Watt You Pay For

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***Abstract* — The objective of this project is to design a power monitoring system. The power monitoring system is made up of three devices: an outlet, a switch, and a thermostat. These three devices will monitor the power the devices connected to it are using and show the user this data on a web based server. Each device will also have some features to be controlled remotely, such as controlling a relay to turn a device on or off and monitoring ambient temperature from the thermostat.**

***Index Terms* — Power, power monitoring, outlet, light switch, air conditioner, thermostat.**

I. Introduction

Electrical energy has become a necessity for nearly all people in the world. With increasing human population and as non-renewable energies such as fossil fuels begin dwindling, power conservation has become increasingly more important. As our energy sources dwindle and greenhouse gas pollution becomes an increasingly bigger issue, saving energy will be one of the biggest problems in the 21st century. A large portion of our energy usage that people have a direct control over comes directly from household and residential users consuming power for their everyday needs. Giving people the ability to see their energy usage and give them the power to easily manage it will have the effect of reducing electrical energy consumption by empowering users to see their real time power usage and the cost associated with it.

There are many different devices in the average household, which all contribute different amounts to the home utility bill. The main contribution of energy usage can be broken down into specific categories. Table 1 shows the breakdown of energy use of each category in an average household [1].

TABLE 1
HOME ENERGY USE BREAKDOWN

End Use	Share of Total
Space Cooling	15.4%
Water Heating	9.5%
Lighting	9.4%
Refrigeration	7.2%
Space Heating	6.2%
Televisions and Related	5.9%
Clothes Dryers	4.1%
Furnace Fans	2.3%
Computers and Related	2.2%
Cooking	2.2%
Dishwashers	2.0%
Freezers	1.6%
Clothes Washers	0.5%
Other	31.3%

Table 1 shows that some of the largest contributors of energy consumption in the average household are air conditioning, lighting, and other miscellaneous appliances that are plugged into outlets. Because these are the main consumers of electrical energy, we chose to make modules that are simple for a user to monitor and control these devices. Our system is composed of three main components and a web-based interface. The three devices are a smart light switch, smart outlet and a smart thermostat. These devices will be monitoring the current consumption of the respective devices hooked up to them, and send this data over the home's Wi-Fi network. The user will be able to control these devices and see their power consumption statistics via a web-based user interface.

II. Overall System Design

The system was designed so that it would be a single enclosed device that has its own connection to the server over Wi-Fi. With this design, it is easily possible to add as many smart light switch and outlet modules as the user desires. Another benefit of this design is that every device would use the same PCB, making the construction process easier and the cost lower.

A. Specifications

The goal of each device is to accurately measure the real power a device is using, while not considering reactive power in the user's cost. This measured data is centralize onto a server so that the user has a seamless interaction. Since the data will be uploaded onto a server it will be possible for the user to access the data from either a smartphone or a computer. The data will be displayed in kilowatt hours by the minute, hour, day, week, or month, that way the user will be able to see how much power a single device, or multiple devices has used over any given period of time. In order to help the user be more power conscious the modules have the ability to remotely turn a device or light on or off. This way when the user sees that they left a device or light on when it is not needed, it will be easy for the user to turn it off via the website. The figure below shows the overall block diagram of the system.

The goal of the thermostat is to be able to accurately measure the ambient room temperature and turn the air conditioner or heater on and off according to the users preferences. The user will be able to set the desired temperature at the thermostat itself and monitor the ambient temperature of from the web interface.. This will make it easy for a user to monitor and control one of the largest power consumers in the household. The figure below shows the overall block diagram that all three modules are based off of.

