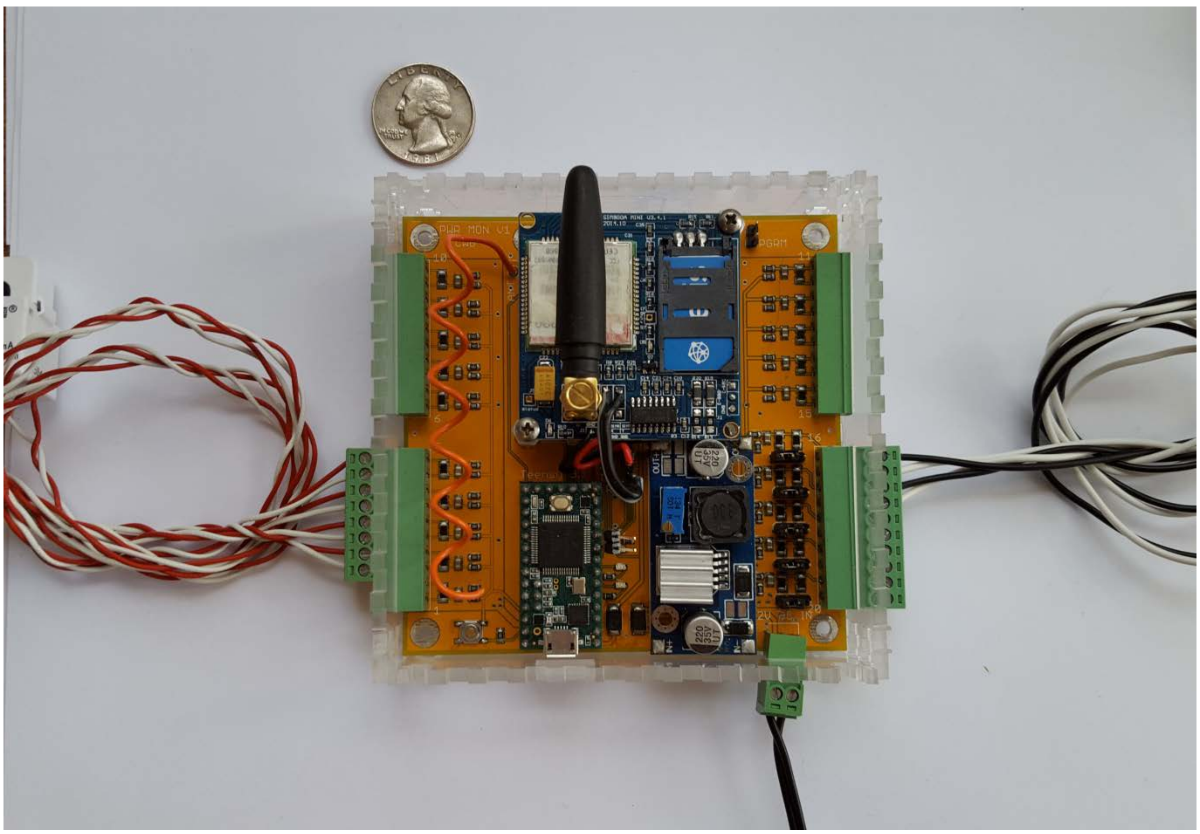
Design, Prototype, and Manufacture of a Circuit Level Submetering System for Household Installations



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Introduction

Engineering and business often go hand in hand. The following project is a direct result of this relationship. Over the summer of 2015 a startup business was formed with the intention of designing, building, and selling a device to allow landlords of multi-tenant properties to accurately record and bill tenants for their power usage. Further business details aside, several constraints were placed on the product including its proposed functionality, size, ease of installation, and price. The overall system would consist of two parts – a hardware component installed in the property to be monitored, and a remote server for collecting, analyzing, and displaying the recorded data. This technical report will detail the design, prototype, and manufacture of the former, as this was the task of the author. The first half of the following discussion is organized into a system overview followed by details of each subsystem. The remainder will present the work performed in a semi-chronological order.

System Architecture and Constraints

Before hardware could be designed, an outline for the system was thought up based on several constraints. It was decided that the power monitoring functionality would work by the use of small clip on current transformers, or CTs, attached to every circuit in the house. In this way, current draw, and thus power, on each circuit can be measured. Alternatives to CT's, such as Hall Effect sensors, current shunts, and Rogowski coils were considered, but CT's were chosen due to cost and ease of use. These CTs would be installed on the wires immediately leaving the circuit breakers in the standard household breaker box. The benefit of this method lies in the isolating properties of CT's. With clip on CT's, no wire inside the breaker box needs to be disconnected to install the current monitoring system. Furthermore, a wide range of inexpensive CT's are available which met the design requirements. The majority of household circuit breakers are rated at 30A, so a CT with an upper limit of this value was chosen. Dechang Electronics model SCT-006 30A split core current transformer was ultimately chosen because it met a low price point of $2.50 per CT, had a very small size allowing several in a breaker box, and met the electrical requirements [1]. Collecting current data to this CT will be discussed later. 20 SCT-006 CT's would be needed per metering system as this is an estimate of the number of 30A breakers in the average household breaker box. Designs were also implemented allowing up to five larger CT's to be attached for monitoring of 240V appliances such as air conditioning units, water heaters, stoves, etc…

Telemetry methods were carefully selected so the accumulated power data would not be lost in transit to the internet connected server for display. Two separate internet connections were implemented - the first and main method was the use of the new ESP8266 by Espressif, a small microcontroller with built in Wi-Fi capability. This chip allows the power monitoring system to connect to a household Wi-Fi network. The second method is via a GSM cellular modem, specifically the SIMCOM SIM900 quad-band module. This module allows TCP/IP data containing the power readings to be transmitted to the internet if Wi-Fi is not available. Both of these devices were selected due to their low cost (~$5 for the ESP8266 and ~$20 for the SIM900) as well as their ease of use and thorough online documentation. As an additional feature and the 3rd wireless device on the system, a small and inexpensive UHF data radio/modem was added. This modem allows future sensor nodes to be designed and linked to the power monitoring system creating a Home Area Network or HAN if you will.

Devices for power measurement and subsequent telemetry have been selected. As this is an embedded system a Microcontroller is needed as the brain to tie everything together. Reviewing the requirements, this Microcontroller must contain an Analog to Digital Converter with at least 21 physical inputs to poll the CT's for power data. It must also have the capability to communicate with the ESP8266 Wi-Fi module, the SIM900 GSM module, and the UHF modem. Ease of programming was also a large factor in this choice. The Teensy 3.1 Development Board by PJRC fits the bill with its use of a powerful 32bit ARM processor by Freescale along with its $20 price point and extensive online documentation [2].

