a wide range of power factors, it is necessary to have the same delays on both current and voltage channels. Any difference in values between the two delays will cause undesirable variations in the measurement of power and energy, as shown on the display, according to the power factor. The external passive components can induce a phase shift because of the part's value tolerances.

The MCP3901 device contains a phase delay compensation block that adds extra delays on one channel relative to the other, compensating for the power factor variations.

The extra delays added are controlled by the user through an internal Phase Delay register (*kk*) on the MCP3901 device. Figure 2-3 illustrates the measurement accuracy at different power factors and for different Phase Delay register values. It shows how a small delay was necessary on one of the channels to achieve minimum errors on a wider range of angles.

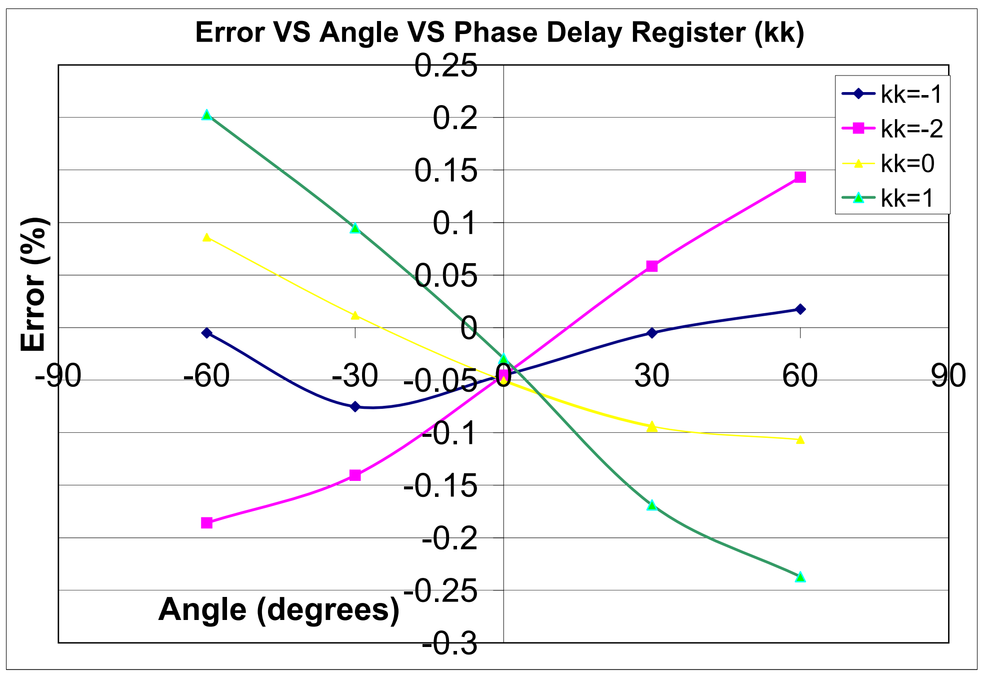

FIGURE 2-3: *Error vs. Phase Angle vs. Phase Delay Register.*

The value of the Phase Delay register is automatically computed during the meter calibration routine. Power meter calibration and all of the processes that are performed are described in **Section 2.2 “Calibration Procedure”**.

Once written into the MCP3901 ADC Phase Delay register, the Phase Delay block inside the MCP3901 ADC compensates for power-factor-related errors. This method decreases the computation requirement on the PIC18F25K20 MCU.

2.1.4 Line Frequency Compensation

A 50 Hz line frequency is used, which is the typical frequency most of the time. However, this is not a constant and can vary above or below this value by a few Hertz. This line frequency shift can cause measurement errors because of the characteristics of the Sinc filter at low sampling speeds. The Sinc filter transfer function is similar to a low-pass filter. Depending on the sampling speed of the ADC, this low-pass filter can be narrower or wider.

Figure 2-4 shows the following line frequency situations:

- 880 sps (as in this meter)
- 1200 sps
- 3200 sps

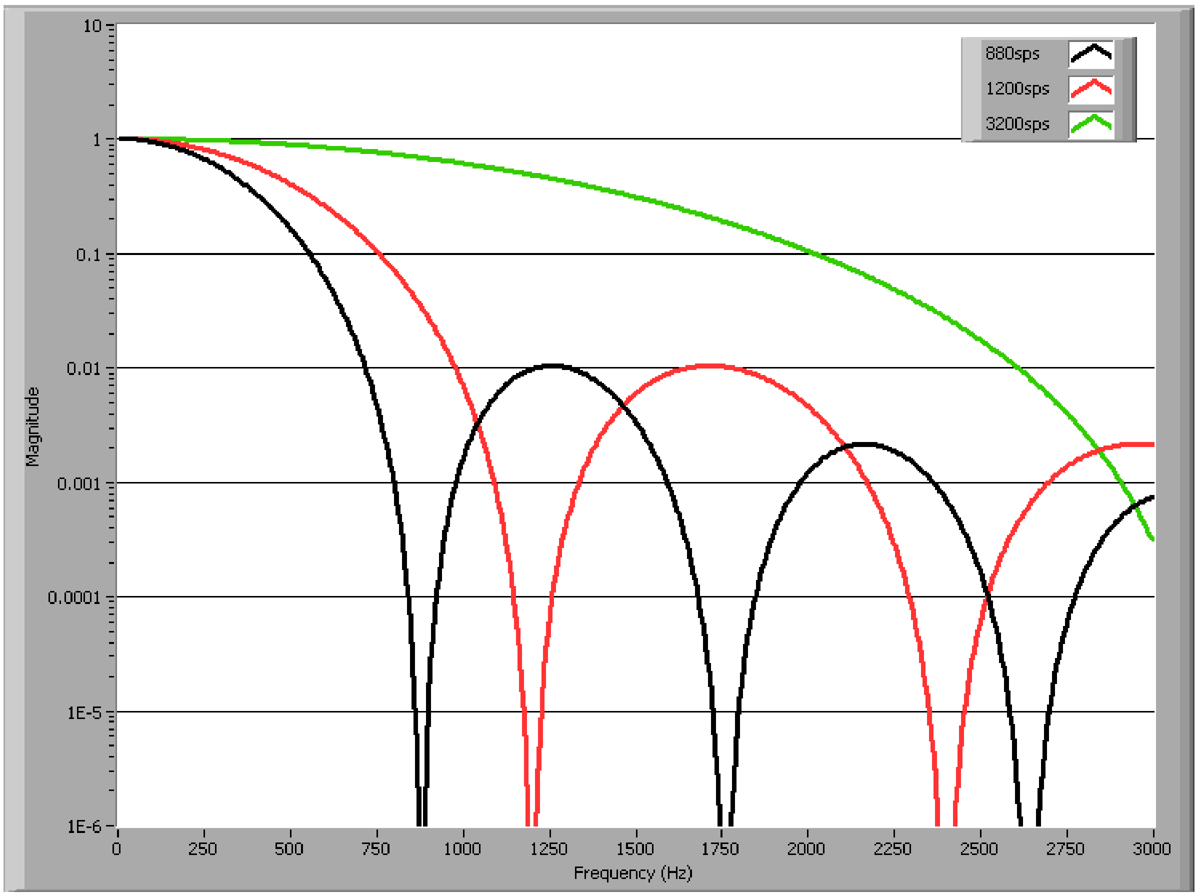

FIGURE 2-4: *Sinc Filters Transfer Functions.*

In Figure 2-5, the frequency range is magnified and the Y axis is scaled to cross at 50 Hz for all three cases. Notice that the low speed ADC causes a sensitive attenuation of the signal when the line frequency is higher than 50 Hz compared to situations when the line frequency is lower than 50 Hz. The measurement differences can be higher than 0.2%. To have accurate measurements, without regard for the line frequency, it is necessary to compensate for these low-pass filter situations.

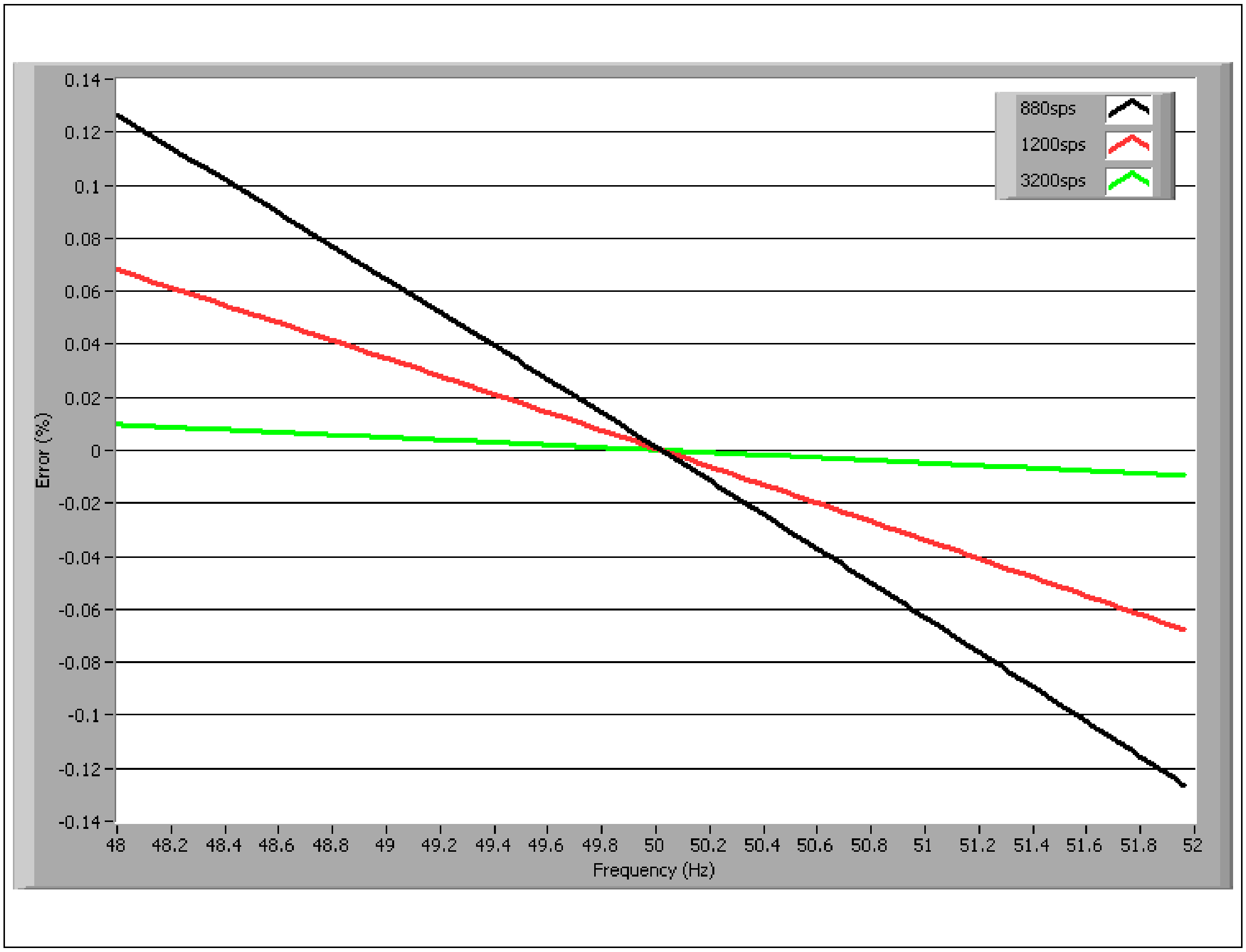

FIGURE 2-5: *Errors Caused by Line Frequency.*

Although complex, long, finite impulse response (FIR) structures called Sinc Compensation Filters are usually used to compensate for low-pass filter difficulties, they cannot be implemented in this application because the MCU is being used at close to maximum computation power.

