ECEB SUBMETERING DEVICE

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Abstract

We designed, constructed, and tested a meter that samples the instantaneous value of a 60Hz single phase input of a load up to $208V_{pp}$ and 400A every 0.1 seconds, uploads the data to an online database, and displays the current measurements on an on-device LCD display. The sensor circuit was able to transform mains input into an acceptable range for the device to sample, and the signal processing system sampled instantaneous voltage and current calculated real and apparent power under 2% for small waveform inputs. However, the combination of the sensor circuit with mains power input and the signal processing subsystem did not yield our goal of 4% error in the apparent and real power measurements.

Contents

1. Introduction

The ECEB, having achieved platinum LEED certification and net zero draw from the power grid, wants to be able to monitor power consumption on a more precise basis. By measuring power usage of individual rooms and labs over time, we can identify areas of improvement and better observe existing measures. To do this, each circuit in the building needs its own independent metering device. The purpose of our project has been to construct such a submetering device.

The first functionality we aimed for was to sample the instantaneous value of a 60Hz single phase input of a load up to 208V_{pp} and 400A every 0.1 seconds. The peak load allows the meter to read the mains voltages circuits in the building. Calculating the voltage and current frequently allows a user to catch brief spikes or drops, such as those that occur when an induction motor is turned on.

The second functionality was to process samples to calculate real and apparent power with 4% accuracy, store them in an SD card and upload the data to an online database every 15 minutes. The SD card would provide security in the case of signal failure or power loss, and the online database allows for the collection of and access to the data over longer periods of time.

The third functionality was to display the calculated real and apparent power, along with RMS voltage and current, on an LCD display. This way, a person could verify that the data collected by the meter matched expected values and be sure that the meter was on and working.

1.1 Block Diagram

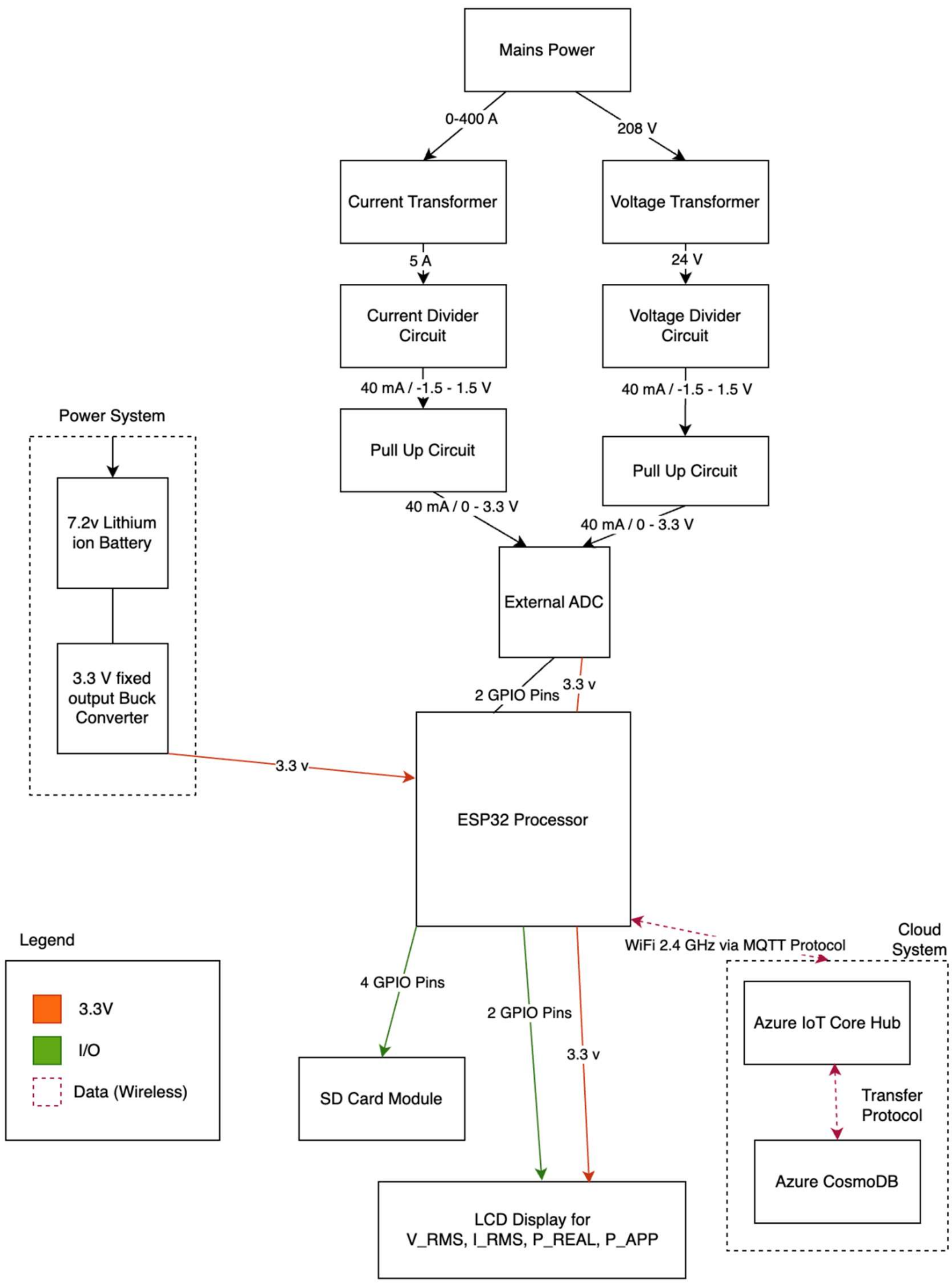


Figure 1: Block Diagram

1.2 Subsystems

The sensor unit is used to monitor the voltage and current of a single-phase input. The sensor circuit connects to the measured circuit through transformers for isolation. Using the transformers and analog divider circuits, the readings are stepped down to a level that can be read by the processing system.