Figure 1 PJRC's Teensy 3.1

Physical and electrical design of the sub metering system necessitates a printed circuit board (PCB) to connect and support all individual systems. Cost and size dictated the use of a two layer 10 cm by 10cm PCB because this is a standard size for manufacturing overseas at a cost of approximately $15 for 10 boards. An acrylic case was laser cut to fit around the PCB and components. Power for the system is provided by a small 12 volt AC to AC adapter followed by a rectifier circuit and a switch mode power supply regulator to produce clean 5 volt power for the system. The AC to AC adapter must not include a built in rectifier because voltage waveform samples are taken on the output of this adapter by the microcontroller for use in power calculations.

Current Transformer Interface Circuitry

Measuring power draw by an AC circuit is relatively simple. The current draw as well as the voltage at any point in time must be known. These values are multiplied together and then accumulated and integrated over a certain time period. This will result in the real power used in watts per time period.

As discussed above, small current transformers are used to get instantaneous current values. The secondary current amplitude of a CT will be proportional to the primary current divided by some factor (turns ratio of CT). We need these current values to be numbers inside the microcontroller, so we must sample this output thousands of times a second and scale it appropriately in software to represent a real current value.

The MK20DX256 processor [3] on the Teensy 3.1 has an internal analog to digital converter (ADC) capable of approximately 2MSPS (Mega samples per second) at 12 bit (0 to 4096) resolution. Internally this ADC is connected to an analog multiplexer allowing 21 physical connections to be sampled by the ADC. Each of the 21 pins can accept a voltage to be sampled in a range of 0 to 3.3 volts. For the most accurate samples, we would like to use the entire 12bit range. This means we need an analog circuit to scale the differential AC current output from the CTs to a voltage so the lowest negative part of its waveform is at zero volts and its highest waveform value is at +3.3V.

For this analog circuit, we will copy a design from a similar open source project called the OpenEnergyMonitor, or EmonTx [4]. This design uses a burden resistor across the CT secondary to convert the current waveform into a voltage waveform. The burden resistor is calculated so it creates a voltage drop of one half the highest needed value (3.3V / 0.5 = 1.65V) when CT primary current is at a max (30A). The result is a voltage waveform +- 1.65V for max primary current. To shift this value up to 0 to 3.3V, we connect the output of a resistor divider with equal resistors referenced between 0V and 3.3V to one terminal of the CT secondary. The opposite CT terminal will now provide the voltage waveform we need for sampling. Once digitized, the Teensy ADC should return a value of 4096 for a current of 30A.

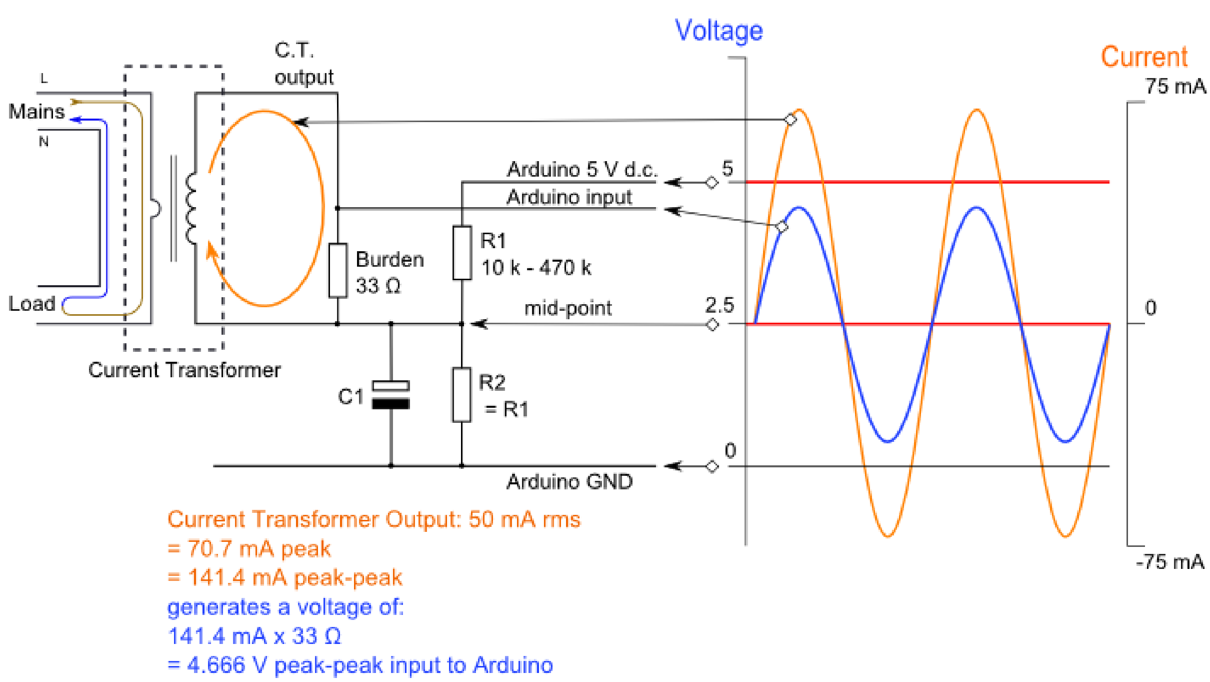


Figure 2 Image copied from EmonTX project

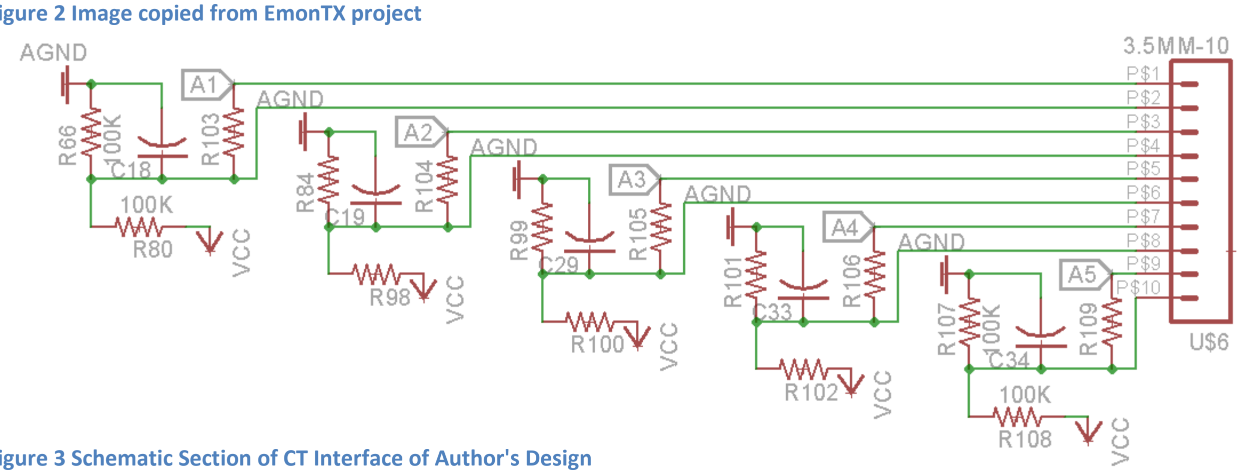


Figure 3 Schematic Section of CT Interface of Author's Design

With this analog circuit design, component values were calculated to interface the 30A SCT-006 YHDC CT's as well as 80A SCT-010 YHDC CT's for 240V appliance measurements.