The appropriate solution is to adjust the cutoff frequency of the IIR HPF to a value at which the transfer function of the HPF will compensate the Sinc transfer function to approximately the 50 Hz value. The simulation and the measurements indicate that a cutoff frequency of 9 Hz for the HPF is the best choice in this case (see Figure 2-6).

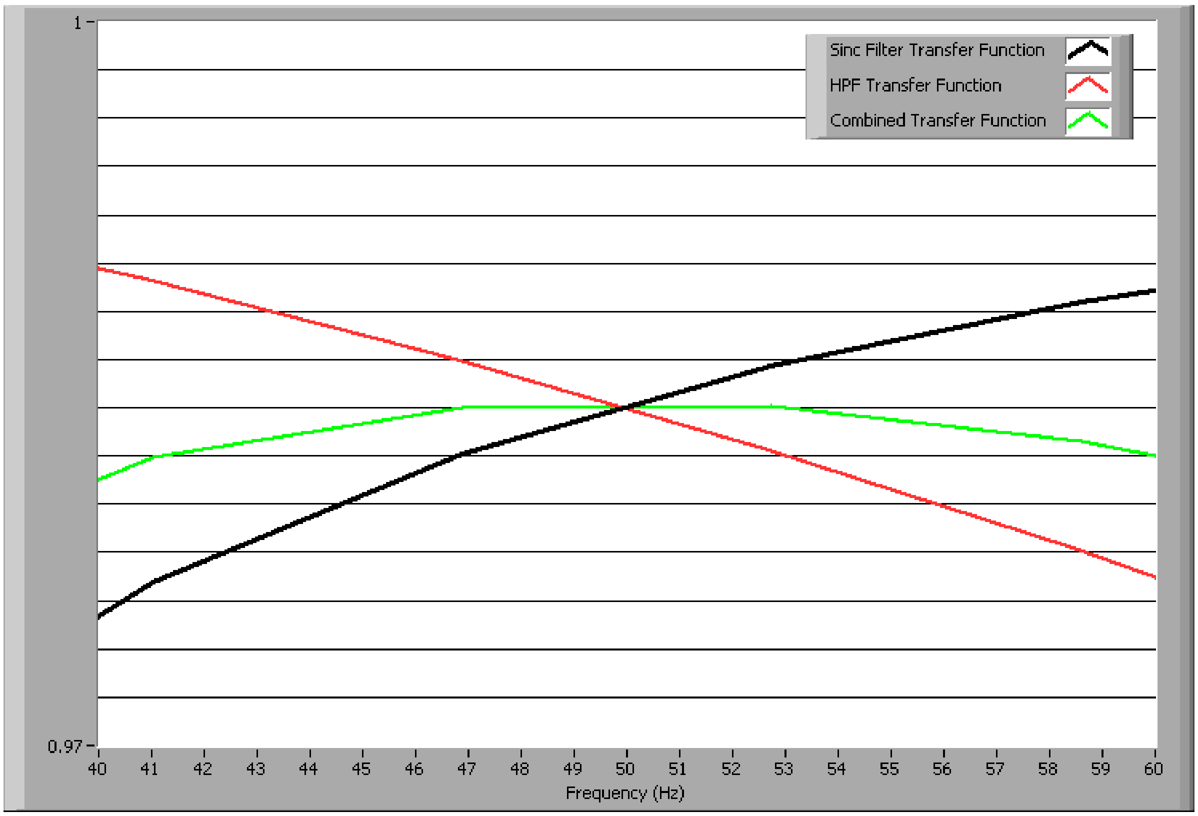

FIGURE 2-6: *Sinc Filter Compensation Using HPF.*

Figure 2-7 illustrates the error measurements in the frequency range of 48-52 Hz at 5 A_{RMS} current.

