

FINAL REPORT

By

Isaac Herink

Joseph Kim

Jeffrey Pohlman

Final Report for ECE 445, Senior Design, Spring 2026

TA: Eric Tang

Project No. 72

Abstract

In this report we will cover our design, requirements, and verification of our project. Our project is a single-phase power quality analyzer that measures RMS voltage, RMS current, real and apparent power, and power factor in real-time. We found that our design has comparable accuracy, is cheaper, and more portable when compared to a commercial power quality analyzer.

Contents

1. Introduction.....	1
1.1 Problem.....	1
1.2 Solution.....	1
1.3 High Level Requirements	1
1.3.1 Measurement Accuracy.....	1
1.3.2 Time-Synchronized Sampling.....	2
1.3.3 Real-Time Reporting.....	2
1.4 Block Diagram.....	2
2. Design	3
2.1 Signal Conditioning/Sensing	3
2.2 Board Power.....	6
2.3 Embedded Processing	7
2.3.1 Overview.....	7
2.3.2 ADC Configuration and Sampling.....	7
2.3.3 DMA Buffering and Data Acquisition.....	7
2.3.4 Signal Processing and Computation	8
2.4 High Voltage Protection and Enclosure.....	9
3. Design Verification.....	10
3.5 Results.....	10
3.5.1 Measurement Update Rate	10
3.5.2 Test 1: 40W Incandescent Bulb	10
Table 1: 40W Incandescent Bulb Test Results.	Error! Bookmark not defined.
3.5.3 Test 2: Soldering Fan	10
3.5.4 Test 3: Laptop & Charger	11
3.6 Result Discussion.....	11
4. Costs.....	12
4.1 Parts	12
4.1.1 Power Path Parts:	12
4.1.2 Display Parts	13

4.1.3 MCU Parts	14
4.1.4 Enclosure / Main Wiring Parts.....	15
4.1.5 Analog Signal Sensing/Conditioning Parts.....	16
4.2 Labor.....	19
4.3 Schedule.....	19
5. Conclusion	19
5.1 Accomplishments.....	19
5.2 Uncertainties	20
5.3 Ethical considerations	20
5.4 Future work.....	20
References.....	21
Appendix A Requirement and Verification Table.....	22
A.1 Signal Conditioning/Sensing Verifications.....	22
A.2 Board Power Verifications.....	22
A.3 Embedded Processing Verifications	23
A.4 High Voltage Protection and Enclosure Verifications	24

1. Introduction

Our project is a single-phase power quality analyzer. It measures voltage and current supplied to a load using isolated sensing circuits. The microcontroller will sample both signals at the same time and compute RMS values, real power, and power factor in real time. Measurement data will be transmitted to an OLED screen for display and analysis. Example use cases include comparing real power and power factor across common loads (incandescent lamp vs. fan motor vs laptop charger), observing changes in RMS voltage, current, and power during load startup, and identifying inefficient or abnormal load behavior in educational lab experiments. It provides students with hands-on exposure to AC power measurements without needing expensive commercial equipment. The final system will provide a low-cost, embedded tool for monitoring and analyzing AC power behavior in laboratory and educational environments.

1.1 Problem

Basic voltage and current measurements do not provide insight into how power is being consumed by an AC load. Relevant quantities such as real power and power factor require time-synchronized measurements of voltage and current, which are typically only available from commercial power analyzers. These commercial analyzers are expensive and unnecessary for small-scale laboratory or educational purposes.

1.2 Solution

Design and build a microcontroller-based, single-phase AC power analyzer that measures voltage and current supplied to a load using isolated sensing circuits. The microcontroller will sample both signals at the same time and compute RMS values, real power, and power factor in real time. Measurement data will be transmitted to a computer over USB for display and analysis. Example use cases include comparing real power and power factor across common loads (incandescent lamp vs. fan motor vs phone charger), observing changes in RMS voltage, current, and power during load startup, and identifying inefficient or abnormal load behavior in educational lab experiments. It provides students with hands-on exposure to AC power measurements without needing expensive commercial equipment. The final system will provide a low-cost, embedded tool for monitoring and analyzing AC power behavior in laboratory and educational environments.

1.3 High Level Requirements

1.3.1 Measurement Accuracy

The analyzer shall measure RMS voltage, RMS current, real power, and power factor of a single-phase 120 VAC load with accuracy within $\pm 5\%$ for RMS voltage, $\pm 10\%$ for RMS current, $\pm 10\%$ for real power, and ± 0.10 for power factor when compared against a calibrated commercial power analyzer for steady state loads up to 5 A RMS.

1.3.2 Time-Synchronized Sampling

The analyzer shall acquire voltage and current measurements using time-synchronized sampling at a minimum sampling rate of 3kHz, such that computed values of real power and power factor remain within the accuracy limits specified above.

1.3.3 Real-Time Reporting

The analyzer shall compute and transmit RMS voltage, RMS current, power (P), and power factor (PF) to a host computer at a minimum update rate of 5 Hz, where values are displayed to the user in real time.