For SCT-006: 30A:37.5mA or 1:800 turns ratio

$$Secondary\ Peak\ Current = \frac{30A_{rms} * \sqrt{2}}{800} = 53mA$$

$$Ideal\ Burden: \frac{(3.3V \div 2)}{53mA} = 31.132\ Ohms$$

$$Peak\ Power\ Dissipation: 53mA * 3.3V = 0.1748\ Watts$$

31 Ohm +- 1% 0.25W Burden Resistor was chosen

Figure 4 SCT-006 CT

For SCT-010: 1:3000 turns ratio

$$Secondary\ Peak\ Current = \frac{80A_{rms} * \sqrt{2}}{3000} = 37.7mA$$

$$Ideal\ Burden: \frac{(3.3V \div 2)}{37.7mA} = 43.75\ Ohms$$

$$Peak\ Power\ Dissipation: 37.7mA * 3.3V = 0.1244\ Watts$$

44 Ohm +- 1% 0.25W Burden Resistor was chosen

Figure 5 STC-010 CT

Voltage Transformer Interface Circuitry

Circuitry used to interface with and sample the household voltage waveform is nearly identical to the circuitry used to scale the CTs discussed above. Again, a great diagram showing this method taken from the EmonTX project is below [4]. Ultimately, a 174KOhm resistor and a 10KOhm resistor were used for the main divider.

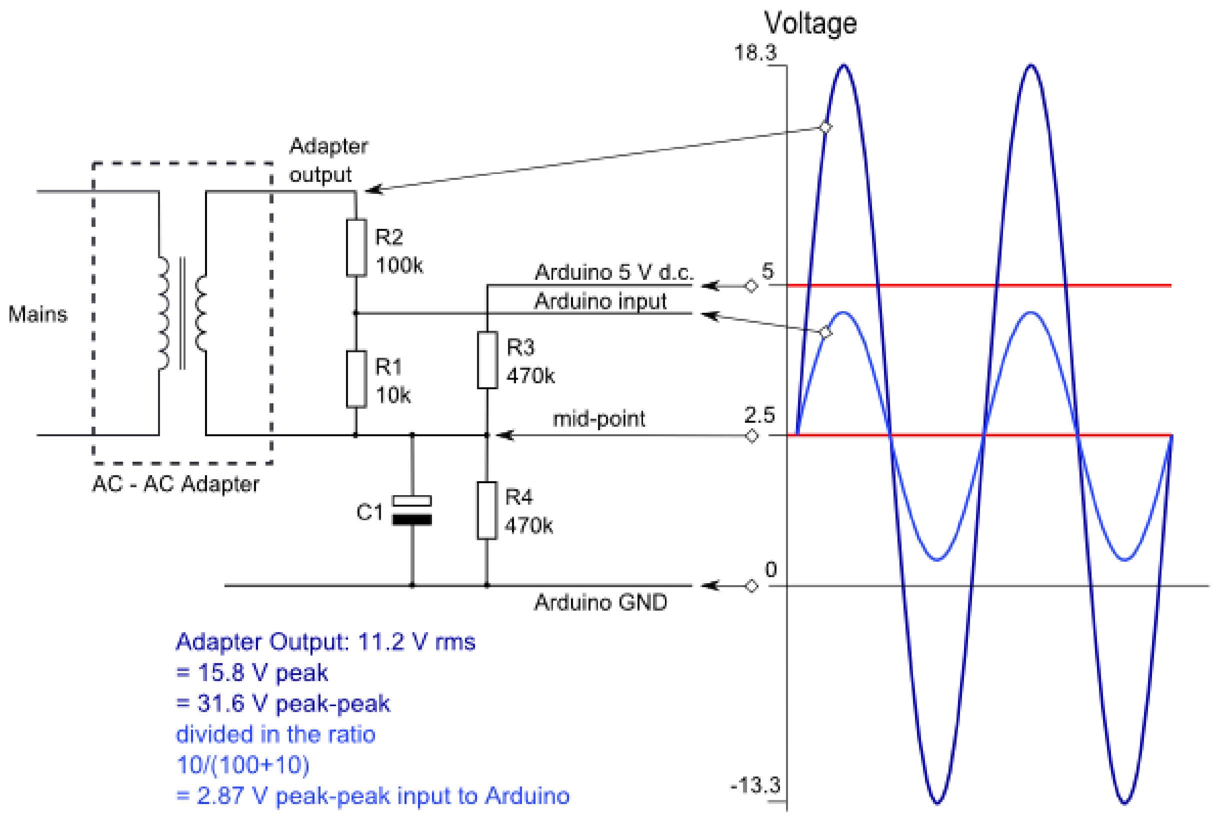


Figure 6 Image copied from EmonTX project

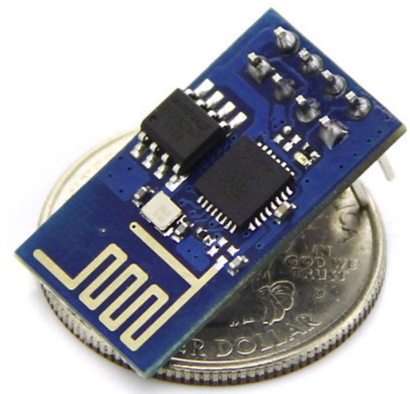
System Power Supply

The same 12 volt AC – AC adapter used to take voltage samples above is also used to power the entire system. After the AC voltage enters the PCB, it is immediately sampled. Following the sampling connection, it passes through one diode for half wave rectification and into a LM2596 based switch mode step down regulator board (please see “Counterfeit Power Supply Modules” section below). This regulator is adjustable and is set to drop the voltage down to 5 volts in order to power the SIM900 and Teensy 3.1. The Teensy 3.1 has an onboard linear voltage regulator which further drops the 5 volts down to 3.3V for running the Freescale processor as well as the 3.3V reference supply for the CT analog interface circuitry. A separate higher current 3.3V linear regulator is used to power the ESP8266 Wi-Fi module and the UHF radio from the 5V source.