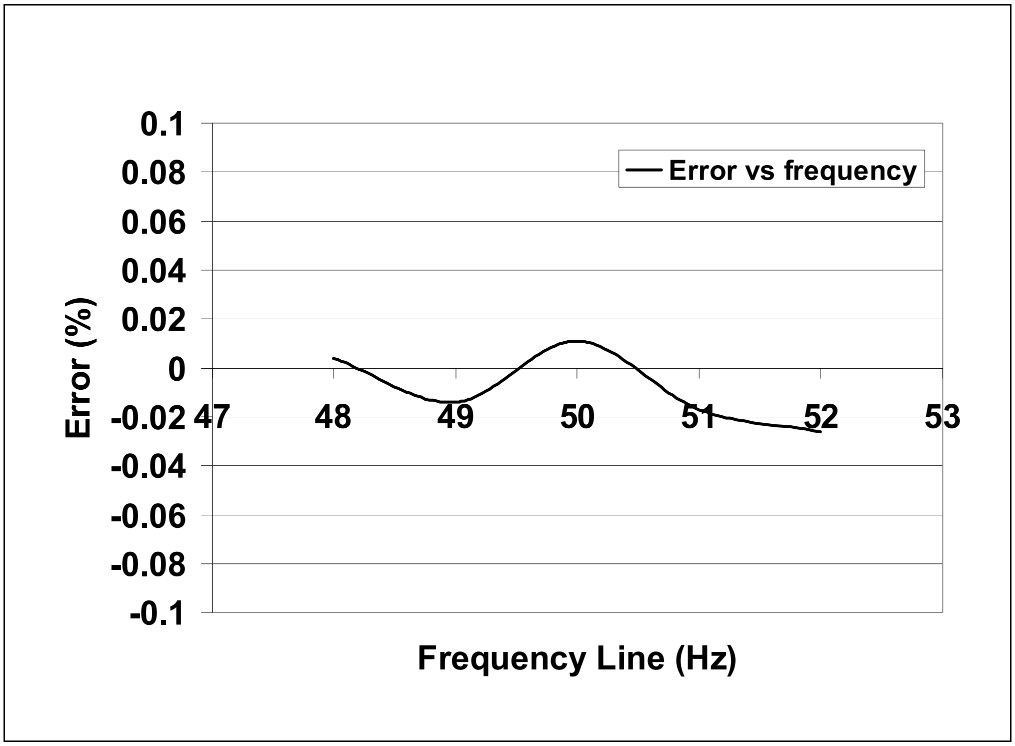

FIGURE 2-7: *Errors vs. Line Frequency.*

Line frequency compensation is a simplified solution and does not compensate for frequencies in which harmonics exist. However, it significantly improves the overall accuracy of the meter.

There is one drawback to using this method. As demonstrated, the signal will be attenuated a little more than it is when the HPF has a lower cutoff frequency. This extra attenuation slightly increases the measurement errors at low currents in which measurement is made more difficult because of the lower signal-to-noise ratio (SNR). In this situation, the accuracy decrease is less than 0.1% and is considered acceptable.

2.2 CALIBRATION PROCEDURE

The power monitor should be calibrated to provide accurate measurements. Due to the implemented signal processing technique, a single-point calibration is sufficient.

To achieve power factor compensations without modifying the hardware, the phase delay block in the MCP3901 power monitor reference design is used. Through having written a correct value in the Phase Delay register, one channel sample is delayed relative to the other channel sample.

Most of the phase errors are caused by phase delays induced by the various components of the meter (i.e., RC filters, current transformers, etc.), from one of the two channels. This block can induce an extra phase delay on the other channel, so the phase delay is compensated, and measurement errors caused by power factor variations are decreased.

The correct value for the Phase Delay register is determined automatically during the calibration routine using the following method. First, determine the influence of the Phase Delay register (kk) over measurement variation for the design. Five points are enough to see a linear dependency, and by choosing the best fit, the Power Factor compensation equation is obtained, as shown in Figure 2-8:

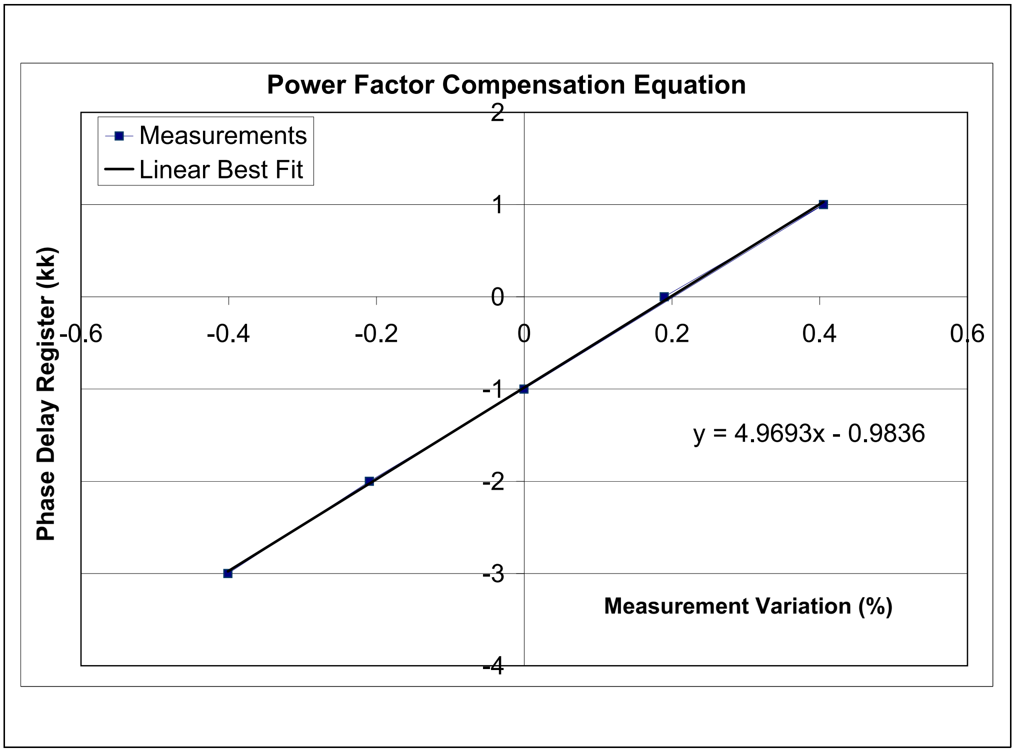

FIGURE 2-8: *Influence of the Phase Delay Register Over Measurement Accuracy at Different Phase Angles.*

The measurement variation is, in fact, the variation of the indication for the Active Power value at 45 degrees and -45 degrees. These two points were chosen because the measurement indication is varying almost linearly in this interval, as shown in Figure 2-3.

The appropriate Phase Delay register value is determined by the measurement of the indication variation during the following calibration routine.

As calibration is initiated, the values of the Active Power Scaling Factor, RMS Current Scaling Factor, and RMS Voltage Scaling Factor at a Power Factor of 1 are determined through the following process:

1. Supplying the meter with the following values: 110 of V_{RMS}, 5 A_{RMS}, and Phase at 0 degrees

   The meter takes a few seconds (maximum 20 s) to get stable readings, then the PC virtual port sends the character "`c`" from the PC to the power monitor. The pulse output LED stops blinking for a few seconds, and the LCD shows "Calibrating 110V 5A PF=1". The three constants will be computed and saved to the EEPROM of the MCU. Power can be interrupted without losing this calibration information.