1.4 Block Diagram

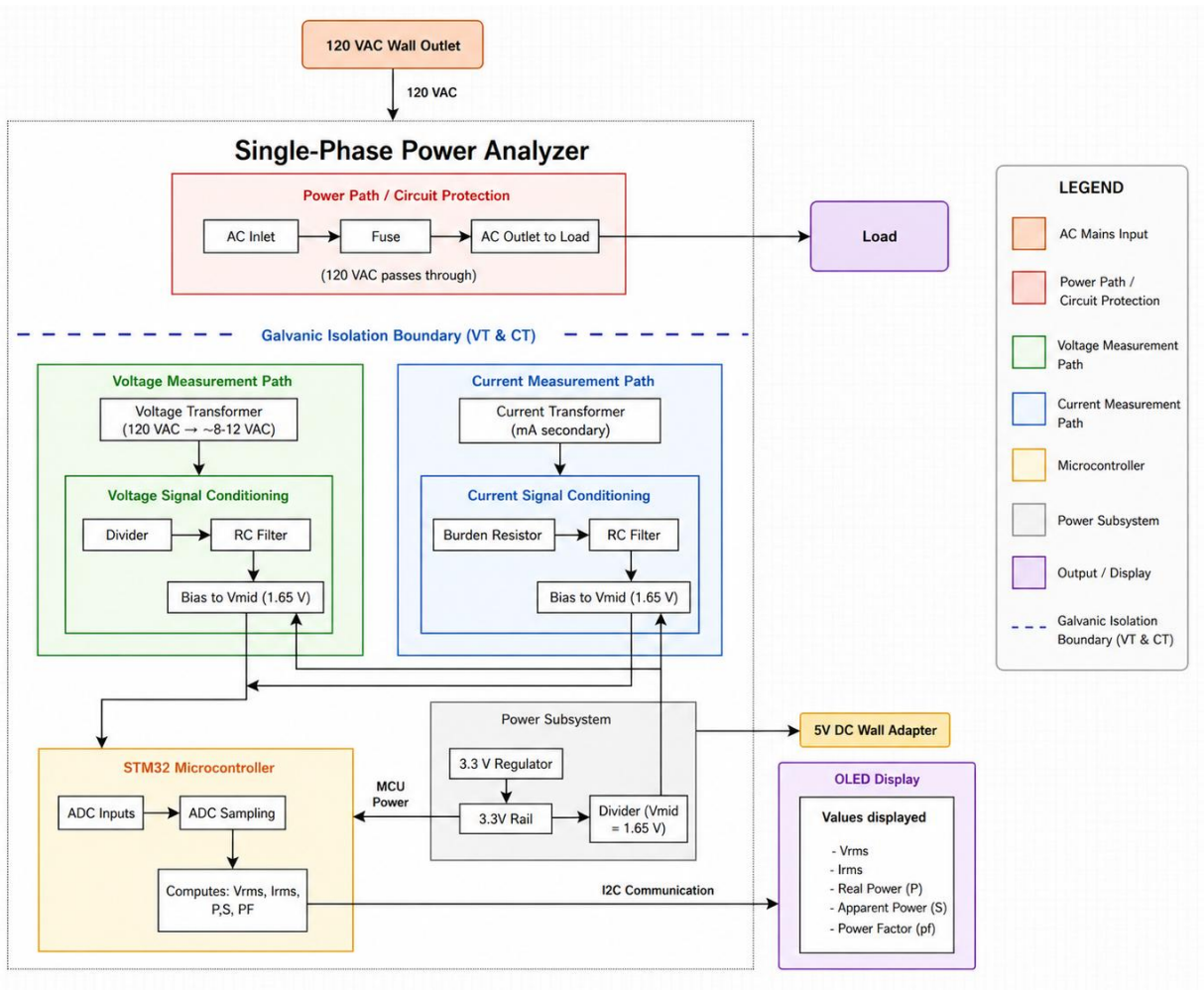


Figure 1 Block diagram overview.

2. Design

In this section we will dissect the design of each subsystem.

2.1 Signal Conditioning/Sensing

The role of this subsystem is to scale the 120VAC into a signal that is suitable for the microcontroller, while also maintaining accuracy of the load signal. To do this we chose to use transformers since they can have high input impedance [1], they have no direct electrical connection to HV, and they can step down the magnitudes of each signal. To further ensure electrical isolation we will put the voltage transformer on its own PCB as seen in Figure 2. The current transformer also reads the current running through the high voltage wire without making any electrical connection [2].

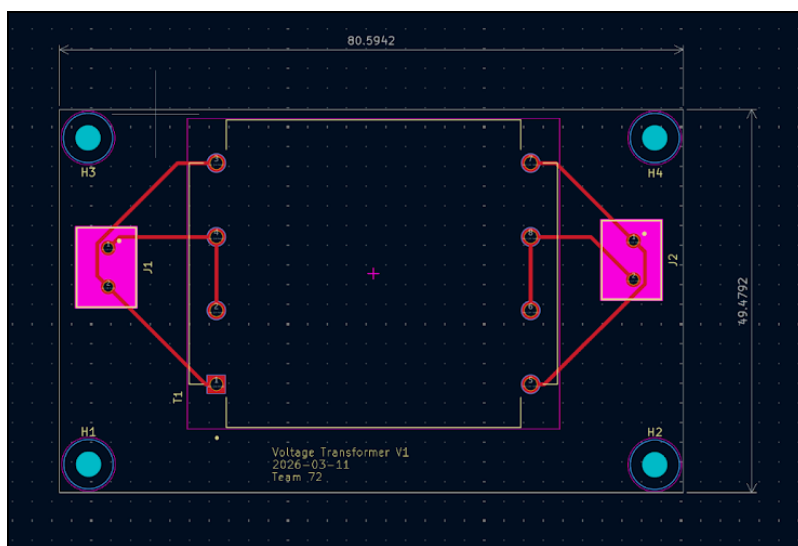


Figure 2: Voltage Transformer PCB.

After the transformers, the signals will no longer be considered high voltage, but they are not suitable for the microcontroller. For the signals to be suitable, we must:

- Center at 1.65V
- Be within 0-3.3V

For it to be an accurate signal for measurement and analysis we have to ensure that the power factor remains the same as the load. This means that we have to make sure the relative phase shift between voltage and current stays the same. This is because power factor depends on the phase shift between voltage and current [3]:

$$PF = \cos(\theta_V - \theta_I)$$

This power factor has the potential to tell us the complex(S), real(P), and reactive(Q) power being consumed by the load [3]:

$$\theta_{PF} = \cos^{-1}(PF)$$

$$P = V_{RMS} * I_{RMS} * \cos (PF)$$

$$Q = P * \cos (PF)$$

$$S = P * PF$$

To ensure this, we needed to make sure that the voltage and current sensing circuits are phase shifted by the same amount. As long as the difference between the two-phase shifts are the same as the difference seen by the load, it will be accurate.