All power on the system comes from either a 5V USB connection built into the Teensy 3.1 or from the 5V Switch Mode Regulator. These two sources are isolated from each other by use of diodes so either source can power the board, but power will not be able to flow backwards into the USB connection as this could damage a computer.

ESP8266 Wifi Module

The ESP8266 is a brilliant new product appearing on the market just a year or so ago. This little module from Chinese manufacturer Espressif and is revolutionizing the Internet of Things “IoT” due to its incredibly low cost. Each ESP8266 is a powerful ARM microcontroller with a full Wi-Fi connection and TCP/IP stack preprogrammed in; all this is available for around $4 to $5. The ESP8266 is currently the cheapest and likely the easiest way to connect an embedded system to the internet at the moment. A simple UART (TTL Level Serial) connection is available on the ESP8266 for interfacing with another microcontroller. Programmatically, simple strings representing commands can be sent over this UART connection so the main Teensy 3.1 microcontroller can connect to a Wi-Fi network, open a TCP or UDP connection to an internet connected server, and send data.

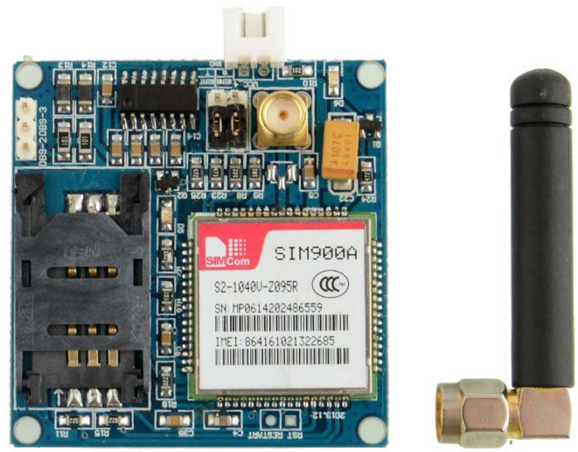


RFM69W Interface

In order to implement remote sensors or other remote devices, a small UHF data radio / modem was included. The RFM69W is one of the best options for this application due to size and cost (less than $6). It operates in the 433MHz ISM band and has a range of several hundred meters depending on the environment. Interfacing the RFM69W to the Teensy 3.1 was via a Serial Peripheral Interface (SPI) connection commonly used in embedded systems. A prototype sensor node containing temperature, humidity,

and CO2 sensors was built and the data from the node was successfully transmitted via RFM69W's to the main power monitoring system.

SIM900 Interface



To transmit TCP/IP data via the GSM cellular network, a SIM900 module was used. This module has an incredible amount of functionality built in – a cell phone could be made with one. This module, as with the ESP8266, is interfaced with the Teensy 3.1 microcontroller by a UART (TTL level) Serial connection. Simple commands are transmitted over the UART connection by the Teensy 3.1 to control the SIM900 and transmit data to the internet.

Some interesting design requirements are necessary for the SIM900 to operate. Mainly, it's voltage requirement is around 4.3V and It can draw up to 2 Amps when first connecting. These requirements resulted in some electrical design problems. To solve the voltage problem, the switch mode power supply can simply be turned a few hundred millivolts down and all other 3.3V regulators will continue to function with no problems (this depends on their "dropout voltage" however – luckily low dropout regulators were used). The larger issue is the 2A current draw – the SIM900 could not draw enough power from the supposedly 3 Amp rated switch mode power supply module (Again, see below).

Lessons Learned from Early Prototyping

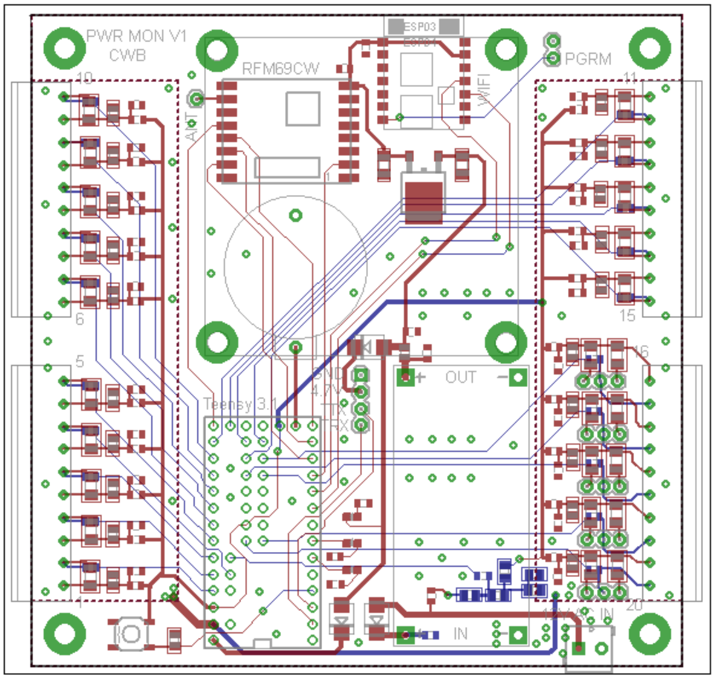
Prototyping a design before having professional PCBs made is almost universally a good idea. Before PCB design, all parts and subsystems were purchased and assembled by hand in order to test functionality. Several design problems were discovered in this stage including many of the power supply issues discussed above such as proper multi-source isolation using diodes and the SIM900 voltage and current draw problems.

The largest problem discovered in the prototyping phase was severe noise and interference being recorded when the CT's were sampled by the ADC. Noise and EMI is an extremely common problem when working with sensitive analog digital converters, so this was not a surprise. Reducing EMI can be a huge engineering challenge however. It was discovered that taking precautions when grounding the CT analog interface circuitry solved the majority of the EMI problems. The Teensy 3.1 has a special analog ground pin (Agnd) which is used as a filtered current return path specifically for sensitive ADC connected circuits. This ground pin is connected on the teensy board to the universal board ground through a high frequency ferrite bead filter. When the CT analog circuits were connected to this filtered ground, EMI was reduced by an order of magnitude. Further precautions were taken during PCB design to reduce the ADC noise even further.