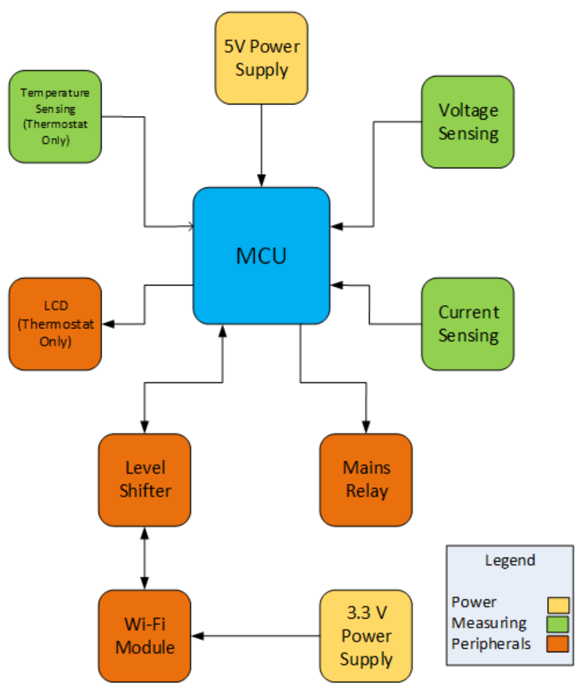


Fig. 1. Overall Block Diagram of System

It is important to note that the PCB is designed to incorporate all block components shown in figure 1, however some blocks are unnecessary depends on the modules functionality. For example the smart outlet and light switch do not need a temperature sensor in order to function as designed. Because of this, some PCBs are not fully populated.

B. Wi-Fi Communication

Wi-Fi was chosen as the method of communication between the main server and control units. One of the desired features for our system was the ability to monitor energy usage of account devices anywhere with internet access without the need of a central hub. Wireless communication protocols such as Bluetooth or Zigbee were deemed unsuitable for the system as they required a central internet connected hub device to achieve this functionality. In addition, Wi-Fi is more scalable than protocols like Bluetooth as multiple devices can easily be spread out across different access points to mitigate congestion.

C. Setup Mode

The control unit has two modes of operation. The first of which is setup mode. While in setup mode the control unit will host a Wi-Fi network of its own and run a web server on that network. The control unit web server will server a configuration web page to devices on its network. The configuration web page allows users to edit the Wi-Fi network the devices will connect to while in connect mode and to register the control unit with their account (created on the main server). The control unit will restart in connect mode when either its configuration settings have been altered or the setup/connect mode button has been pushed while in setup mode.

D. Connect Mode

While in connect mode the control unit will connect to the Wi-Fi network specified in its configuration settings. Once connected to a Wi-Fi network the control unit will connect to the main server using the account information stored in its configuration settings. After establishing a connection with the main sever the control unit will register itself with the main server using the account credentials of the user (stored within configuration settings). Once registered the control unit will synchronize its time with the main server and begin periodically sending energy usage data and relay update requests.

E. Power Measuring Theory

The power bill an individual pays for is calculated based on the amount of energy that an individual uses. Real power cannot simply be calculated by multiplying the RMS voltage and current together. Doing this would result in the apparent power, which would consider the reactive power that the consumer is not charged for. The phase difference between the voltage and current needs to be taken into consideration. Real power can be calculated by using equation 1.

$$P = VI * \cos(\delta_V - \delta_I) \quad (1)$$

This method however has some challenges as it can be difficult to directly measure the phase difference. Because of this, we chose to measure the real power by directly sampling the voltage and current waveforms.

When the voltage waveform and the current waveform are multiplied together, a power waveform becomes the result. The average value of this power waveform is the real power component. In order to calculate this power waveform both the voltage and current will be converted into a voltage in the range of 0 to 5 volts so that the waveform can be read by the analog to digital converter. These waveforms will then be sampled as frequently as possible for one cycle of the voltage and current waveform. This gives the MCU the most accurate representation of the actual waveforms, which may be distorted or not sinusoidal in the real world. The figure below shows what the sampled power waveform would look like.