The voltage and current sensing circuits are nearly identical. This is by design to ensure a similar phase shift. The voltage sensing circuit begins with the input of the secondary terminals of the transformer. This voltage needs to be scaled down to about 1Vpp. To do this we chose a 10:1 voltage divider. The current sensing circuits input will be the secondary current from the current transformer. To transform this into a voltage signal, we will use a burden resistor of 100Ω. This will make our 10mA AC current signal into a 1Vpp voltage signal. From this point forward both circuits are identical.

The AC coupling capacitor blocks any DC component of a signal while allowing the AC portion to pass, so it can transfer the varying signal without disturbing the circuit's DC bias. The DC bias centers the signal at 1.65V. The RC filter smooths the signal by attenuating high-frequency noise and setting a bandwidth limit, so the measured voltage and current reflects the true waveform rather than fast switching or interference components. The protective diodes clamp the signal voltage to a safe range, preventing voltage spikes from exceeding the input limits of our ADC and causing damage. This final output will be input into the ADC for analysis.

Figure 3 shows our circuit in LTspice. Figure 4 shows our simulated outputs of each sensing circuit. As we see, our simulated circuit:

- Centers the signal at 1.65V
- Stays between 0.6-2.6V
- Has a relative phase shift of 0.17°

Phase shift was calculated using the following equations:

$$T = \frac{1}{f} = \frac{1}{60} = 0.01667$$

$$\Delta\theta = \frac{T}{\Delta t} * 360 = \frac{0.01667}{7.89 \times 10^{-6}} * 360 = 0.17^\circ$$

Where T is the period, $\Delta\theta$ is the relative phase shift, and Δt is the time difference of the signals. I got the time difference from a command directive on LTspice.

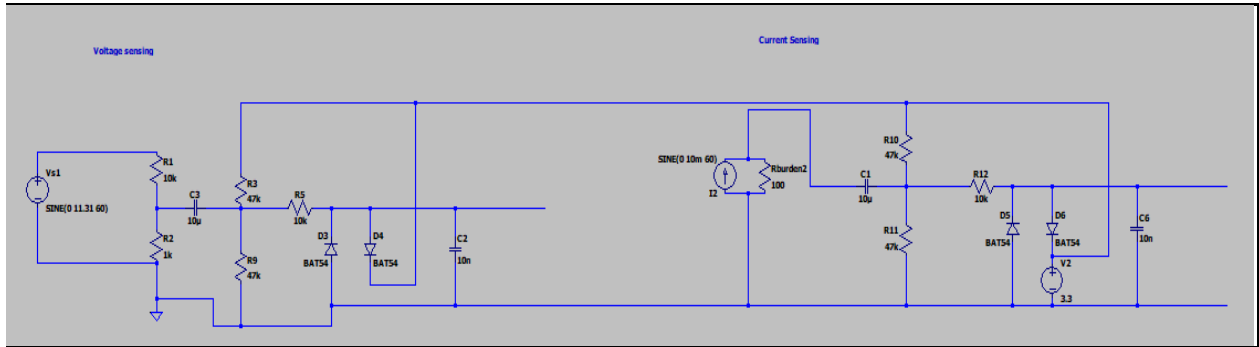


Figure 3: LTspice Voltage/Current Sensing Circuits.

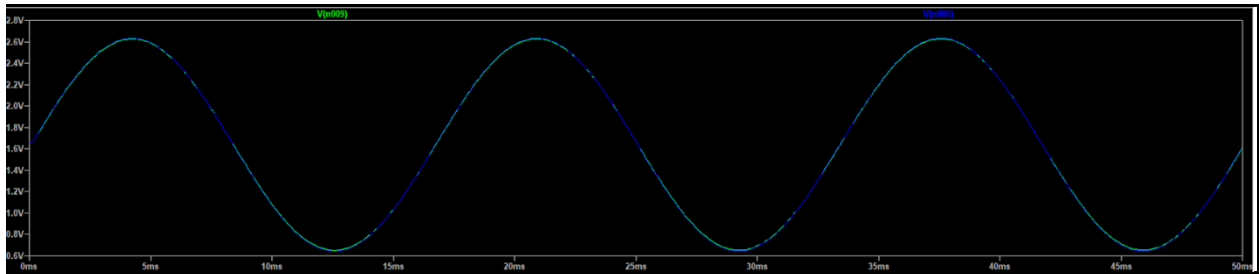


Figure 4: LTspice Simulated Output Waveforms.