2. Powering the monitor with 110V of U_{RMS}, 5V of I_{RMS} and a Phase at -45 degrees

   The meter takes a few seconds to get stable readings, then the PC virtual port sends the character "`n`" (negative phase) from the PC to the power monitor. The the pulse output LED is forced ON for a few seconds, while the LCD shows "Calibrating for -45 degrees". The results collected during this step are not saved into the EEPROM of the MCU. It is important that power is not lost until after Step 3 is complete.

3. Powering the meter with 110V of U_{RMS}, 5A of I_{RMS} and Phase at 45 degrees.

   The meter takes a few seconds to get stable readings, then the PC virtual port sends the character "`p`" (positive phase) from the PC to the power monitor. The pulse output LED is forced ON for a few seconds, while the LCD shows "Calibrating for +45 degrees". When this step finishes, the calibration parameters are saved into the EEPROM. Now power can be disconnected from the meter.

The two power values measured at -45 and +45 degrees are inserted into the equation in Figure 2-8, and the result is the Phase Delay register value required to compensate for the power factor variation.

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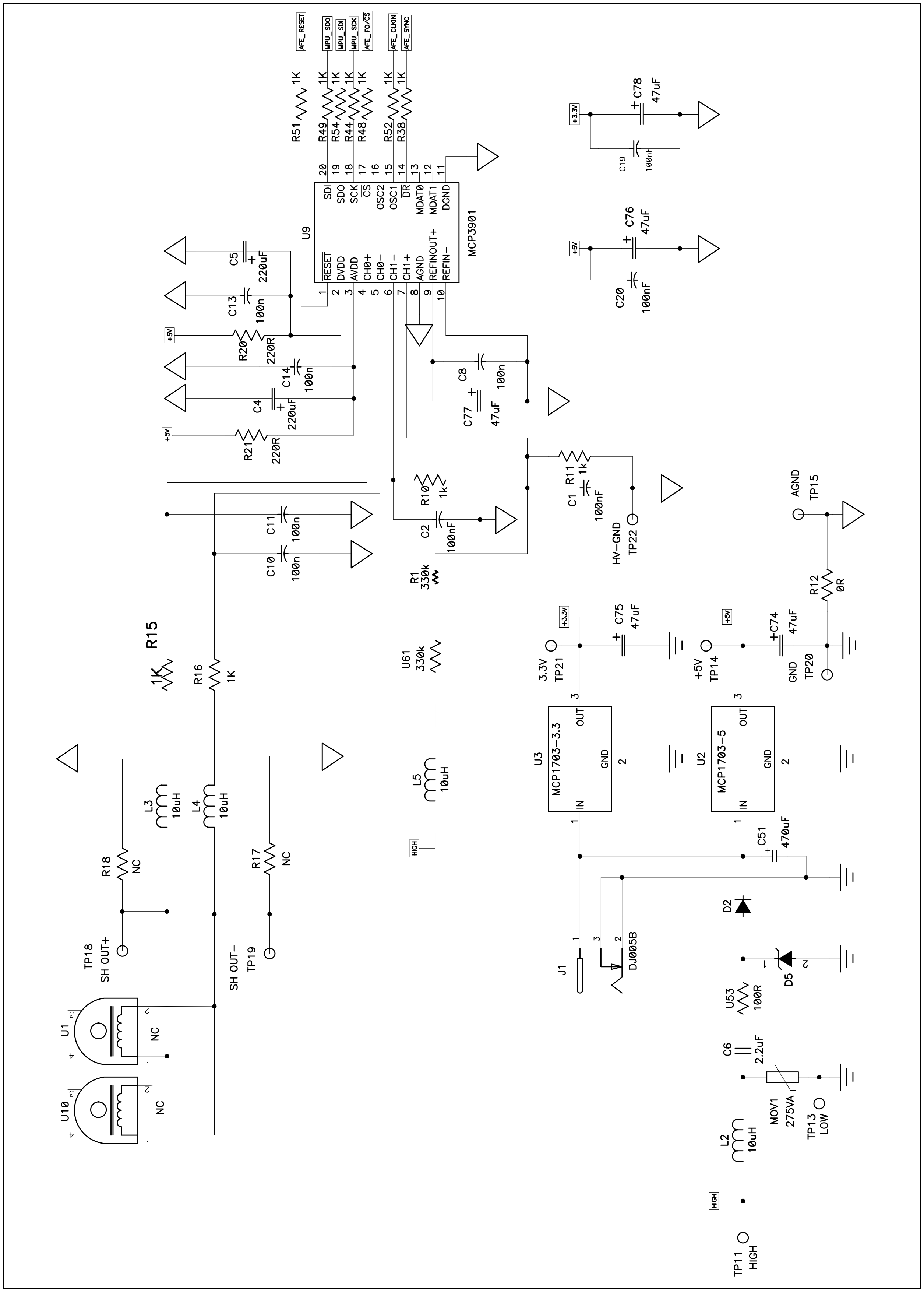
Appendix A. Schematics and Layouts

