Energy Management System

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Presentation Overview

- Customer Needs
- Engineering Specifications
- Concept Selection
- Top Level Design
- Detailed System Diagrams
- Bill of Materials
- Risks
- Testing
- Questions

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Needs Statement

Many homeowners and businesses are not aware of their power usage habits. This lack of awareness leads to potentially inefficient power usage. Existing products are either too expensive or do not include all functionality, such as the ability to remotely control, monitor, and manage power consumption. A system is needed to allow for monitoring and basic management of a home's or business's power usage for a reasonable price.

Needs & Marketing Requirements

1. The system shall accurately monitor power consumption.
2. The system shall allow for control of whether a single gang of outlets is powered.
3. The system shall allow for a schedule to turn gangs on and off automatically.
4. The system shall be safe.
5. The system shall provide intuitive visual representations of usage data.
6. The system shall have low cost in comparison to competitive products.
7. The system shall be easy to install by a professional.
8. The system shall have an easy to use interface.
9. The system shall be of reasonable size in comparison to existing systems.
10. The system shall consume minimal power.
11. The system shall communicate usage data and commands between outlets and the main module.

Engineering Specifications

Marketing Requirements		Engineering Requirement	Justification
6	A	Production cost shall not exceed $200 for the main unit and $50 for each outlet module.	This is based upon analysis of a competitive market and current design requirements.
7	B	Installation time of an outlet module within an electrical box shall not exceed 30 minutes during typical installation.	Using a professional electrician, the outlets can be installed within this time frame.
4	C	The system shall survive a 2500V impulse voltage per IEC-60664-1.	This will prevent devices from being damaged due to transient spikes on the power line.
4	D	Control circuits shall be isolated from power line by 1250V RMS minimum.	Electrical isolation is required by safety agencies for equipment connected to the AC power line.

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Engineering Specifications

Marketing Requirements		Engineering Requirement	Justification
1	E	The control unit shall be capable of varying the load power from 0 to full power for resistive loads.	Dimming function allows reducing load power consumed for energy savings. This is only applicable for purely resistive loads, (e.g., lightbulbs, heaters, etc.).
1	F	The system shall measure power consumption with an accuracy of ± 10 %	This will allow the system to measure usage accurately enough for the typical user.
1,2,3,5,8	G	A web interface or web application shall allow the monitoring and management of the system.	This will allow for user to be able to manage the system and perform various tasks associated with the system.

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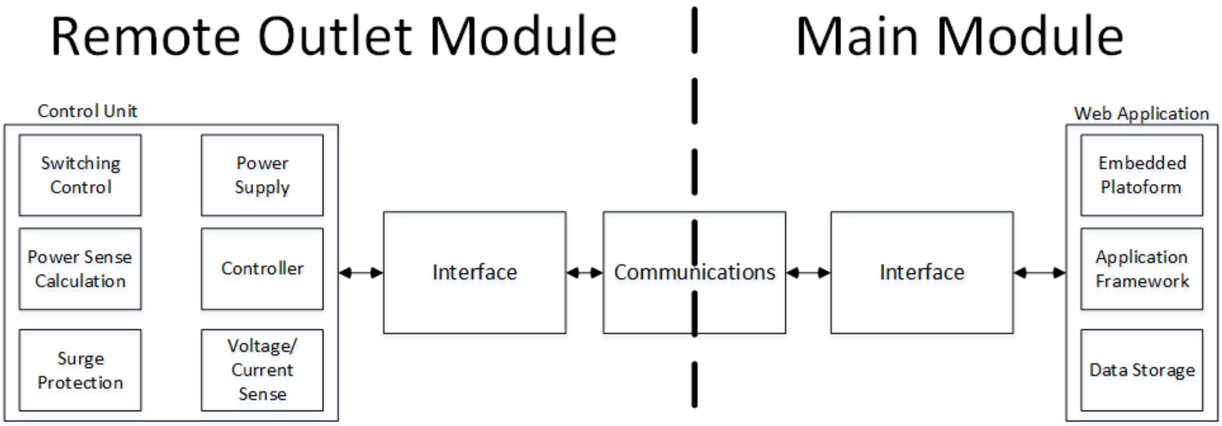
Engineering Specifications

Marketing Requirements		Engineering Requirement	Justification
8	H	The user shall be able to understand complete system functionality within an hour.	Analysis shows that an intuitive interface should require minimal time to operate.
4	I	The system shall use only UL recognized components.	Safety agency approvals will be required to sell product commercially.
9	J	The production system shall be able to fit into current standard electrical outlets.	To be fully integrated and competitive, the system must be able to replace current outlets.

Engineering Specifications

Marketing Requirements		Engineering Requirement	Justification
10	K	The system shall have greater than 95% efficiency at maximum rated load.	To achieve energy savings and to avoid excessive heating of the wall units.
2,3	L	Wall units shall be identifiable.	This allows the system to know what information is coming from what wall unit and to provide individual control.
11	M	All modules shall transmit at a BPS rate sufficient to relay commands and usage data at the chosen sampling frequency.	In order to have reliable communication, the modules must have an adequate minimum communication rate.

Top Level Diagram



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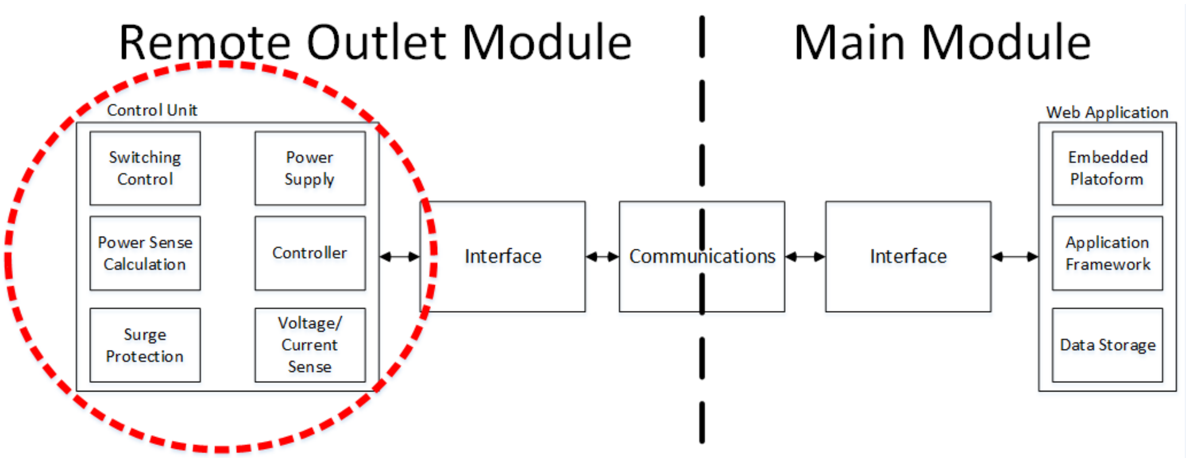
Control Unit



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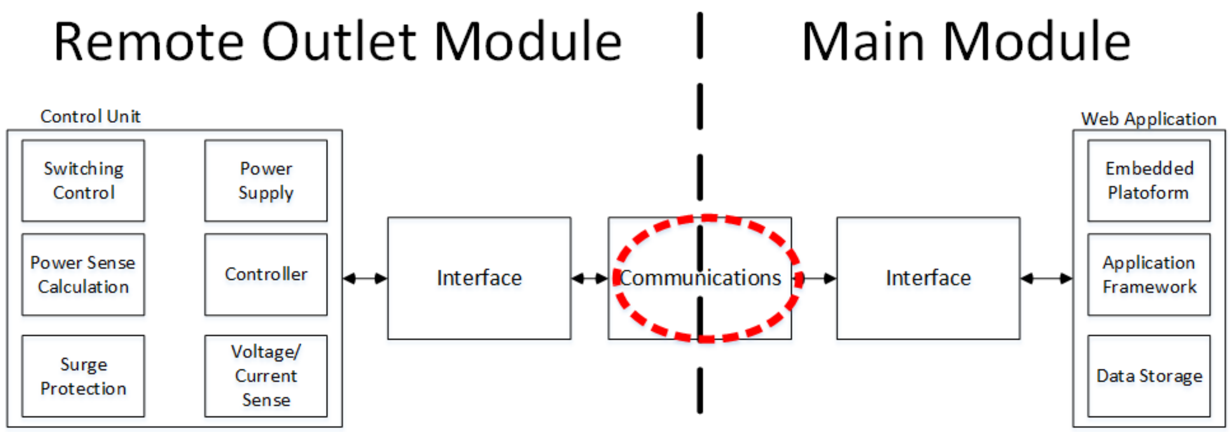
Remote Outlet Module Concepts