The processing system is composed of an analog-digital converter, an ESP 32 microcontroller, and its associated programming circuit. The ADC and ESP32 collect the data and mathematically convert it into V_{rms}, I_{rms}, P_{app}, and P_{real}.

The storage is composed of an SD card, which is directly connected to the microcontroller, and a cloud database, which the ESP32 communicates via its onboard WiFi capabilities. The cloud database keeps the data for 5 years to enable analysis.

The power subsystem is composed of a rechargeable battery and a buck converter. The 7.4V battery provides 8 hours of continuous power to the meter when disconnected from external power, and the buck converter provides a 3.3V output to all digital devices including the microcontroller.

The LCD display allows real-time voltage, current, and power to be seen locally.

2 Design

2.1 Power System

2.1.1 Battery

Our battery needed to have a minimum voltage above 3.3 [1]to maximize the ability of the power electronics to continually supply power to the digital elements of the PCB. [2]As such, we chose a battery with a minimum voltage of 4.8V and an average voltage of 7.4V. The ESP32 has a current draw of 300mA at 3.3V during normal operation [3], so 8 hours of power for the ESP would be 7.92Wh.

$$8hr * 300mA * 3.3V = 7.92Wh \tag{1}$$

In order to supply sufficient current to the external ADC which has a small current draw (typically less than 3mA), the 500mA current when the ESP is being programmed, and 163mA current draw which is the maximum allowable by current SD card standards, we chose a battery with a capacity of 19.24Wh.

$$\frac{19.24\text{Wh}}{(500mA+3mA+163m\ \ )*3.3V} = 8.75\ h \tag{2}$$

While the original design requirements did require a 24-hour battery life, that would have required a battery with at least 53Wh of capacity, and most batteries in our budget of that size were 12V. As we did not initially plan to use a buck converter, we chose the largest battery that fit in our budget.

2.1.2 Buck Converter

Initially, a linear regulator was used to step down the voltage. However, we realized that the that would be dissipated would become excessive. With an expected maximum current draw of 666mA and a voltage drop of 4.1V, even a regulator at 0 C becomes overstressed [1].

$$Tja = Iout(Vin - Vout)(\Theta jc + \Theta ca) = 0.666A * (7.4V - 3.3V)(10 + 90) = 273\ C \quad (3)$$

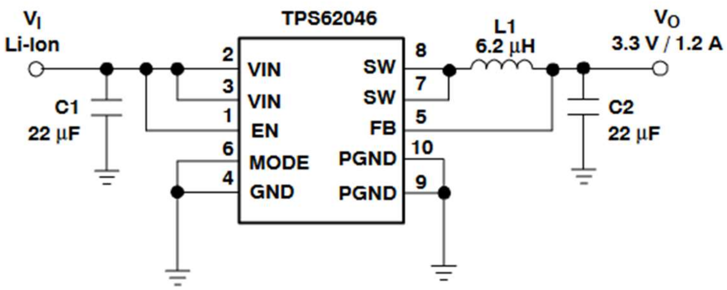


Figure 2: Buck Converter Circuit Diagram

Given that this is more than twice the maximum temperature that the linear regulator requires (125 C) [4], switching to a buck converter was clearly necessary. The buck converter chosen was a fixed output (3.3V) converter [5] which functioned with voltages between 3.3V and 12V and had a maximum rated current of 1.2A.

Because switched converters have an output voltage controlled by the duty ratio of the switches, the only effect of changing the size of the reactive components is to reduce the variance in output voltage. We substituted 33uF capacitors for 22uF capacitors, as that was the only size available in the ECE supply shop.

2.2 Sensor Circuits

2.2.2 Voltage Sensor

The purpose of the voltage sensor is to both isolate the meter from the load and to transform the load voltage into values that can be read by the ADC and then converted back to the original value. The ADC requires inputs between 0-3.3V, and the voltage being read is typically at 120 V_{rms}, as the meter is designed to read single phase AC mains.

The maximum designed input is 208 V_{pp} (147 V_{rms}), to ensure a margin of safety. The ADC input must have an average value of 1.65 to maximize the allowable peak-peak range of the input signal. A 208:24V signal transformer and a 16:1 voltage divider reduces the maximum value of the signal to 1.5. A pull up circuit uses the 3.3V digital voltage to add the +1.65V bias to the sine signal.

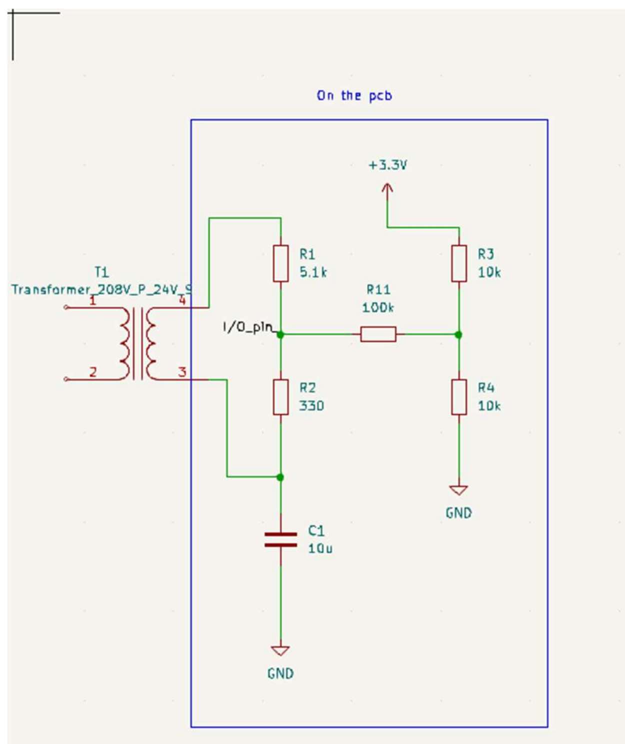


Figure 3: Voltage Divider Circuit

$$\frac{24V}{1.5V} = 16 < \frac{5100\Omega + 330\Omega}{330\Omega} = 16.45 \quad (4)$$

$$V_{source} = \frac{208}{24} * 16.45 * V_{sens} \quad (5)$$

$$V_{source} = 142.6 * \ V_{sensor} \quad (6)$$

In analyzing the various dividers used, the theoretical ratio between the RMS voltage at the ADC and the RMS voltage at the source is 142.6.