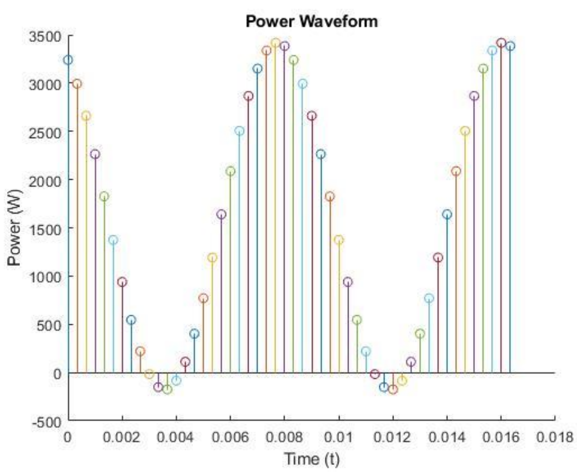


Fig. 2. Power Monitoring Sampling

The MCU will then sum up all of the sampled values and average them over 1 period. Since mains voltage is at 60 Hz, the sampling will need to be done over a 16 millisecond period so that the sampling does not miss or over extend one waveform cycle. If the averaging is not done over this period, the average value will not be correct.

III. System Components

The entire system is made up of multiple different components. These components include: power monitoring sensors, MCU, temperature sensor, display, microcontroller, Wi-Fi module, power relay, and power supply.

A. Voltage Sensor

In order to measure the 170 volt peak sine wave the voltage waveform will need to be scaled down into the required input range of the analog to digital converter, which is 0 to 5 volts. The method that is implemented is a voltage divider. This voltage divider scales the 170 volt peak sine wave down to a 4.75 volt peak, or 9.5 volt peak to peak sine wave. This voltage however is still out of range for the analog to digital converter. The 9.5 volt peak to peak sine wave is then scaled in half using another voltage divider, and then shifted up so that it is centered at 2.5 volts.

The resistors used on the initial voltage step down are a 1 MΩ and a 24 kΩ. This resistor combination results in a 4.75 volt peak sin wave across the 24 kΩ resistor when a 170 volt peak sine wave is set as the input. The reason the 4.75 volt peak was desired was because that way we have the highest possible accuracy while still being able to handle any small fluctuations in the mains voltage. Mains voltage can regularly vary from anywhere between 115 volts to 125 volts RMS, or 177 volt. The 250 mV of unused range is enough to handle these fluctuations without clipping the ADC’s input range. The very large resistance is used in order to only use a small amount of current, and not waste energy. This resistor voltage divider will only use 28 mW, so wasting energy or producing heat is not an issue. After the first voltage divider a unity gain buffer is needed so that no current is drawn away from the resistor voltage divider. After the unity gain buffer a second voltage divider, with equal resistor values, is used to finish scaling and shifting the waveform. Finally a 5.1 volt Zener diode was used in order to protect the analog to digital converter from any positive or negative voltage spikes that may occur.

B. Current Sensor

Measuring current has some difficulties as it cannot be read directly by an analog to digital converter. The current needs to be measured as a voltage with a known ratio. Typically current is measured by reading the voltage across a low resistance shunt resistor. The shunt resistor is placed in series with the load on the neutral side of the load. Because this shunt resistor is placed in series with the load and most household outlets are rated for 15 amps, the shunt needs to be able to withstand the same amount of current. The resistance of the shunt resistor also needs to be very small so that the shunt resistor does not impede the flow of current to the load and so that excess heat is not produced from the power loss of the shunt. Because of these factors the OAR3R005FLF 5 mΩ shunt was chosen.

The voltage across the shunt resistor is then be sent to a non-inverting amplifier. Because the voltage across the shunt resistor is so small, the amplifier will need a large gain so that it can be read by the analog to digital converter without losing accuracy. Because the current through the load will range from 0 to 15 amps, the voltage across the shunt will vary greatly. A single amplifier with a fixed gain will work, however there will be a great loss in accuracy at the minimum and maximum ranges. When a large current is flowing through the load the op-amp will amplify the signal into an accurate range for the analog to digital converter, however when a small current flows the signal will not be amplified enough and there will be a loss in accuracy. To get around this problem, a two stage amplifier was used. This way large currents are amplified by the first stage and small current are multiplied by the first and second stage, giving the waveform a much higher resolution. To combat noise and the shunts low voltage signal, the low noise OPA2180IDR op-amp was used along with high frequency filtering capacitors on the output.