- Switching Control
  - Triac driven by MOC3063M, an optically coupled (electrically isolated) driver
- Power Sense Calculation
  - Implementation of root-mean squared (RMS) algorithm in chosen controller
- Surge Protection
  - MOV used to dissipate excess energy in a surge situation
- Power Supply
  - Recom Switch Mode Power Supply
- Controller
  - De-0 Nano board. Lots of GPIO to interface, plus a onboard 8 channel ADC.
- Voltage Sense
  - Optically Isolated Amplifier using sigma delta modulation
- Current Sense
  - Hall effect current sensor

PLC Concepts



PLC Selection

- PLC Chosen for communication to permeate through walls & obstacles
- As a mature technology, most available PLC chips utilize high enough frequencies to avoid interference, and most come with collision handling – The main concern is data rate.
- Wanted potential for near real time measurements (Transmit every .1 seconds)
- Wanted to support 200 outlets (Minimum 8-bit ID)
- Wanted power measurements accurate with 14 bits
- $B > M_O * (P[bits] + D[bits]) * (Fs)$
- B > 44000 bits/second

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PLC Options

Part	Packet Bits	Provided Data Rate	Collision Provisions	Interface
CY8CPLC10	56	2400	Yes	I2C
CY8CPLC20	56	2400	Yes	I2C, UART
ST7540	0	4800	No	UART,SPI
ST7570	112-336	2400	Yes	UART
ST7590		128000	Yes	UART,SPI
MAX2992		300000	Yes	UART,SPI
ATSAM4CP16B		128000	Yes	UART,SPI
TDA5051A	0	1200	no	Digital

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PLC Rethought

- The chips capable of achieving such a data rate have hundreds of pins, so we would like to avoid routing for such chips if possible.
- Rethought what could be possible:
  - Transmit data for gang (2 outlets) instead of one outlet
  - We want to transmit voltage, current, and power factor
    - Adds possibility of additional features & graphs
  - Voltage = 5 bit offset from 100, Current = 10-bit resolution, PF 1:-1, 8 bit resolution.
  - Default transmission interval = 15 sec, near real time = 1 sec
- $B > (MGF_D + M_{GR}F_R - M_{GR}F_D) * (P + [\lceil log_2(2 * M_G)\rceil] + V + I +$

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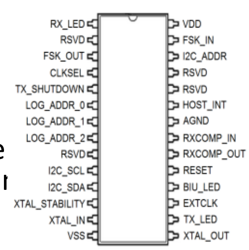
PLC Rethought

- Assuming 100 Gangs, and at most 5 Gangs transmitting at real time, as well as the reductions made here, then the minimum is
  - 340 bps
- Using the desired Cypress chips, with P=56 bits, then
  - 896 bps
  - This is well below the provided 2400 bps, but if it is exceeded, the possible to reduce the number of outlets, as a typical home does r 200.
  - Further, the default rate could be modified.
- Options narrowed to Cypress CY8CPLC10 and CY8CPLC20 (PSoC version of CY8CPLC10).



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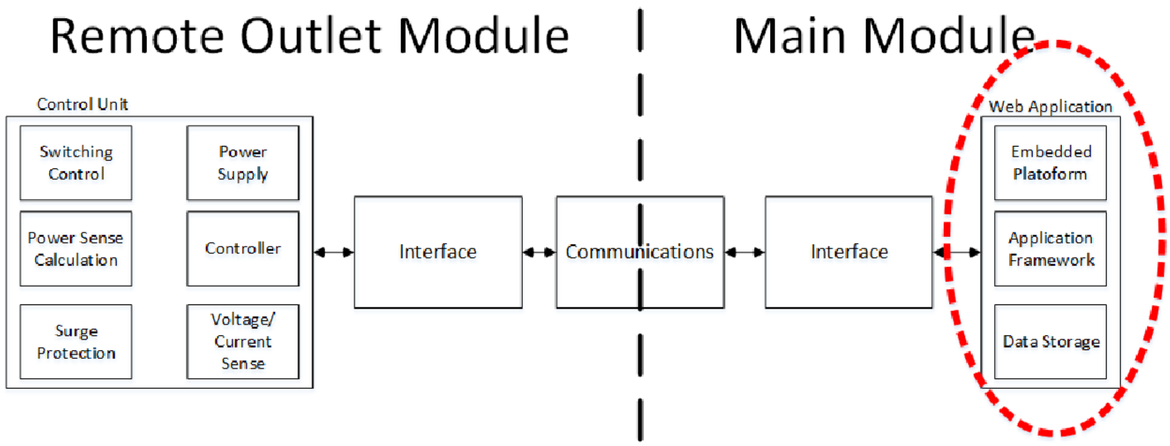
Main Module



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Data Storage

- Data needs to be stored in order for it to be presented to the user
- Can be stored in multiple ways:
  - One single file
  - Database
  - Memory

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Why Choose a Database?

- Queries: being able to search through all of the data
- Large data sets handled easily
- Easier to manage data (DBMS)
- ACID (Atomicity, Consistency, Isolation, Durability) Compliance

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Database Management System (DBMS)

- Creating, Updating, Querying, Administrating Databased
- Popular DBMSs:
  - Microsoft SQL Server
  - MySQL
  - PostgreSQL
  - SQLite

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Microsoft SQL Server

- Developed by Microsoft
- Windows Server OS only
- Commercial license
- ACID Compliant
- Smaller number of programming languages supported
- Multiple locking techniques, based on current transaction

MySQL

- Developed by Oracle
- Available on all operating systems
- GPL open-source commercial license
- ACID compliant (depending on storage engine)
- Many programming languages supported
- Table-level or row-level locking (depending on storage engine)

PostgreSQL

- Developed by PostgreSQL
- Available on all operating systems
- BSD open-source license
- ACID compliant
- Fewer programming languages supported than MySQL
- Both locking mechanisms supported

SQLite

- Developed by Richard Hipp (originally)
- Available on all operating systems
- Open source through public domain license
- ACID Compliant
- Many programming languages supported
- Variation of table-level locking supported

MySQL Storage Engine

- Memory
  - Data is stored in memory, then flushed to disk once enough changes made
  - Quicker access times, but risk of data loss during power outage
- MyISAM
  - Not ACID Compliant
  - Table-level locking (good for read heavy applications)
- InnoDB
  - ACID Compliant
  - Row-level locking (good for write heavy applications)

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Embedded Platform

- Chose the **Raspberry Pi 2**
  - Cheaper
  - More memory
  - Similar power consumption
  - Ease of use
    - Runs full OS
    - Uses Python natively

Product	Raaspberry Pi 2 Model B+	BeagleBone Black Rev. C
Price	$35	$55
Size	3.370" x 2.224"	3.4" x 2.15"
Processor	Broadcom BCM2836	AM3358BZCZ100
Cores	4	1
Clock Speed	900 MHz	1 GHz
RAM	1 GB	512 MB
Onboard Flash	None	4 GB
External Storage	microSD	microSD
Operating Voltage	5V	5V
Power	230 - 800 mA	210 - 460 mA
Digital GPIO	40	65
Analog Inputs	None	7
I2C	Yes	Yes
SPI	Yes	Yes
Ethernet	10/100 RJ45	10/100 RJ45
USB	4	1
Video Out	HDMI	micro HDMI

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Language/Framework

- HTML/CSS/PHP
  - Easy to set up
  - Lightweight
- Django (Python)
  - Completely Python based
  - Fairly Lightweight
- Vaadin Framework (Java)
  - Heaviest
  - Very powerful
  - Familiarity with framework and Java