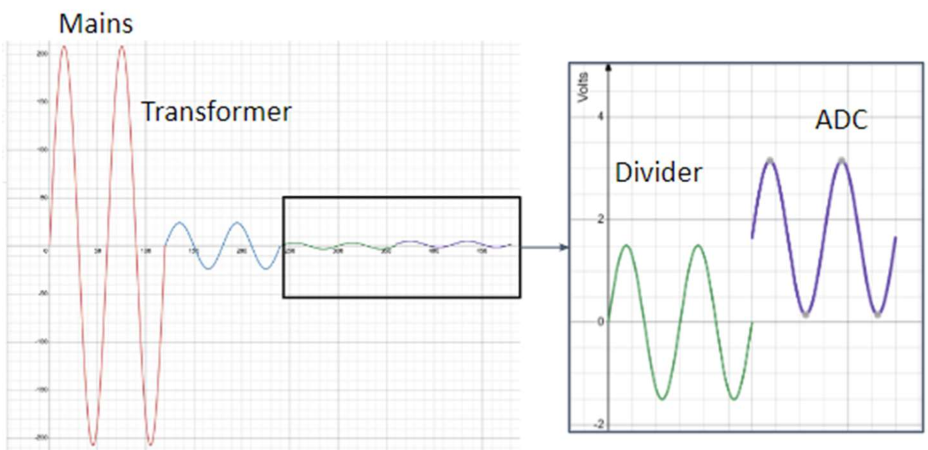


Figure 4: Voltage Signal Transformation from Mains to ADC

2.2.3 Current Sensor

The current sensor has the same function as the voltage sensor- isolation and stepping down in a controlled ratio. Inputs above 40 mA will burn out the ADC, and the maximum current that must be measured is 400A. A 400:5A transformer provides isolation and the first part of the step down. A current divider circuit with a ratio of at least 125:1 provides the second part of the down-step.

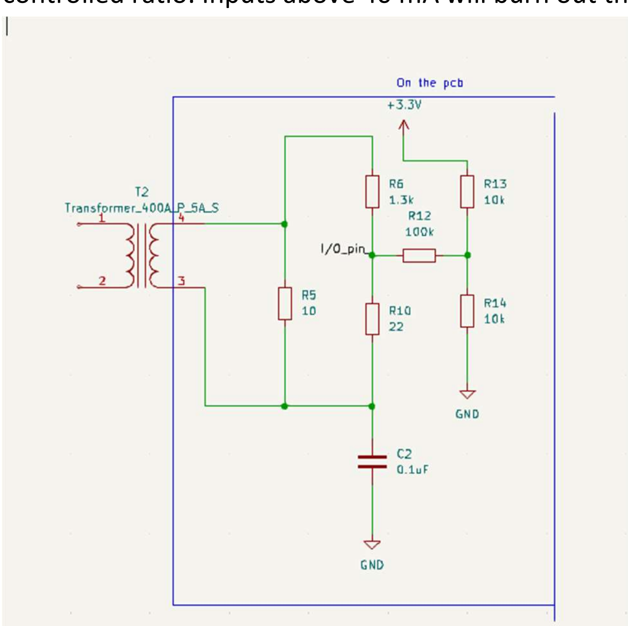


Figure 5: Current Sensor Circuit

A pull up circuit using the 3.3 digital voltage adds a 1.65V bias to the sine signal, such that the new range is safe for the ADC.

A shunt circuit with a 0.2Ω shunt resistor and a 25 Ω measurement resistor was attempted on the PCB to reduce the peak voltage across the current divider. However, the version in Figure 5 was what was tested and demonstrated.

$$\frac{5A}{0.040A} = 125 \tag{7}$$

$$\frac{10\Omega + 1.3\text{k}\Omega + 2}{10\Omega} = 133.6 \tag{8}$$

With a known resistor, finding the current through the branch is as simple as I=V/R. However, the voltage across the 10Ω resistor is now too large for the ADC.

$$5A * 10\Omega = 50\text{V} \tag{9}$$

Therefore, a voltage divider is used to bring the peak voltage across the measured resistor to reasonable levels.

$$50V * \frac{22\Omega}{1.3k\Omega + 22\Omega} = 0.832V \tag{10}$$

With all the step-down components confirmed, the ratio between the ADC sensed voltage and the current going into the load can be confirmed.

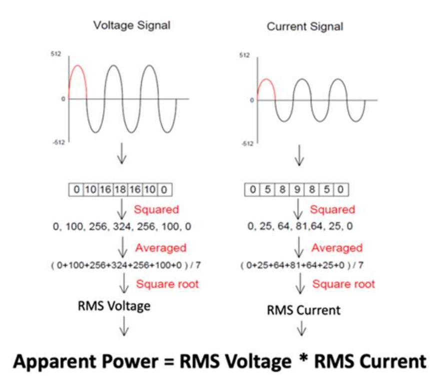
$$I_{source} = \frac{400}{5} * 133.6 * \frac{V_{sensor}}{22\Omega} \tag{11}$$

$$I_{source} = 485.8 * V_{sensor} \tag{12}$$

In analyzing the various dividers used, the theoretical ratio between the RMS voltage at the ADC and the RMS current at the source is 485.8.

2.4 Signal Processing Subsystem

The objective of the signal processing subsystem is to sample the instantaneous voltage, current, and produce real and apparent power calculations. This takes place after the waveform inputs have gone through the ADC, where the ADC output produces instantaneous voltage and current measurements that the ESP32 will sample at 170 HZ, since the mains input operates at 60 HZ. This requires the device to sample above 120 HZ to avoid introducing distortions due to aliasing as described by the Nyquist sampling theorem.