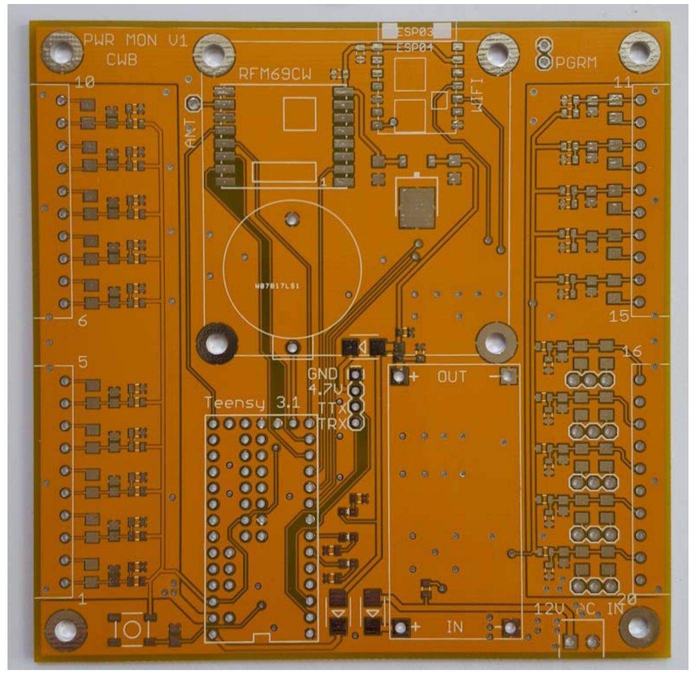
First PCB Design

The design of the first printed circuit boards was completed using CadSoft EAGLE PCB design software. The PCB was standardized at 10cm by 10cm with a single top and bottom layer containing traces along with full silk screen and solder mask. PCBWay was selected as a manufacturer for the boards with cost of 10 10cmx10cm PCBs coming to ~$40 including shipping from China [5]. The PCB was designed with the maximum number of surface mount components, and a homemade solder reflow oven was built with a toaster oven and PID controller to be used to assemble the boards.

Extreme care was taken during the PCB layout to avoid ADC noise and EMI problems. To begin, a copper pour was used over the entire top and bottom of the boards and traces were run through these pours. The copper pours are grounded and act as a ground plane over the entire board allowing any spurious currents to take the shortest path back. Separate “Analog Only” copper pours were arranged over and under the analog CT circuitry and connected back to the aforementioned Agnd pin on the Teensy 3.1 microcontroller. The switch mode power supply was positioned as far away from analog circuitry as possible. Many filtering and decoupling capacitors were placed near the larger modules to reduce voltage and current spikes. Ample external capacitance was added on the immediate output of the switch mode regulator as well as a ferrite bead to filter out high frequency noise. These design rules resulted in very little EMI into the Teensy ADC on the fully assembled PCBs.



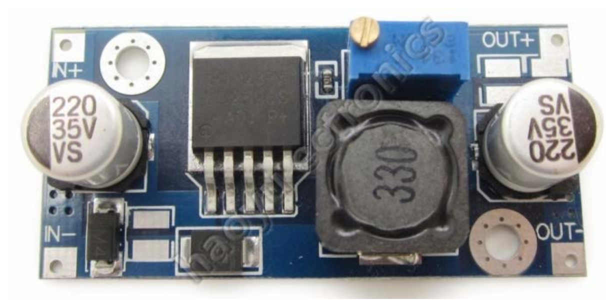
Initial PCB Design



Professional PCB from PCBWay

Fascinating Problem: Counterfeit LM2596 Chips

The switch mode regulator board at the heart of the power monitoring system’s power supply is a very cheap and very common module found with the internet search “LM2596 Buck Converter Module”. These little boards can take in 4V to 40V and produce a regulated output voltage of the user’s choice. The circuit is simple and is based on a reference design from the original TI LM2596 Simple Switcher Chip. These boards are advertised with a 3A output and cost around $1 each. The 3A output was not expected from a cheap board, but just the ~1.5A max draw from the SIM900 was causing some of these modules to fail.



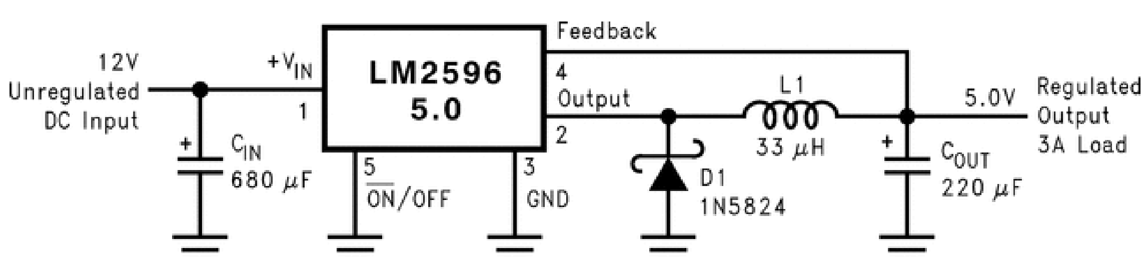


Figure 7 LM2596 Fixed-Voltage Reference Schematic

The first warning is obvious: price. A search for only the LM2596 IC on the reputable website DigiKey lists this component alone at $2.31. The whole module shown above costs less than $1. Furthermore, an article was written by Kerry D. Wong [6] discussing his analysis of these converters and his discovery that the majority are counterfeit. Wong shows the switching frequency of a real LM2596 to be 150 kHz as specified in the datasheet and finds the switching frequency of the cheap modules to be only 50 kHz. To confirm this theory, several different modules purchased for use in this project were tested by viewing the waveform on the output (pin 2) of the LM2596 chip (fig. 8 & 9). The oscilloscope measurements confirm the fake LM2596 chips have a switching frequency of 50 kHz and a good LM2596 has a switching frequency of exactly 150 kHz. The regulator board with the good LM2596 had no problem supplying the needed current to the SIM900 and other board components. If these modules are considered for use in any design, be wary of this problem. In the future, this circuit will be designed onto the PCB in a custom manner and will use a real LM2596 or other genuine power supply control IC from a reputable dealer.