These signals are still centered at 0 volts and not in the range for the analog to digital converter. A voltage divider is used at the output of each stage of the amplifier, so that the waveform is scaled and shifted to be centered at 2.5 volts. A 5.1 volt Zener diode is also used at the input of each ADC so that it clips the waveform when it goes out of the range of the ADC. The figure below shows the schematic of the two stage amplifier for the current sensing.

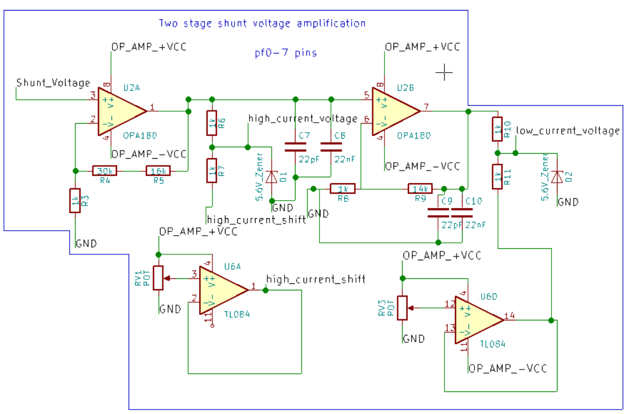


Fig. 3. Current Sensing Schematic

C. Temperature Sensor

The main component of a thermostat is the temperature sensor. The temperature sensor needs to be able to accurately measure the ambient room temperature so that the MCU can decide when the air conditioner or heater should turn on or off. The temperature sensor that was used was the DS18B20. The DS18B20 is a small, three pin thermometer that typically comes in a TO-92 package. This device uses one pin for the data communication and two pins for the powering. The DS18B20 has a very flexible internal EEPROM that allows for many different user configurations. One of the configurations is selecting the resolution of the sample. The digital thermometer is able to sample the current temperature and convert it to a digital signal that is between 9 to 12 bits. Selecting more bits will produce more data but will give much more accurate temperature reading. The DS18B20 has temperature range from –67 to 257 degrees Fahrenheit. This temperature far exceeds the temperature range of the average home user and gives an excellent range for any temperature any household may be. The accuracy of the DS18B20 is also quite good with the error of the thermometer being roughly 1 degree. This accuracy however does decrease if the number of bits is reduced from twelve bits. The powering of the DS18B20 is also quite flexible. The VDD pin can be powered from 3 – 5.5 volts. This device also has the benefit of not needing any external components, except for a simple pull up resistor on the data line, to be fully implemented which greatly increases the ease of use.

D. Display

The thermostat has a small display to tell the user basic information about the system, such as what the current temperature of the house is and what temperature the user has set the device to. In order to display this information, a Crystalfontz CFAH1602B-TMI-JT Liquid Crystal Display was used. This device is a simple 16x2 LCD that operates at 5V with a typical supply current of 1.2 mA. The device interfaces with the microcontroller using either 4-bit or 8-bit parallel communication. An important part of this display is that it is supported by the Sitronix ST7066U controller which is important as it eliminates the need to program a font library. To display whether the unit is in heating or cooling mode, the thermostat module will active a red or blue LED.

E. Microcontroller

The microcontroller is the core of our system. The device is responsible for receiving and storing data it is sent from the ADC, performing manipulation on this data in order to calculate power consumption, send and receive data to the ESP8266, display information on the LCD, read current temperature, and set temperature based on user input. The microcontroller that was used was the ATmega2560. This microcontroller utilizes an 8-bit AVR RISC-based CPU, with 256KB of Flash Memory, 16MIPS CPU speed and 32 general purpose registers. The device also has 86 general purpose I/O pins so supporting the various components is not an issue. Finally the ATMega2560 has an extensive availability to libraries, which made programming significantly easier.