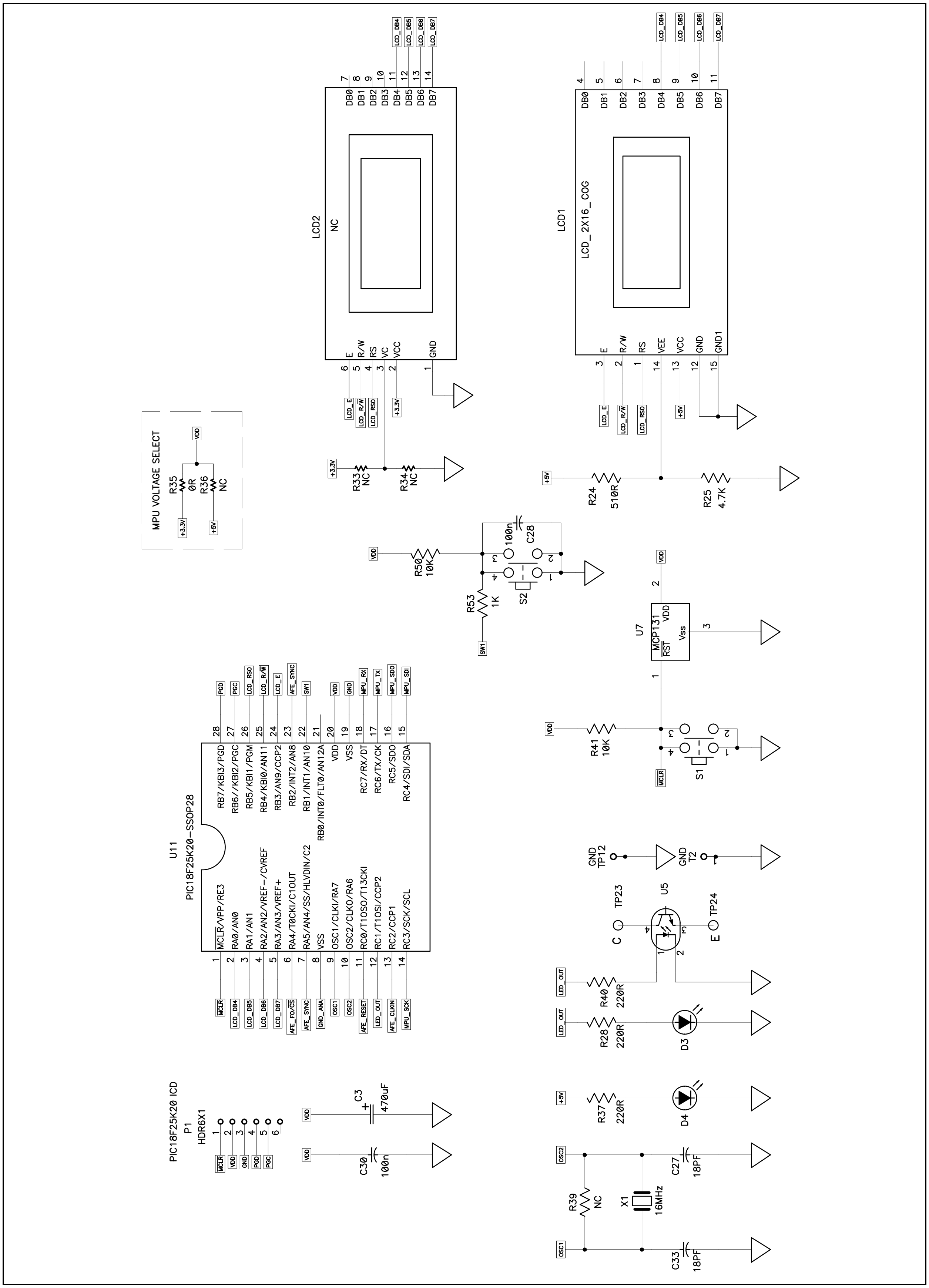
This appendix contains the following schematics of the MCP3901 Low-Cost Power Monitor Reference Design.

- Board Schematic – Analog and Power
- Board Schematic – Microcontroller and LCD
- Board Schematic – Universal Serial Bus
- Board – Top Trace and Top Silk
- Board – Bottom Trace and Bottom Silk