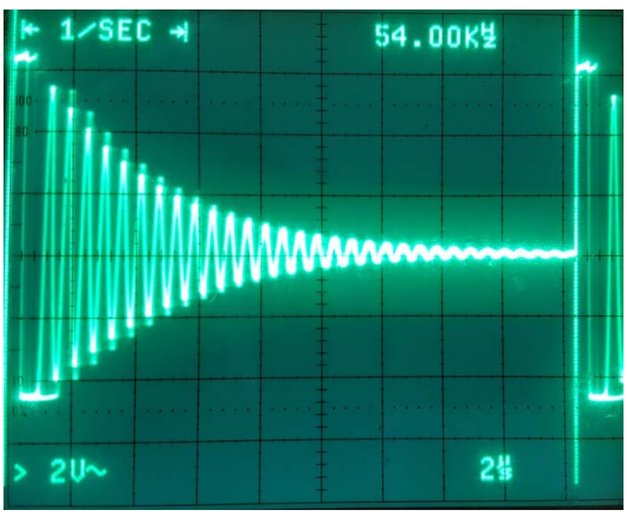


Figure 8 Fake LM2596 Waveform (54 kHz)

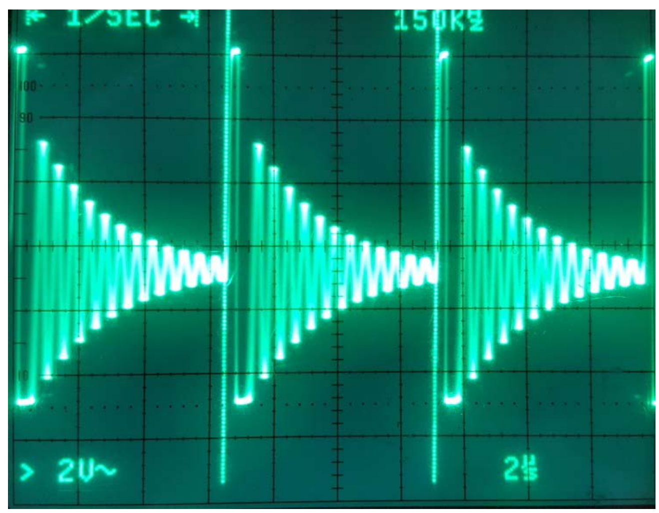
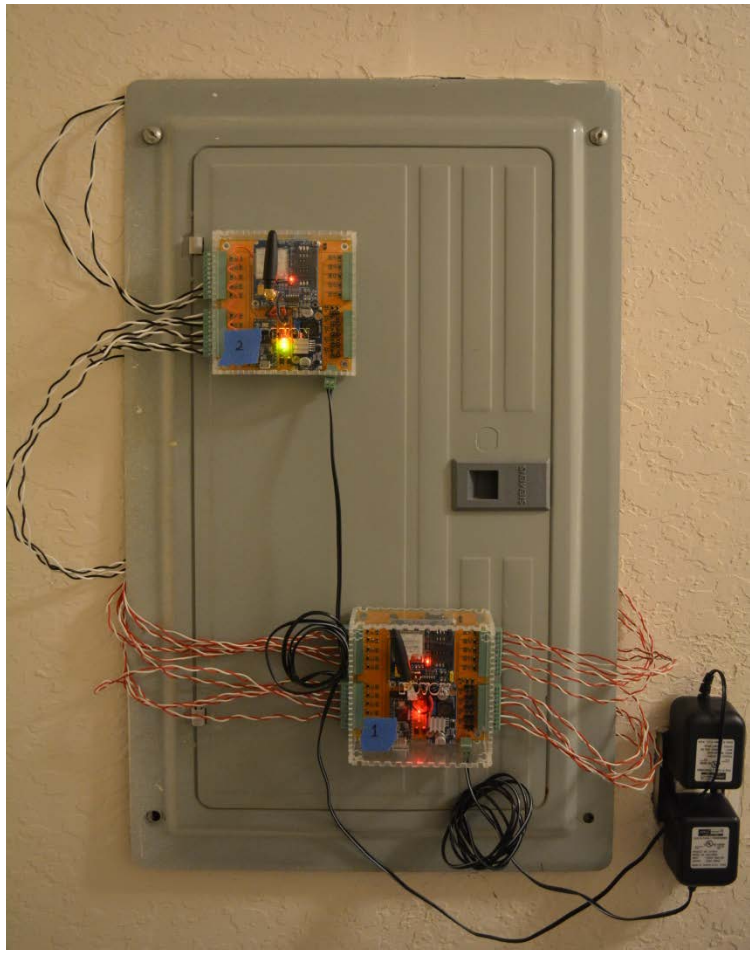


Figure 9 Real LM2596 Waveform (150 kHz)

Installation, Testing, and the Road Forward

At this point, we have designed and built several circuit level sub metering system prototypes. Initial embedded code was written in C for these systems by other team members (credit to USF EE student Alejandro Robles for embedded code architecture) and most basic technical problems were resolved. A working system was the result. Power measurements on all 20 CT's were between 5% and 10% accurate before calibration. The installation, testing, and calibration processes are ongoing at the moment. Several prototypes have been installed in the Author's apartment breaker box as well as in other team members' breaker boxes in order to collect real power data for the development of the internet web application for graphing and displaying the power data (right side picture).



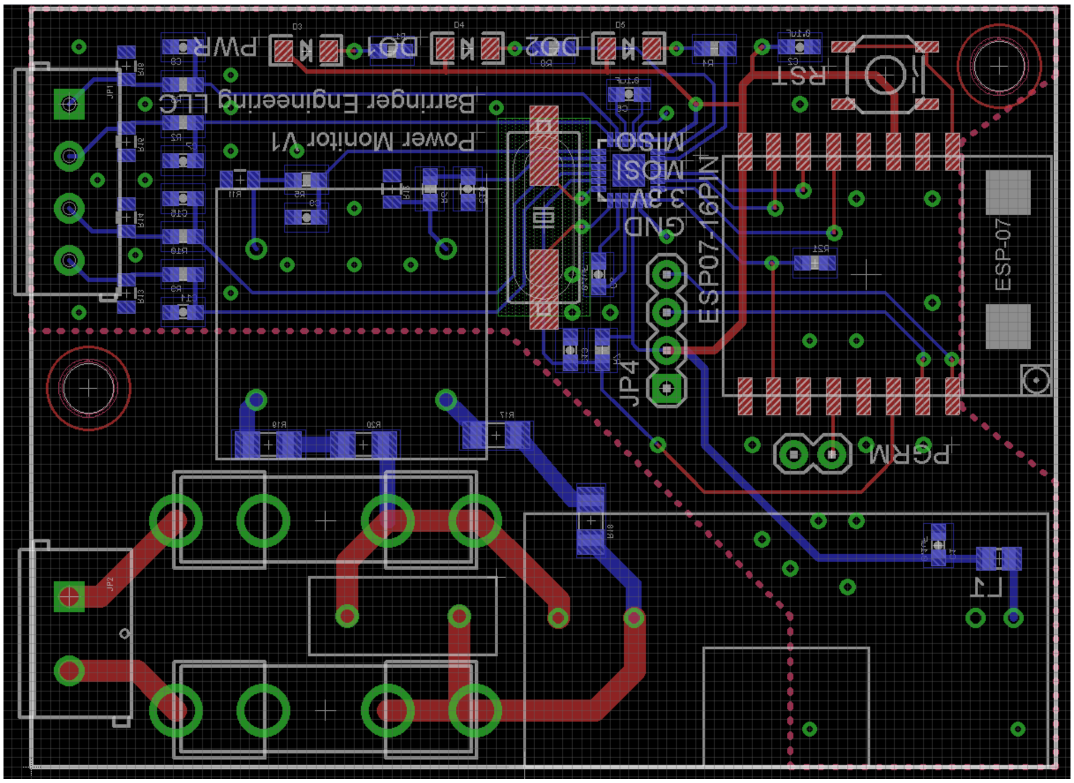
In this process, some fundamental problems with the business model arose. Namely, the goal was to record individual tenant power consumption in a multi-unit household. This was to be done by recording and totaling power usage on only the household circuits solely belonging to that individual tenant. Unfortunately household wiring is often extremely chaotic; this makes tallying power consumption based on individual room extremely difficult. Solutions to this problem are still being discussed.