- Originally chose Django
  - Native Python
  - Low memory usage
- Changed to **Vaadin/Java**
  - More powerful
  - Familiarity

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Hosting

- On-Device Hosting
  - Hosting both the MySQL database and web application directly on the Pi
  - Easy access from local network but only local network
  - Harder to manage (updates)
  - Less secure
- Central Server
  - Databases and application hosted from another location
  - Easy to update
  - Easier to secure
  - Access from any network
  - Managing a datacenter is a huge task
- Chose **On-Device Hosting** for now
  - Easier for a prototype
  - Don't need functionality of a central server yet

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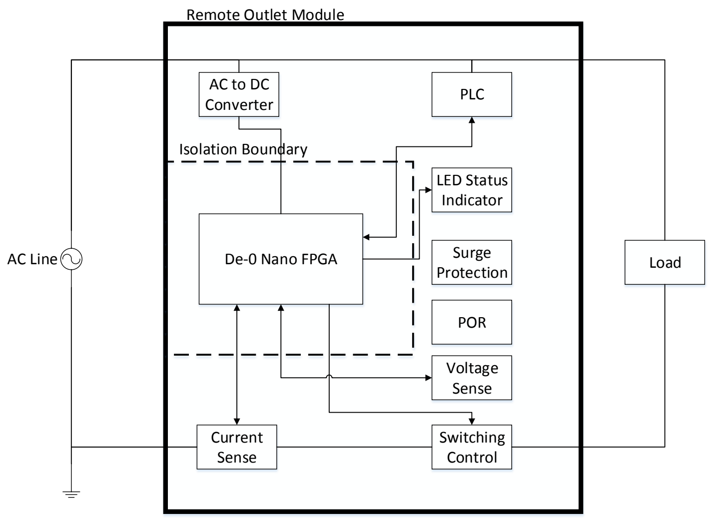
Remote Outlet Top Level Diagram



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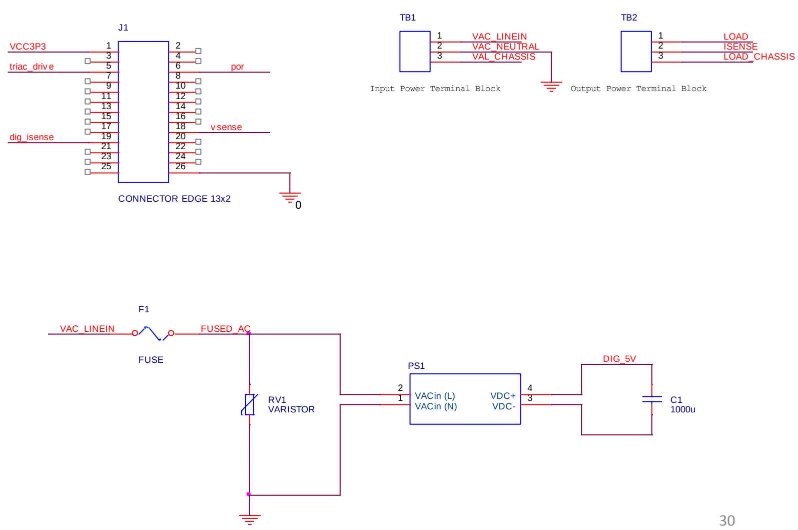
Remote Outlet Hardware Schematic Connectors and AC to DC Supply

- VCC3P3 – 3.3V input power from FPGA
- POR – Power on Reset, active high to FPGA
- Triac_drive – active high to turn on load
- Vsense – 0-3.3V proportional to load voltage
- Isense – 0-3.3V proportional to load current
- TB1 – input power
- TB2 – output to load
- Power Supply 120 VAC to 5VDC at 1W, 1000uF cap to minimize output ripple



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Remote Outlet Hardware Schematic Power on Reset (POR)

- U1 – TPS3808G01, user-defined threshold voltage

SENSE INPUT

The SENSE input provides a terminal at which any system voltage can be monitored. If the voltage on this pin drops below V_{IT}, then $\overline{RESET}$ is asserted. The comparator has a built-in hysteresis to ensure smooth $\overline{RESET}$ assertions and de-assertions. It is good analog design practice to put a 1nF to 10nF bypass capacitor on the SENSE input to reduce sensitivity to transients and layout parasitics.

The TPS3808G01 can be used to monitor any voltage rail down to 0.405V using the circuit shown in Figure 11.

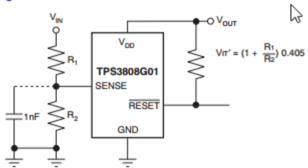
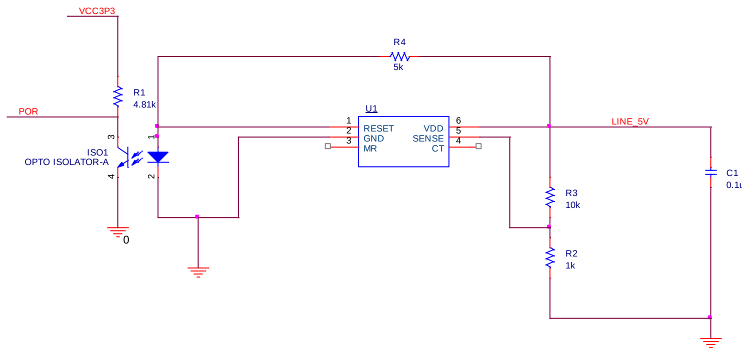


Figure 11. Using the TPS3808G01 to Monitor a User-Defined Threshold Voltage



$$V_{It} = \left(1 + \frac{10k}{1k}\right) * .405 = 4.455\ V$$

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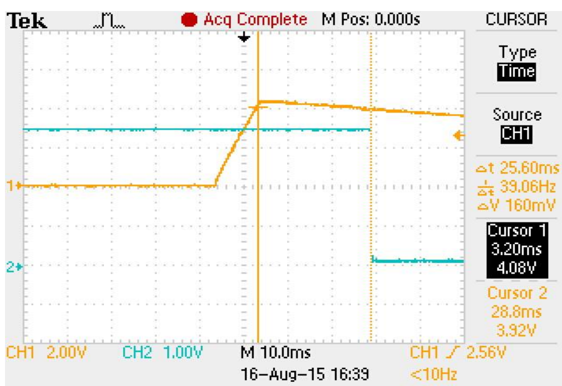
POR Hardware Results

- Channel 1 – 5VDC Bus during power on event
- Channel 2 – POR circuitry output

- Delay between valid 5V DC and POR output about 25 ms as expected per datasheet



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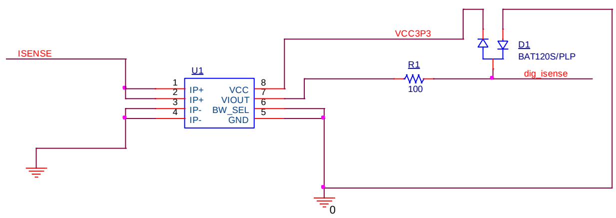
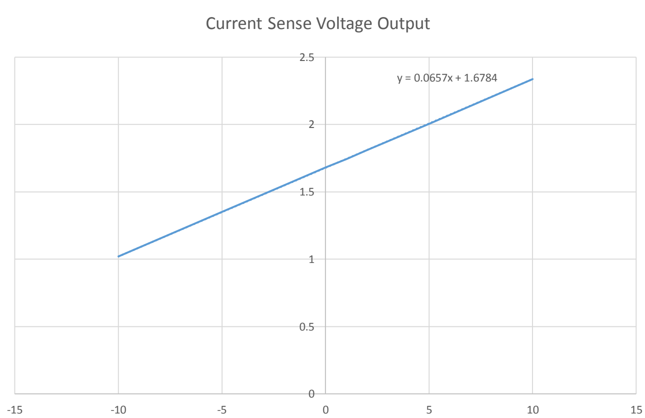
Remote Outlet Hardware Schematic Current Sense

- Block measures current through the load and provides a proportional voltage corresponding to sensed current.
- Voltage output centered around 1.65V (0A) and has resolution of 67 mV per A. Range is -20A to 20A
- Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage.