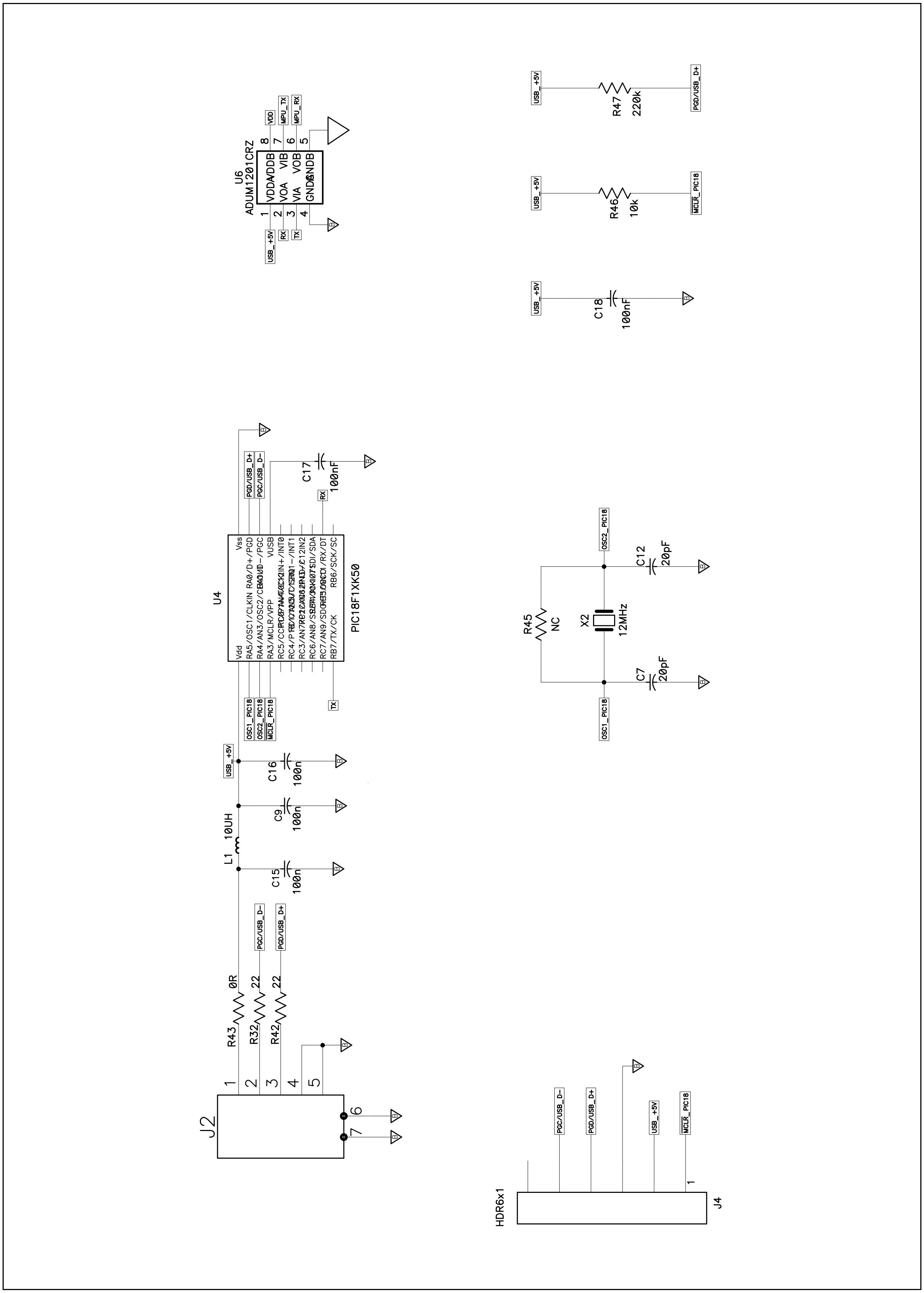
A.1 BOARD SCHEMATIC – ANALOG AND POWER



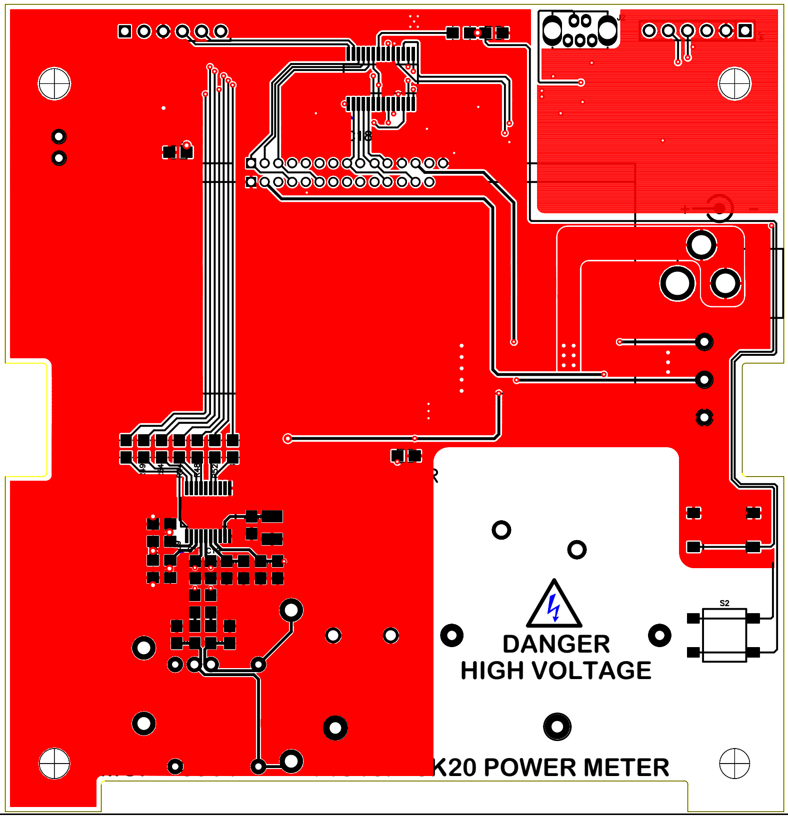
A.2 BOARD SCHEMATIC – MICROCONTROLLER AND LCD



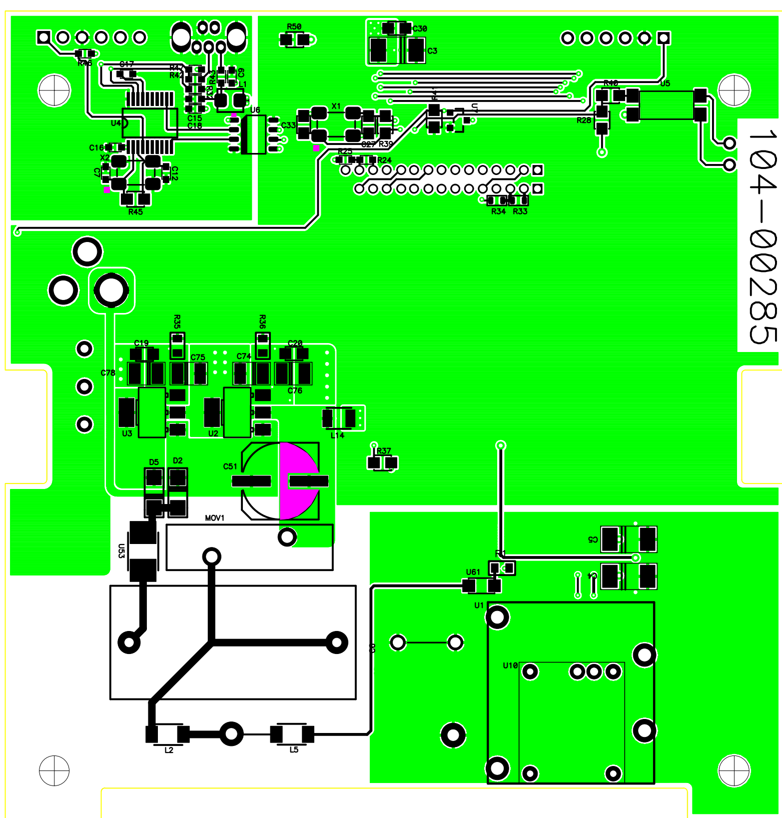
A.3 BOARD SCHEMATIC – UNIVERSAL SERIAL BUS