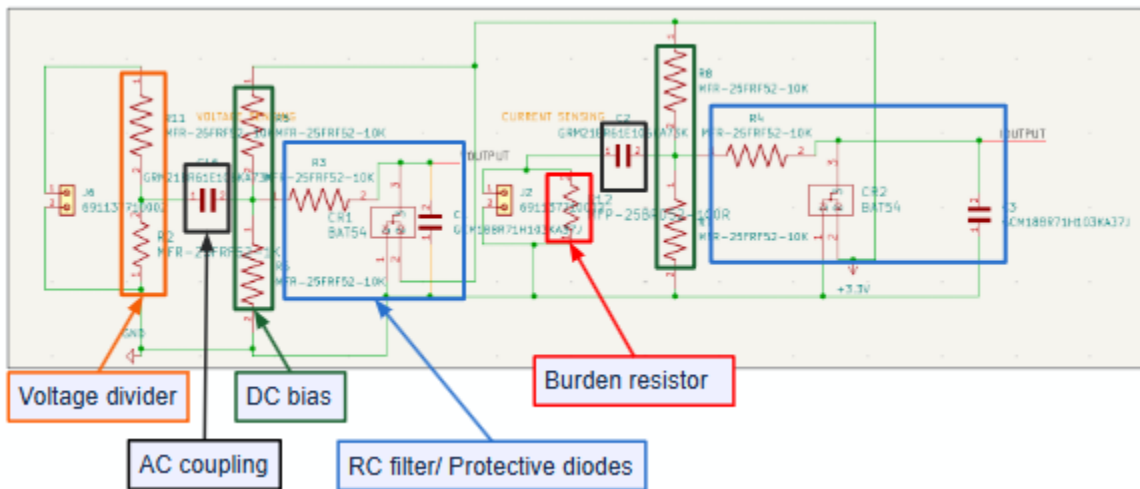


Figure 5: KiCad Schematic

2.2 Board Power

Referencing Figure 6, 5 volts from a wall adapter goes to a terminal block connected to ground and a fuse which prevents current overload while the Schottky diode is placed downstream to enact reverse polarity protection. Based on [7], a 22 μF “bulk” capacitor was necessary to provide a bulk energy source just in case a surge of current occurred or in the event of a sudden change in power, such as in the event of turning on the microcontroller, while the 1 μF capacitor was used for noise filtering. This voltage then goes to the regulator where a decoupling capacitor is placed in between the output voltage and ground based on the specifications/recommendations in [8]. Now 3.3 volts can be provided to other components and subsystems.

Expanding upon the high-level connection between my subsystem and the others, the 3.3-volt rail is utilized throughout the entire PCB. For every VDD port in the microcontroller, there is a wire connected to 3.3 volts as well as a decoupling capacitor that is placed as close as it can be to the IC to minimize supply voltage ripples and prevent switching noise from one chip affecting others [9]. Additionally, by using the 3.3 volts as a source, the current sensing in the analog signal processing subsystem, uses this voltage to establish a bias at 1.65 volts, which is essential for centering the analog signal within the operating range of the STM32's Analog-to-Digital Converter (ADC).

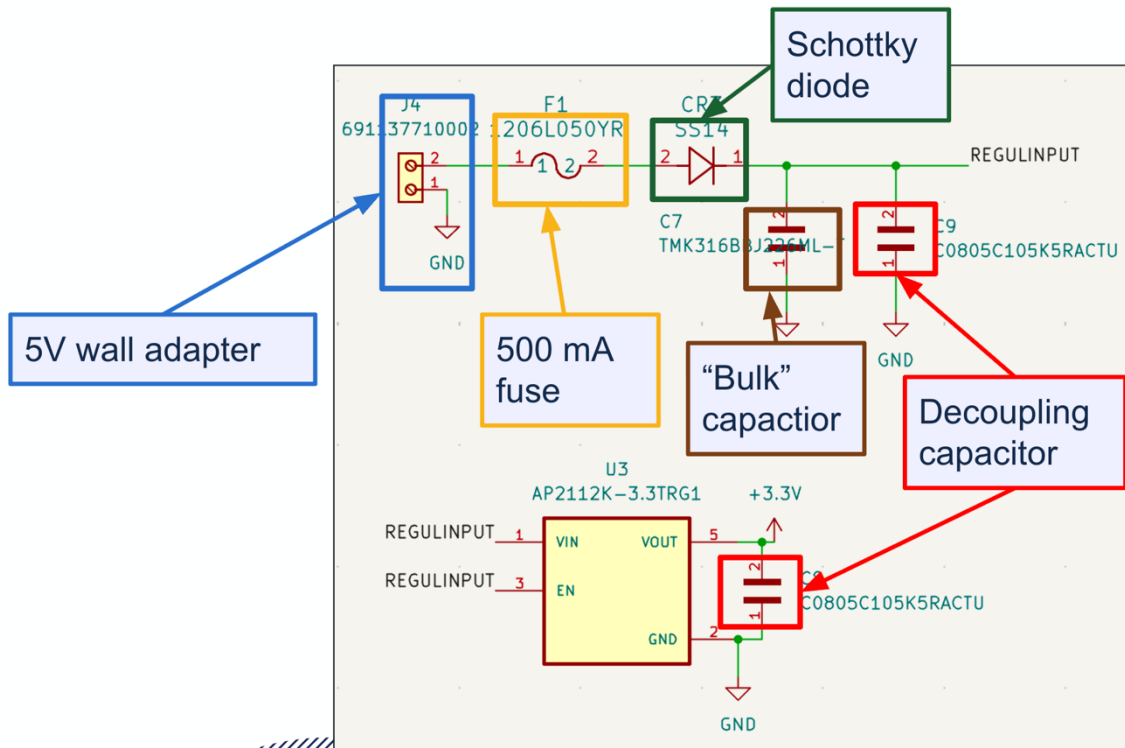


Figure 6. KiCad schematic of the board power subsystem with labels of each component.

2.3 Embedded Processing

2.3.1 Overview

The embedded processing subsystem is responsible for acquiring time-synchronized voltage and current measurements, processing these signals, and computing electrical quantities in real-time. This subsystem connects directly with the analog signal conditioning circuits and serves as the bridge between raw sensor data and readable outputs.

The system is implemented on an STM32 microcontroller and operates continuously using timer-triggered sampling, direct memory access (DMA), and block-based signal processing. This architecture ensures consistent sampling timing, minimal CPU overhead during acquisition, and reliable computation.

The system is designed to meet the time-synchronized sampling and real-time reporting requirements specified in Section 1.4. The chosen sampling rate and processing approach ensure accurate computation of electrical quantities, while update rate limitations are discussed in Section 3.5.

2.3.2 ADC Configuration and Sampling

To satisfy the time-synchronized sampling requirement, a hardware timer is configured to trigger analog-to-digital converter (ADC) conversions at a sampling rate of 6 kHz. Each trigger initiates a scan sequence that samples both voltage and current channels.

Although the STM32 ADC samples channels sequentially rather than simultaneously, the delay between voltage and current samples is fixed and significantly smaller than the sampling period. This deterministic delay introduces negligible phase error and does not meaningfully impact real power or power factor calculations.

A sampling rate of 6 kHz provides approximately 100 samples per cycle for a 60 Hz waveform, which is sufficient to accurately reconstruct the waveform and reduce numerical error in discrete-time calculations.