Current Sense Test Results

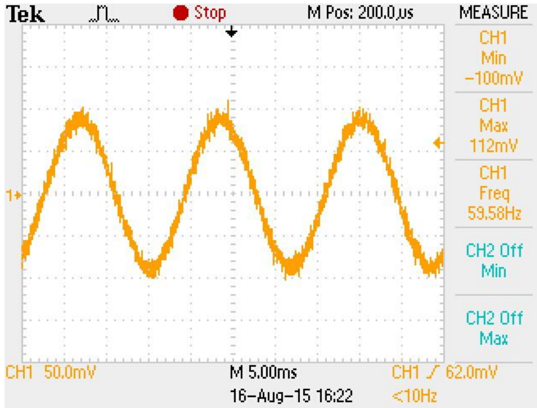
Test Results	
Current (A)	**Voltage (V)**
10	2.337
5	2.005
2	1.809
1	1.742
0	1.68
-1	1.614
-2	1.548
-5	1.351
-10	1.02



- Known amount of current was driven into current sense IC.
- Results show a voltage of 1.68V at 0A with a sensitivity of 65.7 mV

Current Sense Hardware Results

- Current Sense Output with 120 ohm resistive load
- Expected current is 1.414 A
- Waveform shows AC coupled output of current sense circuit
- Measured value was 1.4626A
  - Error of 3.44% assuming resistance value was exactly 120 ohms and line voltage was exactly 120 VRMS



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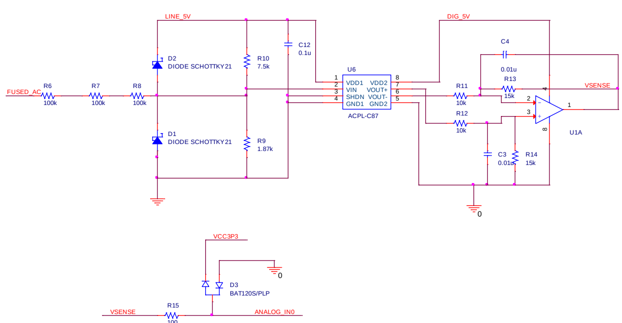
Remote Outlet Hardware Schematic Voltage Sense

- Block provides a proportional analog voltage relative to the line voltage
- Stage one before op-amp scales and shifts voltage such that 2V corresponds to 200V and 0V corresponds to -200V
- (U6) Amplifier provides isolation and has a gain of 1
- Differential amplifier has a passband gain of 1.5 and rejects high frequency noise



$$V_{OUT} = (0.0049645V_{AC} + 0.992) * 1.5$$

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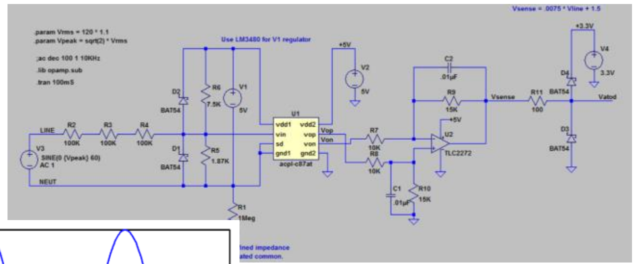
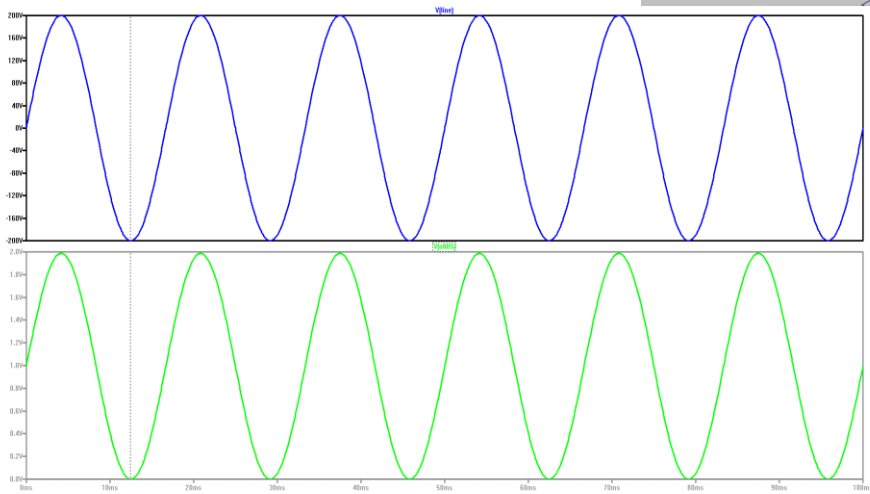
LT Spice Simulations

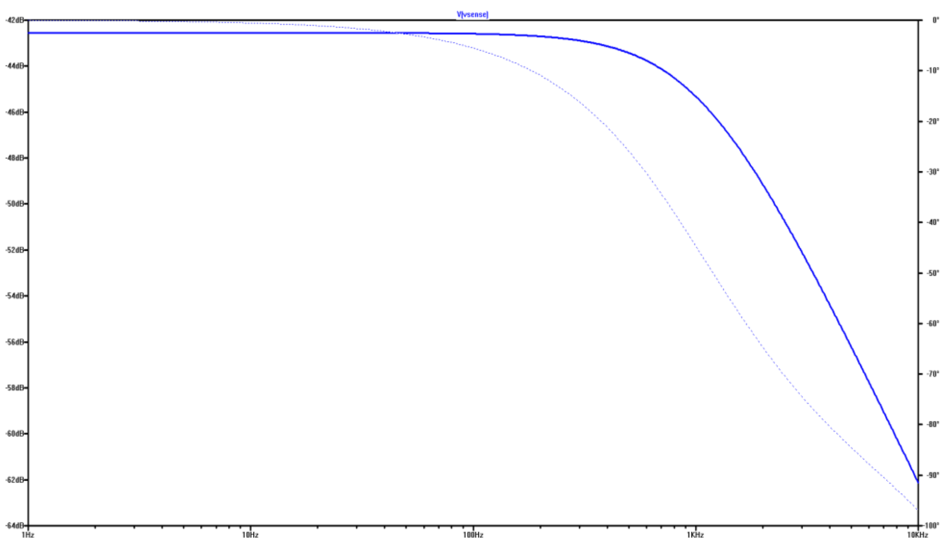




- Top waveform – AC in ranging from 200V to -200V at 60 Hz
- Bottom waveform – output waveform ranging from 2V to 0V

$$V_{OUT} = (0.0049645V_{AC} + 0.992) * 1.5$$

Frequency Response

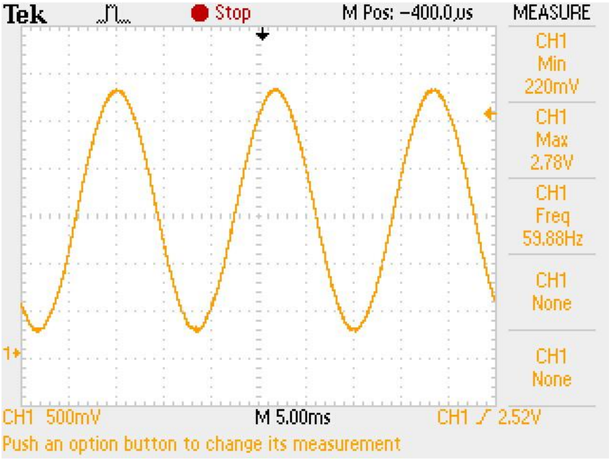


- At 60 Hz, passband gain is -42.8 dB, phase shift of -3.306
- Cutoff frequency of about 1 kHz