A.4 BOARD – TOP TRACE AND TOP SILK



A.5 BOARD – BOTTOM TRACE AND BOTTOM SILK



NOTES:

Appendix B. Bill of Materials

TABLE B-1: BILL OF MATERIALS

Qty	Reference	Description	Manufacturer	Part Number
14	C1, C2, C8, C10, C11, C13, C14, C16, C17, C18, C19, C20, C28, C30	CAP .10UF 50V CERAMIC X7R 0805	Yageo Corporation	CC0805KRX7R9BB104
3	C3, C4, C5	CAP TANT LOESR 220UF 6.3V 10%SMD CASE C	AVX Corporation	TPSC227K006R0125
1	C6	CAP FLM 2.2uF 275VAC POLY-PRO MKP	Kemet	R46KR422000M2K
4	C7, C12, C27, C33	CAP CERAMIC 18PF 50V NP0 0805	Yageo Corporation	CC0805JRNP09BN180
5	C9, C15, C16, C17, C18	CAP .10UF 50V CERAMIC X7R 0603	Yageo Corporation	CC0603KRX7R9BB104
1	C51	CAP ELECT 470UF 16V VS SMD	Panasonic® – ECG	EEE-1CA471P
5	C74, C75, C76, C77, C78	CAP TANT 47UF 6.3V 20% POLY SMD CASE B	AVX Corporation	TCJB476M006R0070
1	D2	DIODE STD REC 1A 600V SMA	ON Semiconductor	MRA4005T3G
2	D3, D4	LED RED ORANGE CLEAR 0805 SMD	Lite-On Inc	LTST-C170EKT
1	D5	DIODE ZENER 15V 1.5W SMA	ON Semiconductor	BZG03C15G
5	L1, L2, L3, L4, L5	INDUCTOR 10UH 1210	TAIYO YUDEN Co., Ltd.	CBC3225T100MR
1	LCD1	16X2 LCD Character Display	Fema Electronics	CG1626-SGR1
8	LCD2, R17, R18, R33, R34, R36, R39, R45	DO NOT POPULATE	—	—
1	MOV1	VARISTOR 275V RMS 20MM RADIAL	EPCOS	S20K275E2
1	PCB	RoHS Compliant Bare PCB, PIC18F1XK50 & MCP3909 Power Meter	—	104-00285
1	R1	RES 330K OHM 1/4W 1% 0805 SMD	Yageo Corporation	RC0805FR-07330KL
13	R10, R11, R15, R16, R38, R44, R48, R49, R51, R52, R53, R54	RES 1.00K OHM 1/8W 1% 0805 SMD	Yageo Corporation	RC0805FR-071KL
5	R20, R21, R28, R37, R40	RES 220 OHM 1/8W 1% 0805 SMD	Yageo Corporation	RC0805FR-07220RL

Note 1: The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

TABLE B-1: BILL OF MATERIALS (CONTINUED)

Qty	Reference	Description	Manufacturer	Part Number
1	R24	RES 510 OHM 1/10W 5% 0603 SMD	Yageo Corporation	RC0603JR-07510RL
1	R25	RES 4.7K OHM 1/10W 5% 0603 SMD	Yageo Corporation	RC0603JR-074K7L
2	R32, R42	RES 22 OHM 1/10W 1% 0606 SMD	Yageo Corporation	RC0603FR-0722RL
1	R35, R43	RES 0.0 OHM 1/3W 5% 0805 SMD	Panasonic – ECG	ERJ-6GEY0R00V
1	R37	RES 309 OHM 1/8W 1% 0805 SMD	Yageo Corporation	RC0805FR-07309RL
2	R41, R50	RES 10K OHM 1/10W 5% 0805 SMD	Yageo Corporation	RC0805JR-0710KL
1	R46	RES 10K OHM 1/10W 5% 0603 SMD	Yageo Corporation	RC0603JR-0710KL
1	R47	RES 220K OHM 1/10W 5% 0603 SMD	Yageo Corporation	RC0603JR-07220KL
2	S1, S2	SWITCH TACT 160GF H=5.0MM SMT	E-Switch, Inc.	TL3301AF160QG
1	U1	MCP3901 energy measurement IC	Microchip Technology Inc.	MCP3901T-I/SS
1	U2	MCP1703 5V 250 mA, 16V, Low Quiescent Current LDO Regulator	Microchip Technology Inc.	MCP1703T-3302E/DB
1	U3	MCP1703 3.3V 250 mA, 16V, Low Quiescent Current LDO Regulator	Microchip Technology Inc.	MCP1703T-3302E/DB
1	U4	PIC18F14K50 Flash Microcontroller	Microchip Technology Inc.	PIC18F14K50-E/SS
1	U5	OPTOCOUPLER TRANS-OUT VDE 4-SMD	Fairchild Semiconductor	H11A8173S
1	U6	IC ISOLATOR DIGITAL DUAL 8-SOIC	Analog Devices, Inc.	ADUM1201CRZ-RL7
1	U7	MCP131 voltage supervisor	Microchip Technology Inc.	MCP131T-270I/TT
1	U11	PIC18F25K20 Flash MCU	Microchip Technology Inc.	PIC18F25K20-E/SS
1	U53	RES100 OHM 1W 2512	Vishay DRALORIC	CRCW2512100RFKEG
1	U61	RES 330K OHM 1/4W 1% 1206 SMD	Yageo Corporation	RC1206FR-07330KL
1	X1	CRYSTAL 16.000MHZ 18PF FUND SMD	Abracon Corporation	ABM3B-16.000MHZ-B2-T
1	X2	CRYSTAL 12.000MHZ 18PF FUND SMD	Abracon Corporation	ABM3B-12.000MHZ-B2-T

Note 1: The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

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