PICA

Power **I**nformation **C**ollection **A**rchitecture

Project Proposal and Feasibility Study

Engineering 339: Senior Design 2010-2011

6 December 2010

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CALVIN

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MY HEART I OFFER TO YOU LORD · PROMPTLY AND SINCERELY ·

Abstract

The proposed senior design project is to develop a power-monitoring system capable of monitoring total and circuit-by-circuit power usage for a given installation. Such a system would use non-invasive load monitoring techniques to monitor the flow of current through the feeder lines; the system can then aggregate all of this data, and perform data analysis to determine kilowatt hours used, reactive power, line frequency, and in some cases power factor. The system then can display this data to a user in real-time over a wall-mounted display unit or a web interface.

The following report outlines the design of this system and the major decisions that the design team made. The major accomplishments thus far have been: Meeting with Consumer's Energy, Product competition research, defining a budget and per-system cost estimates, selecting features for inclusion, establishing rough requirements, investigating design possibilities, selecting a metering device for prototyping, and identifying unforeseen constraints. The remaining work for this project includes: solid-state breaker and monitor/controller design and implementation, base station design and implementation, E-meter design and implementation, component and system testing, and prototype construction.

The final result of the project will be a working prototype which demonstrates the ability to correctly and accurately monitor power consumption. The project is scheduled to be completed by May 7, 2011.

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1 Acronyms

AC Alternating Current . . . 25
AD Analog Devices . . . 35
ADC Analog-to-Digital Converter . . . 34
AES Advanced Encryption Standard . . . 24
AMR Automated Meter Reading . . . 34
ANSI American National Standards Institute . . . 22
CAD Computer Aided Design . . . 10
CDMA Code Devision Multiple Access . . . 56
CF Compact Flash . . . 61
DC Direct Current . . . 18
DHCP Dynamic Host Configuration Protocol . . . 15
DOE United States Department of Energy . . . 88
EEPROM Electronically Erasable Programable Read Only Memory . . . 35
ESP Electronic Signal Processing . . . 35
EM electromagnetic . . . 19
FCC Federal Communications Commission . . . 19
FET Field-Effect Transistors . . . 83
FPGA Field Programable Gate Array . . . 43
GPL GNU General Public License . . . 57
HTTP Hypertext Transfer Protocol . . . 16
IC Integrated Circuit . . . 35
IEC International Electrotechnical Commision . . . 90
IEEE International Electrical and Electronics Engineers . . . 56
JCI Johnson Controls, Inc. . . . 87
LAN Local Area Network . . . 13
LCD Liquid Crystal Display . . . 11
LED Light Emitting Diode . . . 14
MCU Master Control Unit . . . 12
NEMA National Electrical Manufacturers Association . . . 90
NIC Network Interface Card . . . 12

2 Project Introduction

2.1 Overview of the Problem

Standard electric meters were developed decades ago and are still used today, despite many technological advances in the last several years. Along with these technological advances, Americans have become accustomed to having access to large amounts of data, but due to the nature of the standard electric meter, data regarding the usage of power is severely limited. For the power companies, data from the meters is minimal and grid control is limited to manual operation, costing them time and money. As the cost of electricity becomes higher and higher, electricity use in buildings is becoming a bigger concern and people have few cheap or simple ways to monitor this. Of the options available, most only address part of the whole problem, giving some information to the consumer and none to the power company or vice-versa. While there are devices such as breakers and fuses that provide electrical safety for buildings, advances in technology have made it possible to further improve safety but have not been implemented in a cost-effective way or made easily available to an average consumer, which for the purpose of this project shall be defined as a person without a mathematical or scientific education beyond high-school.

2.2 Why the Project was Chosen

Our team chose the project for several reasons; as future homeowners, the team has an interest in knowing more about power usage within a home. There are also many more people who would benefit from more accurate and useful data about power usage.

As good stewards of Earth we want to make sure the natural resources available are not wasted, and we believe that if there is access to more and better information, people will have a better opportunity to manage those resources more effectively. In addition, providing better information and control to the power companies can lead to less wasting of electricity on the provider's end, further contributing towards better use of Earth's resources.

Electricity-related deaths and injuries have been reduced due to devices such as fuses and breakers, but many still happen every year. As fellow human beings, we care and would like to minimize these incidents further. The technology is available and will benefit many people when implemented.

2.3 Team Information

Team 01, Team PICA seen in figure 1 consists of four engineers in Calvin College's Electrical and Computer Engineering concentration: Amy Ball, Nathan Jen, Avery Sterk, and Kendrick Wiersma.

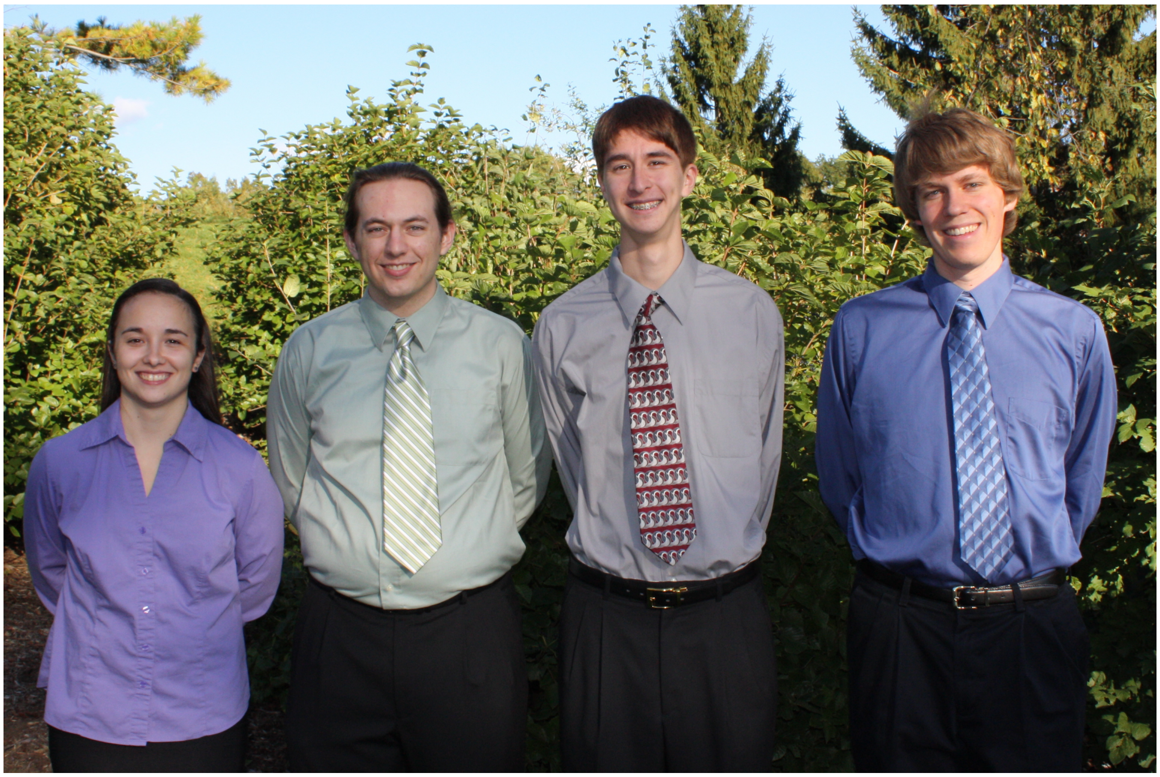


Figure 1: Team PICA, left to right: Amy Ball, Kendrick Wiersma, Nate Jen, and Avery Sterk.

Amy works as an intern at Johnson Controls, where she works as part of the Systems Engineering Team. She brings good communication skills, circuit-building experience, and presentation skills to the project. Her section of the project is the solid-state breakers, especially working closely with much of the analog hardware involved with the project.

Kendrick works as an intern at Raytheon Missile Systems in the Electronics Center, where he performs embedded system design and verification. Kendrick hails from Tucson, Arizona where he was born and raised. He brings real-world project experience and experience working with embedded hardware and software to the team. Kendrick leads the development of the E-meter, which measures whole-building power consumption, reporting data to the power company and the PICA base station.

Nathan has worked at Amway on the production floor and has gained involvement with club leadership at Calvin College. He brings leadership experience and a good understanding of how smaller elements of a system fit together as a whole. His section of the project is the monitoring of individual circuits and some of the control logic for the breakers.

Avery worked as an intern at the SLAC National Accelerator Laboratory doing Computer Aided Design (CAD) design. He brings varied experience with software design and implementation to the project. His section of the project is the base station, especially providing the primary user interface and designing embedded software.

3 System Overview

The Power Information Collection Architecture (PICA) is a collection of components whose purpose is to accurately collect and display information about power quality and consumption to a consumer. Designed to be modular, these components do not require use of all systems, but can also operate individually or together as a suite of sensors and controls to empower the consumer with more accurate and up-to-date information about power usage. The four major systems seen in figure 2 compose the PICA system.

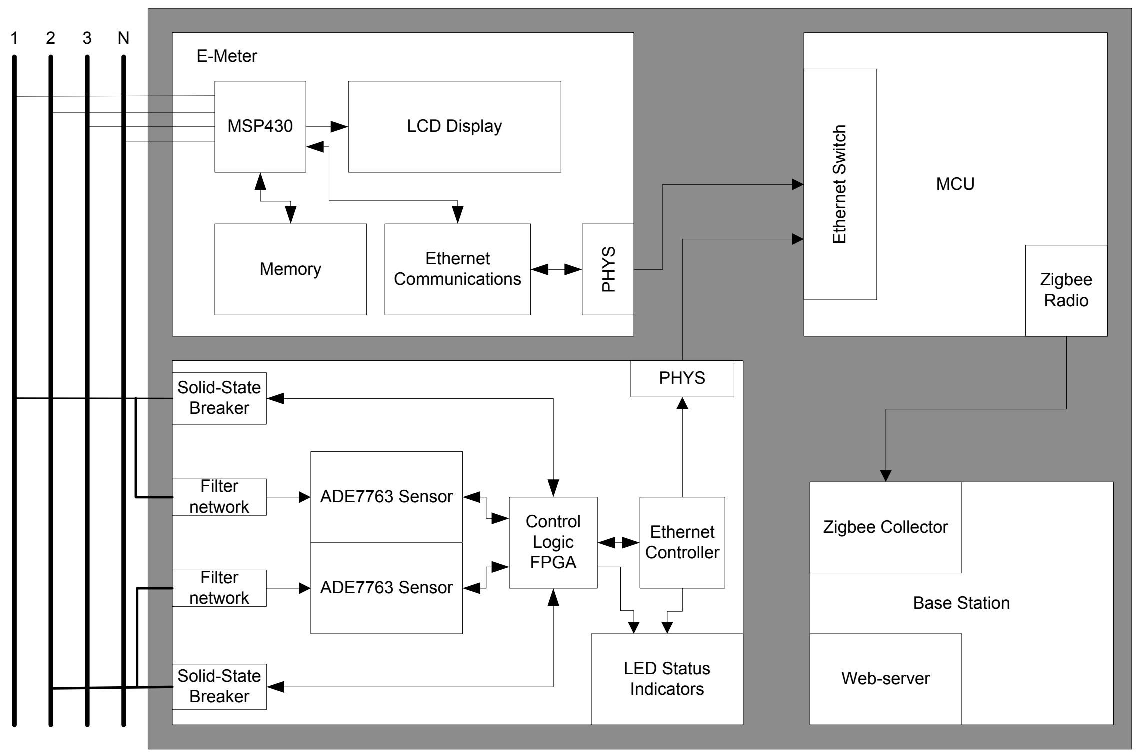


Figure 2: An overview of the four major systems of the PICA monitoring system.

The E-Meter is a smart metering device; capable of monitoring single or multi phase power installations, this device replaces the current ‘dumb’ meter on the exterior of most residential and commercial buildings. The E-Meter monitors how much power an entire installation (e.g. a home or business) consumes. By introducing a smarter power meter, Team PICA can monitor reactive power, flicker voltage, phase angle, frequency, and, peak voltage in addition to total power consumption. The power company uses this information for billing purposes and to understand the health and status of the electric grid more completely. A web interface provides the consumer with an hour-by-hour overview of their power consumption. The E-Meter provides an Liquid Crystal Display (LCD) display on the outside to display the instantaneous power usage in kilowatt-hours. The E-meter is capable of functioning as a stand-alone device without the Master Control Unit (MCU), breakers or base station.

The smart breaker is a solid state replacement for the traditional electromechanical breaker found in electric panels. Using MOSFET technology to mimic a fault-interrupter, these solid state breakers can sense a fault in the circuit and respond in a fraction of the time it takes traditional breakers to trip. Each breaker includes status lights to indicate the status of the circuit (on, off, fault), and a sensor to provide circuit by circuit information on power usage. A System on a Chip (SoC) collects the information provided by the sensors and uses the instantaneous measurements to control the breakers before packaging and shipping the data to the system controller for transmission to the MCU. The base station will also have the ability to reset the breakers. The breakers require the MCU and base station to function.

The MCU controls the transmission of data to the PICA base station over the Zigbee 802.15 radio link. The MCU acts as a buffer and arbitrator for the Zigbee radio and receives data in TCP/IP packages from each subsystem. Onboard, the MCU stores packages until the mesh-network comes up and then transmits packages until its buffers are empty. The prototype MCU comes from a WRT54G wireless router produced by Cisco sold under the name Linksys and targeted at the home networking market. The MCU is necessary if the base station is used.

The base station collects all the sensor data through the MCU, collates the data, and hosts a webpage where it displays the information. The consumer can access the webpage by attaching the base station to a network router or directly to the Network Interface Card (NIC) of a personal computer. The base station acts as the collector node for the Zigbee mesh network. The base station could provide a control point for future smart devices in the home, such as a thermostat or other smart appliances. The base station connects to an in-home display that displays usage information. The base station is capable of working with the E-meter, the breakers or both.

4 Requirements

4.1 Base Station Requirements

All requirements under this heading are to be assumed to be of the base station (“the system”) unless explicitly stated otherwise.

4.1.1 Functional Requirements

1. Shall be capable of upgrading its software and firmware upon administrator requests.
2. Shall be capable of connecting with other PICA sub-systems over a pre-defined and pre-arranged communications protocol.
   (a) Shall receive and store power usage measurements from connected PICA systems.
      i. These measurements will be taken at a frequency that does not exceed the established bandwidth of the chosen protocol.
      ii. These measurements will be summarized or discarded (at the user’s selection) when the storage space of the system nears its capacity.
   (b) Shall receive and store events and alerts from connected PICA systems.
      i. The nature of these events shall be determined by each individual system, but shall be communicated to the base station in a standardized format.
      ii. The system shall organize these events internally and display them to the user.
   (c) Shall function as a Network Time Protocol (NTP) server for connected PICA systems.
   (d) Shall receive and record event log information from connected PICA systems.
3. Shall be capable of connecting to a Local Area Network (LAN).
4. Shall be capable of using settings that the user selects.
   (a) Shall be capable of recognizing an invalid setting.
   (b) Shall be capable of reverting to a default setting when the user setting is not valid.
5. Shall be capable of displaying the most recent measurements from the connected PICA systems.

6. Shall be capable of displaying the status of the connected PICA systems.
   (a) Status shall include whether the connected system is in an error state.
   (b) Status shall include the time since the last observed error state, if applicable.
   (c) Status shall include the nature of the last error, if communicated.
7. Shall be capable of giving an authenticated base-station adminstrator similarly-privileged administrative access to connected PICA systems.
   (a) The extent of this access shall be deteremined by the individual PICA systems.
   (b) The base station shall inform the administrator when the remote administrative access is rejected or unavailable.
8. Shall be capable of distributing system updates for connected PICA systems.
   (a) Shall be capable of sending update data and images to the appropriate subsystems.
   (b) Shall identify whether or not the connected PICA systems require updating.
9. Shall be capable of giving debugging and troubleshooting output.
   (a) Shall display simple status indication using Light Emitting Diodes (LEDs). (See 4.1.5)
   (b) Shall present more detailed debugging and troubleshooting information over a dedicated RS-232 connection.
10. Shall be capable of actively notifying the power-company and consumer.

4.1.2 Behavioral Requirements

1. Shall store user-defined configuration in non-volatile media.
   (a) Shall initialize this configuration using a pre-defined default configuration.
   (b) Shall load the default configuration if the user-defined configuration is unavailable.
      i. This includes the user-defined configuration being absent.
      ii. This includes the user-defined configuration containing invalid data.
2. Shall include a backup firmware in the event of a failed firmware upgrade.

   (a) Firmware upgrade success or failure shall be determined by comparing checksums of the firmware to be written and the firmware present after writing.
   (b) The backup firmware shall be engaged if the system fails to boot from the first firmware.
3. Shall store critical event logs from connected PICA systems in a non-volatile media.
4. Shall host a webpage to display system information when browsed over the LAN connection.
5. Shall store its software in non-volatile media.
6. Shall run an operating system to manage hardware, device drivers, and connections to connected PICA systems.
7. Shall use a defined communication protocol to communicate with connected PICA systems.

4.1.3 Software Requirements

1. Shall include and run an upgradable Operating System (OS).
   (a) The OS shall include the drivers necessary to operate the system hardware.
   (b) The OS shall include the protocols necessary to connect to PICA sub-systems.
2. The OS shall have an administrator-privileged user who may change the configuration of the system and of connected PICA systems.
3. The OS shall give the system owner access this administrator-privileged user account.
   (a) The OS is not required to give such access to connected systems that are not owned by the owner of the base station system (such as those owned by the power company).
   (b) The OS shall authenticate that the user requesting administrator access is authorized to do so using a means configured during system installation.
4. The OS shall include the protocols necessary to connect to an existing LAN.
   (a) The OS shall include a Dynamic Host Configuration Protocol (DHCP) client.
   (b) The OS shall support manual LAN connection configuration.
5. The OS shall control the system connectivity hardware to prevent unwanted devices, such as those owned by other customers, from being connected to the system.

   (a) The OS shall distinguish between wanted and unwanted systems as defined by administrator selection.
      i. By default, ZigBee connection requests will be rejected until authorized by the administrator.
      ii. By default, LAN connection requests will be trusted unless disallows by the administrator.
   (b) The OS shall record connection requests from unwanted devices and display them to the administrator.
6. Shall include and run Hypertext Transfer Protocol (HTTP) server software to provide the web interface.
7. Shall include the necessary tools to download and apply software and firmware updates.

4.1.4 Hardware Requirements

1. Shall include a power supply to power the system from line voltage during regular usage conditions.
2. The power supply shall tolerate moderate expected fluctuations in input voltage from a standard power outlet.
   (a) The power supply is not required to tolerate incorrect voltage input (240V instead of 120V, etc.)
   (b) The power supply is not required to tolerate voltage spikes as may be associated with electrical storms.
3. Shall include an internal power storage device to allow the system to perform necessary data storage immediately after a power failure.
4. Shall have adequate Random-Access Memory (RAM) to contain system software, cache data from other PICA devices, and cache data to send to other PICA devices without requiring a cache flush more than once per minute.
5. Shall have a processor to execute the system software and process data from connected PICA devices.
   (a) The processor must have sufficient processing speed to process the incoming data from other PICA devices at a rate greater than the rate of data incoming.

   (b) The processor must be able to perform all necessary mathematical operations without a co-processor.

6. Shall have an Ethernet controller for connecting to a LAN.
7. Shall have an RS-232 controller for debugging and troubleshooting the system.
8. Shall have ZigBee connectivity hardware for communication with other PICA systems.
9. Shall have non-volatile storage dedicated to storing system firmware.
   (a) Shall have a re-writable non-volatile storage device to contain boot firmware.
   (b) Shall have a separate non-volatile storage device to contain backup firmware to use in the event of boot failure.
10. Shall have non-volatile storage sufficient to store system software.
11. Shall have non-volatile storage sufficient to store recorded events and short-term consumption history for up to a period of 3 years.

4.1.5 User Interface Requirements

1. Shall provide a web interface for viewing collected data over the LAN.
2. Shall provide a web interface for viewing current and predicted pricing information as provided by the power company.
3. Shall provide a web interface for system administration to an authenticated administrator.
   (a) Shall include an interface for managing updates to the system's firmware and software
      i. Shall include an interface for displaying the version numbers or codes of the firmware and software currently installed on the base station.
      ii. Shall include an interface for indicating the availability of system updates for the base station.
      iii. Shall include an interface by which the administrator may request that the base station apply its available updates and be informed on whether or not the base station must be rebooted after the update is installed.

iv. Shall include an interface for indicating the progress of update installation.

(b) Shall include an interface for managing connections to other PICA systems.

i. Shall include an interface for displaying current connections to other PICA systems.

ii. Shall include an interface for adding, removing, or connections made to other PICA systems.

(c) Shall include an interface for administration of connected PICA systems.

i. Shall include interfaces for managing configurations of connected PICA systems.

ii. Shall include an interface for deploying software/firmware upgrades to connected PICA systems.