The method of calculating real and apparent power consists of processing a rolling set of 1000 samples of instantaneous voltage and current and applying mathematical equations to get the desired results. [6]

Calculating apparent power requires first calculating the V_{rms}, I_{rms}. Calculating the RMS value involves squaring each element in the sample set, taking the average, and square root the result. Apparent power can then be obtained by the multiplication of V_{rms} and I_{rms}. [7].

Calculating real power involves multiplying corresponding instantaneous voltage and current samples in the sample set and taking the average.

The details of our calculations are shown in the diagrams to the right.

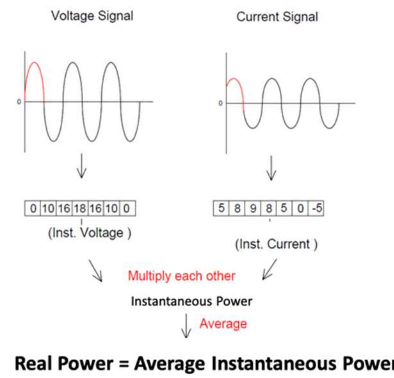


Figure 6 : Signal Processing Calculations

2.5 Online Database

Future analysis of the power consumption of the ECEB requires this project to store the measured V_{rms}, I_{rms}, and calculated P_{app}, and P_{real} with the correlating timestamps to an online database. This was achieved by utilizing the ESP32's WiFi capabilities and connecting the device to the ECEB's IllinoisNet_Guest WiFi. A connection is first established from the ESP32 to Azure IOT Hub, and then data points can be uploaded through a MQTT protocol that is popularly used for IOT devices for light weight. This data is then routed to our selected online database, which was Azure Cosmos DB. The project utilizes Microsoft's Azure microservices since students are given $50 worth of free credit.

2.6 PCB Peripherals

2.6.1 PCB design

The PCB design for our projects contains 3 subsystems: the power supply subsystem, the programming circuit for ESP32 microcontroller, and the sensor circuit.

For the power supply subsystem, a buck convertor was used to drop the voltage down to the 3.3V which is the working voltage for all our system. The circuit was built according to the suggested circuit build from TPS62046 buck convertor's datasheet. Here is the schematic for the power supply subsystem.

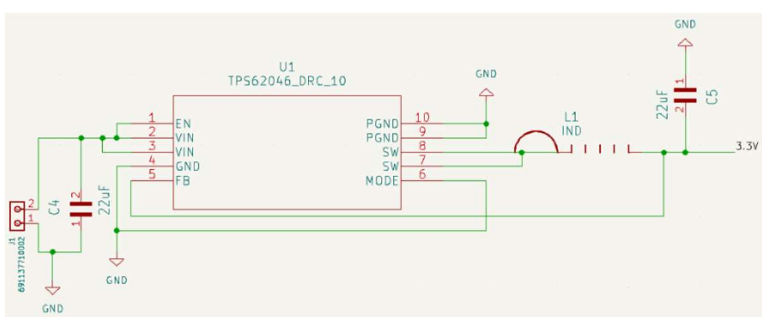


Figure 7: Buck Converter Circuit

The programming circuit references the course wiki's ESP32 example board's programming circuit logic which enables programming the microcontroller with automatically set the ESP32 into the download mode and reset after download. Here is the schematic for the programming circuit subsystem.

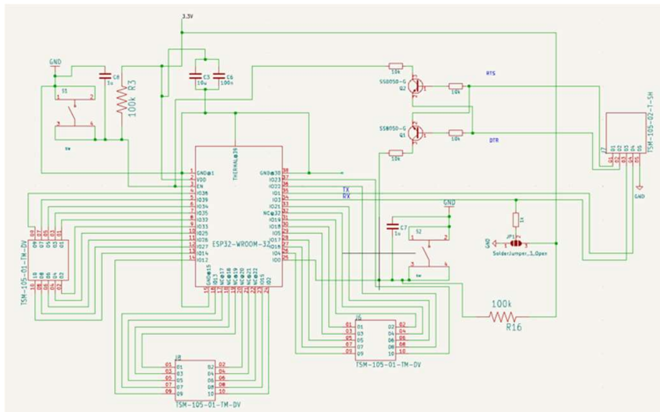


Figure 8: ESP 32 Programming Circuit and External Connections

The sensor circuit, as discussed above, is to drop down the voltage and current received from voltage/current transformers output to the level that the external ADC can accept. Here is the schematic for the sensor circuits.

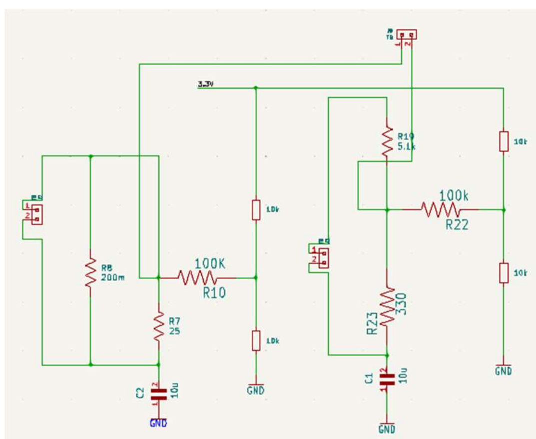


Figure 9: Sensor Circuit

And here is the PCB board review after combining those subsystems.