$V_{OUT} = (0.0049645 V_{AC} + 0.992) * 1.5$

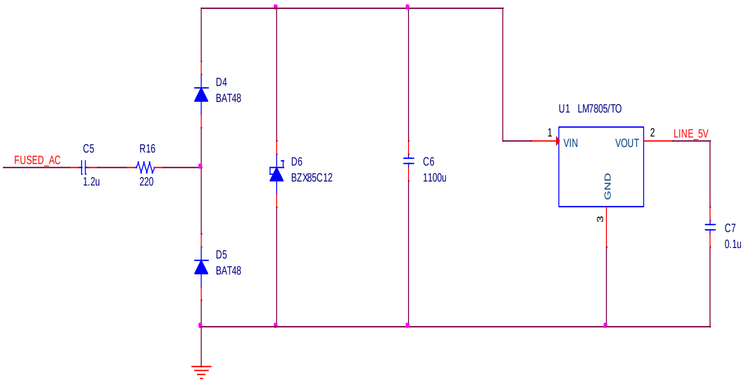
Voltage Sense Hardware Results

- Voltage output for 60Hz 120V RMS input
- Expected Maximum Vout = 2.715
- Actual Maximum Vout = 2.78
- Expected Minimum Vout = 224 mV
- Actual Minimum Vout = 220 mV



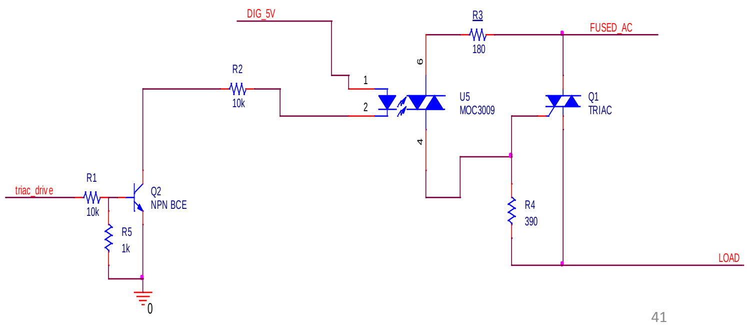
Remote Outlet Hardware Schematic Line 5V Generation

- Need to generate a 5VDC voltage referenced to neutral for voltage sense amplifier.
- 5V reference used to power hot side of isolation amplifier, and also as a reference to center line voltage around 1 V

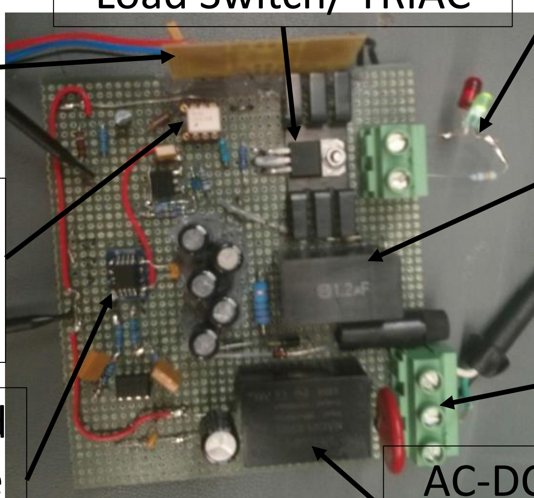


Remote Outlet Hardware Schematic Switching Contol

- Provides a means for controller to switch the power to the load ON and OFF
- Triac is turned on by driving triac_drive input high, selected triac driver MOC3043M provides zero crossing detection, preventing need for multiple fire pulses at every zero crossing



Remote Outlet Hardware Prototype



Remote Outlet Firmware Design

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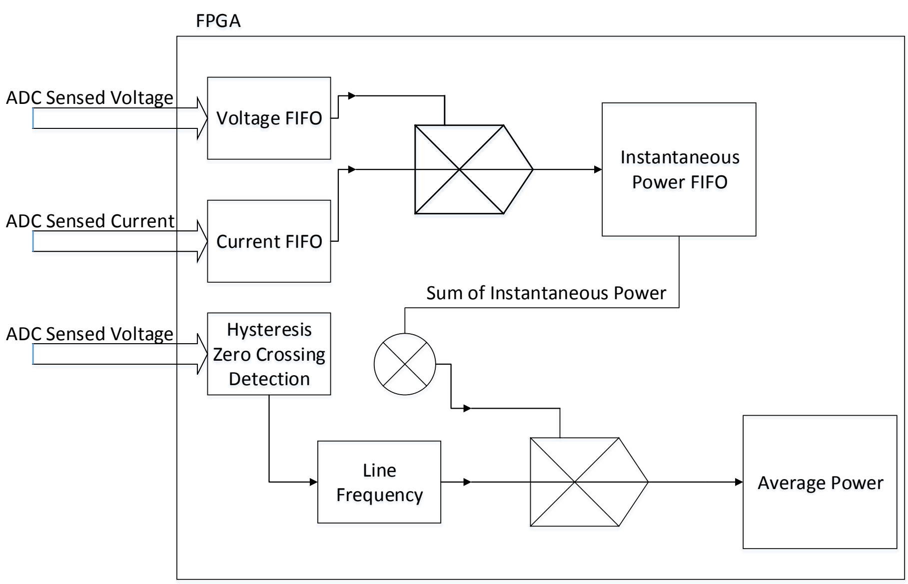
Remote Outlet Firmware Design



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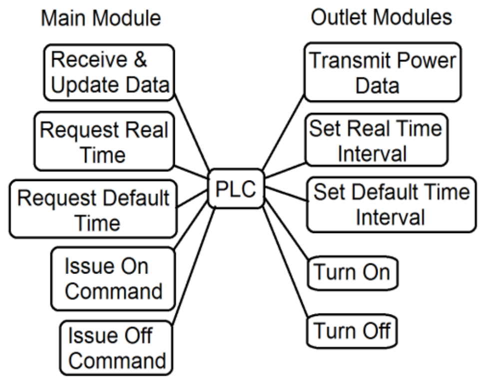
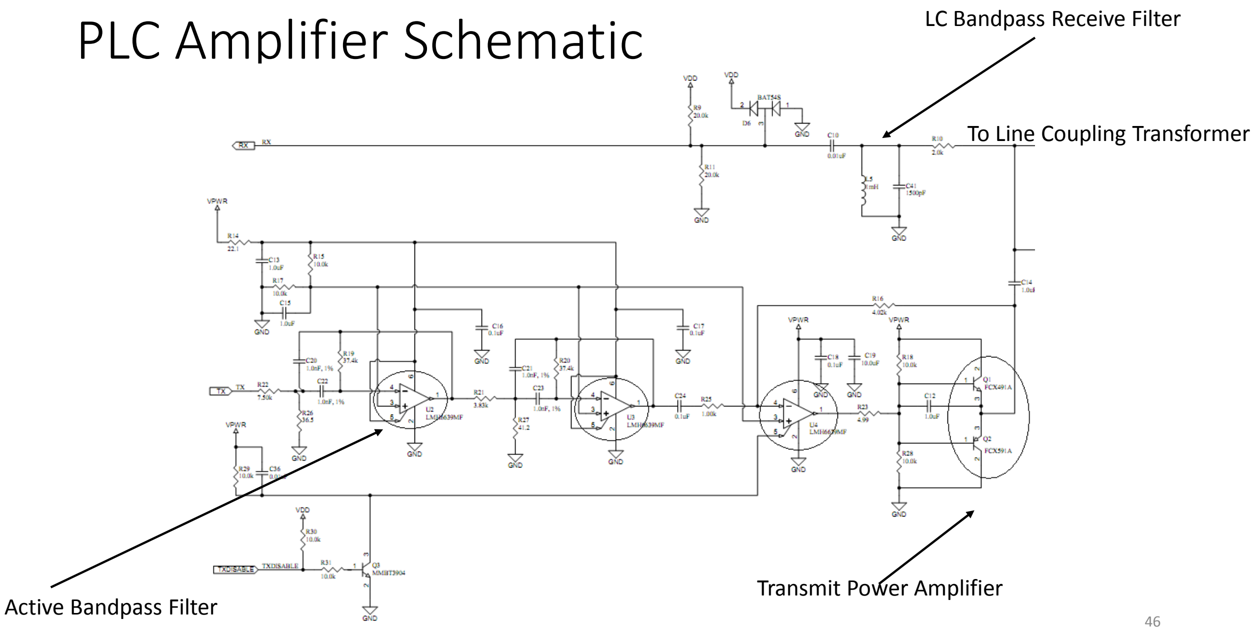
PLC Design