2.3.3 DMA Buffering and Data Acquisition

To ensure continuous sampling without interrupting processor execution, DMA is used to transfer ADC conversion results directly into memory. The ADC operates in scan mode, producing interleaved samples of voltage and current:

$$V_1, I_1, V_2, I_2, \dots, V_N, I_N$$

Half-transfer and full-transfer interrupts indicate when half of the buffer is ready for processing. This allows for one half of the buffer to be processed while the other half continues to be filled. This approach minimizes CPU overhead during acquisition and ensures no samples are missed, even during computation.

2.3.4 Signal Processing and Computation

Once a block of samples is available, the firmware computes RMS voltage, RMS current, real power, and power factor.

First, the DC offset introduced by the analog biasing circuit is removed by computing and subtracting the mean:

$$v_{ac}[n] = v[n] - v_{DC} \quad i_{ac}[n] = i[n] - i_{DC}$$

RMS voltage and current are then computed as:

$$V_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^N v_{ac}[n]^2}$$
$$I_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^N i_{ac}[n]^2}$$

Real power is computed using the discrete-time approximation of average instantaneous power:

$$P = \frac{1}{N} \sum_{n=1}^N v_{ac}[n] \cdot i_{ac}[n]$$

Apparent power is computed as:

$$S = V_{RMS} \cdot I_{RMS}$$

Power factor is then calculated as:

$$PF = \frac{P}{S}$$

These calculations are performed over fixed size sample blocks to reduce noise and improve numerical stability.

To further stabilize the output, a first-order digital smoothing filter is applied to computed values. This reduces fluctuations due to noise while preserving responsiveness to changes in load conditions.

2.4 High Voltage Protection and Enclosure

The role of this subsystem is to ensure safety and efficiency for the user. To do this, we designed our enclosure to be portable, lightweight, and keeps high voltage isolated from the user and low voltage. The overall size of this enclosure is 8in x 8in x 2.5in. A 3D model of the enclosure and lid are shown below in Figure 6. In this design, we had to consider:

- AC inlet
- AC outlet
- 5V Power Jack
- Voltage Transformer PCB standoffs for mounting
- Main PCB standoffs for mounting
- HV -> VT PCB wires
- CT -> Main PCB wires
- OLED Display

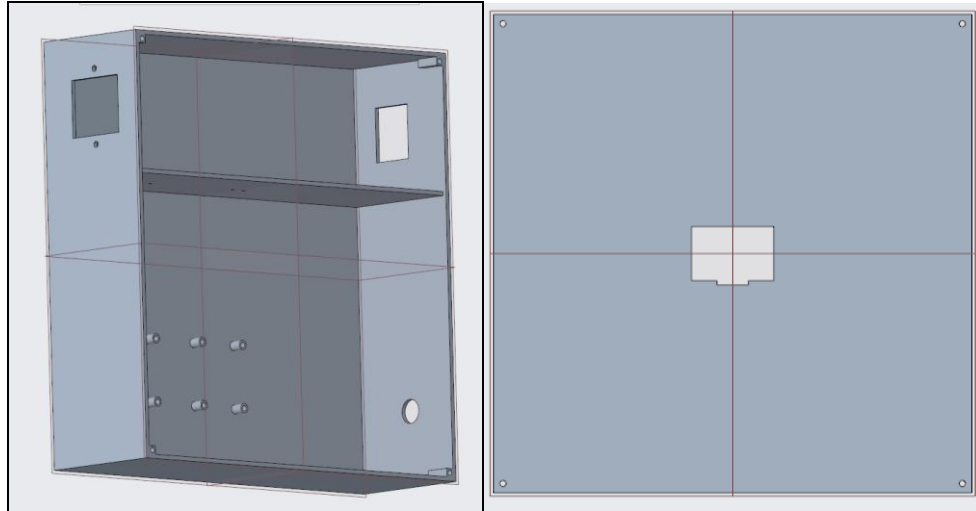


Figure 7: 3D Model of Enclosure

To prevent an overcurrent fault in our design, we incorporated an AC inlet 6.3A slow blow fuse. This fuse is slightly higher than our rated 5A and is a slow-blow type, in case a load has a high start-up current. The AC inlet and outlet are rated for 120VAC [4], [5]. The wires we used to go from inlet to outlet are 18AWG and rated for high voltage. We made sure that each component is within its ratings during its range operation.

3. Design Verification

3.5 Results

3.5.1 Measurement Update Rate

The system was required to update displayed measurements at a minimum rate of 5 Hz to provide near real-time feedback to the user. In testing, the system achieved an update rate of approximately 2-3 Hz, which does not meet the specified requirement. This reduced update rate is primarily attributed to processing overhead within the MCU, including sampling, computation, and communication with the OLED display over I2C. Additionally, the use of averaging to stabilize measurement outputs further increased the effective update interval.

Although the update rate requirement was not satisfied, this limitation does not impact the accuracy of the measured values, and the system remains functional for its intended purpose. Future improvements could include optimizing the firmware, reducing blocking operations, and refining the averaging strategy to achieve faster update rates while maintaining measurement stability.

3.5.2 Test 1: 40W Incandescent Bulb

Measurement	WT310E	PQA	Error	Ideal Error
VRMS [V]	118.49	118.61	0.101%	± 5%
IRMS [A]	0.326	0.328	0.613%	± 10%
P [W]	38.70	39.79	2.817%	± 10%
S [VA]	38.70	40.24	3.979%	± 10%
PF	1.00	0.989	0.011	± 0.10

Table 1: 40W Incandescent Bulb Test Results

3.5.3 Test 2: Soldering Fan

Measurement	WT310E	PQA	Error	Ideal Error
VRMS [V]	118.34	117.95	0.330%	± 5%
IRMS [A]	0.233	0.231	0.858%	± 10%
P [W]	17.59	19.16	8.926%	± 10%

S [VA]	27.61	28.57	3.477%	± 10%
PF	0.637	0.674	0.037	± 0.10

Table 2: Soldering Fan Test Results

3.5.4 Test 3: Laptop & Charger

Measurement	WT310E	PQA	Error	Ideal Error
VRMS [V]	118.74	119.17	0.362%	± 5%
IRMS [A]	0.662	0.666	0.604%	± 10%
P [W]	46.48	45.12	2.926%	± 10%
S [VA]	78.64	80.78	2.721%	± 10%
PF	0.591	0.558	0.033	± 0.10

Table 3: Laptop & Charger Test Results

3.6 Result Discussion

For various loads, we measured the RMS voltage, RMS current, real and apparent power, and power factor using our PQA, and a commercial analyzer (WT310E). Comparing the results of each analyzer, we see that we met our high-level accuracy requirements in every test.