4. Shall provide a debugging interface over an RS-232 serial connection.

5. Shall display status indication lights.

(a) System is connected to power.

(b) System is connected to other PICA subsystems.

(c) System is connected to the home network.

(d) System has encountered an error.

i. Error light shall trigger if a connection to another PICA system is lost and cannot be recovered within 30 seconds.

ii. Error light shall trigger when the storage medium contains less than 5% free space.

iii. Error light shall trigger when the storage medium's file system cannot be mounted.

A. This includes the storage medium being physically absent.

B. This includes the storage medium being corrupt.

4.1.6 Power Requirements

1. Shall be powered from a standard 120V wall outlet.

2. Shall have a Direct Current (DC) power supply to power internal components.

3. Shall have a backup power supply to enable the system to save all measurements residing in memory to the non-volatile storage medium.
4. Shall require less than 10W to operate.

4.1.7 Codes and Compliances

1. Shall have a polarized electrical plug if the power supply features an an off-on control switch.
2. Shall restrict electromagnetic (EM) radiation to comply with Federal Communications Commission (FCC) Title 47 Part 15.

4.2 Solid State Breakers and Monitoring Requirements

All requirements are to be assumed to be of the solid state breakers (“the system”) unless explicitly stated otherwise.

The breaker subsystem must be capable of two major functions; it must protect the connected circuit when a specified threshold is exceeded, and it must pass information to and from the user interface, either directly or through another subsystem.

4.2.1 Functional Requirements

1. Shall be capable of completely disconnecting, either physically or virtually, the power delivered to the connected circuit.
2. Shall provide two-way communications to the base station through the MCU.
   (a) Shall provide power usage information, including at a minimum, instantaneous voltage and current of the connected circuit.
   (b) Shall be capable of providing on/off status of the breaker.
   (c) Shall be capable of turning breakers on and off when requested by the base station.
3. Shall be capable of detecting power sags, brownout conditions and blackouts.

(a) The National Power Corporation (NPC) defines sag as ”80% to 85% below normal [voltage] for a short period of time,” [5]. For project uses, this is below 100V. The team defines “a short period of time” to be for three cycles to ten cycles, based on information given in [6]. The NPC defines a brownout as “a steady lower voltage state,” [5] Blackouts are defined by the NPC as “as zero-voltage condition that lasts for more than two cycles,”[5].

4. Shall store up to a minute of gathered information for at least five minutes in on-chip memory for transmission to the MCU.
5. Shall package the stored information for transmission to MCU.
6. Shall be capable of turning off circuits individually.
7. Shall stop current flow to a circuit when it exceeds a specified threshold.
8. Shall be capable of being reset when stopped, without requiring new parts such as fuses.

4.2.2 Behavioral Requirements

1. Shall initialize all components by writing from non-volatile storage to all necessary registers when power is restored to the circuit.
2. Shall report all system events that are not part of standard operation to the critical event log.
3. Shall measure voltage levels in the connected circuit.
4. Shall measure current flow in the connected circuit.

4.2.3 Hardware Requirements

1. Shall use non-volatile storage to store data when the system is without power.
2. Shall be capable of managing its own data and functions.

4.2.4 User Interface Requirements

1. Shall have an external interface that is understandable by the average consumer.
2. Shall provide a way to control the breakers independent from the base station.

3. Shall encase all circuitry except user interface controls (buttons, switches) so that they cannot be tampered with without breaking the casing.

4.2.5 Power Requirements

1. Shall be powered by line-voltage.
2. Shall be powered such that interrupting the circuit does not cause the breaker control circuitry to lose power.

4.2.6 Physical Requirements

1. Shall have dimensions less than or equal to 1in x 3in x 4in for a single breaker or 2in x 3in x 4in for a breaker pair.
   (a) Dimensions are determined by the standard size of a mechanical breaker, so that smart breakers may be interchangeable with conventional residential or commercial mechanical breakers.
2. Shall not weigh more than one pound.
   (a) Weight is determined by the average weight of a standard mechanical breaker [7], so that smart breakers may be interchangeable with conventional residential or commercial mechanical breakers.
3. Shall accommodate wire sizes from 14-4 Cu to 12-8 Al.
   (a) Wire size is based on the average size wire used with standard mechanical breakers [7], so that smart breakers may be interchangeable with conventional residential or commercial mechanical breakers.

4.2.7 Safety Requirements

1. Shall protect everything connected to the circuit from current exceeding a specified threshold by providing circuit interruption.
2. Shall have safety hazards clearly marked and visible from outside the system.
3. Shall safely isolate high-voltage areas so that they provide no more threat than a standard wall outlet.

4.2.8 Codes and Compliances

1. Shall be compliant with American National Standards Institute (ANSI) C12.19 [8].
2. Shall be compliant with ANSI C12.21 [9].
3. Shall be compliant with FCC Title 47 Part 15 [10].

4.3 Electric Panel Meter Requirements

All requirements are to be assumed to be of the electric panel meter ("the system") unless explicitly stated otherwise.

4.3.1 Functional Requirements

1. Shall continuously monitor the power used from either a single-phase or a multi-phase installation.
2. Shall store power usage data locally, to be transmitted back to the base station at regular intervals.
3. Shall by default display instantaneous and historical power usage data on an LCD module integrated into the electric panel.
4. Shall provide two-way communication with the MCU to report usage data.
5. Shall be capable of detecting a brownout condition and storing critical data before shutting down.
6. Shall be capable of restarting and restoring stored data after a brownout condition.
7. Shall be capable of detecting any tampering, such as opening the sealed metering unit, and transmitting a tamper message to both the power-company and the consumer.
8. Shall monitor current flow through the main service lines for automated meter reading.
9. Shall monitor voltage levels on the main service lines for automated meter reading.
10. Shall control the service shutoff switch by receiving and validating a service shutoff message from the power-company.
11. Shall provide a method for controlling the service shutoff switch from a local interface.

12. Shall provide an interface for 3rd party meters, such as gas, water, or other utility meters to report data over the PICA network.
13. Shall support on-demand reports from the power company via the Zigbee network or the user via the PICA web interface of power usage, energy consumption, demand, power quality and system status.
14. Shall support bi-directional metering and calculation of net power usage to support alternative energy generation systems.
15. Shall support automatic meter reads.
16. Shall analyze the voltage flicker, logging a warning when the flicker exceeds 20% of the stated $117V_{RMS}$.
17. Shall meter reactive power consumption, logging data for billing purposes.

4.3.2 Behavioral Requirements

1. Shall, in the event of wireless link loss; attempt to re-establish the wireless link.
2. Shall, in the event of a wireless link loss, revert to stand-alone mode, storing data internally until internal storage is full, at which point the system will begin overwriting the oldest data with the newest data.
3. Shall, in the event of a wireless link loss, notify the user via the LCD display.
4. Shall perform a built-in self-test upon system boot up to verify onboard storage integrity and to verify proper operating software.
5. Shall, in the event of a brownout, save all volatile information to non-volatile storage space.
6. Shall be capable of detecting corrupted data, via parity bits, when brought out of a brownout condition.
7. Shall log all events processed into the following four categories:
   (a) critical: messages requiring immediate attention.
   (b) error: messages requiring attention and may affect system functionality.
   (c) warning: messages that require attention but do no impact system functionality.

(d) note: messages that require no attention but provide verification of proper operation.

8. Shall report all events to the PICA base station.
9. Shall report to the power-company as specified by event criticality.
10. Shall have dedicated non-volatile storage for all critical settings and configuration data.
11. Shall compute the total power used in kilowatt-hours.
12. Shall be capable of receiving messages from the power-company, providing the user with the current cost of a kilowatt-hour.
13. Shall use 128-bit Advanced Encryption Standard (AES) encryption for all messages transmitted outside of the device.
14. Shall report the total amount of outage time to both the power company and the PICA base station.
15. Shall date-stamp all detected outages with the date, time, and duration of the outage.

4.3.3 Software Requirements

1. Shall verify system firmware on boot up.
2. Shall periodically, minimum once per day, perform a system check to verify the health and status of the system.
3. Shall perform an on-demand system health and status check as demanded by the PICA base station or the power-company.
4. Shall contain sufficient non-volatile storage for all system configuration settings.
5. Shall be updateable through the power-company wireless interface.
6. Shall be capable of properly recovering from a failed software update.
7. Shall give authorized access to components of the system configuration as appropriate to the power-company and consumer.
8. Shall notify the power-company and the PICA base station once service has been restored containing the time of restoration and a voltage measurement.
9. Shall have a unique IPv6 address for the power-company mesh network.

10. Shall have a unique IPv4 or IPv6 network address for the local home-area-network.
11. Shall receive an NTP message from the PICA base station to set the hardware clock.
12. Shall synchronize the hardware clock with the base station time once per day.
13. Shall support on-demand hardware clock synchronization via the PICA base station web interface.

4.3.4 Hardware Requirements

1. Shall be completely enclosed in a weatherproof case, tolerant of extreme temperature differences.
2. Shall be completely Alternating Current (AC) coupled against transient AC voltages.
3. Shall be mounted in the same location as a standard power meter.
4. Shall provide non-volatile storage.
5. Shall be grounded.
6. Shall provide a hardware system clock, set by the software and synchronized with the PICA base station.

4.3.5 User Interface Requirements

1. Shall have a 160-segment LCD display module, viewable from outside the electric panel.
2. Shall be capable of interfacing with a web-based application for stand-alone configuration.
3. Shall provide push-buttons for changing the viewing contents on the display module between metering and system status views.

4.3.6 Power Requirements

1. Shall be capable of operating from line-voltage.
2. Shall be powered from before the master breaker, preventing the meter from losing power when the master breaker is switched off.

4.3.7 Safety Requirements

1. Shall meet or exceed safety requirements for devices inside an electric panel.

2. Shall provide a grounding point to ground the system when installed.

3. Shall be protected against the elements. 4. Shall safely isolate high-voltage areas.

4.3.8 Codes and Compliances

1. Shall be compliant with ANSI C12.19.

2. Shall be compliant with ANSI C12.21.

3. Shall be compliant with FCC Title 47 Part 15.

5 Design Goals

5.1 Provide a physical system that accurately monitors power usage

Inaccurate information provides no benefit to either the power company or the consumer, despite any added features. Therefore, the system should be as accurate as or more accurate than monitors currently used.

5.2 Provide manuals for maintenance and general use

The design team recognizes that no system is perfect and will eventually need maintenance and that most consumers do not have extensive knowledge of electrical systems or components. Providing manuals will assist the consumer in understanding their system and getting the most benefit from it. The design team will look to create a manual that will include an overview of how the system works, how to install and configure the system, and how to maintain the system during the course of normal use. This manual will also contain a troubleshooting guide, support information, liabilities, safety information, and any other pertinent information.

5.3 Design the system to be modular

Providing information to both the power company and to the consumer is the main goal of the project, but it is possible that an installation will not include all the subsystems. For example, a consumer may want the consumer-oriented part of the system, while the power company does not want the power-company-oriented subsystem, or vice versa. The modularity goal aims to satisfy all situations without forcing extra costs on any party. To do this, the design team will design the system so that the subsystems providing information to the power company and the subsystems providing information to the consumer do not depend on or require each other.

5.4 Present power usage information in a way that is understandable to an average consumer

The goal of the design team is to present the information in an understandable format for the consumer. Because the average consumer does not have an engineering background, the design team would like to display the power usage information in dollars per minute, per hour, per day, per week, per month and per yearly. The system will report these costs in addition to more technical information including voltage, current, power factor and more.

5.5 Minimize on-site maintenance as much as possible

In many cases, the consumer calls the power company to fix something as simple as a tripped breaker, and the power companies waste a lot of time just driving to and from the site. The ability to do work remotely allows the power company to minimize this cost. Remotely controlling or monitoring different aspects of the meter also lets the power company quickly assess if a problem still needs attention. Aggravated customers may also become violent towards power-company technicians, so by having remote access, the power company's employees are safer from these threats.

6 Major Design Decisions

The design team selected two categories or concerns by which to evaluate large design decisions. The first of these is that the project produces a unique product that is differentiable from any commercial product. The second concern is that the project must produce a product that has justified features, not merely innovative ones. This chapter gives a brief summary of these two criteria and a sample of design decisions in which they played a role in reaching the final decision.

The first of the two criteria requires that the result of any design decision must help identify the final product as unique. Several commercial companies produce smart meters and have much greater market influence than a simple one-year project can assert. Therefore, in order to ensure market viability of the project's final product, the product must have unique and distinguishing characteristics, rather than trying to compete in price. This uniqueness should allow the project to succeed commercially. Accordingly, the final product of the project must include features that clearly distinguish it from the existing smart metering options.

6.1 System Design Decisions

No matter how unique or novel a product is, it must still justify itself and prove that it provides benefit to the consumer, to the power company, or even to both. There is a plethora of aspects to consider in defining benefits, but the design team selected six to target in particular:

1. Safety: The feature does not adversely decrease the safe operation of a power monitoring system.
2. Benefit to grid operation: The feature does not negatively affect the grid operation and has the potential to remove wasted grid loads.
3. Dependability: Allows for transparent operation in a way that is functionally identical to what power monitoring system would do.
4. Acceptability of physical size: Acceptability of increasing the physical dimensions of the product to include a feature.
5. Ease of use: The features makes the system easier to use or more accessible with an ideal implementation.
6. Acceptability of financial cost: The feature adds value to the system

While many extra features provide novelty or additional value, the time and budget constraints on the project limit the number and type of features that can be included. As such, a careful and guided selection of features is necessary to arriving at a final product. To assist in making these decisions, the design team created a decision matrix, see table 1, using the criteria listed above to evaluate a set of features that had been suggested for the project. Of the evaluated features, three clearly emerged as essential to the product: the ability to measure total power consumption, the ability for the monitored systems to still use electrical power, and the ability for the breakers to trip on user demand. As nearly every electrical system with a meter and breaker panel already has these features, the threshold of inclusion needed adjusting. By expanding the range of acceptable matrix scores, several more features joined the group of selected and justified test: throttling power availability, tamper detection, power quality monitoring, calculating the current system load, multiphase monitoring (where applicable), and circuit-by-circuit power usage measurements.

Table 1: Design matrix relating features to design norms

Features	Safety	Effects on Grid	Dependable	Size	Ease-of-Use	Cost	Weighted Score
Weight	25	25	25	10	10	5	100
Throttle total power consumption	0.9	0.8	0.7	0.8	0.5	0.7	76.5
Measure total power consumption	0.5	1	1	1	1	1	87.5
Remote power shutoff/lockout	0.6	0.7	0.4	0.7	0.6	0.8	59.5
Remote power reset/unlock	0.4	0.5	0.6	0.7	0.8	0.8	56.5
Distributed generation control	0.5	0.8	0.7	0.7	0.7	0.6	67
Tamper detection	0.9	0.7	0.8	0.9	0.2	0.9	75.5
Alert users in real time	0.8	0.6	0.7	0.6	0.6	0.7	68
Power quality monitoring	0.6	1	0.9	0.9	0.5	1	81.5
Current system load	0.5	0.9	1	0.9	0.5	1	79

Continued on next page

Table 1: Continued from previous page

Features	Safety	Effects on Grid	Dependable	Size	Ease-of-Use	Cost	Weighted Score
Multi-phase monitoring	0.5	0.9	1	1	0.5	1	80
Power "budgeting"	0.5	0.6	0.6	0.6	0.5	0.7	57
Ability to use power	1	0.5	1	1	1	1	87.5
Breaker status	0.6	0.5	0.5	0.5	0.8	0.6	56
Circuit-by-circuit power usage	0.5	0.5	1	1	1	1	75
Remote reset/set/unset	0.3	0.5	0.5	0.6	0.8	0.7	50
Manual breaker shutoff	1	0.5	1	1	1	1	87.5

6.2 Solid-State Breaker Design Decisions

The decision to include circuit-by-circuit monitoring and solid-state circuit breakers also received support from the first criterion, safety. From the sum of the team's research, and by additional affirmation from Consumer's Energy, circuit-by-circuit power monitoring would enter an empty consumer market niche. In other words, a product that provides circuit-by-circuit monitoring would face no competition from other companies, as no other device would have that feature. This realization affirmed the attractiveness of the circuit-by-circuit monitoring as determined by the second criterion, the effect on the electric grid.

6.2.1 Circuit Monitoring and Interruption Design

The relationship between the circuit-by-circuit measurements and the circuit breakers has evolved through several design decisions. The design team went through three primary designs, each listed below:

1. A processor attached to a sensor examines a circuit's current measurements and compare the reading to a pre-determined value. If the measurement exceeded that value, the controller would signal the interruption device to stop the flow of power through the circuit. However, this requirement did not specify the exact method by which to interrupt the circuits, nor how this be functionally distinguished from a standard circuit breaker.

2. The design team decided to enhance a standard breaker by adding sensors between the breaker and the circuit it controls. In this fashion, the design team could rely on standard and proven technology to perform the circuit interrupting while enhancing it with the sensors and electronics needed to collect information and establish a unique functionality. This idea stood for some time before the design team considered how such an approach would affect the total size required for each circuit.
3. The team resolved instead to replace the standard breakers entirely and incorporate both power monitoring and solid-state circuit interrupting in the same form factor as the older parts. Using solid-state breakers eliminates the possibility of electric arcing, which allows current to flow even when the circuit breaker is tripped. In addition, eliminating moving parts should greatly reduce the delay between the time of the current overage and the electrical disconnect that the overage warrants.

6.2.2 Solid-State Circuit Interruption

The design team envisions these solid-state breakers to act and ship in groups, rather than individually. The team reached this conclusion after considering the technical requirements of the components within the breakers and the amount of circuitry involved in handling each breaker individually. The circuit-monitoring components of the solid-state breaker system will require configuration data at power-up, so combining monitors together for joint initialization, data collection, and management by one controller decreases the material cost and complexity. Additionally, as installation of any of these breakers will likely replace most or all of the traditional breakers in a breaker panel at the same time, bundling the circuit breakers and monitors into groups should convenience the installation personnel.

6.2.3 Ethical Considerations

One feature with ethical implications involved whether or not the main electrical meter should have the ability to disconnect the electricity to the building by receiving a remote command from the power company. From the power company's perspective, such a feature saves the cost of labor to disconnect the building from the power lines manually. This doubles as a safety feature: electrical workers will not endanger themselves by working with residential voltage as often, and they will avoid confrontation with aggravated customers who have not paid their bills. The customer, on the other hand, might worry that a system error can occur and cause a complete loss of power because of this feature, even if it slightly decreases the overhead costs that the power companies pass on to their paying customers. The design team decided that the remote shutoff and re-connection feature provides a sufficient benefit to all parties involved to outweigh the risk of a system malfunction removing the power from a building. In addition, other smart meters already include this feature, so excluding it would put the project at a competitive disadvantage among smart meters.

7 E-Meter System Design and Alternatives

The following section examines the E-meter system design at a functional level. Figure 3 breaks down each of the major functional levels of the E-metering system: electronic hardware, mechanical hardware, and software.

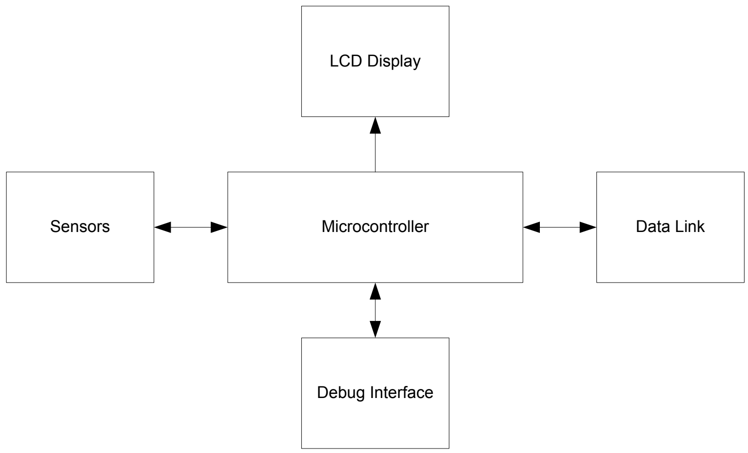


Figure 3: E-Meter functional block diagram.

7.1 Electronic Hardware

At the center of the PICA E-meter is a Texas Instruments (TI) MSP430 processor, specifically tailored for three-phase metering applications. TI constructed the F471xx family of processors to be power efficient, running on 1.8V and drawing 350uA running at 1MHz. The system includes seven 16-bit Sigma-Delta analogue-to-digital converters, six of which perform metering while the seventh can be used for tamper protection or temperature readings. The MSP430 drives a 160-segment LCD display showing the real-time usage as measured in kilowatt-hours. Two LEDs provide visual indication of system status (power and activity).