A second PCB design with vast improvements to the original is also being planned. The goal of the second would be to reduce cost significantly by integrating power supply circuitry, the standalone MK20DX256 microcontroller, and the SIM900 chip onto the PCB without the use of pre-built development modules such as the Teensy 3.1 board used above. A redesigned power supply system would use a continuously charged Lithium Polymer battery to ensure power during a power outage. A battery system could be used as a current buffer for the intermittent high current draw of the SIM900 and other components allowing a vast reduction in size and cost of the power supply circuitry; read, no more LM2596 problems. 120V AC line voltage would be introduced to the board and the AC - AC adapter eliminated. This will allow direct AC line voltage sampling by the ADC and should improve overall accuracy of power measurements when compared to sampling on the secondary of an AC – AC adapter as originally used. These 2nd PCB design improvements are significantly more complex and are still being developed. In the meantime, a smaller intermediate system is being built.

Mini Smart Meter

Before the second complex 20+ CT sub metering system is developed, it was decided that a small "Smart Meter" would be designed in order to test several new ideas. This mini Smart Meter would use only 2 CT's to record, to a very high accuracy, the main power supply to an entire household just as a utility installed Smart Meter would. It was to be as small and as inexpensive as possible in order to easily rest inside a normal breaker box; specifically, a price point around $50 and a PCB size smaller than a business card. The heart of the design uses a Cirrus Logic CS5480 Three Channel Energy Measurement IC [7] along with an ESP8266 WI-FI chip for data transmission to the internet. The CS5480 is an Analog Front End Energy Measurement device which is preprogrammed to tabulate power data when attached to sensors such as CTs. The ESP8266 simply reads power data from this chip and sends it over the internet.

Images of the designed PCB are shown below. This PCB is being prepared for order from PCBWay and assembly, programming, and testing will follow. The onboard analog circuitry was designed based on the CS5480 reference designs provided by Cirrus Logic [2]. The small PCB, only 2 inches by 2.7 inches, features full AC line isolation and protection with onboard power supply, CS5480 chip with support circuitry, ESP8266 microcontroller with WI-FI connectivity, and connections to two Dechang Electronics SCT-016 CTs for full 240V 120A service split phase household power measurement. See appendix for full schematic.



Mini Smart Meter PCB Design

Conclusion

Development of the metering systems discussed above was an extremely interesting and rewarding engineering challenge; many aspects of engineering and business must be used together to build a successful system. We began by describing the goals and initial design decisions and progressed into technical aspects of those decisions. Some decisions, such as the use of the LM2596 power supply due to low cost, led to unforeseen problems requiring time and money to resolve later. Low cost components aren't always a problem as demonstrated by the ESP8266 WI-FI module and the low cost PCBWay PCB manufacturer. Making a WI-FI enabled enabled system just a couple years ago would have been cost prohibitive as would getting any PCBs professionally made. In reality, this is just the beginning of development for these metering systems. The level of success upon completion of the Mini Smart Meter will drive further design and business decisions with regard to the next version of the more advanced circuit level sub metering system.

References

[1] Dechang Electronics Co. (YHDC) Current Transformers

http://www.yhdc.com/en/product/category/Spilt-core-current-transformer/

[2] PJRC Teensy 3.1 Development Board

https://www.pjrc.com/store/teensy31.html

[3] Freescale MK20DX256VLH7 Microcontroller Data Sheet

https://www.pjrc.com/teensy/K20P64M72SF1RM.pdf

[4] Open Energy Monitor Project (EmonTX)