Specifically, we see a low percent error in our voltage, current, and power factor values, but a slightly larger percent error in real and apparent power. We will discuss this satisfactory but unwanted percent error in Section 5.2.

4. Costs

4.1 Parts

4.1.1 Power Path Parts:

Description:	Manufacturer Part #:	Manufacturer:	Quantity:	Price per unit:	Link:	Notes:
AC/DC WALL MOUNT ADAPTER 5V 6W	QFWB-5-5-US01	Qualtek	1	\$7.45	link	5V Power cord
DC Power Connector, Jack, 2 A, 2.1 mm, Chassis Mount, Push In	27-4360	MCM	2	\$1.56	link	Barrel Jack
PTC RESET FUSE 6V 500MA 1206	1206L050YR	Littelfuse Inc.	10	\$0.426	link	Polyfuse
Diode 40 V 1A Surface Mount DO-214AC (SMA)	SS14	onsemi	10	\$0.195	link	Diode (goes after polyfuse)
22 μ F \pm 20% 25V Ceramic Capacitor X5R 1206	TMK316BBJ226ML-T	Taiyo Yuden	10	\$0.09	link	22 uF bulk capacitor

(3216 Metric)						
Linear Voltage Regulator IC Positive Fixed 1 Output 600mA SOT-25	AP2112K-3.3TRG1	Diodes Incorporated	5	\$0.22	link	3.3V Regulator
1 μ F \pm 10% 50V Ceramic Capacitor X7R 0805 (2012 Metric)	C0805C105K5RACTU	KEMET	10	\$0.296	link	Caps used at voltage regulator input and output

Table 4: Power Path Parts

4.1.2 Display Parts:

Description:	Manufacturer Part #:	Manufacturer:	Quantity:	Price per unit:	Link:	Notes:
GRAPHIC DISPLAY OLED WHITE 1.3"	938	Adafruit Industries LLC	1	\$20.90	link	Display
Connector Header Through Hole 4 position 0.100" (2.54mm)	61300411121	Würth Elektronik	5	\$0.19	link	4-pin header for display
JST SH 4-PIN CABLE - QWIIC COMPA	4210	Adafruit Industries LLC	1	\$0.95	link	I2C Jumper Cable

4.1.3 MCU Parts:

Description:	Manufacturer Part #:	Manufacturer:	Quantity :	Price per unit:	Link :	Notes:
ARM® Cortex®-M4 STM32F3 Microcontroller IC 32-Bit 72MHz 512KB (512K x 8) FLASH 64-LQFP (10x10)	STM32F303RET6	STMicroelectronics	4	\$9.84	link	MCU
Connector Header Through Hole 6 position 0.100" (2.54mm)	10129378-906001BLF	Amphenol ICC (FCI)	5	\$0.14	link	SWD programming header
0.1 μ F \pm 10% 50V Ceramic Capacitor X7R 0603 (1608 Metric)	C0603C104K5RACTU	KEMET	100	\$0.011	link	VDD decoupling capacitors
Tactile Switch SPST-NO Top Actuated Through Hole	1825910-6	TE Connectivity ALCOSWITCH Switches	5	\$0.13	link	Reset Button

Table 6: MCU Parts

4.1.4 Enclosure / Main Wiring Parts:

Description:	Manufacturer Part #:	Manufacturer:	Quantity:	Price per unit:	Link:	Notes:
StarTech.com 3ft (1m) Computer Power Cord, NEMA 5-15P to C13, 10A 125V, 18AWG, Black Replacement AC Power Cord, Printer Power Cord, PC Power Supply Cable, Monitor Power Cable - UL Listed (PXT101_3)		Amazon	1	\$5.16	link	Power Cord
PWR ENT MOD RCPT IEC320-C14 PNL	6200.23	SCHURTER Inc.	1	\$4.44	link	Inlet
Power Connector Receptacle, Female Sockets NEMA 5-15R Panel Mount, Snap-In	738W-X2/03	Qualtek	1	\$1.30	link	Outlet
Terminal Butt Splice, Closed End, Individual Openings Connector Push In 12-24 AWG Transparent - Orange	221-413	WAGO Corporation	4	\$0.74	link	3-way terminal connect
0.250" (6.35mm) Quick Connect Female 18-22 AWG Crimp Connector Fully Insulated	0190050001	Molex	10	\$0.225	link	Crimp connector (for inlet – 0.250" tab)
0.187" (4.75mm) Quick Connect Female 18-22 AWG Crimp Connector Fully Insulated	2-520193-2	TE Connectivity AMP Connectors	10	\$0.236	link	Crimp connector (for outlet – 0.187" tab)

NAOEVO 18 Gauge Wire 90ft, 18 AWG Wire 6 Colors 15ft Each Spool, Flexible Silicone Tinned Copper Electrical Cable, Wiring kit for Breadboard/Automotive/DIY/Bat tery, 200°C		Amazon	1	\$21.9 9	link	Wire spools
FUSE CERAMIC 6.3A 250VAC 5X20MM	5HT 6.3-R	Bel Fuse Inc.	10	\$0.44	link	Fuse