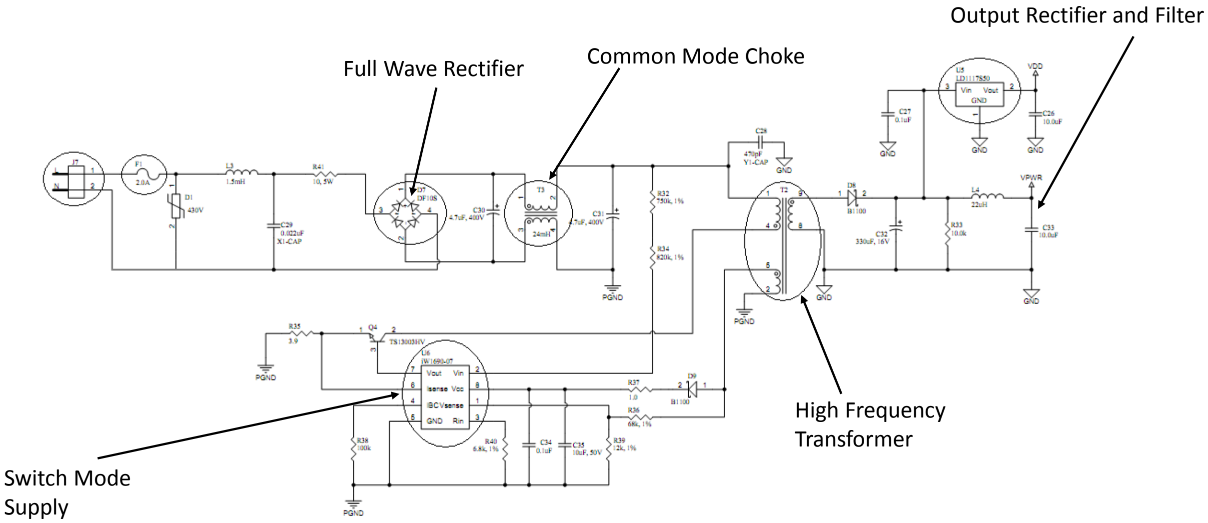
- Given our concept of what will be communicated, the actions and commands are shown on the right.
- The CY8CPLC10 and CY8CPLC20 both need various hardware components to actually operate. Fortunately, both have development kits detailing the amplifiers, frequency modulators, power line coupling, power supply, etc. in the form of schematics.
- The following schematics are included from the CY3272 Evaluation Kit Guide.



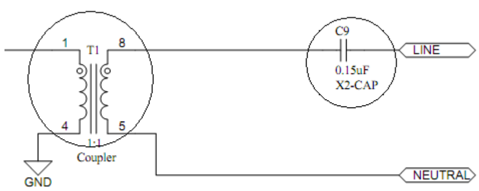
PLC Amplifier Schematic



PLC Power Supply



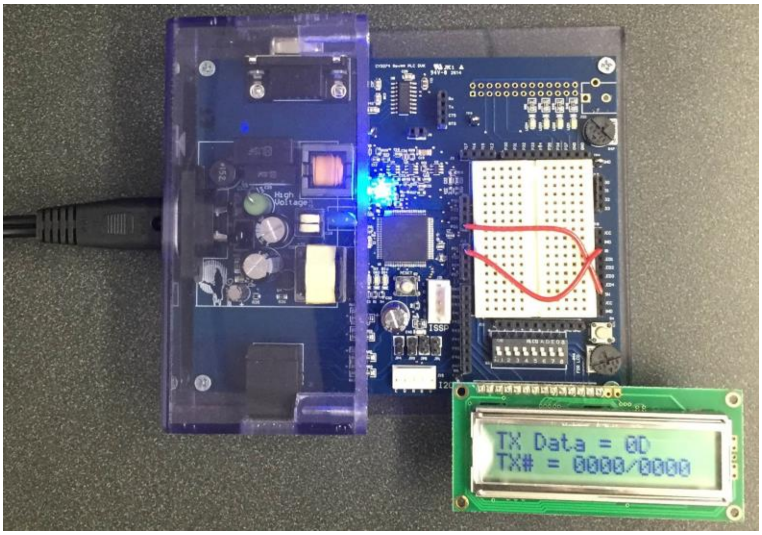
PLC Coupling



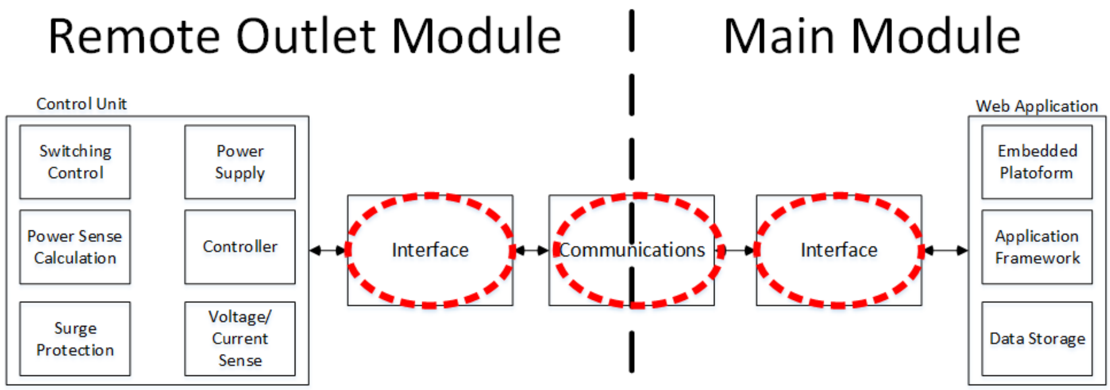
PLC Final Selection

- Fortunately for our team, we were actually provided 2 dev. Boards for the CY8CPLC20, which cemented the CY8CPLC20 as our choice device.
- Eliminates the need for us to manually implement each of the prior schematics, yet we know they are and could utilize them in production.
- Should shorten the development time for utilization of the PLC
  - Concerns:
    - One board is non-operational, and must be replaced or repaired.
    - Utilizing an unfamiliar PSoC, potentially unknown development time.
      - There appear to be a good number of samples, and I was able to get the first board transmitting in under 10 minutes.

PLC Single Board Demonstration



PLC Dev Board



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Database Overview

- Outlet Table
  - Stores essential information about each outlet module
- GroupLines Table
  - Stores which outlet belongs to which group
- Group Table
  - Stores information about each group
- Measurement Table
  - Stores the measurements received by the outlet module
- Settings / Schedule / User Tables
  - Store information primarily used by the web app

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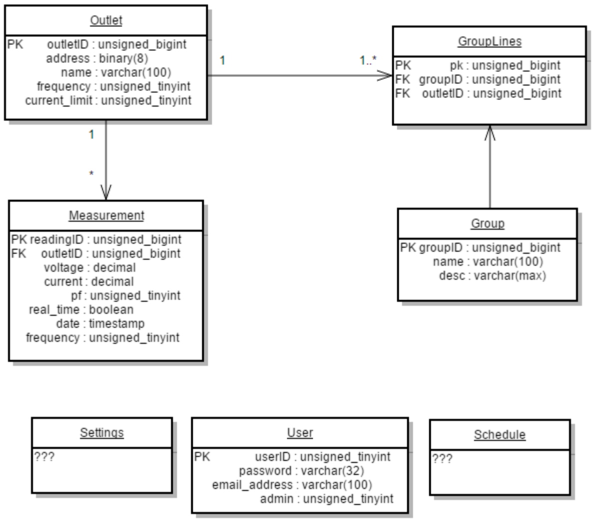
Database UML Diagram



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Expected Row/Table Sizes

Table Name	Est. Size Per Row	Est. Entries Per Table	Est. Size Per Table
Outlet	119 B	50 – 100	6 – 11 KB
GroupLines	24 B	50 – 100	1 – 2 KB
Group*	365 B	~25	~9 KB
Measurement*	31 B	5,760 * # Outlets Per Day	8.5 – 17 MB Per Day
Settings	???	< 20	1 – 5 KB
Schedule	???	< 50	1 – 10 KB
User	136 B	< 10	1- 2 KB