F. Wi-Fi Module

The Wi-Fi module is a necessary component that will connect each device to the home Wi-Fi network and to the main web server. The Wi-Fi module that the device uses is the ESP8266. The ESP8266 is a widely used low power Wi-Fi module. The ESP8266 does however operate at 3.3V, while the MCU operates at 5V. This can cause potential damage to the ESP8266 when the two devices are communicating between themselves. To solve this issue the TXB0108 level shifter is used to raise 3.3V logic to 5V logic and to lower 5V logic to 3.3V logic. This allows safe communication between the two devices.

G. Power Relay

The power relay will turn the outlet or switch on or off based on user input. This will be able to be controlled remotely, which will help the user save power by remotely shutting off devices when they are not in use. Since the relay is placed in series with the load it needs to be able to withstand at least 15 amps continuously. This power relay is designed to withstand 16 amps continuous with peaks up to 30 amps. The power relay can be wired in to be used in a normally open or a normally closed position. The power relay has a turn on voltage of 5 volts, however the current draw is larger than the microcontroller can provide. To combat this, an n-channel MOSFET was used to power the relay. Additionally a flyback diode was included to remove voltage spikes caused by the inductor.

H. Power Supply

The power monitoring device is a single enclosed unit that does not use any batteries. It uses a power supply that converts the 120 volt mains into a +/-8V, +6.9V, +5V, and +3.3V power supply. The 6.9V is used to provide level shifting, the +6.9V and -8V supply is used to power the op-amps, the +3.3V supply is required for the ESP8266, and the +5 volt power supply is needed for everything else. In order to transform the voltage from a 120 volt sine wave into a +/-8V DC voltage, a center tapped transformer was used. The center of the transformer was set to be the reference ground, so the output on one line of the transformer would be +8V AC and the output on the other would be -8V AC. These AC voltages are then sent to a rectifier and then a capacitor filter in order to turn the AC into DC. The positive 8V line is then sent to a positive 5 volt regulator and an adjustable 6.9V regulator with filtering capacitors on both outputs. This positive 5 volt output is then sent to a 3.3V regulator with a filtering capacitor on the output. The figure below shows the schematic for the power supply unit.

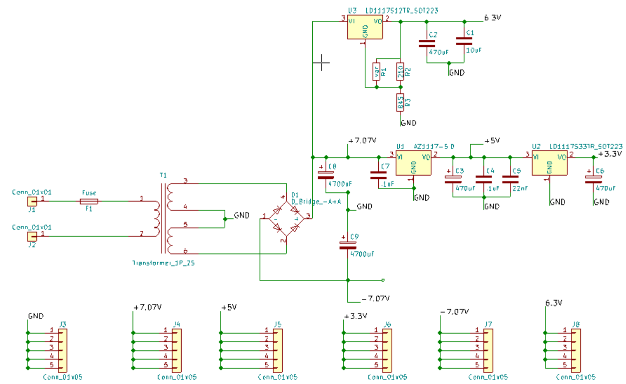


Fig. 4. Power Supply Unit Schematic

Large filtering capacitors are used on the output of the rectifier, so ideally the voltage ripple will be nearly negligible. The 5V output also has small high frequency filtering capacitors to get the signal to be as noiseless as possible for the ADC reference voltage.

IV. Software Design Details

A. Setup/Connect Mode Logic Flow

Upon first boot the control unit will start in set up mode. After initial boot if the user presses the setup/connect mode button while in set up mode the control unit will restart in connect mode. When the user presses the setup/connect mode button while in connect mode the control unit will restart in setup mode. As long as the control unit's configuration parameters have not been modified it will start in setup mode. The flow chart shown below illustrates the logic behind this.