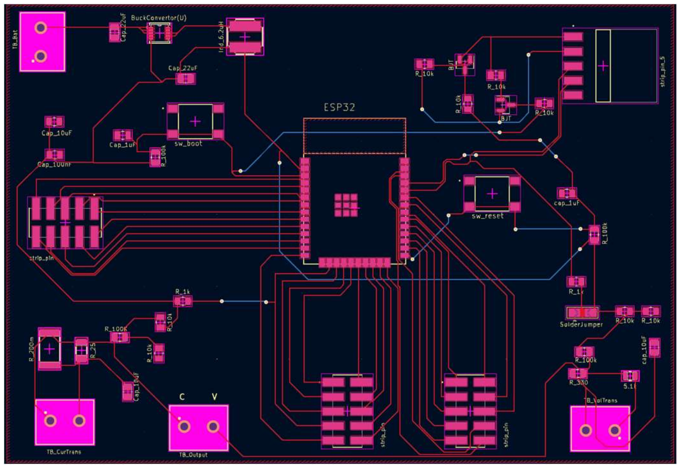


Figure 10: Final Circuit Board Design

2.6.2 External ADC

Since the project requires sampling a voltage input and a current reference voltage input at a high frequency, it is better to use an external ADC instead of the existing ones on the ESP32. An external ADC allowed for a higher resolution for our samples and at a higher sample rate. [8]

2.6.3 SD Card

To handle scenarios where the device cannot upload data to the online database, our design included the capability of writing to a local SD card. Once a connection is established again to be able to upload data online, the device would utilize the SD card to restore any missing history.

2.6.4 LCD Display Screen

In addition to monitoring real-time power consumption from the online database, an LCD Display is installed with the device to display the current V_{rms} , I_{rms}, P_{app}, and P_{real}.

3. Design Verification

3.1 Power Supply System

3.1.1 Battery

The verification process for testing whether the battery would last the required 24 hours involved turning on the metering device and measuring how many hours it took to turn off. However, because the power supply system provided no output voltage at all, it was not possible to complete this verification. The battery could not be directly connected to the digital circuits without destroying them. However, it was verified that the battery correctly output DC voltage, with an average of 7.63V.

3.1.2 Regulation

The buck converter used to regulate the voltage did not function properly. The traces were too small to solder by hand and resulted in overlap and burning the chip. An attempt to resolve this was made by ordering a stencil, but the stencil did not arrive in time for the demo. Paste and flux was also attempted but was unsuccessful.

3.2 Sensor Circuit

3.2.1 Voltage Sensor

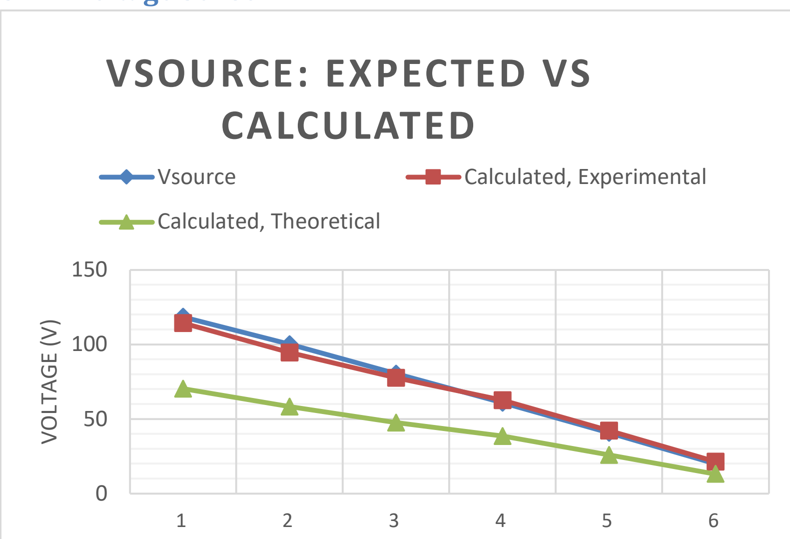


Figure 11: Comparison of Actual Vsource to Calculated Vsource

The voltage sensor did not meet the requirement of 3% error, though a proportional relationship was created. The voltage sensor had an experimental factor between the sensor output and the source voltage of 232, when the expected, theoretical factor was 142.6, an error of 38%.

This indicates that there were unaccounted-for losses. One likely source of losses is the transformer itself, as non-ideal transformers do include both resistive and inductive properties. The wires connecting the source to the transformer and the transformer to the resistor network were also quite long, which is another source of potential losses.

Even when comparing the actual voltage to Vsense*232, there is still an average error of 4%. This can be explained by the transformer's 15% voltage regulation [9], which causes the output of the transformer to drop the more heavily it is loaded.

3.2.2 Current Sensor

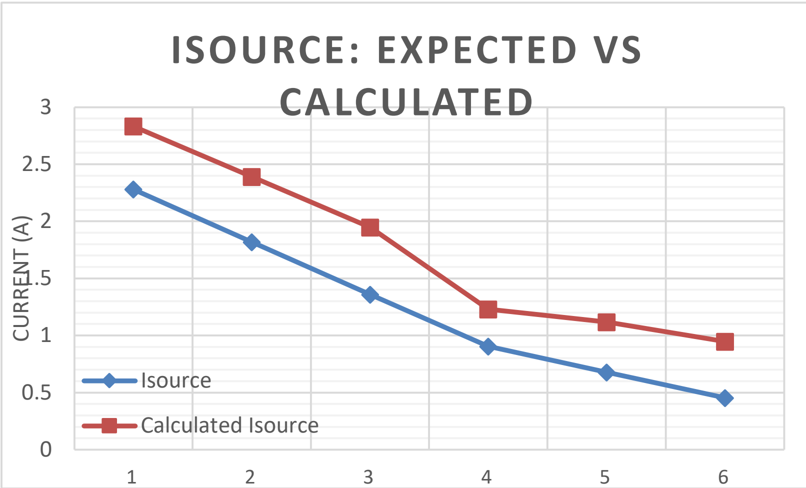


Figure 12: Comparison of Actual Isource to Calculated Isource

The current sensor has an average error of 51%, clearly failing the requirement of a 1% error. However, this conceals the fact that as the source current increases, the error decreases significantly. The error when the source current is 2.28A is 24%, in comparison to a 108% error when the source current is 455mA. If it were possible to test this circuit with larger current intervals and at higher currents, a reduced error would be predicted. This is a known problem when attempting to cover a very wide bandwidth of measurements, and correction factors are often used in practical contexts.