http://openenergymonitor.org/emon/modules/emonTxV3

[5] PCBWay Custom PCB Manufacturer

http://www.pcbway.com/

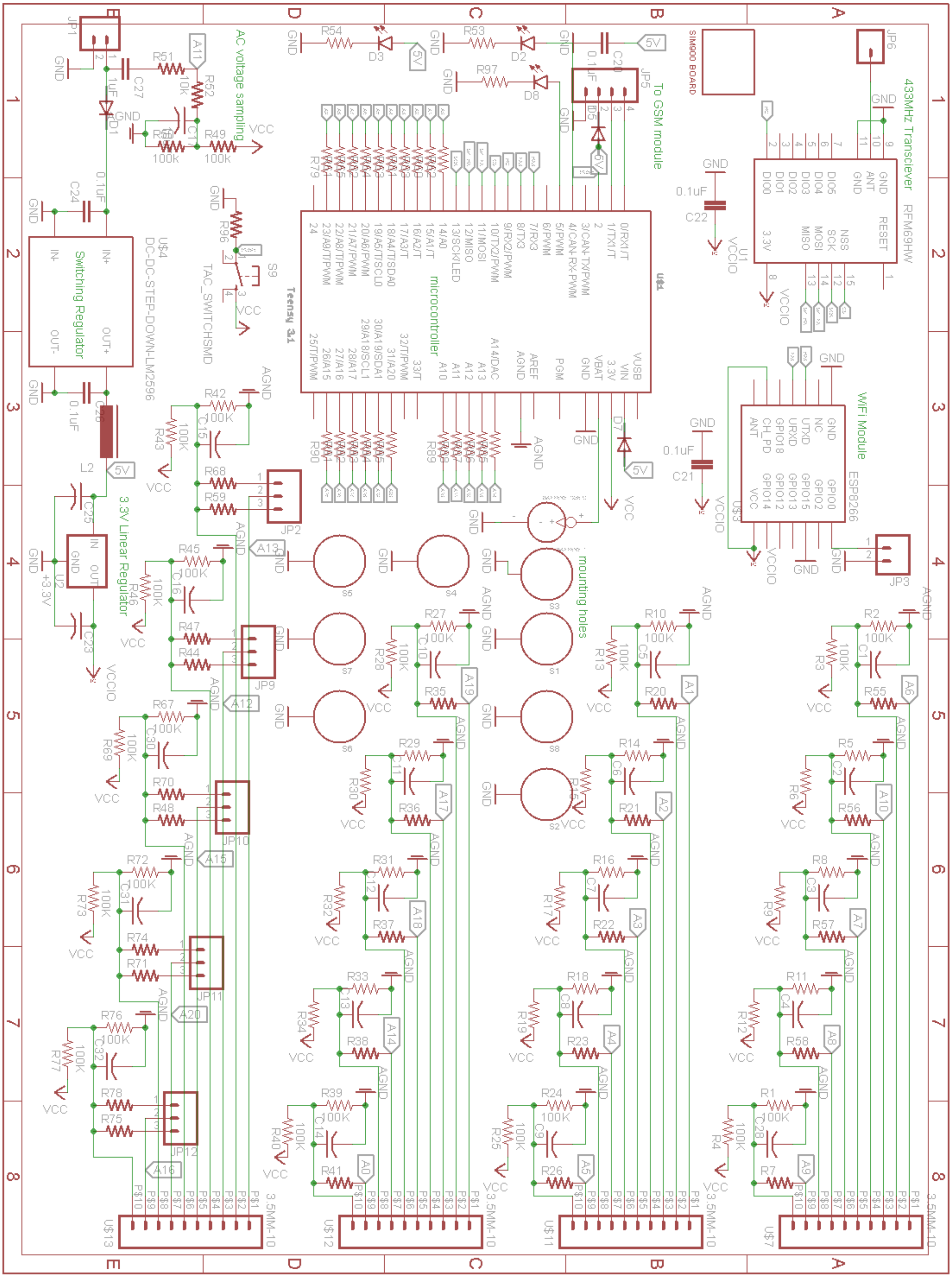
[6] Kerry D. Wong "LM2596 DC-DC Converter Module Testing"

http://www.kerrywong.com/2015/07/24/lm2596-dc-dc-converter-module-testing/

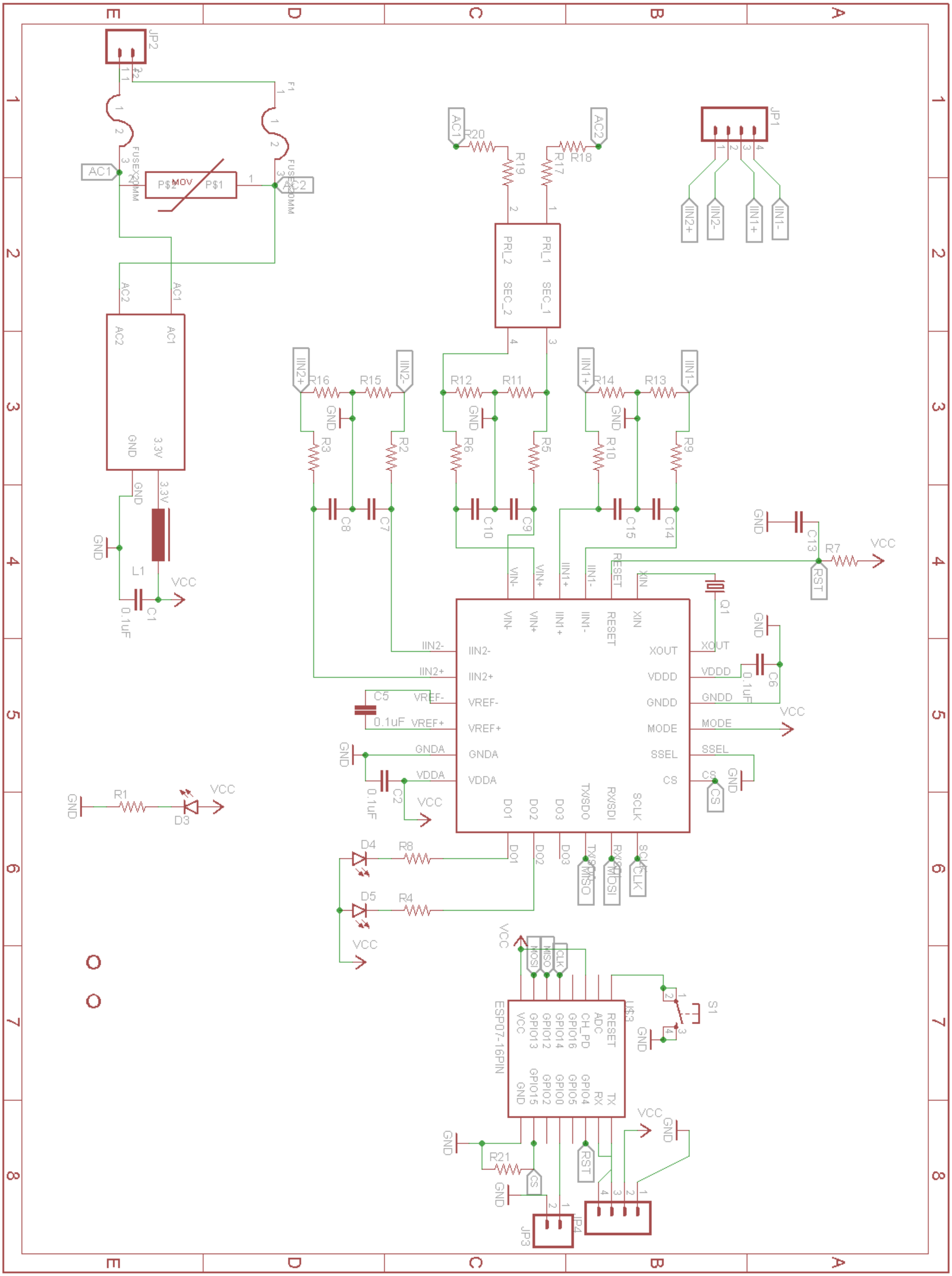
[7] Cirrus Logic CS5480 Three Channel Energy Measurement IC Datasheet

http://www.cirrus.com/en/pubs/proDatasheet/CS5480_F3.pdf

Appendix Items Follow Below



Appendix: PCB Version 1 Schematic



Appendix: Mini Smart Meter Version 1 Schematic