Table 7: Enclosure/Main Wiring Parts

4.1.5 Analog Signal Sensing/Conditioning Parts:

Description :	Manufacturer Part #:	Manufacturer :	Quantity :	Price per unit:	Link :	Notes:
6VA 115/8V PCB Mounted Transformer	FP16-375	TRIAD Magnetics	2	\$12.0 6	link	VT
5 A 500:1 Current Sense Transformer 50/60Hz Through Hole	CT-06-50	KEMET	2	\$7.99	link	CT
Diode Array 1 Pair Series	BAT54S	SMC Diode Solutions	24	\$0.18 4	link	Dual clamp diode for ADC input protection

100 Ohms ±1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	MFR-25FRF52-100R	YAGEO	10	\$0.03 9	link	Burden Resistor
47 kOhms ±1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	MFR-25FTF52-47K	YAGEO	10	\$0.03 7	link	3.3V Divider Resistors
1 kOhms ±1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	MFR-25FRF52-1K	YAGEO	10	\$0.03 9	link	1k resistor for VT secondary divider
10 kOhms ±1% 0.25W, 1/4W Through Hole Resistor Axial Metal Film	MFR-25FRF52-10K	YAGEO	25	\$0.10	link	Used for series resistor into ADC pin, VT secondary divider, perhaps other pull- up/pull- down

10000 pF ±10% 50V Ceramic Capacitor X7R 0603 (1608 Metric)	GCM188R71H103KA37J	Murata Electronics	15	\$0.06 2	link	10nF cap used for ADC input (keep close to adc pin)
10 µF ±10% 25V Ceramic Capacitor X5R 0805 (2012 Metric)	GRM21BR61E106KA73 K	Murata Electronics	15	\$0.08 7	link	10uF cap used for ac coupling into dc network
2 Position Wire to Board Terminal Block Horizontal with Board 0.197" (5.00mm) Through Hole	691137710002	Würth Elektronik	12	\$0.37	link	Used for VT secondary and primary, connectin g the two pcbs. Also used for CT secondary. And Barrel Jack output

Table 8: Analog Signal Sensing/Conditioning Parts

Adding the cost of all parts in this list totals to:

Total cost of parts = \$185.95

The cost of parts would be significantly reduced if we didn't order extra in case of errors in the building/soldered process.

4.2 Labor

In addition to parts, we must account for cost of labor. The starting salary for a UIUC Electrical Engineering graduate is about \$90k or \$43 an hour. We work an average of 10 hours a week for about 14 weeks.

$$\text{Total cost of labor} = \$43/\text{hr} \times 10\text{hrs/week} \times 14 \text{ weeks} \times 3 \text{ persons} = \$18,060$$

This brings out total cost to:

$$\text{Total cost} = \text{cost of labor} + \text{cost of parts} = \$18,245.95$$

4.3 Schedule

Week	Task	Person
February 23rd – March 2nd	Order parts	Isaac/Jeffrey
	Design review sign-up/document	Everyone
	First Round PCB Orders Feb. 26th	Joseph
March 2nd – March 9th	Finalize PCB Design	Joseph
	Design review	Everyone
	Second Round PCB Orders March 5th	Joseph
	Breadboard implementation	Jeffrey
March 9th – March 16th	Breadboard demo	Jeffrey
	Teamwork Eval. 1	Everyone
	Third Round PCB Orders March 12th	
	Begin PCB assembly	
March 16th – March 23rd (Spring Break)		
March 23rd – March 30th	Final PCB Orders March 26th	Joseph
	Design/print enclosure	Jeffrey
	Finalize PCB assembly	
March 30th – April 6th	Individual Progress reports	Everyone
	Build full design	Jeffrey
April 13th – April 20th	Progress demo	Everyone
	Team contract assessment	Everyone
April 20th – May 27th	Mock demo/presentation	Everyone
	Prepare for final demo, finishing touches	Everyone
May 27 th – May 4th	Final demo/presentation	Everyone
May 4 th – May 11th	Final papers, lab notebook	Everyone

5. Conclusion

5.1 Accomplishments

The product successfully displays real-time Vrms, Irms, real power, apparent power, and power factor of a load, achieving measurement accuracy comparable to a commercial analyzer.

Furthermore, our lightweight, portable design plugs directly into a standard wall outlet, allowing a load to be easily connected and measured. Finally, we developed a design that is much cheaper than a commercial analyzer at around \$200.

5.2 Uncertainties

When testing the soldering fan load, we noticed that the real power had an unusually high error of 8.926%. This came as a surprise as the measured V_{rms} and I_{rms} percent errors were 0.330% and 0.858% respectively while the power factor had an error difference of 0.037. Through further analysis, we determined that this discrepancy came from the fact that our analyzer's displayed measurements fluctuated. Therefore, if we caught the real power at a higher value, the percent error would be greater than the commercial power analyzer that had stable readings. For future updates to our design, we will implement a way to average out the fluctuating values and display the average instead of an instantaneous measurement to get more accurate readings that align closer to the commercial analyzer.

5.3 Ethical considerations

During the making of this project, we must consider the IEEE code of Ethics [6] that states the following:

1. To uphold the highest standards of integrity, responsible behavior, and ethical conduct in professional activities.
2. To treat all persons fairly and with respect, to not engage in harassment or discrimination, and to avoid injuring others.
3. To strive to ensure this code is upheld by colleagues and co-workers.

Working with high voltage, there was a great importance on following these standards and making sure that not only were we safe, but the users of our project as well, by ensuring to separate the high and low voltage by putting each high or low voltage component on their own PCB and physically separating them in the enclosure with space and a barrier. Furthermore, we utilized fuses in both the low voltage board power subsystem as well as on the AC inlet that directly plugged into the outlet.

5.4 Future work

Even though this project has fulfilled its requirements, we would like to add some additional features to improve utility and usability. Most importantly, a bigger screen with touchscreen capabilities. This would improve the usability of our project by making each value easier to read while also allowing us to display more measurements such as kWh usage and power factor correction. Given this bigger screen and more measurements, we would like to add a custom UI to display this information neatly and uniquely. In addition to this we would optimize our enclosure design to make it smaller, increase the durability, and finally, make it more visually appealing.