3.3 Signal Processing

To test the signal processing algorithm, the lab waveform generators were used with a small waveform input. The verification process consisted of utilizing a waveform generator which had set parameters of phase offset and input V_{rms} and I_{rms} and comparing these fixed inputs with what the device had outputted.

As shown in table 6, the device had a percent error below 2% which meets the specified requirement. However, it is important to note that the accuracy had been met only when using small waveforms, and measuring large waveforms resulted in inaccurate results which did not meet our requirements.

3.4 Online Database

Verifying the requirement of uploading to the online database involved visiting the Azure website and viewing the items in the database. As shown in figure 7, the database has an encoded message that can be decoded to reveal a timestamp with corresponding datapoints.

4. Costs

4.1 Parts

Table 1: Components and Costs

Description	Part Number	Manufacturer	Retail Cost ($)	Quantity Ordered	Bulk Purchase Cost ($)	Actual Cost ($)

ESP32 Processor	SP32-WROOM-32E-N4	Expressif Systems	2.50	3	-	7.50
I2C LCD Display	CN0295D	SunFounder	8.95	1	-	8.95
Micro SD Card Module	DFR0229	DFRobot	5.20	1	-	5.20
Micro SD Card	TF64GKT*3	KOOTION	7.55	1	-	7.55
208V/24V Voltage Transformer	TCT40-05E07AB	Triad Magnetics	19.43	1	-	19.43
400A/5A Current Transformer	CTF-5RL-0400	AcuAmp	26.00	1	-	26.00
10Ω 50W Resistor	KAL50FB10R0	Stackpole Electronics Inc	4.10	2	4.100	8.20
7.4V Lithium Ion Battery	31004	Tenergy	21.75	1	-	21.75
1A Smart Charger for Li-Ion/Polymer Battery Pack	01281	Tenergy	29.99	1	-	29.99
Button Switch	CKN11907CT-ND	C&K	0.28	10	0.2750	2.75
10 Position Connection Header	SAM12231-ND	SAMTEC INC	1.29	10	1.0890	10.89
2 Position Terminal Block	732-10955-ND	WURTH ELECTRONICS INC	0.41	16	0.3630	5.81
5 Position Connector	612-TSM-105-02-T-SH-P-TRCT-ND	SAMTEC INC	1.39	5	1.3900	6.95
24.9 Ω Resistor	RMCF1206FG24R9CT-ND	Stackpole Electronics	0.10	20	0.0230	0.46
1.2A 3.3V Buck Converter	296-15902-1-ND	Texas Instruments	2.27	6	2.2700	13.62
6.2uH 1.8A Inductor	308-1542-1-ND	Sumida America	0.42	8	0.4200	3.36
0.2 Ω Resistor	738-CSRT2512FTR200-UPCT-ND	Stackpole Electronics	0.68	6	0.6800	4.08
BJT Transistor	641-1790-1-ND	Comchip Technology	0.29	12	0.2900	3.48
External ADC	1528-1461-ND	Adafruit Industries LLC	14.95	1		14.95
Supply Shop Materials						

3.3V Linear Regulator	AZ1117CD-3.3TRG1DITR-ND	Diodes Incorporated	0.44	3	0.4400	1.32
22Ω Resistor	311-22.0HRTR-ND	YAEGO	0.10	10	0.0190	0.19
330Ω Resistor	2019-RK73H2ATTD3300FTR-ND	KOA Speer Electronics, Inc.	0.10	10	0.0270	0.27
1.5kΩ Resistor	RMCF0805FT1K50TR-ND	Stackpole Electronics Inc	0.10	10	0.0200	0.20
100kΩ Resistor	RMCF0805JT100KTR-ND	Stackpole Electronics Inc	0.10	20	0.0170	0.17
10kΩ Resistor	RMCF0805JG10K0TR-ND	Stackpole Electronics Inc	0.10	75	0.0104	0.78
1kΩ Resistor	RMCF0805JT1K00TR-ND	Stackpole Electronics Inc	0.10	10	0.0170	0.17
2.2kΩ Resistor	RMCF0805JT2K20TR-ND	Stackpole Electronics Inc	0.10	10	0.0170	0.17
5.1kΩ Resistor	RMCF0805JT5K10TR-ND	Stackpole Electronics Inc	0.10	10	0.0170	0.17
0.1uF Capacitor	1276-1286-2-ND	Samsung Electro-Mechanics	0.10	20	0.0430	0.86
1uf Capacitor	1276-6470-2-ND	Samsung Electro-Mechanics	0.11	20	0.0750	1.50
10uF Capacitor	490-18664-2-ND	Murata Electronics	0.36	20	0.1350	2.70
33uF Capacitor	445-8238-2-ND	TDK Corporation	0.88	10	0.636	6.36
Subtotal**						**215.78**
Shipping		UPS/FedEx	6.99	6		41.94
Sales Tax			9%			19.42
Final Total						**277.14**

4.2 Labor

Assuming an approximate average salary of an ECE graduate of $40/hour [10], each team member's labor cost comes to ($40/hour) x 2.5 (overhead factor) x 8 hours/week x 11 weeks = $8800.

Since we have 3 team members and will not be utilizing any machine shop labor, our total labor cost comes to $8800 x 3 = $26,400.

4.3 Grand Total Cost

Labor Cost + Part Cost = $26,400 + $277.14 = $26.552.46
The total cost of this project, if implemented by professional engineers, is $26.552.46.