The team selected two devices as possible candidates for the e-meter, TI's MSP430F47197 and Analog Devices' ADE7763. Both devices support automated meter reading applications and provide the same set of data: voltage, current, active power, energy, frequency, apparent power and apparent energy. The team considers each of these measurements as being critical to an Automated Meter Reading (AMR) system. In theory, pairing an adequate Analog-to-Digital Converter (ADC) with a microprocessor could monitor voltage and current, but the team decided to use a part built especially for metering applications.

Availability of reference designs from both TI and Analog Devices (AD) heavily influenced the team's decision to investigate the MSP430 and ADE7763. The MSP430 product line provides components tailored for single or multi-phase monitoring. The low end of the spectrum TI provides the FE42x2 featuring 1-phase monitoring, and a small Electronic Signal Processing (ESP) engine. In the middle of the playing field, TI provides the F47x4 family featuring 2-phase monitoring only. Neither of these options provide enough capability to acceptably fulfill the requirements set forth in section 4.3. Thus, the team chose to use the F471xx line which provides a significantly improved feature set including onboard RAM, an LCD display driver and a 32x32 multiply function [11].

In order to fulfill requirement [find the requirement and put it here] to support both single and multi-phase metering two analogue-to-digital converters are needed for each measured phase. The ADE7763 Apparent Energy Monitoring Integrated Circuit (IC), contain two ADCs, one for voltage monitoring the other for current monitoring, and associated logic to store any measured or calculated values before transmission. While these devices work nicely for single phase metering, moving to a multi-phase meter requires additional components: a microprocessor and Electronically Erasable Programable Read Only Memory (EEPROM). The application note provided by AD for using the ADE7763 in AMR applications suggest a PIC16C62B processor with a 512x8 EEPROM [4].

The design team used power consumption as one of the criteria for deciding between the ADE7763 and MSP430 based systems. The ADE7763 requires more power than the TI MSP430F47197, requiring a 2.4V reference voltage and a 5V power supply [12]. By comparison, the TI MSP430F47197 runs on a 1.8V power supply with no external reference voltage [11].

In order to verify accuracy and proper metering, any metering device must undergo a calibration process. This calibration process includes removing any significant offset from the measurement and setting the gain of any gain-stage. Because the MSP430 integrates all of the components needed for an AMR application, the calibration happens entirely in software. By contrast, the ADE7763 requires some initialization data, loaded by a microprocessor over its Serial Peripheral Bus (SPI) bus [4].

ANSI codes C12.19 [8] and C12.21 [9] require that any electronic metering device display the instantaneous usage at the local metering unit. To accommodate this, the LCD display on the E-meter refreshes after every measurement to show the updated instantaneous usage, cumulative usage, and system status. In order to be compliant with FCC Title 47 part 15 [10], regarding low-power radio transmissions from electronic equipment, only parts built in compliance with this statute will be used in the design.

Attaching current transformers to each phase of the line voltage allows the E-meter to monitor the current draw from each phase. The hot and neutral lines of each phase pass through the meter to allow for measurement on each phase. The wiring inside the meter that passes through the current transformer must be capable of handling 10-15A current draw of the installation; thus, #4/0 wiring is used for any line voltage. Similarly, a resistor and capacitor network provides input to measure the voltage on each of the 3 phases. Figure 4 describes a high-level overview of the E-meter system centered around the MSP430F47197.

As the E-meter collects data, it transmits the data to the MCU which sends it to the PICA base station or the utility company via a customizable interface which supports Zigbee radio, Ethernet, and serial RS232 communication protocols. The MSP430 provides support for all of these communications directly with one exception; Ethernet requires an extra microprocessor and hardware to handle the TCP/IP protocol.

In an eventual production unit, Zigbee radio can provide the most bandwidth and longer range transmission of data back to the utility company. Additionally, the RS-232 interface may disconnect to prevent tampering with internal settings.

7.2 Mechanical Hardware

7.2.1 Line Attachment Hardware

The E-meter system provides six screw-terminals on the base of the unit for connecting the differential output of the current transformers. Likewise, four screw-terminals connect the three phases and neutral lines to the meter input networks.

7.2.2 Enclosure

In order to protect the E-meter components from the outdoor environment the system must be enclosed in a weatherproof case. The E-meter enclosure is composed of ABS, a heat resistant plastic. Plastics ensure that a loose wire cannot energize the case while still providing the durability of many metals. The case design allows for easy mounting on a variety of surfaces using standard fasteners and allows for access to the user interface controls.

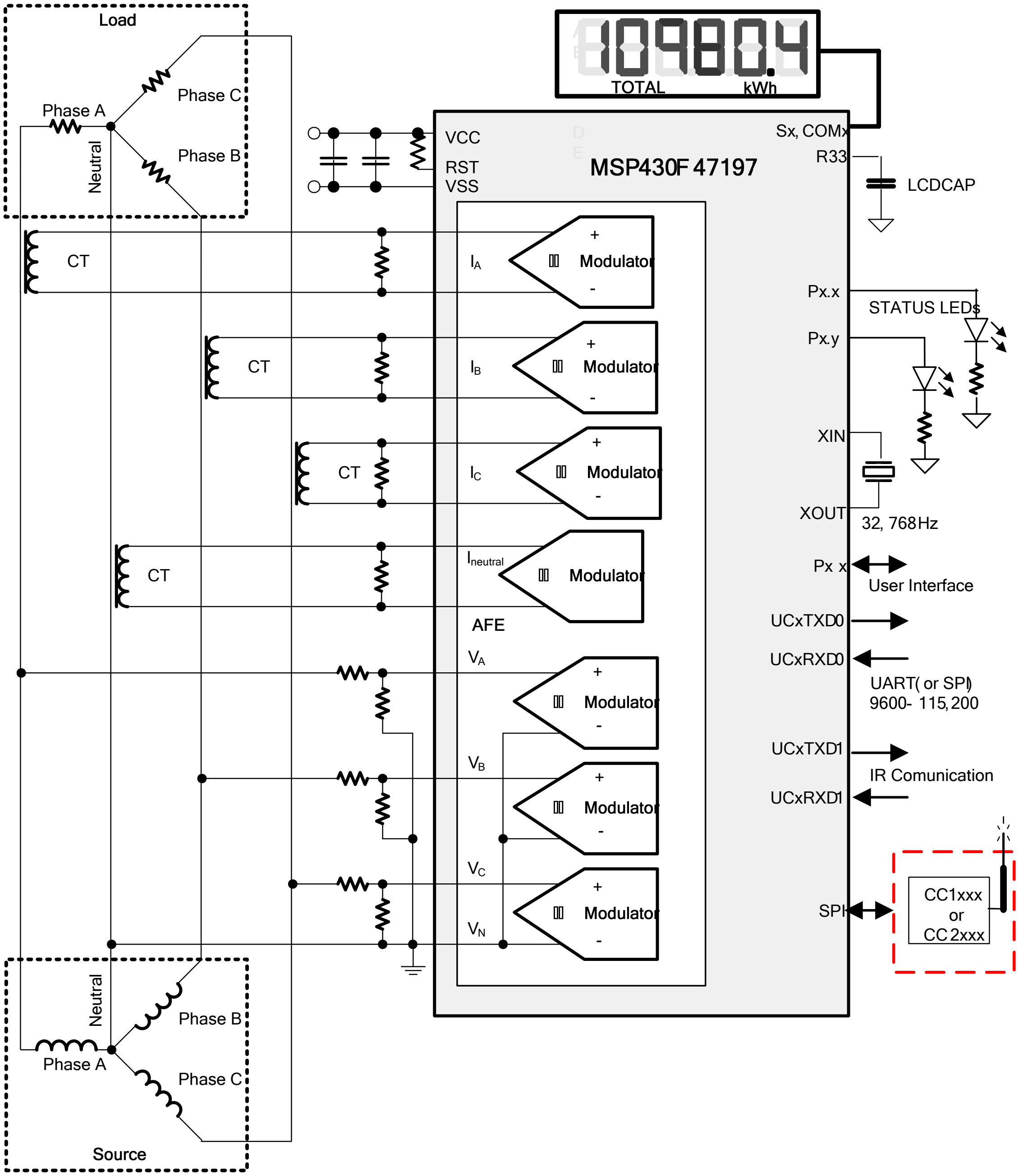


Figure 4: MSP430 system as shown in TI application note slaa409 [1].

7.2.3 UI Hardware

The E-meter provides two push buttons for changing the displayed contents of the built-in LCD screen. A closable lid protects the push buttons from the weather, as the power meter must be mounted on the exterior of the building. To prevent rain from entering the case, a protective rubber weather seal installed around the edge of the lid creates an air-tight seal. A protective glass window covers the LCD display. The design team chose glass because it can resist yellowing and remain transparent for a longer time than plastics when exposed to extreme outdoor temperatures.

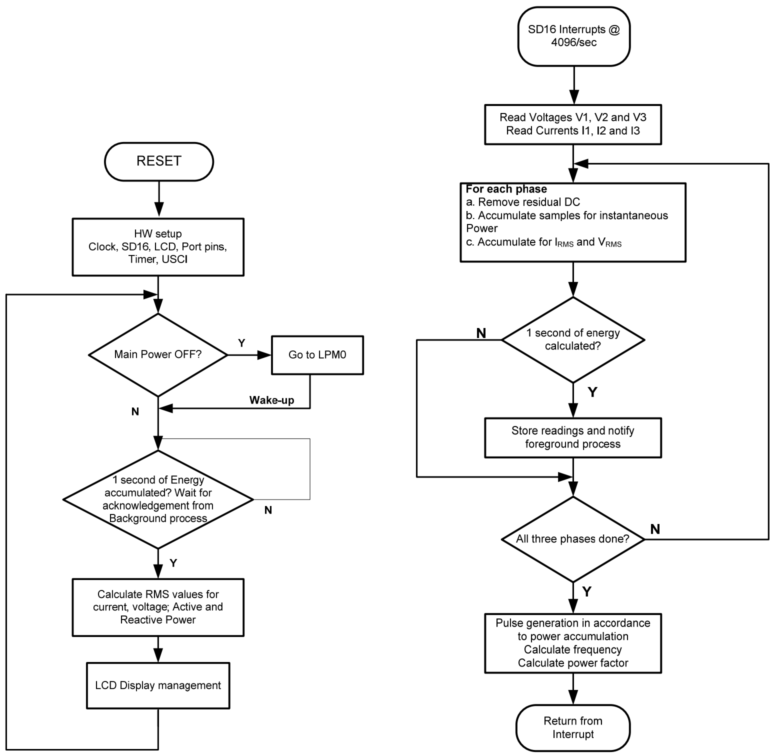
7.3 Software

7.3.1 User Interface

The user interface for the E-meter consists of two push buttons and a 160 segment LCD display module. The MSP430 chosen for the microcontroller in the E-meter supports up to a 160 segment LCD display, a larger display relays more information to the user than would a smaller display. The initial prototype includes an RS-232 port capable of interfacing with Personal Computer (PC) software to load configurations and monitor internal dataflow.

7.3.2 Monitoring Algorithms

The background monitoring algorithm inside of the MSP430 microcontroller take measurements from the seven Sigma-Delta ADCs containing current and voltage data. Then for each monitored phase, the E-meter removes any residual DC offset present in the measurement, accumulates samples for instantaneous power measurements, and accumulates I_{RMS} and V_{RMS} computations. This algorithm will monitor for 1 second, storing each reading in onboard memory; then after 1 second of collecting data, generate an interrupt to the main process, calculate frequency and power factor, and transmit all data to the foreground process. A flowchart for this process, the background process, can be seen in figure 5b. The foreground, flowchart in figure 5a process then updates the LCD display, calculates values for Root Mean Square (RMS) current and voltage, and calculates active and reactive power, and finishes by transmitting all data out over the Ethernet link before waiting for a new interrupt from the background process.



(a) Foreground process (b) Background process

Figure 5: Software flowcharts [1].

8 Solid-state Breaker Monitor and Controller Design and Alternatives

The breaker monitoring system has four primary functions; it must automatically control the breakers and it must handle control commands for the breakers given through the MCU from the base station. The system must also provides circuit level information to both the breaker box indicators and to the base station through the MCU, and it provides an interface for giving control commands directly to the breakers. Figure 1 shows the basic parts of the system. The display and controls represent the direct user interface while the communication to and from the MCU represents the user interface through the MCU/base station. The monitoring chip represents the chip and circuitry used to sample the voltage, current, etc. of the connected circuit. The breaker is not directly part of the system, but the diagram shows it because the system interacts with it on several different ways. The controller represents the processing core used to properly direct information between much of the system.

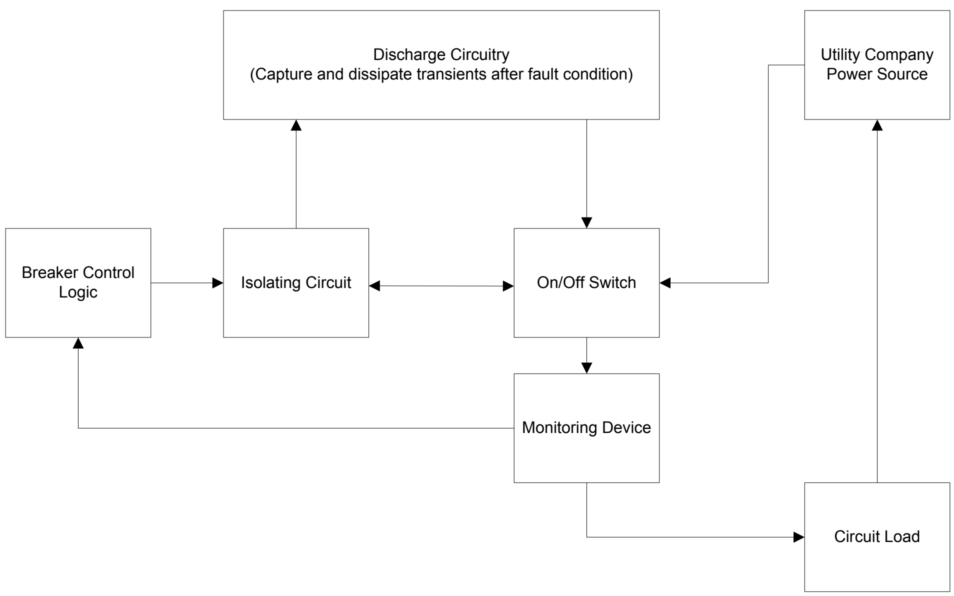


Figure 6: Functional block diagram of the breaker system.

8.1 Design Process

For prototyping purposes, cost, availability and compatibility are the major criteria for design decisions. Because the prototyping budget is limited to $750, low cost is a significant design criterion. Availability is a significant factor in deciding parts because of the time constraints imposed by both Engr. 339 (Senior Design) and Engr. 315 (Control Systems). The breaker monitoring system is a project in Control Systems, scheduled for completion by the week of 06 December 2010, so the team cannot wait more than a couple weeks for parts to ship or it delays the project and too many things become crammed together at the end of the semester. Compatibility is an important criterion for selection because if part of the system does not work with another part, the purpose of the prototype is invalidated.

For prototyping, ease of use for the designer, low supporting part count and flexibility are also criteria used in choosing parts. Parts that are easy for the designer to use require less time to integrate into the system, and as time is limited, this is highly beneficial. Parts that require many supporting parts are not ideal because having more parts increases the chances that a part will not ship in time. A part's functional flexibility is desirable because as the project progresses, the design will change. A flexible part can change to fit the new design instead of needing to order new parts, presenting cost and availability issues.

For production purposes, cost, ease of use to the consumer, size and reliability are the major criteria. A part must be inexpensive so that the final cost of the product is competitively marketable. As the consumer will interact with the system more than the designers will, using parts that make the system easier to understand from the user's perspective are beneficial, even if it makes the actual design process more difficult. Size is important because the final product must be able to fit inside the breaker box as specified by the requirements. A part should be reliable to minimize maintenance and replacement costs to the consumer.

As the system depends on its ability to monitor the circuit to automatically shut off and provide information to the base station, the monitoring chip was the first prototype part chosen. The controller is critical to the system's ability to perform all of its functions, but it is easier to pick a controller to match a monitoring chip than to pick a monitoring chip to match a controller, so the controller selection was second. Less rigid requirements for the communication to the MCU allowed the team to select parts for that last. Selection of the breaker box indicators and controls were independent of the other functions because as a backup interface, they are standalone components.

8.2 System Components

8.2.1 Monitoring

The purpose of the monitoring part of the system is to give relevant values measured on the connected circuit to the MCU. It may do this directly or through some sort of processing core. Relevant values

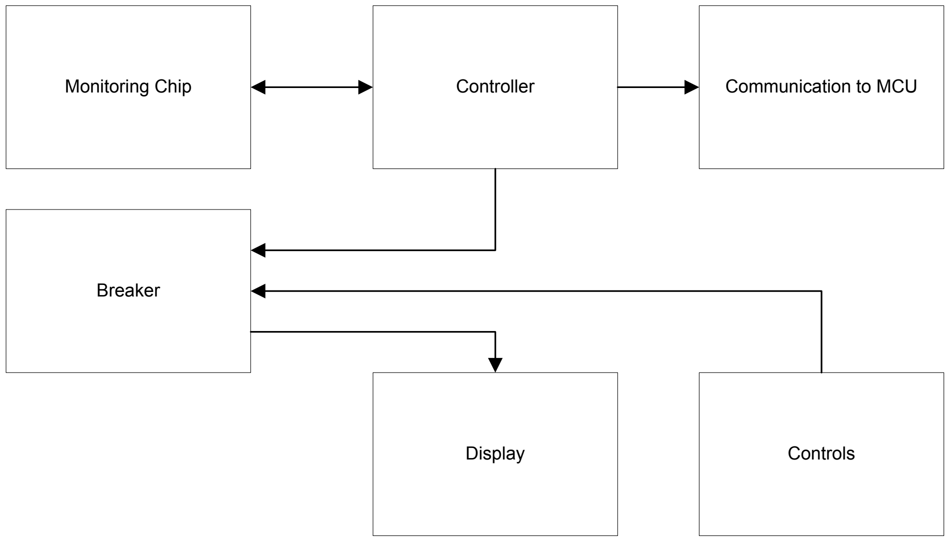


Figure 7: Functional components for the breaker monitor.

include at a minimum the voltage, current and frequency of the connected circuit. If a chip can provide other measurements including, but not limited to, power factor, reactive power and peak values it may be beneficial, but is not necessary as a processor core can calculate all of these from the known instantaneous voltage and current.

The Analog Devices ADE7763 chip works well for the prototype design because it measures the minimum relevant values and free samples of the chip are available. This was an acceptable choice because it fit the two major criteria of cost and availability. Because the monitoring part was the first selection, compatibility was not as much of a concern as for other parts of the monitoring subsystem.

The team is still analyzing and selecting full-scale production parts. The ADE7763 chips will cost $1.61 per part [13]. In addition to the minimum relevant values, it can calculate reactive power, power factor and peak voltage (ADE7763 datasheet). The Cirrus Logic CS5463 chip measures the minimum relevant values, along with instantaneous power, I_{RMS}, V_{RMS}, real power, apparent power and power factor. It uses a serial interface and cost is $2.47 per part [14] [15]. The Teridan 78M6612 chip costs from $3.00 per part to $3.61 per part [16] and includes an MPU core, embedded memory and external interface [17]. The HVQFN33 from NFX also comes with a processor and memory, and costs from $1.50 per part to $3.00 per part [16].

Table 2: Comparison of monitoring chips.

Part	Supplier	Extra Features	Cost
ADE7763	Analog Devices	Reactive Power, Power Factor, Peaks	$1.61
CS5463	Cirrus Logic	Instantaneous power, Real Power, Apparent power, Power factor, RMS current, RMS voltage	$2.47
78MM6612	Teridan	Includes MPU core, embedded memory	$3.00 to $3.50
HVQFN33	NFX	Includes processor, memory	$1.50 to $3.00

8.2.2 Controller

The purpose of the controller is to manage data transfer from the monitoring chip to the MCU, to control the breakers automatically and to initialize components as necessary. The controller is the part that detects when the current through the connected circuit is above the specified threshold and automatically shuts off the breaker. When requested by the base station (through the MCU), it should be capable of shutting off and resetting the breaker. The controller is independent of the at-the-box display and controls.

For the purpose of prototyping, the team chose a generic Field Programable Gate Array (FPGA) because it provides more benefits than a microcontroller does. The primary design criteria include compatibility and flexibility. While a microcontroller typically runs modifiable software, designers can reconfigure an FPGA to represent an entirely different hardware design in addition to software-like behavior. The FPGA is therefore still usable even when significantly redesigning part of the system. A microcontroller may be able to modify its software to work with a different monitoring chip, but because of the many different designs of both microcontrollers and monitoring chips, the chances the microcontroller will still be able to work well with the chip are smaller. The time constraint does not allow time to be wasted figuring out if the parts can work together. An FPGA also fit the criterion of availability, as they are common and easily obtained in a variety of sizes. The team is familiar with programming an FPGA, so the ease-of-use-to-the-designer criterion is also applicable. In several cases, a microcontroller requires external memory instead of building the memory in like an FPGA does. Cost is the criterion that an FPGA does not satisfy as FPGAs considered cost about $20 to $40 [18] while microcontrollers generally cost less than $10 [19] [16], but can be justified as the flexibility it offers is highly beneficial for development.