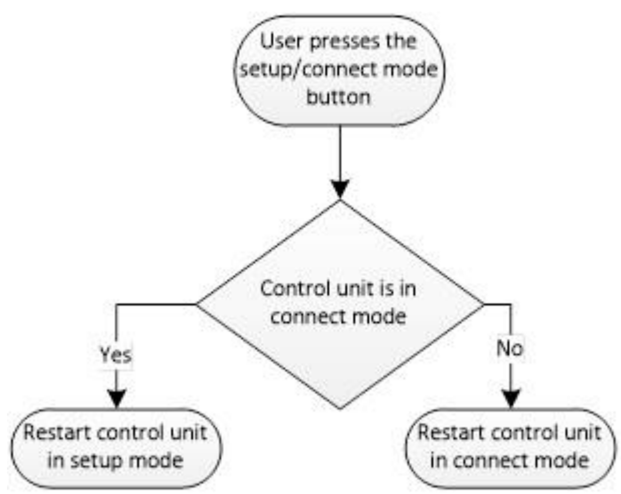


Fig. 5. Setup/Connect Mode Toggle

Whenever the control unit powers on with default configuration settings or the control unit mode variable is set to setup mode it will start in setup mode. When in setup mode the control unit will create its own Wi-Fi network and sets up a web server on it. After the web server and Wi-Fi network are initialized the setup mode main module is initialized.

When in connect mode the control unit will attempt to connect to the Wi-Fi network specified with in its configuration parameters with the credentials provided in its configuration parameters. If the control unit fails to connect it will periodically attempt re-connection. Once the control unit has successfully connected to the user Wi-Fi network it will attempt to establish a connection with the main server. If the control unit is unable to connect to the main server, it will periodically attempt reconnection. Once the control unit establishes a connection with the main server it will call the connect main module. The figure below shows the flow chart for the control unit power on sequence.

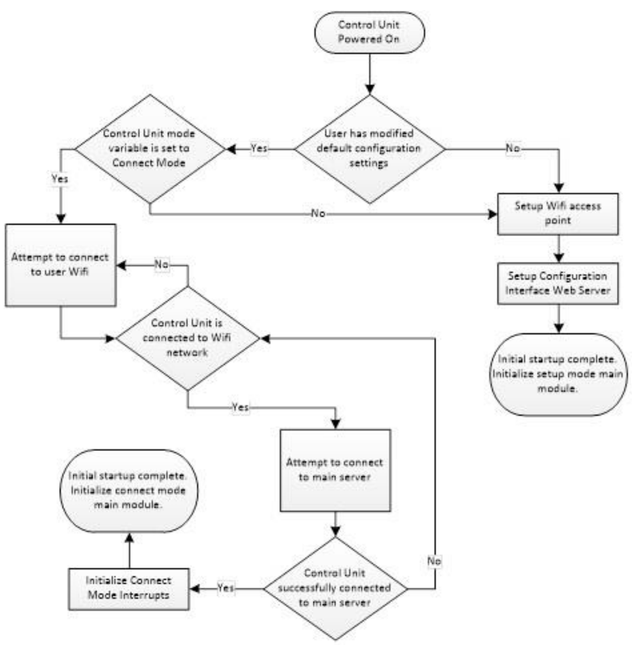


Fig. 6. Control Unit Power On Flow Chart

The Wi-Fi network id and password will be varied for each control unit. The user can connect to the Wi-Fi network using a Wi-Fi enabled device. Once connected to the control units Wi-Fi network the user enters the IP address of the control unit (which is the same for each unit) into their browser and requests the control unit web configuration interface from the control unit. The user then uses the interface to modify the control unit's configuration parameters so that it can connect to the user's Wi-Fi network. The user then switches the control unit into connect mode. If the control unit establishes a connection with the main server, it will determine the current time using the main server. Once the current time has been determined the control unit will determine its current time slot and begin periodically sending power usage data packets to the main server. Power usage data packets consist of two main elements: the recorded power usage measurement for a given time slot and the time slot in which the measurement was recorded. The control unit will respond to switch control commands received from the main server by switching the outlet on or off. When in connect mode the control unit alternates between two sub modes: record and transmit. While in record mode the control unit will record power usage data for the current time slot. At the start of transmit mode the control unit will send the oldest power usage data packet in its buffer to the main server and wait for the main server to reply with either an acknowledgement or a command.