4.3 Schedule

Table 2: Responsibilities by Week

Week	Sophia	Vincent	Houji	Everyone

9/25	Research methods to measure single phase power and research local power supply	Familiarize with ESP32 by uploading and running code	Get familiar with SD card module and how to connect it with ESP32	Design Document finalized
10/2	Order components. Design PCB and construct early versions of sensor circuits.	Program uploading to cloud database capability	Construct the PCB design with Sophia and program SD card storage	Prototype on breadboard, verify calculations, Attend design review.
10/9	Develop calibrations for sensors. Verify PCB Design. Ordered parts.	Write program to show data on an LCD Display.	PCB Design work	PCB Design
10/16	Help with theoretical design of code. Redesign sensors and power system. Ordered parts.	Start programming signal processing code to output power calculations from mock input.	Finish first PCB design Testing SD card reading and writing.	PCB Ordering
10/23	Construct, test, debug sensor circuits. Refine parameters for sensor inputs.	Incorporate sampling form ADC instead of mock for the program.	Incorporate TA feedback into PCB design	PCB Ordering
10/30	Ordered parts. Continue testing sensor circuits. Work with Vincent to debug code.	Finalize programming signal processing code to output power calculations	Revise PCB design. Start to get familiar with SD card's file system.	Testing
11/6	Execute tests on PCB and help Vincent test processing system. Ordered more parts.	Help solder PCB Soldering. Test signal processing code.	Solder parts on PCB. Test and debug the on-board performance. Verify accurate results	Testing
11/13	Execute tests on sensor circuit in high power conditions, attempt to test power system.	Design and 3D print housing unit.	Practice present SD card and PCB design. Execute tests on sensor circuit with Sophia.	Mock Demo. Final Testing
11/20	Fall Break	Fall Break	Fall Break	Fall Break
11/27	Practice presenting voltage/current measurement methods and PCB Design. Present voltage/current measurement methods and PCB Design.	Practice presenting database, display, and housing unit. Present database, display, and housing unit.	Practice presenting database, display, and housing unit. Present SD card, data calculation, and PCB design.	Final Demo
12/4	Present voltage/current measurement methods and PCB Design. Responsible for technical explanations regarding power measurements.	Present database, display, and housing unit. Responsible for diagrams and some programming explanations.	Present SD card, data calculation, and PCB design. Responsible for technical explanations regarding on-board data handling.	Final Presentation Final Paper

5. Conclusion

5.1 Accomplishments

The project successfully created a sensor circuit that converted mains input into a waveform input that the ADC could accept with voltage error of 4% and current error of 51%. The signal processing subsystem successfully was able to sample low power instantaneous voltage and current and create accurate calculations of real and apparent power of under 2% error. The device also successfully presented the data points on an LCD display and uploaded them to an online database every 15 minutes.

5.3 Uncertainties

PCB implementation was not met due to being unable to program the ESP32 as it outputted an error of "No Serial Data". The hypothesis for this error is due to the attempt of hand soldering, there likely was overlap or unsoldered pins.

Although our sensor circuit and signal processing system were reasonably accurate on their own, the combination produced measurements that did not meet our requirements. Our hypotheses include a potential insufficient current from sensor circuits to external ADC, and incorrectly grounding parts of the combined subsystem. It is also possible that because the power system did not function, the pull-up circuits would not have worked, and without the pull up circuits the sensor signals would not be in a range that the ADC could pick up.

The device was able unable to locally store our data on an SD card. It is believed that the purchased SD card was either damaged or incompatible with the SD module since there was an error writing to any file on the SD card.

5.4 Future work

One major area for work is improving our measurement accuracy. One way to improve accuracy on the sensor circuit includes switching to an op-amp focused circuit when scaling voltage and current, rather than using exclusively analog methods. Using a transformer with a lower voltage regulation would also improve the accuracy of the sensor circuits. To compensate for current error, testing different correction factors would be useful.

Also, debugging the error when combining our signal processing and sensor circuit would be valuable. Acquiring an ADC that can capture more precise voltages or a larger range would help to improve the interface between analog and digital. Using separate ADCs to capture the voltage and current signals would improve the delay in the existing device, which results in phase angle error.

Replacing the existing buck converter with a buck with a larger voltage range and easier to solder would certainly improve the power system. Increasing the range for input voltages would allow for the use of a 12V battery, which is more economical per Wh, and would improve the battery life.

In the longer term, the goal is to accommodate for three phase inputs, which would require a transformer with a larger turn ratio or a larger voltage divider. After that, all the issues would be mathematical. Once three-phase inputs were implemented, the meters could be installed in circuit panels. The last feature that we would hope to implement involves generating visuals based on our data and broadcasting them onto the ECEB Lobby TV.

5.4 Ethical considerations

The data being handled by our meter is not personal in nature, and will be posted in a public location, so we will not need to account for data privacy in our design. The primary safety risk is that of shock from single-phase power. To protect the safety and health of the public, we will ground the outside of our metering box and electrically isolate the interior. We will also label it clearly as a high voltage device.

We do not know of any conflicts of interest at play, and certainly do not anticipate unlawful conduct.

We will review our work with others to ensure its accuracy, carefully track testing data to ensure honesty in our claims and make every effort to credit any reference we use in developing this device. This device is a technical project which will improve our competence in power sensing, data gathering, and database management.

References

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Appendix Requirement and Verification Table

Table 3: Power System Requirements and Verification

Requirements	Verification	Verification Status
A rechargeable battery that can power the metering unit without being charged for at least 24 hours, with a margin of 15%.	The metering unit will be left on without being connected to wall power, and the time of the last communication with the server before the battery died will be observed.	No, data limited.
Power regulators must provide 3.3V DC power to each sensor, the microcontroller, the SD card, and the local display. The pull up circuits in the sensors have a +1.65 V bias and the microcontroller I/O pins have outputs between 0 and 3.3V.	Use Keysight multimeters as voltmeters to test that the SD card and ESP32 have an input voltage of no more than 3.3V.	No, data impossible

Table 4: Battery Voltage by Date

11/16	7.4V
11/16	7.3V
11/27	7.8V
11/27	7.85
11/27	7.82
Avg Battery Voltage	7.63

Table 5: Sensor Requirements and Verifications

Requirements	Verification	
Measured voltage is no more than 3% off from actual voltage.	The voltage at the voltage sensor's analog input pin scales proportionally to the measured voltage. A multimeter or voltmeter will be connected in parallel with the source such that it can be compared to the measured voltage for inputs 0V-208V.	No, verification data and calculations in table 6
Measured current is no more than 1% off from actual current.	The current at the current sensor's analog input pin scales proportionally to the measured current. A multimeter or ammeter	No, verification data and calculations in table 7

	will be connected in series with the source such that it can be compared to the measured current for inputs between 0A-400A.	