For the purposes of full production, an FPGA is not a likely option due primarily to the higher cost. Also, the benefit of flexibility that an FPGA offers will not be applicable as the design should not have to be changed after the system board has been produced. The team has not chosen a specific microcontroller, and needs to do more research, but options include the NPX HVQFN33 and the Teridan 78M6612. The final choice of monitoring chip will significantly affect the controller decision as several chips including the HVQFN33 and 78M6612 come as a processor and monitor combination. As these likely can perform all of the functions required of the system controller, the choice would be simple. Cost will still be considered, but as the cost per part only varies up to about $5 [19] [16], it is not as big of a factor as the choice of monitoring chip.

Table 3: Comparison of controllers.

Part	Supplier	Extra Features	Cost
FPGA	Digikey, Mouser	Very flexible	$20 to $40
78MM6612	Teridan	Includes MPU core, embedded memory	$3.00 to $3.50
HVQFN33	NFX	Includes processor, memory	$1.50 to $3.00

8.2.3 Communication

The purpose of the communication part of the system is to transmit and receive data to and from the controller and the MCU, which acts as a buffer between the controller and base station.

The team considered communication through a wireless connection (either wireless or ZigBee) because it allows greater flexibility in placement of the MCU. However, both wireless and ZigBee take up a large amount of space. This would violate the production design criteria for space, and would be unnecessarily complicated, causing costs to go up as well. Serial communication was another prototype option because the ADE7763 chip interfaces directly over serial [12], eliminating the need for extra processing power, therefore simplifying the design and decreasing the chance something will break. Cost of serial is also low, which is good for both prototyping and production, and it requires very little on-board space. However, ethernet is the option chosen for communicating with the MCU. Ethernet is a common option [20], making it easy to obtain parts and is inexpensive, keeping to the cost design criteria. One possible drawback the team is looking into is that ethernet sometimes requires enough board space that it may be difficult to fit inside a breaker. A big benefit to using ethernet is that it is easy to connect many breakers to the MCU. This is beneficial because even a small apartment, such as those at Calvin, can have seven breakers, meaning the MCU must connect to and keep track of four or more different breaker sets.

Table 4: Comparison of communication options.

Part	Supplier	Cost	Other
Wireless	Digikey	\$13 to \$32	large board space
Zigbee	Zigbee	\$2.73 to \$12.92	large board space
Ethernet	Digikey	\$3.80 to \$30	common, easily connects to many devices
Serial	Digikey	\$3.80 to \$7.00	Easily interfaced with monitor chips

8.2.4 Display

The purpose of the display is to present information relevant to the breaker. This includes on/off status for both the breaker and connected circuit and indication of when data transfers to the MCU. Knowing information for both the breaker and circuit is important in determining if the breaker is working properly. Indicating data transfer shows that the system is working with the rest of the PICA system. While all of the information is available through the base station, the safety criticality of knowing the breakers' status led the team to include multiple backup options for displaying this. Including this display also helps meet the goal to make the system modular because the breakers do not require the base station or MCU.

The three criteria for the display are that it must be easy for the user to read, it must be reliable and it must have a short critical path from the power line to display. The display is not easy to read if there is no information displayed, so the display must be capable of showing information for all the breakers in the box. As part of the last defense for shutting off current, it must be trustworthy, and users must be able to easily understand it. Ideally, users will never have to use the breaker box display as the base station can display all of the information. However, if they do have to go to the breaker box, they will likely be under stress so the display must be simple to understand since studies show that the ability to understand a complex situation significantly decreases [21] [22]. Often, the last defense is the most reliable [23], and one of the easiest ways to make something more reliable is to lower the number of points of failure by lowering the number of parts in the critical path.

The team considered two configurations for displaying information for all breakers; breakers could each have their own display or multiplex all breakers to a single display. To display information, the team considered LCD screens and LEDs. LCD screens are beneficial because they can very easily give information in clear written language and instantaneous power usage. A 20x4-character LCD screen costs about $25 [18] and has a 5V supply. It would also require a controller to convert the information before putting it to the display. For this reason, the team decided that an LCD screen would be most effect only for a single display. Numerically meaningful information including instantaneous power usage is difficult to display with LEDs, but for basic on/off and above/below threshold information, different color LEDs can be very effective. However, given the multiplexed single display, they do not give any indication as to which breaker they connect to, putting them at a big disadvantage when using that configuration. Cost is a benefit to LEDs as each one only costs between $0.50 and $1.50, depending on brightness and color, and as LEDs can be easily integrated into the design for a breaker, they would work well in the first display configuration.

The team chose to display information on a per breaker basis, using LEDs as indicators due to reliability since they have a shorter critical path from the power line to display. Another factor is that if a single display is used, the consumer must scroll through all of the breakers to find the breaker to turn off or reset. In the case of turning the breaker off, this is a problem because the consumer likely needs to do this as fast as possible. The team decided that providing instantaneous usage in the breaker box was not as important as providing critical information fast.

Table 5: Comparison of display options.

Part	Supplier	Cost	Other
LED	Digikey, Mouser	$0.50 to $1.50	Minimum of 2 colors
LCD	Digikey, Mouser	approx $25	20x4 char, needs external controller

8.3 Breaker Box Controls

The purpose of the breaker box controls is to provide a way of shutting off and resetting the breakers. Ideally, the system will automatically turn the breakers on and off, or the base station can perform these functions, but as the breakers are a safety critical feature of the system, the team wished to add yet another method since no system is perfect. Like with the breaker box display, these controls help meet the team's goal to make the system fully modular.

The three criteria for the controls are that it must be easy to use, it must be reliable and it must have a short critical path to the power line. As part of the last defense for shutting off current, it must be trustworthy, no matter what situation. Ideally, the user will never have to go to the breaker box controls, as the system should handle the overcurrent situation automatically. However, there is no guarantee of this, so for reasons stated above under the breaker box display section, the controls must be simple. In addition, as with the display, shortening the critical path is a good way to lower the possibility of failure.

The team considered the same configurations for the controls as for the display, where controls could be on a per breaker basis or a single set of controls de-multiplexed to all of the breakers. The team chose the controls per breaker option mainly because it allows for a shorter critical path and is more reliable. For a set of controls to be de-multiplexed, the system must include another controller and the system must remember which breakers are on and which ones are off. This is generally something that memory can handle very easily, but putting a switch directly in the path of the control line to each breaker, eliminates the need for memory altogether. The team considered using push buttons and slide switches. Push buttons were eliminated primarily because of cost and the risk of the user double tapping the switch. The time needed to scroll through the breakers for display purposes is also relevant for the controls. Exact implementation is unknown, but the control panel will have the ability to override the automatic and base station breaker controls.

Table 6: Comparison of breaker control interface.

Part	Supplier	Cost	Other
Switch	Digikey, Mouser	\$0.38 to \$2.00	No double tap
Button	Digikey, Mouser	\$7.00	Potential for double tap

8.4 Breaker Box Control Panel

The team considered putting both the breaker box controls and display in a control panel to isolate the high voltage areas of the system. Because the controls and display both use comparatively low voltages, the user would not be as exposed to danger from electrical shock. This is beneficial because part of the overall goal of the system is to keep the consumer safe. However, as the team decided to use controls and displays on a per breaker basis, using a control panel would require the control panel to accommodate as many or more breakers as the breaker box. Since there is little convention for the number of breakers a breaker box holds, this is difficult to accurately gauge and it is likely there will either be too few or too many sets of controls and displays. Instead, the team decided to integrate both the LED display and control switch into each breaker because it then is very clear which set of controls is associated with each display. It also makes it easier to add breakers into the system after initial installation.

9 Solid-state Breaker Design and Alternatives

The Solid-State Breaker design will have three main parts, an isolator circuit, a discharge circuit, and an interrupter circuit seen in figure 8. The solid-state breaker section will act as the switch, capable of interrupting the flow of current. A sensor measures critical information about the power signal, which a controller uses to interrupt power on a circuit. The controller also transmits the measured data to the MCU over an Ethernet link.

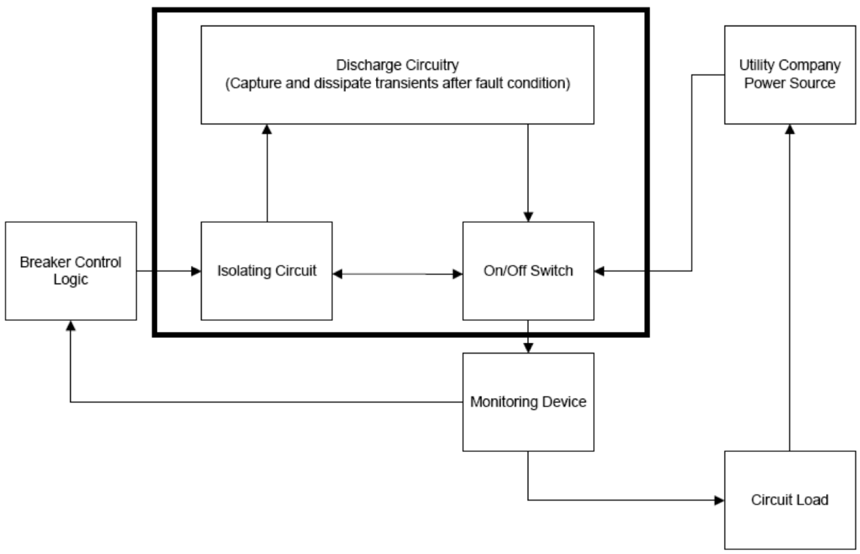


Figure 8: Functional block diagram of the solid-state breakers.

A standard United States home uses two voltages, 120VRMS and 240VRMS, to support this the solid-state breakers require 2 models. Standard circuit breakers for home use are rated for either 10 or 20 amperes. Thus, for each voltage level, 2 overcurrent ratings are required. This brings the total number of models of circuit interrupt to 4, summarized in the table below.

The requirements section outlines the specifics regarding system functionality. The most important requirement is that once the current rises to an unsafe value the circuit interrupter trips stopping current flow. Additionally, the circuit interrupter must be reliable and safe to operate. If possible, the design team desires to keep the cost of the replacement circuit interrupters and associated controller comparable to a standard circuit interrupter system. However, if added functionality pushes the cost higher it is acceptable.

For safety reasons, the current controller must also be able to stop the AC current flow through the device. If too much current is flowing through a circuit, the wires can overheat, causing a fire. When the current reaches an unsafe level, generally considered as 10% of the interrupter rating, the controller sends a signal to open the circuit. In order to effectively control the circuit interrupter, the control signals require isolation from the (relatively) high voltages in the interrupter circuit. Research has shown that many circuit interrupters use optocouplers to this end.

Both overcurrent and overvoltage can cause damage to electrical devices attached to a circuit. However, many devices can withstand a small spike for a very short period time. Because of this the design team is aiming for the fastest circuit interruption possible. Solid-state devices lend themselves nicely to speed requirements as their switching capabilities greatly exceed that of a mechanical lever. The use of solid-state devices brings about another concern part fatigue over the life of the components caused by the on/off cycles. With this in mind, the team has added a discharge network to catch and deplete any transients caused by the rapid disconnection of the circuit load. Such a network should prolong the life of the components. A standard mechanical circuit interrupter is rated to last 10 years, PICA circuit interrupters should last at least as long, if not longer.

The team considered keeping the standard mechanical breakers, but adding a monitor wrapper to gather data. However, after meeting with Consumer's Energy decided to move to a controllable circuit interrupter. The technicians the team spoke with expressed that the ability to remotely switch breakers on or off would provide a substantial cost savings in terms of labor hours for turning service on or off to buildings. While mechanical breakers could be augmented with devices to set or reset the breaker from a remote signal, the team questioned the size of implementation and practicality of such a design. However, this decision may limit the customer base of the PICA system by requiring all circuit interrupters to be replaced.

9.1 Component Selection

Several solid-state components have shown promise for replacing mechanical circuit breakers: power MOSFETs and Thyristors. Thyristors come in several different types: silicon controlled rectifiers (SCR) and the triode for alternating current (TRIAC). An SCR is a unidirectional thyristor and a TRIAC is a bidirectional thyristor.

Two SCRs in inverse parallel will create a TRIAC.

Typical SCRs have a high current and high voltage rating, meaning finding components capable of functioning with 15A and 117VRMS should not be difficult [24]. SCRs characteristics state that for each ampere conducted 1.5 watts of power are emitted [25]. As PICA circuit interrupters are required to conduct

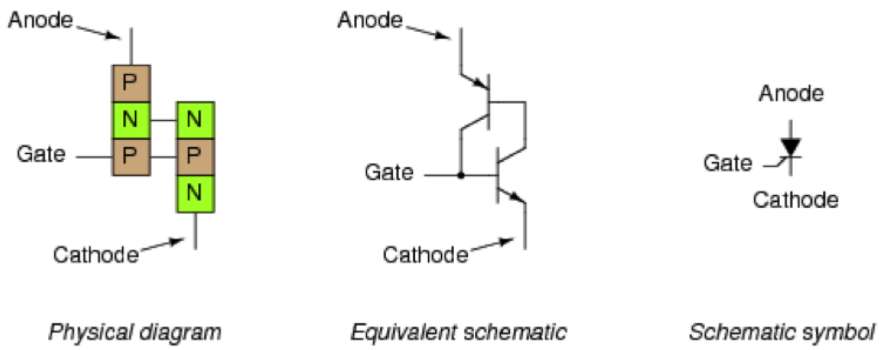


Figure 9: SCR diagrams

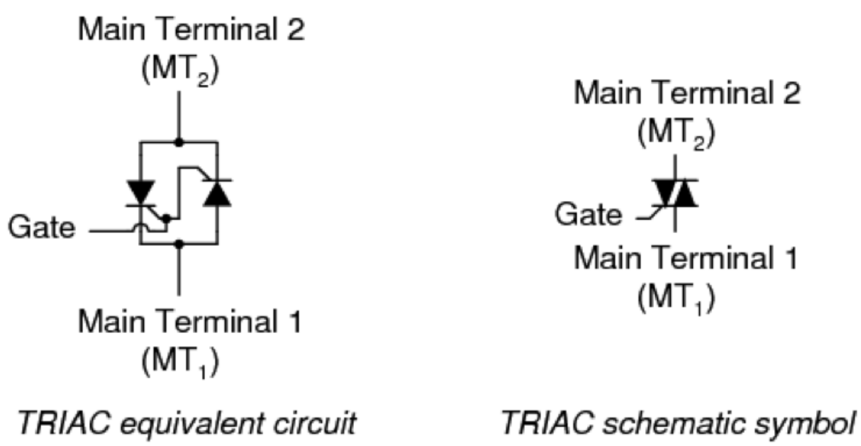


Figure 10: TRIAC diagrams

15-20A, the amount of energy dissipated will be 22.5-30W of energy [25]. This will require a heat sink to keep the SCR from melting. A downside of designing with SCRs is that it cannot be directly turned off, only prohibited from starting up again at the beginning of the next phase. A gate turn off (GTO) thyristor solves this, however is rated for lower current flows than an SCR [26].

The strengths and weaknesses for SCRs are the same as for TRIACs, except that TRIACs are bidirectional. For an SCR on an alternating current feed, current can flows through an attached load resistor for half of the input cycle. Replacing an SCR with a TRIAC allows current to flow through the load resistor during both halves of the input cycle [2]. The figures shown below are examples of these cases.

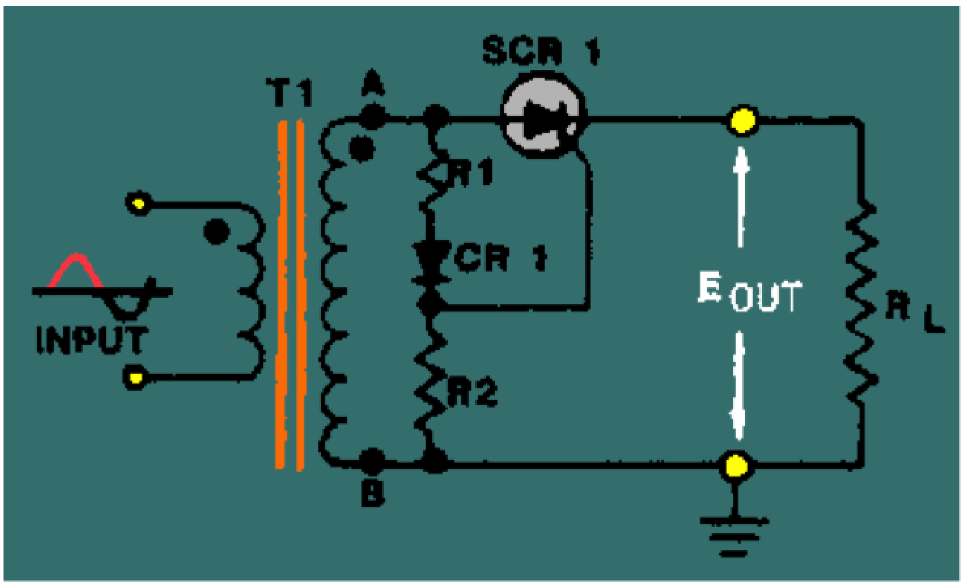


Figure 11: SCR circuit [2].

The design team is also considering power MOSFETs, because they are designed to handle significant power levels. In comparison to other power semi-conductor devices, power MOSFETs features higher commutation speed and higher efficiency at voltages lower than 200V. The isolated gate on a power MOSFET makes it easy to use these devices as a switch, as only a small voltage is required to drive the gate. Members of the design team have more experience working with MOSFET circuits than with thyristor circuits.

Power MOSFETs provide the switching characteristics necessary to shut off power to a circuit. The voltage on the load will also have to be 117 volts RMS, since the source terminal of the MOSFET is attached to the top of the load. The figure shown below is an example of what this could look like.

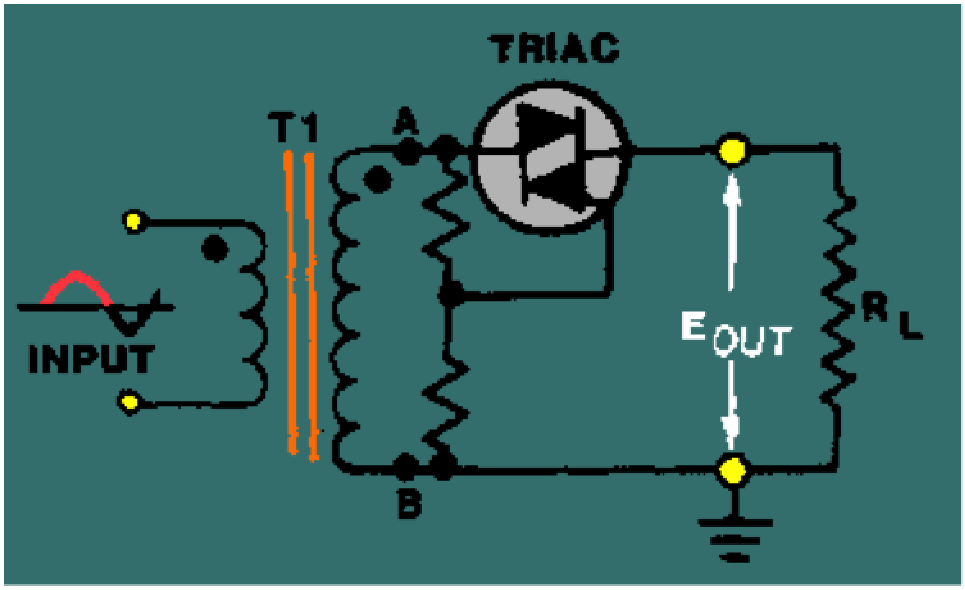


Figure 12: TRIAC Circuit [2].

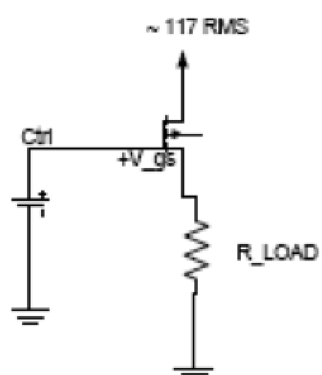


Figure 13: MOSFET interrupter.

9.2 Analyzed Designs

Figure 14 shows a circuit provided by Micrel for a solid-state breaker device based upon their MIC5013 chip. The team noticed that the given design is constructed for DC circuits whereas the PICA system controls AC circuits. Thus, the design from Micrel did not meet the team's specifications and was eliminated as a potential design.