B. Power Monitoring Logic Flow

The power bill is calculated based on energy used, or measured power over a period of time, in the unit of kWh. To calculate this power, first the voltage and current are sampled using the analog to digital converter. Next the voltage is converted to its actual value based on the voltage divider ratios. The current is also converted based on the shunt resistance and the amplifier gain. Once the actual values of both the current and voltage are found they are multiplied together to get a value for the power at that sample. The process then repeats and adds that power sample into a sum, until 16 milliseconds has elapsed. Once the 16 milliseconds has passed the sum is divided by the number of samples that occurred, producing the average value of the power, or real power, measured over that cycle. The measured power is then obtained and can then be converted into an energy value, and then added to the energy sum.

The measured power needs to be converted into kWh. To do this the measured power over one second needs to be converted into kWh. The measured power for one second is divided by 3.6 million in order to convert it into kWh. Finally this value is added into the energy sum and will be sent to the main web server every minute.

C. Main Server Components

The main server uses a set of software modules to provide the services necessary for the overall system to function. A MySQL database is used to store account data, device data, browser sessions and device energy usage history. Account passwords are stored as Bcrypt hashes. The user browser interface is served via an Apache2 web server. Device information such as energy usage history are served by the user websocket server. The device websocket server is used to receive energy usage measurements from devices, register devices with user accounts and send status updates to connected devices.

D. System Data Flow

The main server acts as the medium between user browser interfaces and the control units. Control units send energy measurements to the main server. They also request status updates such as relay status or current time from the main server. User browser interfaces request device energy usage history and status updates such as relay status from the main server. User browser interfaces also send device relay status updates to the main server.

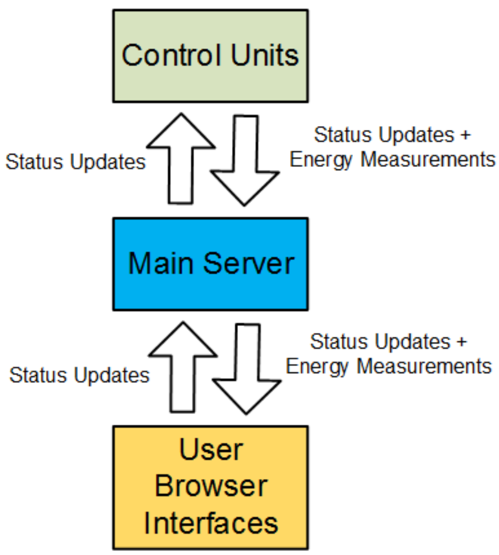


Fig. 7. Main Server and Client Interaction Diagram

V. Project Prototyping

Prototyping was a very important aspect that we focused on when working on this device. Before ordering PCBs we wanted to make sure that all of our theory worked exactly the way we intended it to. We attempted to prototype as much of the system as possible.

A. Power Monitoring Sensors Prototyping

The prototyping process was done in multiple sections. First the voltage sensor and current sensor were simulated using LTspice. As expected the theory of the sensors was correct. All of the scaling and shifting worked as expected, so the next step was to test the sensors on a breadboard. The hardware testing of the sensors worked with no issues, except that the waveforms had to be shifted by roughly 200mV. The next step was to test the sampling theory.

B. Power Monitoring Sampling Prototyping

In order to test to make sure that the sampling theory worked correctly we used a function generator and an Arduino. We used the function generator to produce a sine wave with a peak to peak voltage of 5 volts, centered at 2.5 volts. This waveform will mimic both the voltage and current waveform. Next we connected this waveform to an analog pin of the Arduino. The Arduino was programmed to sample the analog signal every millisecond. Using the serial plotter we were able to see that the Arduino was able to accurately measure the waveform. With this information we felt confident that our designed would work so we moved on to PCB prototyping.