Table 6: Voltage Sensor Verification

Vsource (Vrms)	Vsense (Vrms)	Actual Factor	Anticipated Factor	Experimentally Discovered Factor	Calculated Vsource (Theory)	Calculated Vsource (Exp)	Percent Error (Theory)	Percent Error (Exp)
118.54	0.493	240.2	142.6	232	70.3018	114.376	41%	4%
100.17	0.408	245.5	142.6	232	58.1808	94.656	42%	6%
80.3	0.334	240.2	142.6	232	47.6284	77.488	41%	4%
60.9	0.27	225.56	142.6	232	38.502	62.64	37%	3%
40.7	0.182	223.6	142.6	232	25.9532	42.224	36%	4%
20	0.092	217.39	142.6	232	13.1192	21.344	34%	7%
	Avg Experimental Factor	232.075				Avg Error	38%	4%

Table 7: Current Sensor Verification

Isource (A,rms)	Vsense (mV,rms)	Actual Factor	Correct Factor	Calculated Isource	Expected Vsense	Percent Error
2.28	5.83	391	485.8	2.83	0.004693289	24%
1.82	4.92	369	485.8	2.39	0.003746398	31%
1.36	4.01	339.15	485.8	1.95	0.002799506	43%
0.906	2.53	358.1	485.8	1.23	0.001864965	36%
0.679	2.3	295.2	485.8	1.12	0.001397695	65%
0.455	1.95	233.3	485.8	0.95	0.000936599	108%
					Average Error	51%

Table 8: Processing System Requirements and Verifications

Requirements	**Verification**	**Verification Status**
Output real and apparent power measurements.	Measure power within 4% of the actual value based on sampled	Partial, the accuracy is met with low power inputs using the in-lab waveform

	measurements from the voltage and current sensor. Comparison measurements can be found by observing the real power from the source using a wattmeter calculate the apparent power from the RMS voltage and current, which can be observed by placing a voltmeter in parallel and an ammeter in series with the load.	generators, accuracy was not met when using with high power inputs.
Offload measurements onto the SD card.	Insert SD card into a computer and verify that power, current, and voltage measurements are saved at 0.1 second intervals.	N
Store voltage, current, and power measurements to the Azure Cosmos database every 15 minutes.	Check the database for power, current, and voltage measurements are saved at 0.1 second intervals.	Y
Present real-time measurements on the LCD Display.	The LCD Display accurately shows the voltage, current, and power measurement that matches the values from the ESP32.	Y

Table 9: Signal Processing Verifications

Trial #	Phase Difference	V_pp	V_RMS Actual	V_RMS Expected	V_RMS % Error	I_PP	I_RMS Actual	I_RMS Expected	I_RMS % Error
1	0	0.2	0.070937	0.07071067812	0.3200674741	0.2	0.069185	0.07071067812	2.157634687
2	30	0.2	0.070919	0.07071067812	0.2946116299	0.2	0.069246	0.07071067812	2.07136766
3	0	0.2	0.070979	0.07071067812	0.3794644437	0.3	0.104668	0.1060660172	1.318063236
4	45	0.2	0.070948	0.07071067812	0.3356238232	0.3	0.104691	0.1060660172	1.296378628
5	0	0.4	0.140436	0.1414213562	0.6967520773	0.4	0.139988	0.1414213562	1.013535915
6	60	0.4	0.140413	0.1414213562	0.7130155333	0.4	0.140014	0.1414213562	0.9951511389

Trial #	Phase Difference		P_Real Actual	P_Real Expected	P_REAL % Error		P_APP Actual	P_APP Expected	P_APP % Error
1	0		0.004908	0.005	1.84		0.004908	0.005	1.84
2	30		0.004253	0.004330127019	1.781172205		0.004911	0.005	1.78
3	0		0.007425	0.0075	1		0.007431	0.0075	0.92
4	45		0.005256	0.005303300859	0.8919135489		0.007428	0.0075	0.96
5	0		0.019659	0.02	1.705		0.019659	0.02	1.705
6	60		0.009845	0.01	1.55		0.019658	0.02	1.71

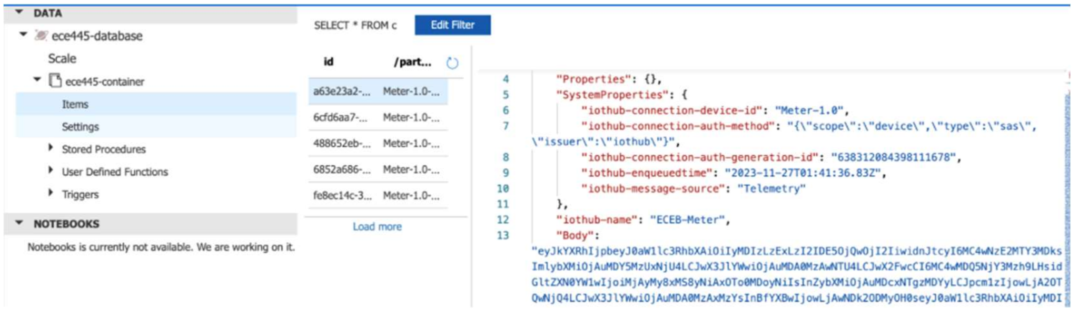

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Figure 13: Online Database Verification