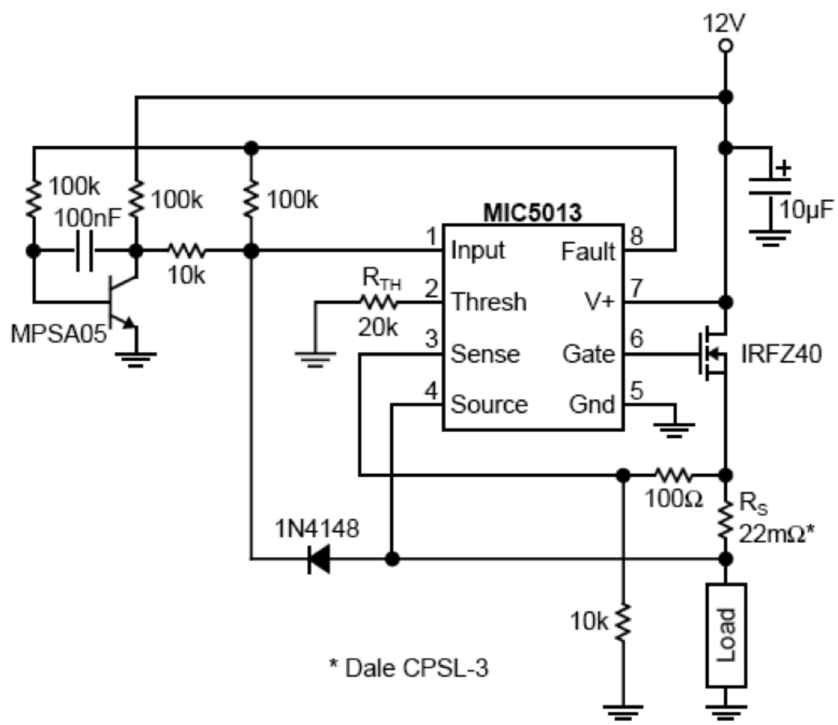


Figure 14: A solid state breaker design from Micrel using a MIC5013 IC [3].

Figure 15 shows a solid-state breaker design by David Johnson of David Johnson and Associates using a TRIAC to control 600 watts of power [27]. The team considered making changes to push the power rating up to 1800 watts. Where the defining equation is:

$$Power = Current \times Voltage \tag{1}$$

where voltage is that of a typical power outlet of 120V and current is from a typical breaker threshold of 15A). Reverse-engineering this design has provided information on designing with thyristors.

The controller will need to be isolated from voltage or current spikes that are associated with rapid shut on

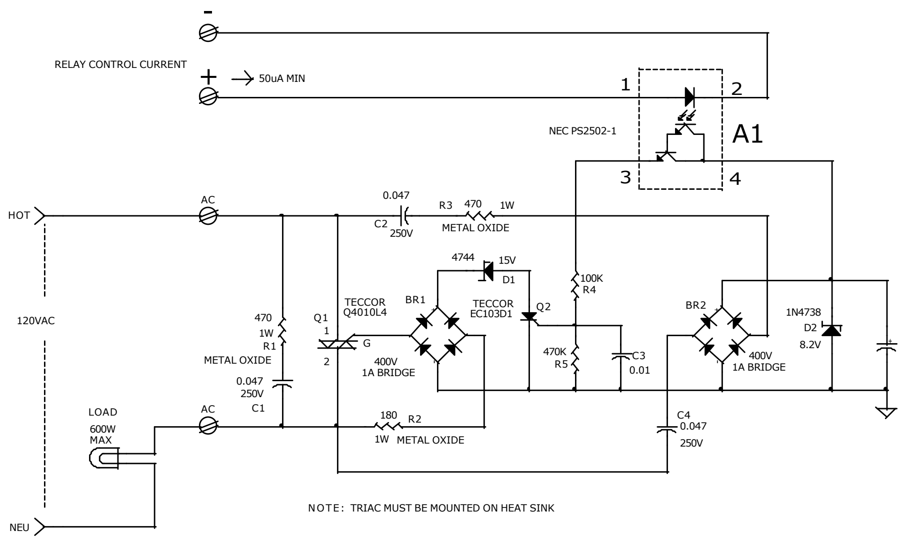


Figure 15: Solid-state breaker design using a TRIAC from David Johnson and Associates.

and off. An optocoupler achieves the goal of controller isolation. The control signal is applied to one side of the device, which using light transmits the signal to a receiver on the other side reproducing the signal but without any electrical connection between the two halves of the component.

Table 7: Summary table of components.

Component	Pros	Cons
Mechanical Breakers	Proven design, already used in homes, no need to replace	No remote shutoff, has air-gap, slower response time
SCR	High current, high voltage	No shutoff until current stops, requires heat-sinks
TRIAC	High current, high voltage, bidirectional	No shutoff until current stops, requires heatsinks
Power MOSFET	High current, high voltage, have resources describing use	Gate and source voltage restrictions

Before making a final decision on which technology discussed in this section provides the best solution the design team plans to perform additional analysis. This includes a transient analysis of a feeder line when going from steady state to open-circuit conditions and modeling how a MOSFET based device would function as a circuit interrupter.

10 Base Station Design and Alternatives

The primary function of the base station is to collect, archive, and display usage information from other subsystems. To accomplish this function, the base station requires mechanisms by which to connect to the other subsystems, collect their data, process the data, store the data, and display the data.

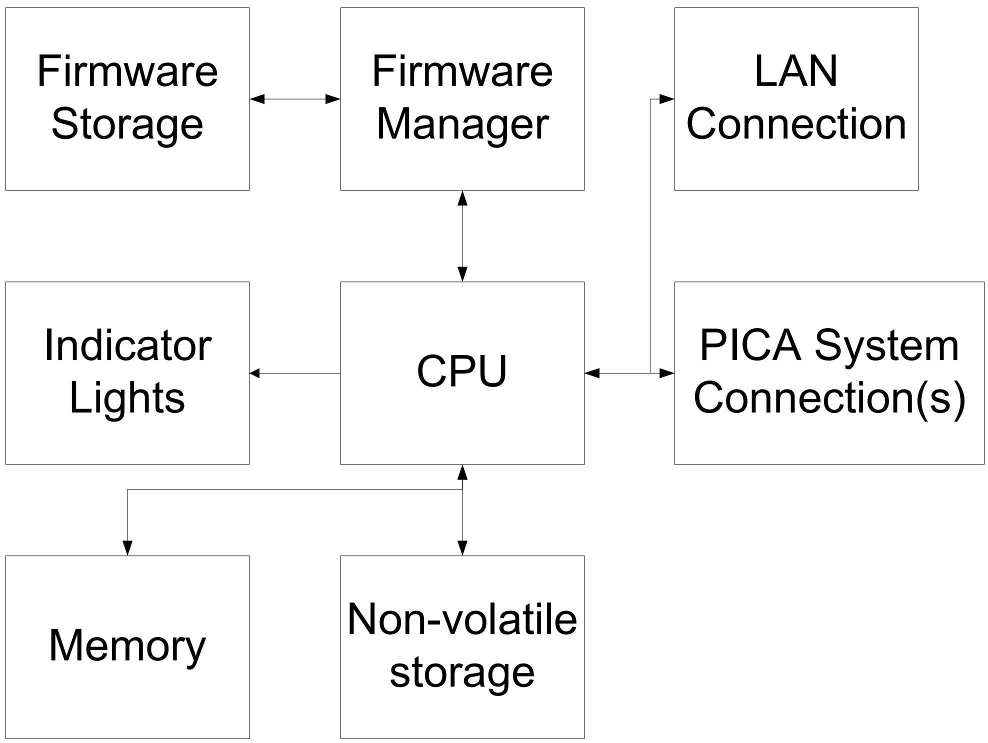


Figure 16: Base Station functional block diagram

10.1 Connectivity

In order to gather data from other subsystems, the base station requires the ability to create and configure connections with the other devices. As the design team is not designing the overall system with a particular house or building in mind, these connections must be flexible concerning the physical locations of the subsystems and must not assume that a medium of connection, such as a wired network, already exists between these two points. To minimize the invasiveness of installation, a wireless connection provides the best solution, as it requires no additional materials beyond the devices themselves in order to convey data from point to point.

10.1.1 Wireless Protocol Selection

The design team selected the low-power mesh-networking protocol ZigBee (International Electrical and Electronics Engineers (IEEE) 802.15.4), rather than the more conventional Wi-Fi (IEEE 802.11) protocol. Many other common protocols could be used, as could a new proprietary method, but in the interest of reliability and fast design time, options such as Bluetooth, Radio Frequency Identification Device (RFID), and Code Devision Multiple Access (CDMA) do not fit the project goals. Although Wi-Fi technology is plentiful and familiar to a large part of the population, this makes it somewhat insecure, as a great many devices that can collect the data packets sent between the PICA system devices. This vulnerability could potentially breach the consumer's expectations of privacy and raise doubts as to the trustworthiness of the PICA product. ZigBee devices are considerably less common and are usually single-purpose devices, so a device with the ability to capture and analyze ZigBee packets in the same way a computer can with Wi-Fi packets would be much more uncommon. In this way, ZigBee provides security by obscurity, which Wi-Fi cannot. Wi-Fi does offer encrypted network connections, which can greatly increase the difficulty of data extraction, but this encryption also increases the difficulty of configuring the connection between the various subsystems. Likewise, the ZigBee protocol allows for encrypted connections between devices by exchanging encryptions keys, which would again increase the complexity of setup, unless such exchanges do not require a human to visit the individual devices.

10.2 Data Transfer

Once the different subsystems have connected to the base station, the base station must collect their measurements and notifications. In theory, this should be a simple process after establishing a ZigBee connection; the devices would simply send their data over the ZigBee mesh to the base station. One issue is that unlike Wi-Fi, the ZigBee protocol meets its reduced power requirements by transmitting intermittent bursts of information, which restricts the flow of the time-sensitive measurements. Although the client devices determine the required rate of data transfer, the base station may not be able to acquire every measurement from every device in real-time over the ZigBee mesh. That is, even though a measuring device could take thousands of measurements per second, it might not be able to transmit all of them within the narrow bandwidth of the ZigBee protocol, which can range from 1200 bps to 250 kbps[28]. The ADE7763, in particular, measures several quantities as 16-bit numbers with a sampling rate of 16kHz. If eight such quantities are to be transmitted for each sample, the resulting dataflow would amount to 2Mbps, which exceeds the maximum ZigBee speed. Using Wi-Fi would get around this limitation, as raw data transfer speeds can reach beyond 50 Mbps using the common 802.11g standard, which, even with the overhead of packet addressing, error correction, and other protocol data, should provide more than enough bandwidth for these purposes. but ZigBee should still facilitate communicating hundreds of samples per second, which should be more than enough for archiving and displaying the information.

10.3 Data Processing

After collecting data from the other subsystems, the base station must process the information before making it available for display and review. A wide variety of processor hardware and software would fit this purpose, as would many different kinds of storage media.

10.3.1 Software and Operating Systems

In order to provide the flexibility and expandability of the base station functionality, the base station should run an operating system that a software developer can design and test on other machines as well as on the base station. The design team members who are familiar with Linux select Linux to serve as the base station's operating system, as it is readily configurable and, with the proper tool-chain, allows the software developer to compile and test the software on a different machine. Linux is also a popular choice for running web-serving software and manage wireless networks, both of which are critical to the base station's functionality. Additionally, Linux, through cross-compilation, can run a wide range of processor architectures, which does not restrict the hardware selection based on the software decision.

Including Linux and its associated utilities with the base station, however, presents a legal obstacle: the software is licensed under an assortment of open-source licenses. While this means that the design team may use and modify the pre-existing source code to this software, it also requires that any and all freedoms available to the distributors of the software also be available to the users, at least in the case of the commonly-user GNU General Public License (GPL)[29]. This does not require that any PICA-produced Linux code must be distributed free-of-charge, but rather that the users who receive the operating system will have a right to acquire and redistribute the source code and the modifications specific to the copy they received. As the users are free to redistribute and change the source code as they desire, the project will gain little financial profit by selling the software. While this does not immediately make economic sense, the natural alternative may present an even less attractive option.

Using closed-source and proprietary software grants the project exclusive rights to distribute the software, and makes no requirements on price. However, in order to claim any piece of software as being the sole property of the project, the development of the software must only take place as part of the project. Although the selling price of the software may vary in order to gain a profit, the development time and labor required to produce the proprietary software from the ground up could drive the profitable price of the software beyond what customers would be willing to pay.

While the high initial costs of developing a completely proprietary package of software make pre-existing open-source software seem appealing, there are some circumstances where the two may meet. In particular, the ZigBee protocol stack cannot be distributed under the GPL: developing ZigBee software or hardware for commercial purposes requires membership in the ZigBee alliance, which includes a financial cost. The two licenses (GPL and ZigBee) conflict over who can be a developer: the GPL maintains that all users can be developers for any purpose, while ZigBee restricts commercial development to a significantly narrowed set of people[30]. In this case, a small module of closed-source code written by authorized ZigBee developers could be linked by other software (such as the Linux kernel) without incorporating it on a source-code level. In this scheme, all open-source code remains separate from closed-source code except at runtime, which is permissible by the GPL and other open-source licenses. Creating a closed-source proprietary module for the Linux kernel to use would allow the project to gain some associated revenue without constructing a new operating system or violating the GPL.

10.4 Physical Components

As the base station requires relatively few internal components to meet its design requirements, it will likely take the form of a single-board computer in a production scenario. However, due to the somewhat atypical ZigBee input and output, the design team decided to use an FPGA development board rather than acquire and modify an existing single-board computer. The FPGA will provide the central processing unit of the base station, which mandates the selection of a processor core. Initially, the design team considered an open-source implementation of the Texas Instruments MSP430 processor, but upon review and further investigation, lack of standard features such as a memory management unit, which Linux requires in order to function. Instead, the design team selected an open-source UltraSPARC core, as it seemed more full-featured and provided a more common architecture for compiling Linux and any associated programs.

10.5 Data Storage

Storing the gathered and processed data requires a non-volatile storage medium so that the user may review past measurements and so that this data will survive through power failures. The design team evaluated several different options to accomplish this data storage: Internet storage, external storage, internal storage, and removable storage. To determine the optimal medium, the team evaluated each of the options with respect to reliability, capacity, security, and cost.

10.5.1 Reliability

If the PICA system is to function without constant user intervention, its components must be reliable and require little maintenance. A storage medium is reliable if it can be easily accessed on demand, retains its stored data, and can operate for extended periods of time without failing or crashing. For the sake of establishing a baseline, the storage medium shall retain its stored data and sustain functionality for at least five years.

Internet-based storage easily meets the retention and functionality requirements, as the data may be stored redundantly and archived without interrupting service to the user. It does not fare as well in the accessibility category, as it requires a constant Internet connection, which not all potential users may have. Additionally, even for customers with Internet connections, relying upon Internet-based storage would implicitly rely on the Internet connection to be free of latency or interruptions. Lengthy delays in transmission could cause the base station's short-term memory to fill with measurements, which could lead to data loss, slowed overall performance, or other undesirable consequences. Additionally, the available upload bandwidth in any location may vary substantially with time or other factors, which might cause the available bandwidth to decrease below the rate at which information arrives at the base station. While Internet storage is attractive in some measures of reliability, its reliability in other aspects is worrisome or critically lacking, depending on the customer's situation.

External storage devices include devices that the user would connect to the base station while the devices remains physically separate from the base station. An external hard drive, for example, would be connected in a data sense but would remain wholly outside the device. Devices of this nature generally do not suffer from accessibility issues, aside from loss of power if they use dedicated power supplies and the supplies fail. External devices usually do not have issues with storing data or having it be retrievable later, but unless the data is backed up onto another device on a regular basis, the data is not guaranteed to be safe from hardware failure. The specific failure rates depend on the specific implementation and vendor chosen. One benefit of the external storage scheme is that if the device fails, the user can easily replace it without opening the base station.

Internal storage encompasses all storage devices that are physically internal to the base station and are not easily removable. This would essentially remove the chance of the the device losing power while the base station remains on, so accessibility should be nearly flawless while the station remains powered on. The retention and lifetime factors are also favorable but vendor-dependent. Internal storage, therefore has only a small improvement over external storage.

Removal storage devices plug directly into the base station and draw power from the base station as well. The user can remove the device, which allows for simple replacement in the event of hardware failure, but may pose a risk in accessibility if it becomes unplugged. Because it removes the possibility of power supply failure, removable storage has an improved reliability over external devices. As removable devices can be replaced if damaged, they have a reliability advantage over internal devices, as well.

Overall, removable devices seem to provide a high degree of reliability while remaining independent from Internet availability in a user's home. While they may not excel in any particular aspect of reliability as defined above, they provide a balance of the three. Internal storage provides the next-best option, as it is always accessible but does not have the replacement ability that removable storage offers.

10.5.2 Capacity

Each of the four options can be configured for different storage sizes, but they each have typical ranges of sizes available. The required device capacity will depend on the number of measurements the base station stores, which is in turn dependent on the length of time measurements should be retained, the size and detail of these measurements, and the rate at which the connect PICA devices submit their measurements to the base station. If the base station is to write 1kB of measurements each second for five years, the resulting body of measurements would occupy more than 150GB of space. This does not include the events and alerts that the systems report to the base station, which would increase the amount of required space. If the base station condenses the measurements into 1kB summaries of a minute's worth data, the resulting space requirement would be less than 3GB. While this does decrease the size to be stored, it might not decrease the usability; it is rather unlikely that the user would desire to know information by-the-second five years after the date of measurement, but a minute or even hourly summary would be useful. In any case, these data estimates do not include disk formatting or other overhead on disk space.

Internet-based storage has no practical size limit, as it is stored off-site and is can therefore change. Furthermore, it can expand if the user's needs increase. In this aspect, it more than meets the user's data requirements.

External storage can also hold a large amount of data. At present, consumers can purchase external hard drives in excess of 1TB (1000 GB) rather easily. They cannot be dynamically resized, but they can be replaced if necessary. External storage devices meet the data requirements.

Internal storage can similarly reach large sizes. Unlike the external storage, it cannot be replaced when full, which makes its limits hard-and-fast limits. Despite this drawback, internal storage can meet both the larger and smaller data requirements.

Removable storage devices are still rather limited in their capacity, but the technology is still improving. Most common formats of removable solid-state storage, such as Compact Flash (CF) and Secure Digital (SD) cards, can contain more than the 3GB required for the minute-by-minute data, but the upper target of around 150GB remains elusive in these devices. In this manner, removable storage devices can accommodate the data storage needs if the data can be compressed or summarized.

As far as storage capacity is concerned, Internet storage provides the greatest amount of storage space. External and internal storage can also meet the expected storage needs. Removable storage can still meet a lower standard of data storage, but cannot fit the larger expectation using the current technology.

10.5.3 Cost

The cost of each option indicates how the relative financial cost of including it with the base station, or of maintaining it. In most cases, one-time costs will contribute to the sale price of the device, but ongoing costs do not convert into sale prices as directly. Adding a service charge could offset this expense, but would add a significant amount of complexity with billing and handling payments.

Using Internet-based storage presents a unique challenge in calculating price: it incurs an ongoing expense. Unlike the other options, the storage devices for Internet-based storage will reside outside of the user's property. As such, the power and connectivity costs will fall on the service provider, rather than being absorbed by the user. In this fashion, using Internet-based storage could justify charging the users an service fee to cover the operating expenses of running a data storage center and connecting it to the

Internet. The cost of running such a data center cannot be compared as easily with a one-time payment, but it certainly presents the largest cost to the service providers.

External storage will pose a one-time cost, unlike the Internet storage options. In theory, as the user could replace the device if it were to fail, a base station designed to use external storage could ship to users and require them to provide their own hardware, but as this introduces many uncontrolled factors into the base-station system, it may not be the best course of action. Providing an external storage device would add to the final sales price, but would keep issues such as pre-existing data and unusual file-systems from affecting the system. Providing the storage device would likely cost about the same as it would for the consumer to purchase the same device, which is about $100 for a magnetic hard disk with more than ample capacity as defined above.

Internal storage will also pose a one-time cost. As the device would be contained inside the base station, allowing the user to provide their own drive would be nonsensical. Internal storage may cost slightly less than external media for the same capacity.

Removable storage will also pose a one-time cost. As the medium can be removed or replaced, it could be user-supplied, aside from the reservations stated for the external device plan. Removable solid-state storage does not typically provide the same storage capacity as the previous storage media do, but a 4GB device would meet the smaller target and might cost less than $50.

If the lower data storage rate is acceptable, the removable storage media may cost less than the others. The Internet storage implementation will almost assuredly present a large up-front cost and a substantial ongoing cost to power and support the facility. The external and internal storage options have comparable costs, and can accommodate the larger space requirement if necessary.