C. PCB Prototyping

Since none of the group members had any PCB design experience or surface mount soldering experience, we elected to first essentially replicate the Arduino mega. We chose to initially design this PCB so that we would be able to practice and become familiar with laying out a PCB as well as soldering surface mount devices, specifically the ATMega2560. Once the PCB was soldered and finished it was seen that everything worked as expected. With this prototype board we were able to do a majority of the testing. One test we did was to make sure we were able to program the ATMega2560 using an Arduino board. The programming went smoothly and we were able to control our PCB. With our first design a success, we moved onto the final PCB that will encompass all modules needed in our project. While our first board had some oversights and issues, our final PCB functioned as expected. Figure 8 shows the final PCB design.

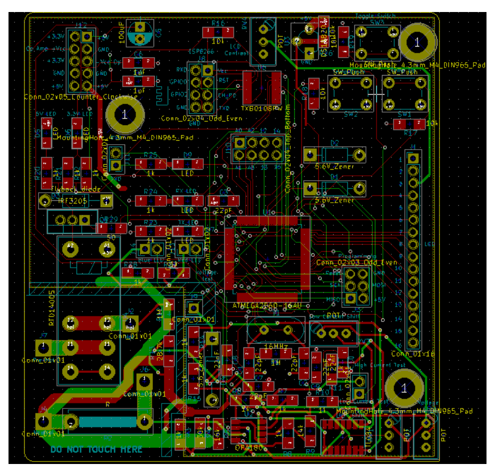


Fig. 8. Final PCB design

D. Power Supply Unit Prototyping

The whole unit will be a single unit with its own power supply. For the power supply we opted to use a power transformer to step down the 60 Hz, 120 volt sine wave down to a 16V sine wave, or 8V with the center tap as the reference point. Before designing the PCB we built an entire power supply with step down transformer using a breadboard. We wanted to make sure that we were able to power the prototype PCB fully from this power supply alone. As expected the design worked and we had a full single working unit. We then began designing the PCB for the power supply. We essentially based it exactly on our prototype design, except added more filtering capacitors.

VI. Conclusion

The goal of the Watt You Pay For project was to have a single enclosed unit for an outlet, light switch, and thermostat that would monitor power usage and display that information remotely. The goals of this project were met and it was a great learning experience for the group. There were some challenges, however it shows that a significant amount of research, testing, and prototyping can greatly help when it comes to the final PCB design and assembly.

Acknowledgements

The authors wish to acknowledge the assistance and support of Dr. Samuel Richie, Dr. Lei Wei, and the rest of the UCF ECE department.

References

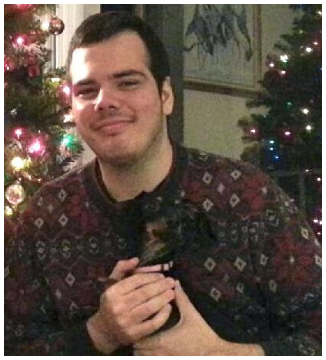
[1] 'Use of Electricity', 2018. [Online]. Available: https://www.eia.gov/energyexplained/index.php?page=electricity_use. [Accessed: 10- Jul- 2018].

Biography

Adam Althar will be graduating from the UCF with a B.S. in Computer Engineering. After graduation Adam will work for Renesas Electronics in Melbourne Florida as an Applications Engineer.

Charles Desowitz will be graduating from the University of Central Florida with a Bachelor's of Science in Electrical Engineering in the Summer of 2018. After graduating he will hopefully start a job as an electrical engineer.

Anders Hauge will be graduating from the University of Central Florida with a Bachelor's of Science in Electrical Engineering in the Summer of 2018. After graduating he plans to pursue a career in the marine industry as an electrical engineer. In the future he plans on returning to school for an MS in Power Systems.



Jonathan Killeen will be graduating from the University of Central Florida with a Bachelor's of Science in Computer Engineering in the Summer of 2018. After graduating he plans to pursue a career in software.