References

- [1] W. E. Anderson, "Calibration of voltage transformers and high-voltage capacitors at NIST," *Journal of Research of the National Bureau of Standards*, vol. 94, no. 3, p. 179, May 1989, doi: <https://doi.org/10.6028/jres.094.019>
- [2] Electronics Tutorials, "Current Transformer Basics and Current Transformer Theory," Basic Electronics Tutorials, Oct. 05, 2018. <https://www.electronics-tutorials.ws/transformer/current-transformer.html>
- [3] "Complex Power Concepts: Real, Reactive, and Apparent Power," Monolithicpower.com, 2024. <https://www.monolithicpower.com/en/learning/mpscholar/ac-power/theory-and-analysis/complex-power-concepts>
- [4] "Power Entry Modules without Line Filter Connectors IEC Appliance Inlet C14 with Fuseholder 1-pole, wired Screw-on mounting Snap-in version Approvals and Compliances C14 70° C." Accessed: Mar. 31, 2026. [Online]. Available: https://www.schurter.com/en/datasheet/typ_6200.pdf
- [5] https://www.qualtekusa.com/images/AC_Receptacles/pdfs/738wx203.pdf
- [6] IEEE, "IEEE Code of Ethics | IEEE," *Ieee.org*, 2020. <https://www.ieee.org/about/corporate/governance/p7-8>
- [7] "De-coupling capacitor and bulk capacitor," Electrical Engineering Stack Exchange. [Online]. Available. <https://electronics.stackexchange.com/questions/170957/de-coupling-capacitor-and-bulk-capacitor>
- [8] AP2112: 600mA High Speed, Extremely Low Noise LDO Regulator, Diodes Incorporated, Plano, TX, USA, 2017. [Online]. Available: <https://www.diodes.com/assets/Datasheets/AP2112.pdf>
- [9] Capacitors - Application Examples," SparkFun Learn. [Online]. Available: <https://learn.sparkfun.com/tutorials/capacitors/application-examples>

Appendix A Requirement and Verification Table

A.1 Signal Conditioning/Sensing Verifications

Requirement	Verification	Verification Status (Y/N)
<ul style="list-style-type: none"> Transformers step down signals as expected 	<ul style="list-style-type: none"> Measure secondaries with an oscilloscope during operation (turns test) 	Y
<ul style="list-style-type: none"> Centered at 1.65V Range within 0-3.3V Phase shift of less than 1 degree 	<ul style="list-style-type: none"> Vary input waveforms (magnitude, phase shift) and check outputs with an oscilloscope 	Y
<ul style="list-style-type: none"> Current transformer outputs 1Vpp AC signal after burden resistor 	<ul style="list-style-type: none"> Measure the voltage across the burden resistor to ensure our expected voltage of 0-1V using an oscilloscope 	Y
<ul style="list-style-type: none"> Voltage transformer outputs 1Vpp AC signal after voltage divider 	<ul style="list-style-type: none"> Measure the voltage across the voltage divider to ensure our expected voltage of 0-1V using an oscilloscope 	Y

Table 9: Signal Conditioning/Sensing R&V

A.2 Board Power Verifications

Requirement	Verification	Verification Status (Y/N)
<ul style="list-style-type: none"> Convert 5 volts to 3.3 volts for a current load ranging from 0mA to 500mA 	<ul style="list-style-type: none"> Use bench power supply to provide 5V Use oscilloscope to see if 3.3V is 	Y

	<p>outputted from regulator</p> <ul style="list-style-type: none"> • Ensure that different test resistors still output the same 3.3V 	
<ul style="list-style-type: none"> • The voltage divider must use high precision resistors to ensure the 1.65V offset remains consistent 	<ul style="list-style-type: none"> • Place oscilloscope across the voltage divider and ground • See 1.65 V during steady state 	Y
<ul style="list-style-type: none"> • No voltage fluctuations or drops 	<ul style="list-style-type: none"> • Run a transient simulation • Turn on microcontroller with an oscilloscope attached to the test resistor to see if sudden drop of voltage occurs 	Y

Table 10: Board Power R&V

A.3 Embedded Processing Verifications

Requirement	Verification	Verification Status (Y/N)
<ul style="list-style-type: none"> • Time-synchronized sampling 	<ul style="list-style-type: none"> • Apply identical sinusoidal signal to both ADC channels and compare sampled waveforms 	Y
<ul style="list-style-type: none"> • Sampling rate $\geq 3\text{kHz}$ 	<ul style="list-style-type: none"> • Timer configuration measurement 	Y
<ul style="list-style-type: none"> • ADC input within 0-3.3 V 	<ul style="list-style-type: none"> • Oscilloscope measurement of conditioned ADC signals during operation 	Y
<ul style="list-style-type: none"> • RMS and power calculation 	<ul style="list-style-type: none"> • Comparison with reference meter, results within high-level accuracy goals 	Y

<ul style="list-style-type: none"> • Measurement update ≥ 5 Hz 	<ul style="list-style-type: none"> • Log PC display update timestamps 	N (see section 3.5)
<ul style="list-style-type: none"> • Calibration scaling applied 	<ul style="list-style-type: none"> • Measure known resistive load and compare computed physical units 	Y

Table 11: Embedded Processing R&V

A.4 High Voltage Protection and Enclosure Verifications

Requirement	Verification	Verification Status (Y/N)
<ul style="list-style-type: none"> • Maintain isolation between high voltage and low voltage 	<ul style="list-style-type: none"> • Visual inspection • Continuity and isolation testing 	Y
<ul style="list-style-type: none"> • Components rated for at least 120VAC, 5A 	<ul style="list-style-type: none"> • Check each components data sheets for certifications 	Y

Table 12: High Voltage Protection and Enclosure R&V