10.5.4 Conclusion

Removable storage devices provides good reliability with a reasonable cost. The only drawback with such devices is the limited storage size, which may be excusable depending on the granularity of measurements required. The internal storage option is the next-best alternative, followed by external storage. Internet storage presents unique reliability concerns and an ongoing cost, which makes it the least attractive of these four options.

A combination of two or more of these options could allow for a good blend of strengths and weaknesses.

In particular, providing a small internal storage device to store minute-by-minute data could satisfy most users' needs; allowing an optional external device would increase the value of the system. In particularly, using an external drive as an optional expansion or backup device would increase the reliability and storage of the system overall.

10.5.5 Prototype

In order to accommodate the development board used for the base station, compact flash cards will function as the storage medium. A production model of the base station could also use compact flash cards as a form of removable storage, but SD cards provide several advantages for large-scale distribution. In particular, SD cards are more commonplace in consumer devices than compact flash, so more potential customers have already encountered SD cards and are likely to be comfortable with handling or changing them if necessary. Additionally, SD cards occupy less physical space, so the physical design of the production model would have more freedom in its dimensions than if it included support for the bulkier compact flash devices.

10.6 Interfaces

In considering different methods of providing a user interface, it is important that the interface encourage interaction with the system. That is, it should be easy to understand and accessible to customers with a variety of technical skills and backgrounds. This requires a balance between the complexity required for showing large amounts of information and the elegance required for relaying essential information quickly. In this regard, the interface should present useful information at-a-glance, but also allow for displaying more detailed or specific information by explicit human selection and interaction. Presenting this interface as a series of linked webpages over a local Ethernet connection provides this level of detailed information and configuration in a familiar format. Although the web interface presents an easily understandable interface to those who have a home computer network, it still presents a barrier of access to customers who might not have a home network. To accommodate such users, a separate display device will accompany the base station and can connect directly to it using ZigBee. This device may draw heavily from the web display, but its intent is to make that interface available to those without Internet-capable devices, as well as more convenient for those who do. The dedicated remote display also matches a feature provided by other smart home system vendors. The design team has not yet finalized a design for this device, but the device may become a separate subsystem after further consideration. The primary means of display for the base station will be the web interface, but will also provide a dedicated device for viewing that web interface at all times.

11 Verification and Testing Plan

11.1 ADE7763

11.1.1 Channel 1 Input Test: Current Sense

Test Equipment

- LeCroy Digital Oscilloscope
- Discrete Line-Voltage H-N-G
- Fluke Multimeter
- CR Magnetics 8350-2500-N Current Transformer (2500:1)

Setup

- Pass both Hot and Neutral wires through the current transformer.
- Attach the multimeter, set to measure RMS voltage, to the leads coming from the current transformer.
- Attach a known load between the hot and neutral lines.

Test plan

- Calculate IRMS and VRMS for the circuit created by the known load and the line-voltage.
- Calculate the average power applied to the known load.
- Calculate the expected values on the opposite side of the current transformer.
- Apply power to the circuit and measure, using the multimeter, the RMS voltage on the opposite side of the current transformer.
- Verify that the reading is within tolerances for the oscilloscope.
- Attach the CH1 probe of the oscilloscope to the output from the current transformer.
- Attach the CH2 probe of the oscilloscope to the terminals of the known load.

- Plot 1 period of both CH1 and CH2 on the same axis and measure the phase shift between the two signals.

11.1.2 Channel 2 Input Test: Voltage Sense

Test Equipment

- 2x255kΩ resistor 1% tolerance $\frac{1}{8}$W
- 1x 1kΩ resistor 1% tolerance $\frac{1}{8}$W
- 33nF Capacitor 50V 10% tolerance
- 120/240V line voltage
- LeCroy Oscilloscope
- Tektronix Function Generator

Test Setup

- Assemble the input network as shown in Figure 4 of the Analogue Devices AN-564.
- Using the function generator, take data points, in log spacing, to generate a bode-plot for the response of the input network. All data should be captured in Microsoft Excel spreadsheets. Frequency sweep should range from approximately 1Hz up to a minimum of 1MHz; with signal amplitude of 10V.
- Attach line voltage to the input network.
- Ensure that the alligator clip of CH1 and CH2 probes are both connected to a common ground.
- Attach oscilloscope CH1 to the input side of the input network and oscilloscope CH2 to the output side of the input network.
- Measure the output against the input to affirm that the input network is functioning as expected and reducing the input voltage to approximately 470mV.

Results

The purpose of the test and verification for the voltage sensing of channel 2 was to verify the ability to step down a 120/240V line voltage to below the maximum differential signal level of +/- 0.5V [4] while also protecting the chip from frequencies above 50kHz. A voltage divider and low-pass filter combination successfully does this without losing other signal characteristics such as phase or frequency.

The procedure followed came from the verification and test plan written by Kendrick Wiersma. Equipment used includes a 1kΩ resistor, 10% tolerance, 1/8W, 2 255kΩ resistors, 10% tolerance, 1/8W, a 0.022μF capacitor, 10% tolerance, a LeCroy Oscilloscope, Tektronix Function Generator and 120/240V line voltage. A 510Ω resistor, 10% tolerance, 1/8W and a 0.044μF capacitor were added as well.

Two 255kΩ resistors are more beneficial than a single 510kΩ resistor because of the lower power dissipation through each. The original plan calls for tolerances of 1%, but only 10% tolerances were available. This was acceptable because the circuit still demonstrated the ability to step down the voltage.

Table 8 shows data taken using figure 17 as the set up for the attenuation network (figure 4 of the Analog Devices AN564 document).

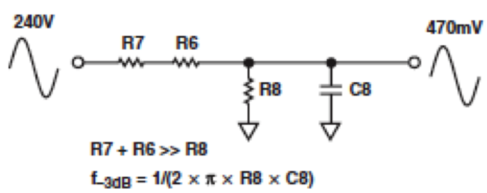


Figure 17: Voltage attenuation network as seen in figure 4 of Analog Devices AN-564 [4].

Table 8: Test data taken during laboratory testing.

Frequency		Input	Output	
(Hz)	(kHz)	(V)	(mV)	(dB)
1	0.001	10	22.1	26.9
10	0.01	10.1	21.8	26.8
20	0.02	10.3	22.1	26.9
40	0.04	10.3	22.1	26.9
80	0.08	10.3	21.8	26.8

Continued on next page

Table 8: Continued from previous page

Frequency		Input	Output	
100	0.1	10.3	21.8	26.8
200	0.2	10.3	22.1	26.9
400	0.4	10.3	21.8	26.8
800	0.8	10.3	21.8	26.8
1000	1	10.3	21.8	26.8
2000	2	10.3	21.5	26.6
4000	4	10.3	19.3	25.7
8000	8	10.3	15.6	23.9
10000	10	10.3	13.7	22.7
20000	20	10.3	9.37	19.4
40000	40	10.3	6.25	15.9
80000	80	10.3	4.37	12.8
100000	100	10.3	4.37	12.8
200000	200	10.3	4.37	12.8
400000	400	10.3	3.75	11.5
800000	800	10.3	4.37	12.8
1000000	1000	10.3	4.37	12.8
2000000	2000	10.3	4.37	12.8

Hand calculations using the equation:

$$V = \frac{V_{in} R_{6+7}}{R_{6+7} + R_8} \tag{2}$$

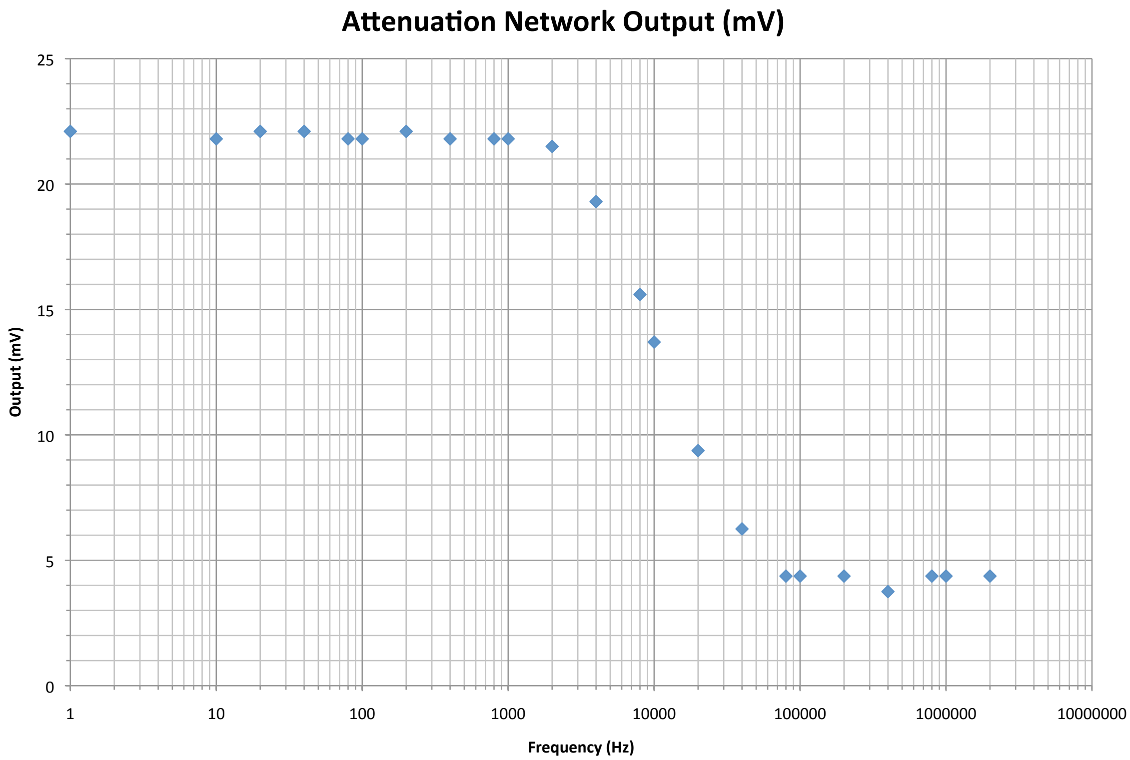
for determining voltage and equation 2

$$f = \frac{1}{R_8 C} \tag{3}$$

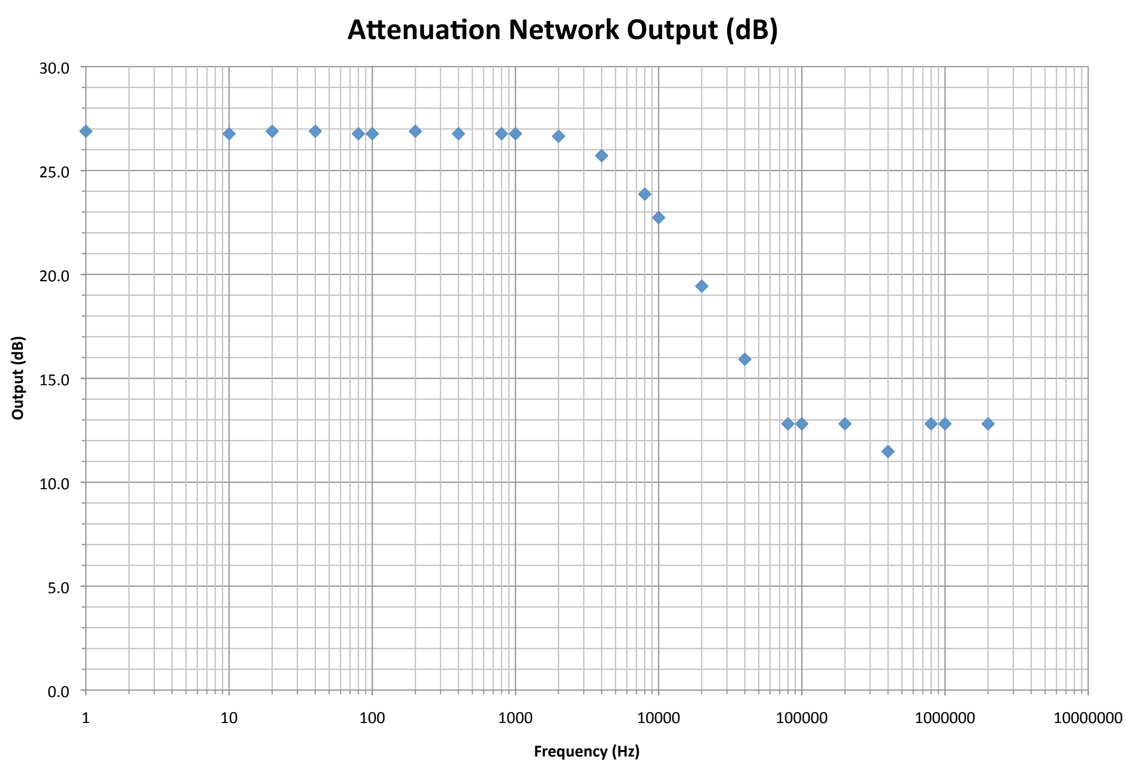
for determining frequency confirm these results. Running simulations in both PSpice and LTspice also verified this data. Figure 19 shows results for both simulations below.

Using line voltage as the input to the network, the output was 730mV, which exceeds the maximum allowable input for channel 2 of the chip. To fix this, a 510Ω resistor and a 0.044μF capacitor replaced the 1kΩ resistor and the 0.022μF capacitor originally specified. This lowered the voltage to 350mV and had no effect on the 3dB point of the frequency plot.

These results consistently show that the input network setup can successfully protect the ADE7763 chip

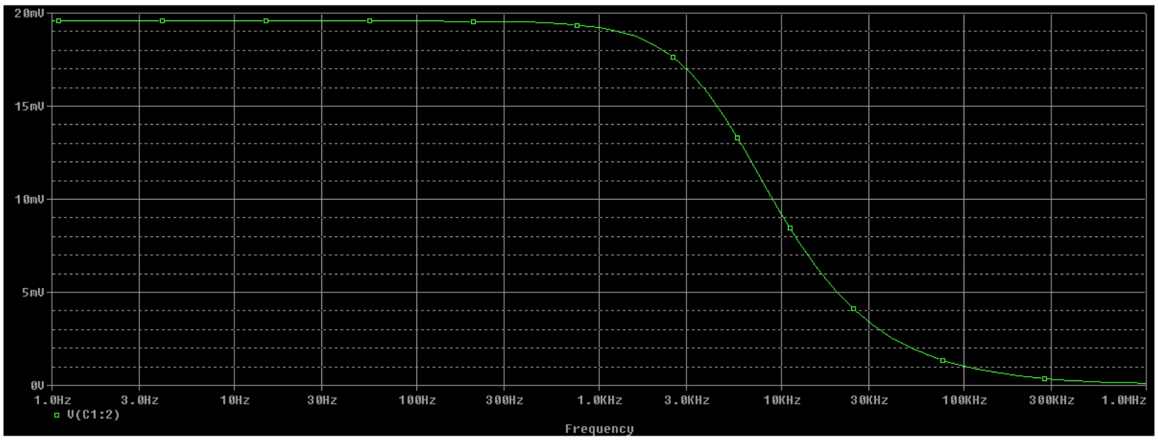


(a) Attenuation as a function of frequency plotted in mV

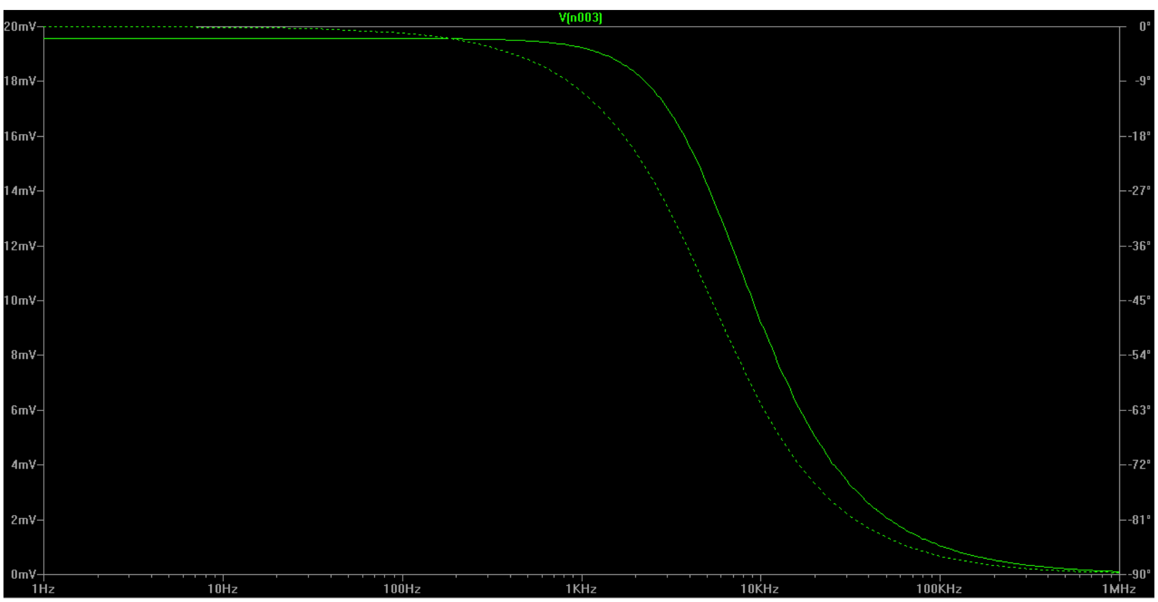


(b) Attenuation as a function of frequency plotted in dB

Figure 18: Graph of attenuation network analysis.



(a) Input attentuation network OrCad Cadence simulation



(b) Input attentuation network LTspice simulation

Figure 19: Attenuation network simulation.

from excessive input voltages and high frequencies.

11.1.3 Analogue Devices ADE7756 Power Supply

Equipment and Supplies

- Capacitor C1, 100nF, 50V 10%
- Capacitor C2, 220µF, 6.3V 20% (electrolytic)
- Capacitor C3, 330µF, 50V, 20%
- Inductor L1, Ferrite Bead
- Inductor L2, Ferrite Bead
- MOV1, Metal Oxide Varistors
- R2-R4, 00Ω, 1/8W
- T1 Transformer, 10VCT, .110A
- VR1, 5V Regulator (7805)
- Z1, Bridge Rectifier, 1A 100V
- Fluke DMM
- LeCroy Digital Oscilloscope
- Soldering iron
- Known load (resistive)
- Known load (switching)

Test setup

- Assemble the power supply as seen in figure 17 of the ADE7756 AN-564 [4] on a breadboard. All connections to the left of the bridge rectifier must be soldered directly.
- Attach ferrite beads L1 and L2 to the hot line voltage.

- Power on the supply, visually inspecting for any faulty operation.
- Measure the voltage on both sides of the metal oxide varistor.
- Attach oscilloscope CH1 and CH2 to points 1 and 4 of the bridge rectifier.
- Validate that the bridge rectifier is functioning as expected.
- Measure the voltage, with reference to ground coming from the right side of the 7805-voltage regulator.
- Attach a known resistive load to the power supply, validate that the voltage remains steady.
- Attach a known resistive load to the power supply, validate that the current-draw does not exceed 0.110A.
- Attach a known switching load to the power supply, validate that the voltage remains at 5V steady.
- Attach a known switching load to the power supply, validate that the current-draw does not exceed 0.110A.

11.2 Future Testing

The team has not written up test plans for many other aspects of the project, but recognizes that the tests are an important aspect of the project and plans to work the details out second semester. These tests include validating measurements from the ADE7763 and MSP430, measuring data throughput of the MCU and determining the response time of the breakers.

12 Project Management

12.1 Team Organization

See figure 20 for the team organizational chart.

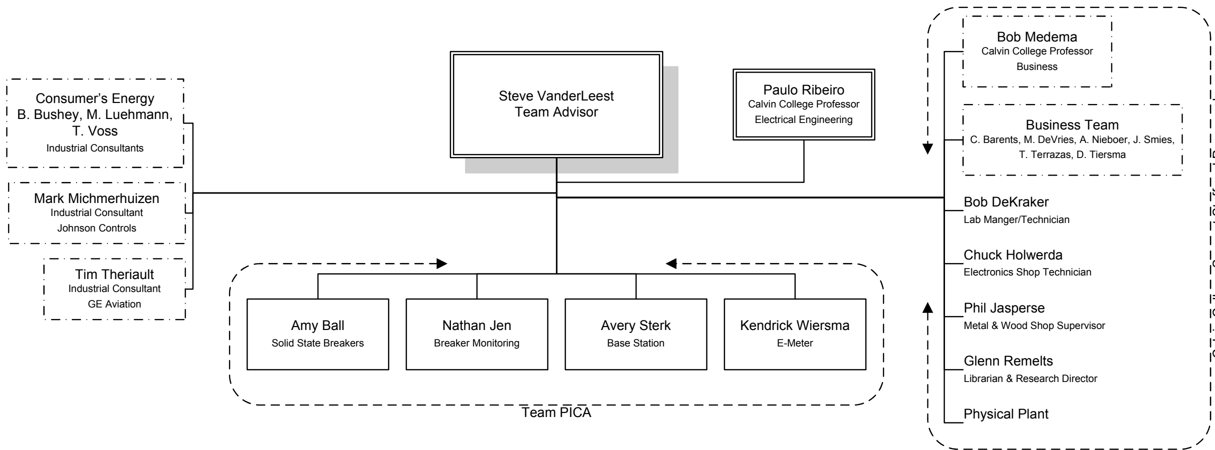


Figure 20: Team PICA Organizational chart.