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Data Compression

- Consumers don't need to know power consumption per minute from one month ago
- Take the measurements from 30-31 days ago (or sooner)
- Average some number of measurements into 1 measurement
  - 4 Measurements @ 15 seconds = 1 Measurement @ 1 minute
  - 240 Measurements @ 15 seconds = 1 Measurement @ 1 hour
  - 5,760 Measurements @ 15 seconds = 1 Measurement @ 1 day
- Averaging keeps the data the same while saving disk space

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Data Compression

# Outlet Modules	Original Size / Day	Original Size / Year	4 -> 1 Size / Day	4 -> 1 Size / Year	240 -> 1 Size / Day	240 -> 1 Size / Year
1	175 KB	62 MB	44 KB	15 MB	744 B	265 KB
10	1.7 MB	621 MB	435 KB	155 MB	7.3 KB	2.6 MB
50	8.5 MB	3.03 GB	2.1 MB	777 MB	36 KB	13 MB
100	17 MB	6.06 GB	4.3 MB	1.51 GB	73 KB	26 MB

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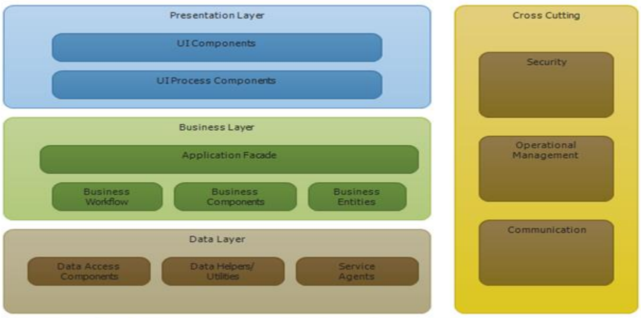
Web App – Overall Design



Source: patterns &practices Application Architecture Guide 2nd Edition. Refer to "Chapter 21: Designing Web Applications" for more information.
URL:http://msdn.microsoft.com/en-us/library/ee658099.aspx

- Following the standard web application layered construction
- UI Layer
  - Holds all UI components
  - Where user interacts
- Service layer
  - Business logic
- Data Access layer
  - Makes calls to DB
- Additional Security layer

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Web App - Communication

- Communication with outlet modules will all happen with Python scripts
  - Using built-in I2C library on Pi to communicate with PLC
- Sending from web app
  - Java code will call Python script (Jython)
- Receiving
  - Python scripts will be listening for I2C communication
  - Scripts to convert and store measurement data independently of the web application

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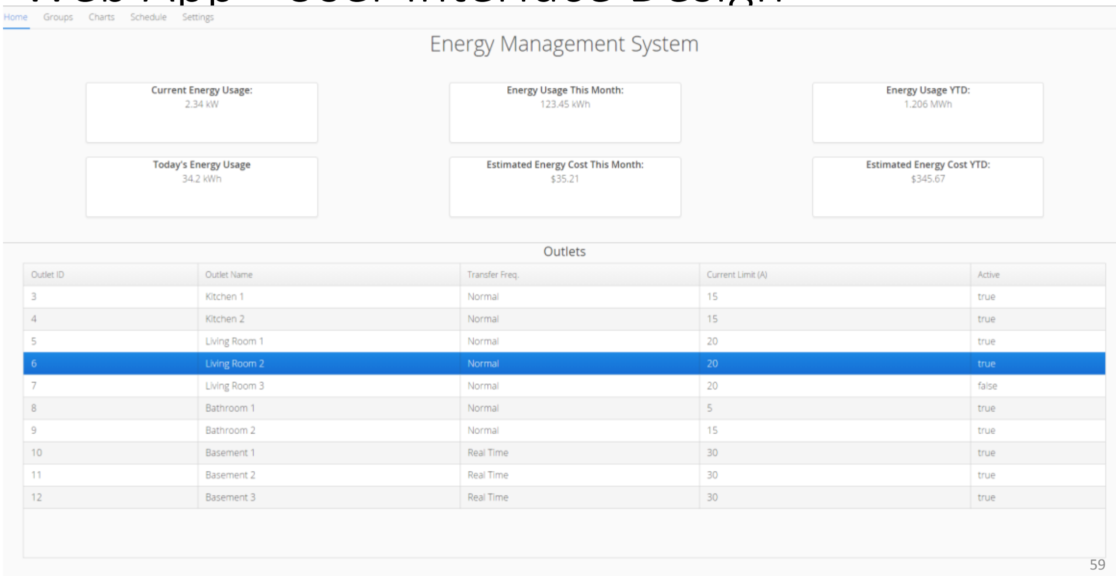
Web App - User Interface Design



Outlet ID	Outlet Name	Transfer Freq.	Current Limit (A)	Active
3	Kitchen 1	Normal	15	true
4	Kitchen 2	Normal	15	true
5	Living Room 1	Normal	20	true
6	Living Room 2	Normal	20	true
7	Living Room 3	Normal	20	false
8	Bathroom 1	Normal	5	true
9	Bathroom 2	Normal	15	true
10	Basement 1	Real Time	30	true
11	Basement 2	Real Time	30	true
12	Basement 3	Real Time	30	true

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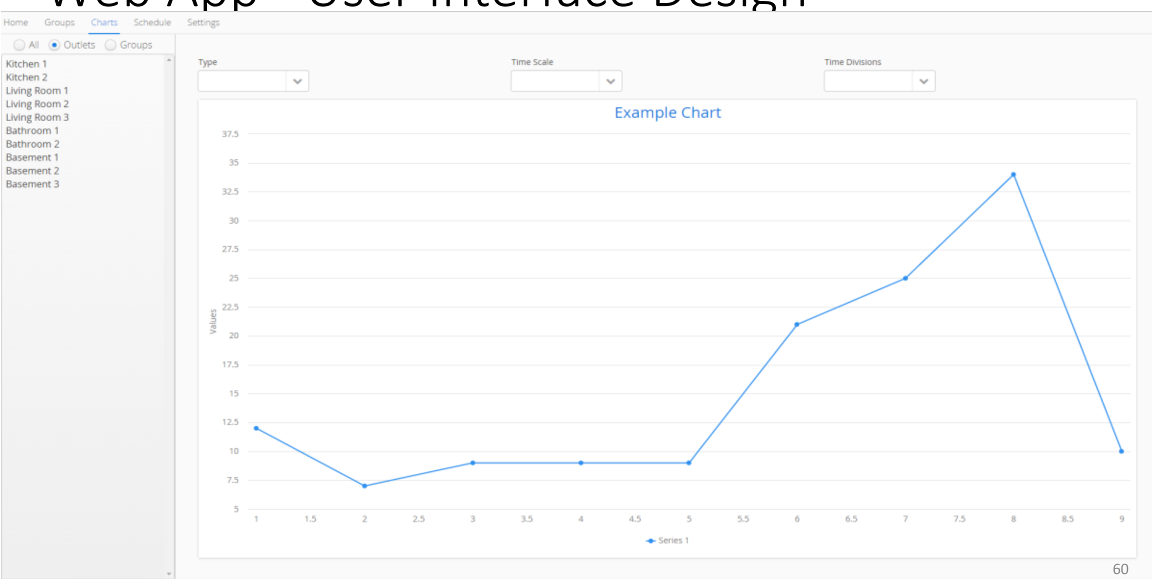
Web App - User Interface Design