12.2 Team Responsibilities

12.2.1 Amy

Amy, along with Nathan, makes up the hardware part of the team. They are in charge making decisions regarding hardware-specific sections of the project. Amy is also in charge of the Breaker sub-system of the project. She has the most complete understanding of their functions and specific requirements, she may delegate sub-sections to other team members, but she will have a good grasp of how they fit into the larger system. A sub-system of the Breakers is the monitoring section, which the team delegates to Nathan. Nathan and Amy will be working together closely with the full sub-system of the solid-state breakers.

12.2.2 Nathan

Nathan is co-leader with Kendrick. They are in charge of scheduling and assigning tasks, scheduling meetings, keeping team on time, on task, and will answer project questions. Nathan, along with Amy, makes up the hardware part of the team. They are in charge making decisions regarding hardware-specific sections of the project. Nathan is also in charge of helping integrate the sub-sections into the whole system, which includes having a detailed, basic understanding of each sub-system, and knowing how each relates to the overall requirements and goals. Nathan is also in charge of the monitoring section of the solid-state breakers.

12.2.3 Avery

Avery is in charge of the Base Station section of the project. He has the most complete understanding of it's function and specific requirements. He may delegate sub-sections to other team members, but he will have a good grasp of how they fit into the larger system. He, along with Kendrick, makes up the software part of the team; they make decisions regarding software-heavy sections of the project.

12.2.4 Kendrick

Kendrick is in charge of the E-Panel section of the project. He has the most complete understanding of it's function and specific requirements. He may delegate sub-sections to other team members, but he will have a good grasp of how they fit into the larger system. He is also co-leader with Nathan and they will share duties as necessary. He, along with Avery, makes up the software part of the team; they make decisions regarding software-heavy sections of the project.

12.3 Schedule

In order to complete the project within the established deadlines, the design team established a schedule and task-oriented deadlines to supplement the larger senior design program-established deadlines. In doing so, the design team selected to address the subsystems individually. The design team will first focus on the solid-state circuit breakers and circuit-monitoring devices, which they hope to complete by the end of the fall semester. The other two subsystems, the base station and the main smart meter, will gain focus in the second semester. Table 9 shows a list of major milestones for the project with the estimated date of completion for each. The chart also shows the number of hours estimated needed for each task and any dependencies. Items in bold indicate tasks scheduled for completion by the current date and labor totals are shown in the bottom right.

Table 9: Task lists

Milestone	Estimated Completion	Dependence	Estimated Labor	
Project scope and functionality determined	Oct 25, 2010	none	40	
Project goals and requirements set	Nov 16, 2010	Scope and functionality	60	
Design criteria determined	Nov 19, 2010	Goals and requirements	15	
Preliminary breaker design set	Nov 23, 2010	Criteria	50	
Preliminary e-meter design set	Feb 2, 2010	Criteria	50	
Preliminary base station design set	Mar 6, 2010	Criteria	50	
Breaker prototyped and tested	Dec 1, 2010	Design set	30	
E-meter prototyped and tested	Feb 13, 2010	Design set	30	
Base station prototyped and tested	Mar 19, 2010	Design set	30	
Full system integration	Apr 17, 2010	All subsystems prototyped	40	
PPFS turned in	Dec 7, 2010	Criteria	130	
Project presented	May 16, 2010	Prototyped	40	
			325	1st Semester
			240	2nd Semester
			565	Total

While subsystems should be able to be completed independent of each other, the design team decided to address the circuit-by-circuit monitoring component of the project first because of its application to control systems. As members of the design team are taking a class in control systems during the fall semester, working on the breakers while also learning control theory seemed to create an advantageous symbiosis between working and learning. The control systems course also seeks to use aspects of the senior design project as learning experiences, so the motivation to combine the controls assignment and the breaker modules is twofold.

The design team has assembled its internal schedule into Gantt chart to show the deadlines of tasks and the linkages between different tasks. Despite having this planning tool and list of tasks, the actual flow and completion of work is frequently different from originally expected. This is partially due to unexpected emergence of assignments and deadlines for the design project itself, but other classes also contribute unforeseen and time-consuming work that impedes progress in the project. To deal with outside deadlines and work, the team tried to think of deadlines focus on work and deadlines to two or three weeks out. Team members were encouraged to think in general terms only about deadlines more than a couple weeks out to help keep focus on current progress. As the semester progresses, these emergent due-dates should decrease in number and severity, allowing the design team to devote more time to the project.

In order to complete the project, the team needs to accomplish a variety of tasks shown in the work breakdown structure below. Much of the early work includes a lot of paperwork outside of the actual design of the system. This includes determining exactly what problem the team is addressing and the requirements needed to solve it. Project goals and design criteria also make up some of the pre-design work. In industry, the customer would already have set many of these requirements, goals and criteria, so to make the project as 'real-world-like' as possible, the team put these before the design stage of the project. To make the requirements and goals realistic, the team decided to meet with a variety of professionals in fields including marketing, business and engineering in addition to potential customers.

Once the project goals, requirements and criteria are set, the team can begin some preliminary design. As another way to limit the project and keep it from getting out of control, the project scope needs to be determined early in the project. A big factor in setting the scope is making the system unique from products that solve similar problems. The first step the team would like to take is to determine the basic functionality of both systems and subsystems and set up functional block diagrams to show this. After the basic functions of each of the subsystems are determined, the team will explore various solutions through general research and trade studies. When the team has compiled a number of different solutions, they can start to eliminate possibilities based on criteria established earlier. To assist with this, the team will use design matrices and comparison tables as visual aids.

After narrowing down the possible solutions, the team will begin the design and implementation stage. Further criteria may include power efficiency, cost of building the system, and availability of components. As design aspects apply to all subsystems, and since development of the subsystems will occur at different rates as mentioned earlier, the finalized designs will not finish simultaneously. Testing will occur after designing and building the various parts of the subsystems. The team decided that the breakers, breaker monitors, main system monitor and wireless communication should be the first parts of the system completed. Other parts that will require finalization and building include the upgrade mechanism, base station, display module and firmware. Each of the parts will require modifications based on the testing results. Modifications to each of the parts may be necessary based on the testing results, so this section may take multiple iterations before it is complete.

Assembly of the full system will follow the individual parts' completion, along with testing for a variety of things. Some specific things the team hopes to include in the testing are tests based on outside criteria, tests based on requirements set by the team and testing common possible failure points. As the team is working with a limited amount of time that may not allow for full testing of the system, some of the long term testing procedures including accelerated lifetime testing will be written up for later use outside of the class.

Communication will be critical to the success of the project, both during and after so the team aims to provide documentation of all design decisions and testing done throughout the year. As the customer will need to interact with the system effectively, the team hopes to provide a user manual as well. For the class, the team needs to present the project on a number of occasions and hopes to demonstrate their work to all groups associated with the project, including business groups, customers and technical professionals.

12.3.1 Work Breakdown Structure

1. Meet with marketing professionals, business group, potential clients, and power monitoring field expert
   (a) Description of the problem
   (b) Develop objectives and constraints
   (c) Determine the final target price for the customer
2. Develop project scope and functionality
   (a) Brainstorm system functionality
   (b) Determine alternative solutions
   (c) Determine how system is unique from alternative solutions
   (d) Meet and discuss with field experts and possible clients
   (e) Create design matrices
   (f) Trade studies

3. Design
    (a) Determine the methods of implementation based on the design matrices
        i. Power efficiency
        ii. Level of functionality
        iii. Cost to build design
        iv. Meet design goals and requirements
        v. Overall system integration with current grid
        vi. Availability of parts/materials
    (b) Prototype small subsystems
        i. E-Meter
            A. Power Monitor
            B. Display Module
        ii. Breakers
            A. Current Switch
            B. Breaker Monitors
        iii. Base Station
            A. Operating System
        iv. Inter-system components
            A. Firmware
            B. Communication Devices
            C. Configurable Logic Blocks
            D. Upgrade Mechanism
    (c) Test functionality and accuracy of subsystems
    (d) Revise subsystem design based on above test results

   (e) Test subsystems interoperability
      i. Test to see if subsystems affect each other
      ii. Test to see if data is properly communicated between subsystems

4. Construct system prototype
   (a) Test system prototype based on the criteria for presently functioning power meters
   (b) Test system prototype based on the criteria set for added features
   (c) Test soldering points for possible failure
   (d) Determine other possible points of failure and test for proper system functionality
   (e) Create a long term testing plan that could be used outside the scope of senior design
   (f) Ensure prototype meets customer/field expert set requirements

5. Communicate Results
   (a) Document results of system testing in written format
   (b) Document design decisions in written format
   (c) Create a written manual showing implementation of all systems and subsystems
   (d) Write a plan for further testing of all systems
   (e) Make known that all of the above documents are available for viewing
   (f) Present project in PPFS
   (g) Present PPFS to business group, potential customers and technical professionals who helped us

13 Business Plan

13.1 Target Market Definition

The target market for the entire PICA system comprises both electricity producers and electricity consumers, as set forth by the nature of the subsystems. As the power companies supply and own the electricity meters attached to the buildings to which they supply power, the PICA E-meter appeals only to the market of electricity-producing companies. The other two subsystems, the solid-state breakers and base station, target the power-consuming audience, as the devices will assist in monitoring power flow inside the building, where the power company has no presence. As these two markets are essentially exclusive in both membership and interest in the PICA subsystems, the E-meter will be able to function independently of the other consumer-targeted subsystems, and vice versa.

13.1.1 Power Companies

As power companies currently distribute the whole-building metering hardware that determines how much energy their customer used, the E-meter clearly targets power companies. In fact, the power companies own the power-measuring hardware external to the buildings to while they provide power, so only they may replace or upgrade those devices. At present, power companies send trained meter-readers to read the data from most traditional power meters under their control. The PICA E-meter subsystem aims to improve on this process by automatically sending the measurements to the power company using a means and protocol selected by the particular company. While this will require some hardware customization for each company, the volume of company-specific production should allow the cost to develop the design to spread into a small per-unit cost.

The PICA E-meter subsystem also provides numerous more measures of power than the simple spinning-dial meters. For example, the E-meter will measure the frequency and the RMS voltage of the incoming supply lines, which help indicate the overall quality of power delivered to the customers in the area. This information may also help diagnose any observed issues with power delivery without dispatching a worker to take measurements by hand. In this way, power companies using the PICA E-meter can improve the quality of the service they provide and can save on the labor costs associated with making a site visit.

13.1.2 Power Consumers

Although the power company's customers cannot modify the metering panel installed by the power company, they are free to modify the other power distribution components inside their own buildings. The solid-state breakers fall into this category, and provide previously unavailable measurements regarding power consumption and its location within the building. However, as these breakers will replace the pre-existing breakers inside the building, the consumer must be convinced that using the PICA system is worth the trouble and cost of replacing the mechanical circuit breakers with the more feature-rich PICA breakers. To this effect, the most receptive market for the solid-state breakers includes homeowners and building managers who are curious or concerned about power usage inside their building. That is, the people for whom this information can inspire a meaningful change in practice will likely become the first adopters of the subsystem.

The product may also gain a following as an alternative to mechanical breakers in during the construction of a new home or building. This would likely require that the product already have a proven history of reliability and safety, so the previous group of cost- or environmentally-concerned individuals might have to adopt the produce first. If the PICA solid-state breakers become an alternative during construction, the net cost to the user will be lessened, as the building-to-be will not have any pre-existing breakers to discard or replace.

The base station may apply to either of these two consumer groups, as its primary purpose is to manage and interface with the other systems. It does not specifically require the solid-state breakers or the E-meter, but provides little value in a building without any installed PICA systems. The base station exists solely to manage and collect data from other PICA subsystems, as well as format and display these measurements, so its target audience consists of power consumers whose buildings contain at least one of the E-meter or solid-state breakers.

13.1.3 Market Coordination

As the E-meter subsystem caters exclusively to power companies while the other subsystems target power consumers, the complete PICA system has no clearly-defined market; neither of the two markets involved desires the entire system. Despite this separation, a clever marketing strategy could motivate one market to pressure the other.

In one scenario, a power company installs the PICA E-meter onto a select set of their customers' buildings. On its own, this should be a transparent change to the consumer. However, marketing the base station as a way to "see what the power company sees" about the power delivered could motivate some of the power-consuming market to purchase a PICA subsystem. Giving the power-consuming market a feeling of empowerment or equality to the power company could therefore motivate more consumer-side subsystem sales.

Conversely, the interests of the power-consuming market could generate interest from the power-producing market. In particular, a consumer who already owns the PICA solid-state breakers may appeal to the power company to provide the PICA E-meter: it would expand the amount of information available and give an accurate sense for the upcoming utility bill. Even without any PICA subsystems, the consumer could prod the power company for a PICA E-meter because it would give the power company more information on power quality, which could in turn increase the quality of service provided to the consumer. In these scenarios, the desires of the power-consumer market could influence demand in the power-producing market.

13.2 Target Market Research

From the team's visit to Consumer's Energy in Jackson Michigan, power companies are very interested in smart home energy meters, such as PICA provides with the E-meter. The team presented a features list to the representative present. who affirmed that the features now included in the E-meter will be valuable to the power companies. However, power companies are already researching and testing smart meter prototypes and samples, so the E-meter will arrive fairly late relative to its competition. Still, of the thousands of power companies in the United States[31], the PICA system will surely prove interesting to others who may not have considered alternatives. Fewer than half of the homes expected to receive the smart-meter conversion have been converted to date, so the E-meter is still viable in the power company market[32].

The remainder of the system, the base station and the solid-state breakers, will compete in a market of power consumers. The devices currently face a market of 6,400,000 customers, according to an estimate from the project's Business 396 companion team. Of these customers, approximately 0.1% may be interested in PICA, giving 64,000 expected sales[33]. Additionally, despite the recent economic downturn, housing spending has experienced an upward trend[34], which may indicate a possible increase in the number of houses that could be constructed with the PICA solid-state breaker technology. The market for the consumer-oriented subsystems seems to be healthy, and even growing, despite the recent economic slump.

13.3 Feasibility Study

13.3.1 Technical Feasibility

The goal of the PICA project is to design and produce a unified system to measure power consumption information and deliver it to the user. In order to judge the technical feasibility of the entire system, one must first judge each of the individual subsystems and then the connections between them.

The E-meter provides similar functionality to existing smart meters, which are demonstrated to be technically feasible. The feasibility of producing one under such a time constraint, however, has not been proven. By using pre-existing components whose purposes are to function as a part of a smart meter, the design team should be able to limit the component-level design to providing the connections between the selected components. Although this task will still require a substantial amount of time and design work, it should be feasible to complete before the end of the spring semester.

The solid-state circuit-breaker subsystem provides functionality that is not as commercially available as smart-meter functionality. In this case, the feasibility of the system cannot be implied by the existence of other products. Although the power-monitoring aspect of the breakers can be constructed from existing parts, the circuit-interrupting behavior is not as easy to duplicate. The difficulties associated with this aspect of the subsystem depend on the hardware selected to interrupt the circuit, but the primary concern at present involves the controllability of the circuits. Using Field-Effect Transistors (FET) hardware to choke the flow of current has been proven to be possible, but the control signal associated with maintaining the flow of current must stay within a certain range of the power-line voltage, which behaves as a $120V_{RMS}$ sinusoid: a varying control line could not be easily implemented using logic-level voltages. If thyristors provide the control hardware, then a constant DC control signal could allow current to flow, but they may not truly shut off for several milliseconds after the control line directs current to stop.

The base station functions largely as a hub for the PICA system's measurements, and accordingly formats and that information for display to the user. Devices of a similar nature already exist: networking switches and routers routinely redirect data to other devices, and have done so reliably even when multiple communications media are involved. The similarity of the base station to these routers should indicate that the subsystem is indeed technically feasible, and may even be feasible to the project schedule. If the power consumption of the base station will be comparable to that of these networking devices, the base station should consume approximately 10 watts, which could feasibly be an acceptable overhead for most users.

The communication between these subsystems completes the PICA system, and should prove economically and time-feasible if it employs a pre-existing standard. Reliability provides the key indication of the feasibility of a given communications method, and it encompasses issues such as range, error tolerance, and bandwidth. Power consumption is also an important factor, but may be minimized if the selected method fits the previous criteria.

13.3.2 Market Feasibility

In order for any product to succeed commercially, its perceived value must meet or exceed the price the customer would pay for it. If the PICA system as a whole is to be a feasible market success, it must surpass its competitors in providing value per price. From a practical standpoint, this involves either selling a comparable product for a lower price than the competition, or producing a superior product at a similar price. The PICA project generally aims to follow the second of these two paths. The solid-state circuit breakers include solid-station circuit breakers and circuit-by-circuit power monitoring, both of which seem to be unusual or even unique features, which in turn means that its feasibility depends on the value of its features rather than a lower price. The base station may be viewed as an accessory to the other subsystems, but its function as the output of the collected information gives it a very high value to anyone who desires the information collected by the other PICA devices, so its feasibility relies on its high perceived value, rather than on undercutting competition. The smart-metering aspects of the E-meter essentially meet the expectations set by other smart meters, so the market feasibility of the E-meter device depends more on the price than on the features, but its ties with the base station can provide additional feature value as well. Overall, the subsystems of the PICA project tend to focus on providing valuable features, rather than on reducing the price below that of the competitors.

13.3.3 Legal Feasibility

The PICA system must meet certain codes in order to be safe enough for the customer to use, which will also protect from unexpected lawsuits. Underwriters Laboratories (UL) is an independent product safety certification organization, which offers safety certifications to products [35]. In order to gain the confidence of customers, the devices of the PICA system will be UL certifiable. The specific qualifications of UL certification remain unknown to the design team, as the documents regarding the certification requirements are not publicly available. The system will also restrict EM radiation to comply with FCC Title 47 Part 15. It will also comply with ANSI C12.19 and ANSI C12.21 standards.

While these standards should ensure the general safety of the PICA devices, defects or unforeseen circumstances could imperil users or their property. The PICA system will provide a limited warranty against defects, but cannot be expected to foresee all possible circumstances. To this end, the devices will ship and work with a disclaimer regarding safe operating conditions and the hazards of tampering with the device.

In addition to ensuring the physical safety of the users, the system should also ensure the privacy and security of the users' information. While any wireless link runs the risk of packet interception and capture by a malicious observer, this will only affect the data currently being transferred, and data encryption schemes may greatly hinder these intrusions. The stored data will likely not be encrypted, but will not be actively transmitted: the only means of accessing this data will be through the software controls set in place by the base station or by physically removing the storage medium and removing the data from it. The base station software will use permissions-based file system access and will require a user to authenticate as an administrator before accessing this information. In this way, the user's data will be stored with access controls and will be kept private.

13.3.4 Schedule Feasibility

As the project deadline has been fixed to be the beginning of May 2011, the timeline of the project is eight months. During these eight months, the team members must develop, prototype, test, and correct the system design. The feasibility of completing the project within this time period depends on the progress of design and the availability of parts, both of which are prone to unexpected obstacles. The design team has established a Gantt chart that establishes major project milestones and their deadlines. According to this Gantt chart, the project is currently behind schedule, as the breaker subsystem has not yet been prototyped or tested. These expectation were established as the design team will first focus on the subsystems individually and then incorporate them all into one coherent system. Although the current project status is not quite up to the expected progress, the project as a whole is still feasible within the time frame.

13.3.5 Resource Feasibility

In order to meet the established goals for the project, the design team will require the major physical components of the devices, software to perform simulations, and knowledge regarding the specific devices and the design process. In general design team has found means of satisfying these requirements, whether by provision or pursuit. This does not, however, mean that no resource bottlenecks will develop.

The material components for the project will be available through an assortment of different channels. On such channel, the Calvin Engineering department, provides components that are fairly simple or common, such as solder, common circuit components, and other parts that the design team may harvest from discarded electronic devices. Calvin also provides the workspaces and equipment to perform the assembly and design. The second channel, corporate donations, provides parts to the project for little or no financial cost to the design budget through a company's academic program. Specifically, Texas Instrumentsdonated an MSP430 development board to the project through their University Program. The final channel, the project budget, provides funds to acquire components not provided by the other channels. The Calvin Senior Design Program established a budget of $750 for the project. Through a combination of these three means, the design team will be able to acquire the material components for the subsystem devices.

To reduce labor and resource usage, the design team should be able to test different systems without physical construction. To facilitate this, the project will require a variety of simulation software to model electronic circuits or higher-level systems. The Calvin College engineering program provides a computer and relevant simulation software to the design project, effectively meeting this need. Should the design team require any software that Calvin does not provide, the design team will attempt to work around the problem or find a cost-free program to accomplish the need. If this cannot be done, the team will investigate the availability of educational demonstration copies of the software. For the foreseeable needs of the project, the software needs remain within the available software.

Even with the necessary components and the proper tools, the design team will need the electrical and engineering knowledge required to design and implement the system. While the design team has already learned about electrical systems through the electrical engineering program at Calvin, they may consult the

Calvin professors or search the Internet for information they do not have. Consumers Energy has additionally agreed to provide information and advice regarding the technical aspects of the project. In addition, the design team continues to learn how to manage themselves in an effective manner. Mark Mitchmerhuizen, a head engineer at Johnson Controls, Inc. (JCI), has volunteered to be a mentor to the design team, and can provide both technical and organizational information. Although the design team will undoubtedly encounter situations or obstacles that they cannot immediately handle, they have the ability to gain the knowledge necessary to overcome these setbacks.

Even with the knowledge required to solve problems, the design team still expects certain bottlenecks or hindrances in the design process. Time will pose the greatest obstacle to the team, as determines how much design can be accomplished before the project deadline. Additionally, ordering parts incurs some time delay between the order placement and the arrival of the part. The project budget, now $750, exceeds some of the preliminary estimates for the project, but this increase should allow for improved flexibility in part costs. Time and money, therefore, present the two greatest bottlenecks to resource availability.

13.4 Consumer Cost Recovery

In 2009, the residential monthly electricity bill in the United States averaged to $104.52[36]. If the PICA base station and solid-state breakers sell with a retail price around $400, then the investment will amount to approximately four months of electricity bills. If, as is intended, the PICA system allows users to more wisely manage their consumption habits, then homeowners who have purchased the base station and have either the solid-state breakers or the E-meter installed at their house should experience a decrease in their monthly bill, which could recover the initial cost of the system installation. A table summarizing the different savings and payback periods appears as table 10.

Table 10: Table of Cost Recovery Rates

Relative Billing Reduced	Average Monthly Savings ($)	Months to Recover $400
0%	0	-
0.5%	0.52	765
1%	1.05	382
2%	2.09	192
3%	3.14	128
5%	5.23	77
10%	10.45	38
20%	20.90	19

As cost reduction rates depend entirely upon the user's response to the information, the recovery period for any given customer cannot be predicted. While reduction rates of 20% and higher may be realized for some individuals, a savings rate of 3% may be somewhat more typical. Using the United States Department of Energy (DOE)'s monthly average of 908 kWh consumed per residence, this represents a decrease in average consumption of about 27 kWh per month per household. This amounts to 113 watts saved for eight hours for each of thirty days per month, equivalent to slightly more than one typical incandescent lightbulb. Such a reduction yields a payback period of 128 months, or slightly less than eleven years. If, however, the system could reduce consumption by twice this amount, the payback period would halve to just over five years, or 64 months.

13.5 Similar Products

This section analyzes a few products with similar features to various components of the PICA system such as Kill-A-Watt, Cent-a-Meter, The Energy Dectective, and Watts Up? Smart Circuit. Finally, these products will be compared to the PICA system in a table.

13.5.1 Kill-A-Watt

Around the turn of the millennium P3 International introduced the Kill-A-Watt device, which they marketed as a "user-friendly power meter that enables people to calculate the cost to use their home appliances," [37]. According to Amazon.com these devices range in price from 52to99 Manufacturer Suggested Retail Price (MSRP) depending on features, most notably how many devices can be monitored simultaneously. P3 produces three models of the Kill-A-Watt devices:

1. Kill-A-Watt PS (P4320): A power strip capable of monitoring voltage, line frequency, amperage, KWH, and current leakage for up to eight devices simultaneously and includes built-in surge protection [38].
2. Kill-A-Watt (P4400): The original Kill-A-Watt device, capable of monitoring voltage, amperage, watts used, line frequency, KWH, uptime, power factor, and reactive power for 1 device [39].
3. Kill-A-Watt EZ (P4460): This device is functionally identical to the P4400 series except that it includes one extra feature, it can calculate how much a device costs the consumer, after being programmed with the $/KWH provided by the power company [40].

All of the Kill-A-Watt devices claim to be accurate to within 0.2% of the actual power the monitored device uses [38][39][40]. The Kill-A-Watt devices cannot replace a power meter, but simply provide a method of supplying a consumer with additional data about their power consumption.

13.5.2 Cent-a-Meter

The Australian company, Clipsal produces the Cent-a-meter also known as the Electrisave or the Owl in the UK. Clipsal only produces one version of the Cent-a-meter which displays the cost of the electricity used in the home along with the temperature and humidity [41]. The device can also measure kW of demand, and kg/hour of greenhouse gas emissions [42]. Unlike the Kill-A-Watt, the centimeter does not accumulate any data, just displays instantaneous data on a receiver unit mounted in the home [41]. Clipsal does not list an MSRP for the Cent-a-meter, however SmartHome USA sells Cent-a-meter devices for $140 [42].

13.5.3 The Energy Detective (TED)

Energy Inc., a division of 3M, recently introduced its TED (The Energy Detective) power monitor. Functionally, TED operates exactly as the meter on the exterior of a consumer's home or business but the display resides indoors in a more convenient viewing location. Energy Inc. currently produces two series of the TED device:

1. TED1000 series: The TED1000 devices monitor current energy consumption in killowatts, and current energy cost in $/hour, and log this data for 13 months to predict energy use for the current billing cycle. TED1000 devices can integrate with a proprietary software package, Footprints, provided by Energy Inc. to visually display usage data [43]. TED1000 series devices range in price from $119.95 to $229.95 depending on the amp-rating of the service installation [44].

2. TED5000 series: The TED5000 sought to improve upon the TED1000 series by extending the functionality of the TED devices. The largest selling point for the TED5000 is integration with the Google Power service to track power usage data on the web [45]. TED5000 series units range in price from $239.95 to $455.80 depending on from how many measurement units the device gathers data [46].

13.5.4 Watts Up?

In 1997 Electronic Educational Devices Inc. introduced the Watts Up? product line to the education market. The product immediately became a hit, and soon utility companies across the United States began to take notice [47]. EED markets the Smart Circuit devices as a replacement for traditional circuit breaker devices for 100V to 250V, 20 amp 50/60Hz circuits [48]. Each Smart Circuit contains a built in web-server that allows for aggregation of collected data at a maximum rate of once per second [48]. These Smart Circuits are typically installed into a standard panel enclosure box, similar to standard circuit breakers, mounting directly to the industry-standard DIN rail inside the enclosure[48]. Alternatively, if needed at one local outlet, the Smart Circuit can be housed in a standard double gang electrical box [48]. Each Smart Circuit device can turn itself on or off when it receives a certain remote-control signal or when it detects one of many programmable stimuli. This self-waking feature makes these devices ideal for home-automation projects [48].

A single Smart Circuit, capable of controlling one circuit, costs $194.95, with enclosures for one, five, or ten Smart Circuits devices going for $325.95, $1495.95, and $2495.95 respectively [48]. A basic account, to view aggregated data and control the devices is free for residential use, but data rates, historical data and devices rules are limited [49]. A top-tier account, featuring the fastest update time, 1 second, up to 25 meters, 1 year of archival data, and 25 rules costs $50.00 a month [49].

13.5.5 Smart-Watt

The Smart-Watt device from Smartworks Inc. takes a similar approach to the Kill-A-Watt device in metering a single device at a time, but monitors much more information including circuit load over any period of time, and number of on/off cycles the attached device undergoes [50]. The biggest advantage to the Smart-Watt devices comes from the proprietary network Smartworks has developed for their devices. Each device attaches to a local network where a central server collects and collates all the data [50]. The Smart-Watt comes in two versions, one for International Electrotechnical Commision (IEC) plugs and receptacles and one for National Electrical Manufacturers Association (NEMA) plugs and receptacles. Both devices are similarly priced ranging from $169 to $249 depending on the current rating [50].

13.5.6 Standard Power Meter

Most homes or businesses attached to the electric grid are metered using a standard analogue power meter. This device provided by the power company, measures the amount of electrical energy consumed over a period of time. Typically, a power meter records in billing units, such as KWH. Each meter requires periodic readings based on the billing cycle of the power company; it is safe to assume that meters are read approximately once per month. In order to read the meter, an employee of the power company will physically go out to the meter and record usage data.

13.5.7 Nonintrusive Appliance Load Monitor

All of the products discussed here use a technique known as Non-intrusive Load Monitoring (NILM) to monitor power consumption without affecting the load on the circuit [51]. However, some more sophisticated products in this area use NILM to estimate the number of individual loads on the circuit [52]. If the research in this field proves that NILM provides accurate and useful data, devices based on the NILM technology would have a large advantage over other single-device power monitors, as such a device could be inserted into the feeder lines from the utility company and monitor all devices in the entire installation from a single point. Research turned up no significant products that claim to be capable of monitoring multiple loads on a circuit from a single point on the circuit. Thus this section is included to provide information, but does not represent a viable competitor in the market just yet.

13.5.8 PICA Competitors Comparison

In order to better understand the competition in the marketplace table 11 reproduces the information laid out above as a comparative table. The column on the far right side describes the PICA component that most directly competes with the product listed in the left column.

13.6 Production and Distribution

See section 14, following.

Table 11: Comparison of PICA Competitors

Product	Monitoring features	Control Features	Cost (Fixed)	Cost (Recur-ring)	PICA Competitor
Kill-A-Watt	voltage, line frequency, amperage, KWH, and current leakage	N/A	$52 to $99	N/A	Ciruit-by-Circuit Monitors
Cent-A-Meter	Cost of electricity, temperature, humidity, kW of demand kg/hour greenhouse gas emissions	N/A	$140	N/A	E-Panel Meter
The Energy Detective	kW load, $/hour	N/A	$119.95 to $455.80	N/A	E-Panel Meter
Watts Up? Smart Circuit	Current, Voltage, kilowatts used	Remote On/Off	$194.95 /circuit	Free to $50.00 /month	Circuit-by-Circuit monitors
Smart-Watt	voltage, line frequency, amperage, KWH, current leakage, circuit load, on/off cycles	N/A	$169 to $249	N/A	Circuit-by-Circuit Monitors

14 Parts and Project Costs

The project costs can be broken into fixed and variable costs, where fixed costs represent the costs the team will incur during the year and production start-up costs, while variable costs represent the long-term costs associated with production.

14.1 Fixed Costs

14.1.1 Prototype parts

Through the Senior Design class, the Calvin College Engineering department provided $750 for prototype parts. Since the project has a large scope, the team needs to minimize the cost of any single part to stay within the given budget. As such, the team chose several parts more because of their low cost rather than for functionality. As such, the team sought donations and free samples whenever possible, including the TI MSP430 development kit from Texas Instruments and the ADE7763 power monitoring chips from Analog Devices. The team also obtained a pre-purchased Xilinx Virtex-5 development board. Table 12 shows the part donations and to-date purchases.

Table 12: Prototype part costs.

Date	Item	Price	Quantity	Total	Running Total
15-Oct	SSOP to DIP Adapter 20-Pin	$3.95	2	$7.9	$7.9
15-Oct	Break Away Headers – Straight	$2.5	1	$2.5	$10.4
3-Nov	TRANSF CURRENT .50" OPENING PCB	$14.25	2	$28.5	$38.9
15-Nov	TI Donation MSP430	$0.00	1	$0.00	$0.00

14.1.2 Labor

Throughout the semester, the team has kept a log of how many hours they worked. Determining the cost of labor for the past semester based on these records, the team can also more accurately forecast the labor cost for next semester. So far, the team has logged 348 hours, with another 40 estimated before the end of the semester. Extending this to next semester, assuming a similar workload with a little extra time for final presentations, the team expects to have 388 hours, putting the yearlong total at about 776 hours. Assuming engineers are paid $100 an hour, the first semester labor cost is $38,800, the second semester cost is $38,800, making the full labor costs for the project $77,600 as calculated in Table 13.

Table 13: Team hours and projected labor costs.

Timeframe	Hours Logged	Cost
start to present	348	34,800
present to end of first semester	40	4,000
first semester	388	38,800
second semester	388	38,800
TOTAL	776	77,600

14.1.3 Manufacturing start-up

In determining the cost for start-up of manufacturing, the team looked strictly at the costs of the product, ignoring many costs associated with starting a business. The team decided to contract out the work needed to build the system. The team will need to determine the exact costs of this next semester, but aspects will include printing circuit boards, populating them and providing cases for each of the parts. Costs associated with buying or renting a building were broken down to a per device cost under the inventory section of the cash flow. The cost of land was determined to be irrelevant in this situation.

14.1.4 Other

Some other costs to consider include software, discrete components, and various other development kits. In a professional engineering firm, these may represent a significant cost if they do not already own these, but as the college generously provides these, the team does not need to include them in their budget.

14.2 Variable Costs

14.2.1 Parts

To calculate the overall cost of parts used in production, the team assumed large quantities for each of the individual components. This means that the low end of the cost range for parts is used. Based on this information and the estimated final cost of the prototype, the team calculates the cost of parts for the breakers, base station and e-meter to be $35, $100, and $200 per subsystem, respectively.

14.2.2 Manufacturing

The manufacturing costs consist primarily of inventory and labor costs associated with production. Table 14 shows the calculations determining the number of devices produced in a year. Table 15 shows calculations determining the amount of floor space needed to store 3 months worth of devices and the cost to add that space to a pre-existing building [53].

Table 14: Calculations showing number of devices expected.

Number	Units	Source
6400000	customers	Calvin Business Team
0.001	percent interested in PICA	Estimate based on [33]
64000	customers interested in PICA	
25	breakers/customer	Estimate
1600000	breakers needed	
64000	base stations needed	
3200	US power companies	[31]
8300000	number converted homes	[32]
24900000	number expected conversions	[32]
130000000	total homes	Calvin Business Team
40625	average homes/company	
5	major meter providers	[54]
3	minors per major	Estimate
15	minor meter providers	Estimate
3	ratio homes provided to by major vs. minor	Estimate
30	effective meter providers	
830000	PICA homes	
830000	E-meters needed	

Table 16 shows the calculations used to determine the labor costs for manufacturing purposes. Estimates given during lecture [55] helped determine the hourly wage and additional costs of labor including insurance, vacation, holiday, sick time etc. The number of hours needed to assemble each system does not include the time needed to print and populate each circuit board as these will be completed by automatic machinery that requires minimal human interaction.

14.2.3 Distribution

The team has not yet contacted a shipping company to determine exact costs, but based on experience, size and weight, the team expects a total cost of $25,400,000. Table 17 shows the cost of distribution for each

Table 15: Cost to add room to store inventory.

	Units	Breaker Storage		E-meter		Base Station		
width	ft	0.0833	given	0.5	given	1	given	
height	ft	0.25	given	0.6666	given	0.6666	given	
length	ft	0.3333	given	0.25	given	0.3333	given	
volume	ft^3	0.0069	calculate	0.08333	calculate	0.2222	calculate	
yr supply	#	1600000	Table 14	830000	Table 14	64000	Table 14	
qrt supply	#	400000	calculate	207500	calculate	16000	calculate	
pallet ht	ft	3	given	3	given	3	given	
pallet stack	#	3		3		3		
total ht	ft	9	calculate	9	calculate	9	calculate	
floor area	ft^2	308.6419	calculate	1921.2962	calculate	395.0617	calculate	2625
floor length, if square	ft	17.5682	calculate	43.8325	calculate	19.8761	calculate	51.2347
cost	$	12288	20x(20+10)	30720	50x(50+10)	12288	20x(20+10)	43000

Table 16: Cost of labour for manufacturing

Line Item	Number
Hourly wage	$20
Insurance, vacation, holiday, etc.	$10
Per worker total	$30
Hours to assemble breakers	1
Hours to assemble base station	0.5
Hours to assemble E-meter	1.5
Breakers per year	1,600,000
Base stations per year	64,000
E-meters per year	830,000
Hours for breaker	1,600,000
Hours for base station	32,000
Hours for e meter	1,245,000
Breaker cost	$48,000,000
Base station Cost	$960,000
E-meter cost	$37,350,000
Total Hours	2,877,000
Total Cost	$86,310,000

subsystem.

Table 17: Cost of distribution

	Breaker	Base Station	E-meter
Number shipped	1,600,000	64,000	830,000
Cost per device	$5	$12	$20
Total cost	$8,000,000	$768,000	$16,600,000
Total Shipping Cost	$25,368,000		

14.2.4 Marketing

The project includes two distinct advertising methods to better accommodate the different target consumers. The e-meter aspect of the project will be sold directly to the power company, and the breakers and base station will be sold to the home and business owners. As the number of power companies is significantly fewer than the number of home and business owners, and will be purchasing in much larger quantities, the team decided it makes sense to appeal to the power companies in a much more personal manner. This includes phone calls, letters, and visits and outside of the cost of paying a few employees will be negligible.

Most of the advertising will aim at the home and business owners, and the team decided that magazines and websites such as Popular Science and Green magazine are the best method of reaching out to potential buyers. Green magazine features news and products related to sustainable energy, reaching thousands of people every year. Approximately 36% of those people are in the building and contracting industry and would be beneficial in spreading news about the team's product [56]. The cost to put a medium size ad on their website is $150 dollars per month [56], so for a year would be $1800. Popular science reaches over 7 million people using printed material. For a 1/3 page ad in four color for 12 months, the cost is $59,900 [57]. The team would like to target 3 to 4 magazines and using Popular Science and Green magazine as boundary cases, estimates a total cost of $120,000 for marketing and advertising.

For the home and business owners' side of the project, the team also would like to work with distributers like Lowe's and Home Depot. The team would like to use a method of advertising similar to the one used for power companies, so the cost will not noticeably increase. The distribution companies may do additional advertising, but any costs associated with that will be their responsibility, so again the cost the design team expects will stay the same.

14.2.5 Legal, warranty and support

The team expects about 10 hours of work for basic legal documentation. Because of the potential for lawsuits, the team built in money to cover the costs of 200 hours of work, assuming $80 an hour, giving a total of $16,800. The team does not intend to pursue any patents, but recognizes there may be infringement lawsuits, which were built into the above 200 hours.

The team expects 5% of all PICA systems that include all three subsystems to fail and need replacement. At a system cost of $519 per system with shipping of $37, the amount needed to cover warranties is $1,800,000.

14.3 Total Costs

Table 18 is a summary of the project costs, including both fixed and variable costs.

Table 18: Cost estimate for the project.

Full Scale Production				
Fixed Costs	Prototyping	$120,700		
	Automated Equipment			
	Marketing/Advertising	$120,000		
	Legal	$168,000		
	Facilities	$0		
	Total	$257,500		
Variable Costs	System	Breakers	Base station	E-meter
	Number of devices	1600000	64000	830000
	Single device parts	35	100	200
	Total device parts	56000000	6400000	166000000
	Labor	$48,000,000	$960,000	$37,350,000
	Shipping	$8,000,000	$768,000	$16,600,000
	Inventory	$5,100	$31,800	$6,500
	Total (per device)	$70	$127	$265
Totals	Total Per Subsystem	$112,262,600	$8,417,300	$220,214,000
	Total per device	$70	$132	$265
	Full System	$340,893,900.00		

15 Acknowledgements

Team PICA would like to acknowledge and thank the following people for their help in the course of the project.

- Professor VanderLeest for his work as the Team Advisor, providing constructive feedback and insights, and for pushing us to always improve.
- Professor Ribeiro for his help in Engr. 315 and insights on power systems.
- Consumer's Energy, for allowing us to visit their Smart Grid Learning Center, and Brian Bushey, Mark Luehmann and Tim Voss specifically for answering many questions about their work as a power company.
- Tim Theriault for his time as the team's Industrial Consultant.
- Mark Michmerhuizen for his work providing feedback on team documents.
- The Business team from Bus. 396 for helping us understand business aspects of our project.
- Professor Medema for helping understand business aspects of our project.
- Bob DeKraker, Chuck Holwerda and Phil Jasperse for their help as shop and lab technicians.
- Glenn Remelts for assisting with team research.
- Texas Instruments for generously providing us with a MSP430 development kit.
- All of our friends and family for supporting, encouraging and putting up with us.

16 Conclusion

Based on Team PICA's initial research, the power monitoring and information collection system is feasible for the purposes of the Engr. 339-340 senior design class. By combining several subsystems to monitor various components of the power system, Team PICA believes they can provide new and useful information to the power company and the consumer, allowing them to make better decisions about how power is consumed. For practical purposes, Team PICA's prototype will function as expected, but feature hardware that may not be part of the final production version.

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