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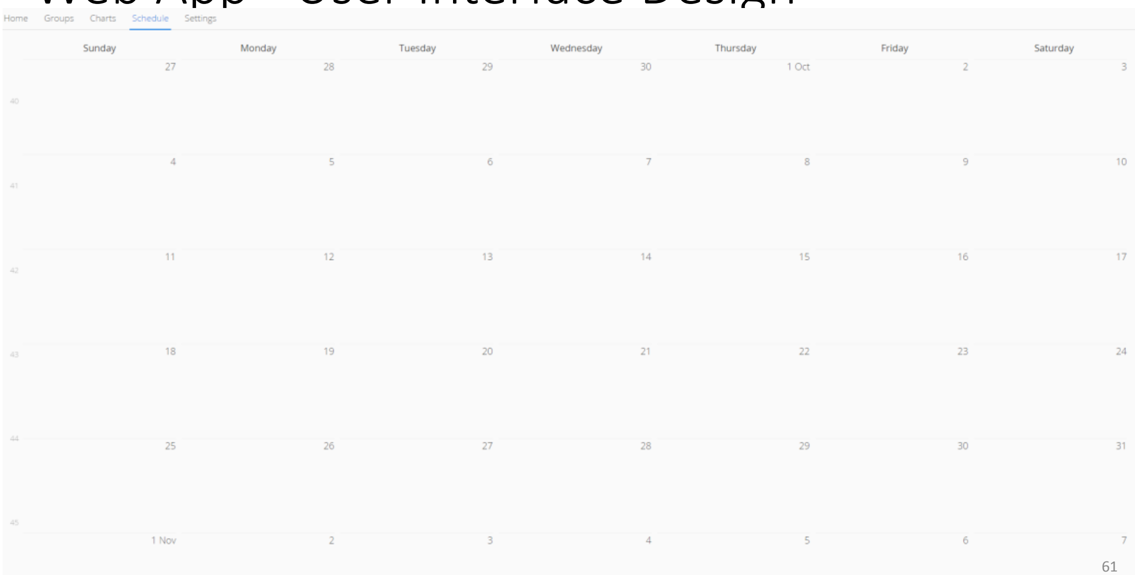
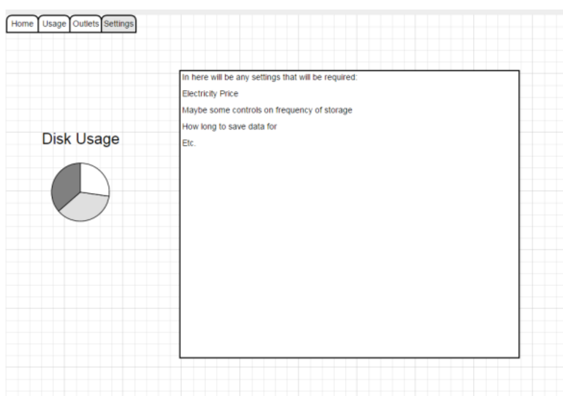
Web App - User Interface Design



Web App - User Interface Design

- Groups and Settings tab not yet constructed
- Idea of Settings tab is shown here ->



Bill of Materials

Part Number	Description	Vendor	Cost per Unit	Quantity	Ext Cost	Our Cost	Lead Time
RAC01-05SC	AC/DC switching power supply	Recom	$ 12.34	1	$ 12.34	$ 12.34	stock
	Various Connectors and Test Points	-	$ 4.76	1	$ 4.76	$ 1.00	stock
V150ZA05P	Varistor	Littelfuse	$ 0.56	1	$ 0.56	$ -	stock
MOC3063M	Optoisolator	Fairchild Semi	$ 0.95	1	$ 0.95	$ 0.95	stock
MMBT3904	NPN Transistor	Fairchild Semi	$ 0.15	1	$ 0.15	$ 0.15	stock
BTA20-600CWRG	Triac	STMicroelectronics	$ 1.97	1	$ 1.97	$ 1.97	stock
ACS722	Hall Effect Current IC	Allegro	$ 5.27	1	$ 5.27	$ 5.27	stock
ACPL-C87A	Isolated Voltage Sense	Avago	$ 6.42	1	$ 6.42	$ 6.42	stock
TLC272A	dual op-amp	TI	$ 1.35	1	$ 1.35	$ 1.35	stock
MMBT3904	NPN Transistor	Fairchild Semi	$ 0.15	1	$ 0.15	$ 0.15	stock
BZX84C5V6	5.6 Zener Diode	Fairchild Semi	$ 0.19	1	$ 0.19	$ 0.19	stock
P0082	De-0 Nano Evaluation Board	Altera	$ 86.25	1	$ 86.25	$ 86.25	stock
BCM2836	Raspberry Pi 2	Element14	$ 35.00	1	$ 35.00	$ -	stock
SDSDQUAN-032G-G4A	32 GB MicroSD Card	MicroSD	$ 16.19	1	$ 16.19	$ 16.19	stock
CY3272	High Voltage Powerline Communication Evaluation Kit	Cypress	$ 249.99	2	$499.98	$ -	stock
	Assorted Passvie Components	Digikey	$ 10.00	1	$ 10.00	$ -	stock
MRA4006	1A, 800V diode	On semi	$ 0.31	2	$ 0.62	$ -	stock
Total Cost					$682.15	$ 132.23	

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Risks

- Until we have a second operational PLC, we have no way to verify operation
  - Need to very quickly find a replacement or to fix the board.
  - Get familiar with development in the mean time to reduce development time once we have 2.
- Interfacing PLC system with rest of the system
- Year 2038 problem
  - TIMESTAMP is 32-bit integer, can only go until January 19th 2038
  - DATETIME is 64-bit integer, can represent up to December 31st 9999
- Storing Non-real-time measurements along with real-time measurements
  - Real time measurements are flagged and deleted after session

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Risks

- Raspberry Pi
  - Enough memory to host both database and web app
  - CPU performance
- Refreshing the UI
  - Vaadin is an event-driven framework meaning it needs events to request a repaint of the screen
  - Might need to "hack in" a refreshing component
- Vaadin Charts library

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Testing

Test Type	Test Name	Engineering Requirements
Unit Tests	Power Supply DC Output Voltage	E,F
	Voltage Sense Output Voltage	F
	Voltage Sense Output Frequency Response	F
	Voltage Sense Power Supply Draw	K
	Current Sense Power Supply Draw	K
	Load Switch Switching Current Monitor	E
	Load Switch Switching Control Voltage Monitor	E
	Load Switch Temperature	I,K
	Web Application Sign In	G
	Web Application Viewing Charts	G
	Web App - Naming Outlets	G,L
	Web App - Grouping Outlets	L
	Web App - Scheduling Interface	G
	Web App - Scheduling Job	G

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Testing

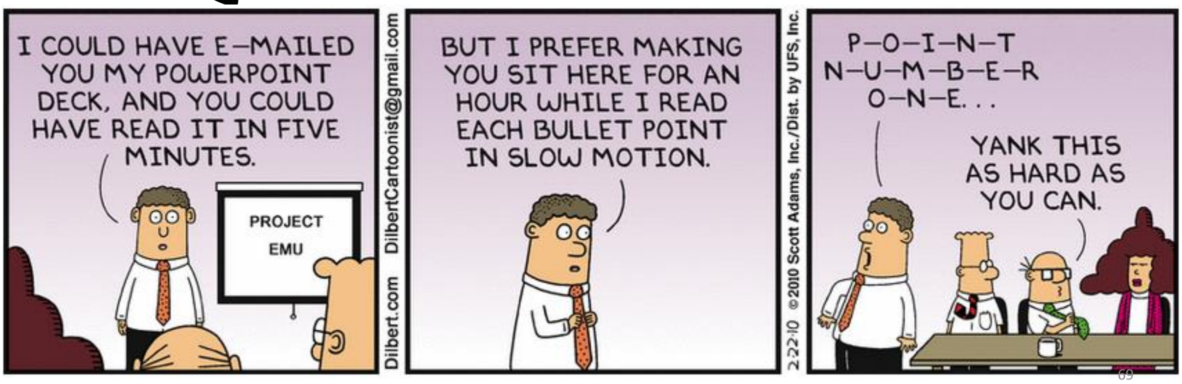
Test Type	Test Name	Engineering Requirements
Unit Tests	Web App - Toggle outlet state	E,L
	Web App – Settings	H
	Load Test	G
	Insert Outlet Module Data	L
	Insert Outlet Reading Data	G
	Compression of Data	G,H
Integration Tests	Voltage Sense With Controller	F
	Current Sense With Controller	F
	Load Switch With Controller	E
	PCB Testing	I
	Receive Database Information	G
	Send Database Information	G
	Requesting Real-Time Readings	G,H

Testing

Test Type	Test Name	Engineering Requirements
Acceptance Tests	Module Costs	A
	Short Installation Time	B
	Power Measurement Accuracy Test	F
	Usability Test	H
	Outlet Module Sizing	J
	Load Testing	G
	Schedule testing	M
	Remote Tests	G
	High Pot Testing	D
	Power Line Transient Survival	C

Thanks!

Questions?



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