ECE 445

Spring 2024

ECEB Submetering

Design Document

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Introduction

Problem

The ECEB is notably a net-zero energy facility, which is possible due to utilization of energy efficient methods such as the use of solar panels. We would like to be able to measure and share data collected from the energy generated by the solar panels in order to help track the efficiency and use of energy of the ECEB building. With regard to the ECEB submeter of previous semesters, we would like to improve upon the accuracy of the data recorded to yield more practical and useful results.

Solution

Our solution is to create power meters that can accurately measure power, voltage, and current of individual rooms within ECEB and be able to accurately get and store these data metrics as well as being able to display them to either an LCD or the TVs within the ECEB. We plan to improve upon many of the shortcomings the previous implementation faced.
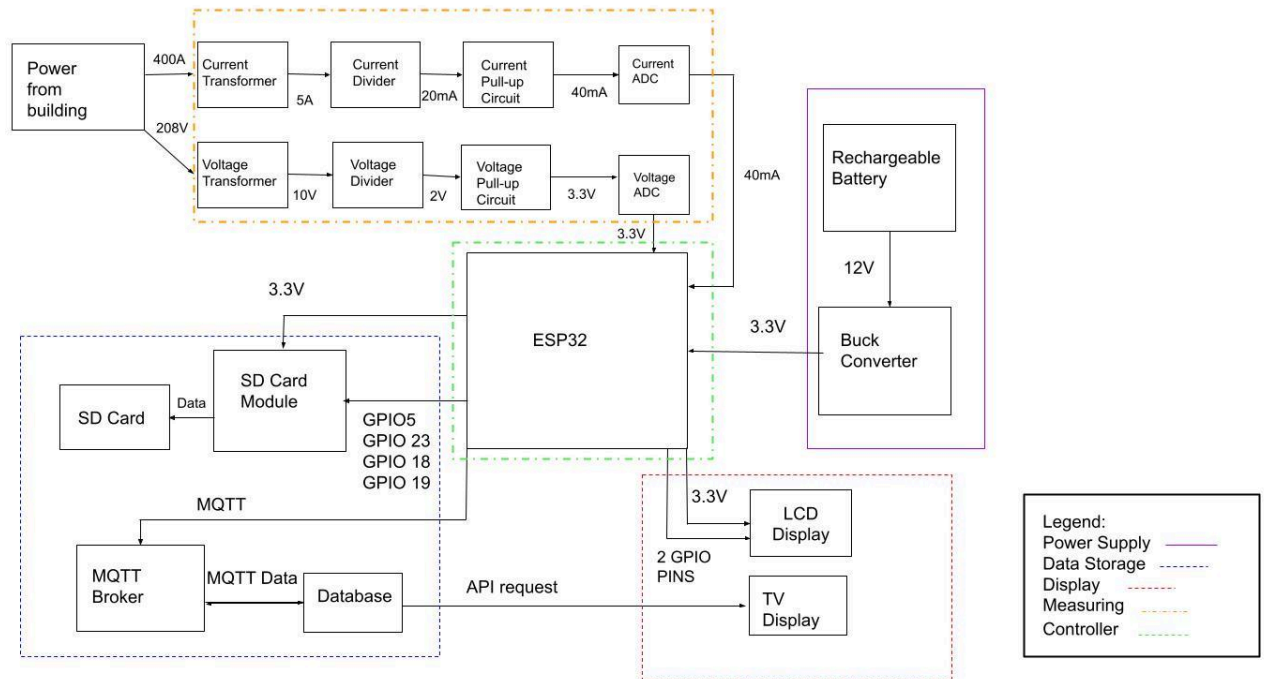
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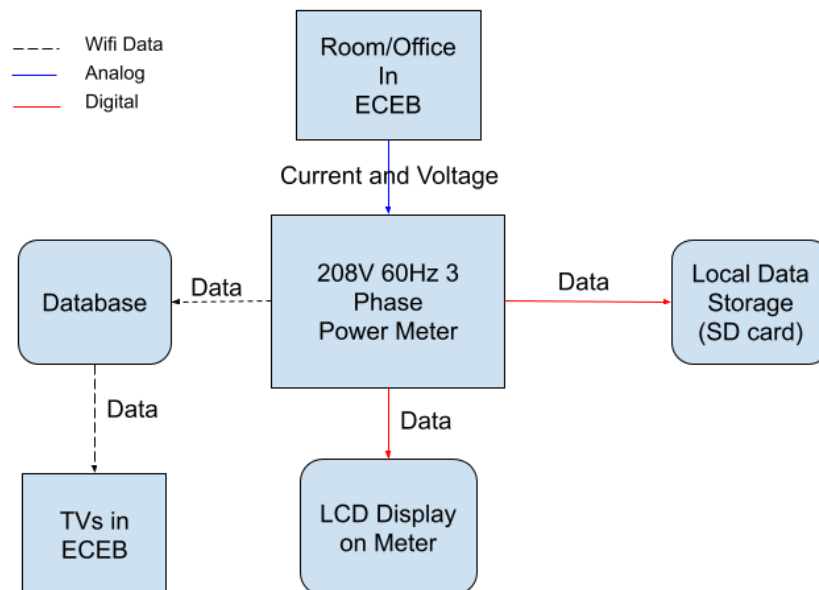
High Level Requirements List

- Be able to measure current and voltage for 3 phase systems within +/- 1% for loads of 200-400A.
- Be able to accurately measure the phase angle within +/- 1% and using the phase angle calculate Power Factor within +/- 2%.
- Be able to display calculated data to an LCD screen and the TVs in ECEB.

Design

Block Diagram:

Physical Design:

Our PCB will be placed in a grounded box with the inputs and outputs exposed. The box will be constructed so it can be mounted on the wall and allows wifi signals to pass through.

Subsystems:

Power Supply Subsystem:

- The system will be powered by a battery, and this battery will be attached to a linear regulator, a buck converter, to bring the voltage to a level usable by the ESP32. This power supply will power a majority of the components in our project as seen in the block diagram. Analog components used in circuit measurements such as the several op amps will be powered by a separate power source. A low noise linear regulator will be needed to power the analog parts as accuracy of analog devices are sensitive to noise. Additionally, we plan on using a back-up battery IC which allows us to redirect the power source to a battery power source in case of an outage.

Requirement	Verification
1. The system must convert the battery	1a. Connect our device to a power source. As

voltage to 3.3V ± 0.3V in order to power the ESP32.	a preventive measure it would be best not to connect the ESP32 until we have measured an acceptable voltage value that will not damage the component. 1b. Using the multimeter on the oscilloscope, measure the output and it should yield a reading of 3.3V ± 0.3V.
2. The system must be able to supply power from a battery of 3.3V ± 0.3V in the case of a power outage.	2a. Begin operation of our system and once it is measuring (on) make sure the battery is connected. 2b. Remove the primary power source and observe if our submeter is still being powered by using the voltmeter on the oscilloscope to measure 3.3V ± 0.3V.

Measuring Subsystem:
- Our measuring system will take the power from the building and scale voltage and current down through a transformer, and then again scale the two down using divider circuits, afterwards using pull-up circuits to bring the values to the max values allowed by the ESP32, being 40mA and 3.3V. These analog values will then be converted to digital using ADC's and be inputted into the ESP32 to be measured.
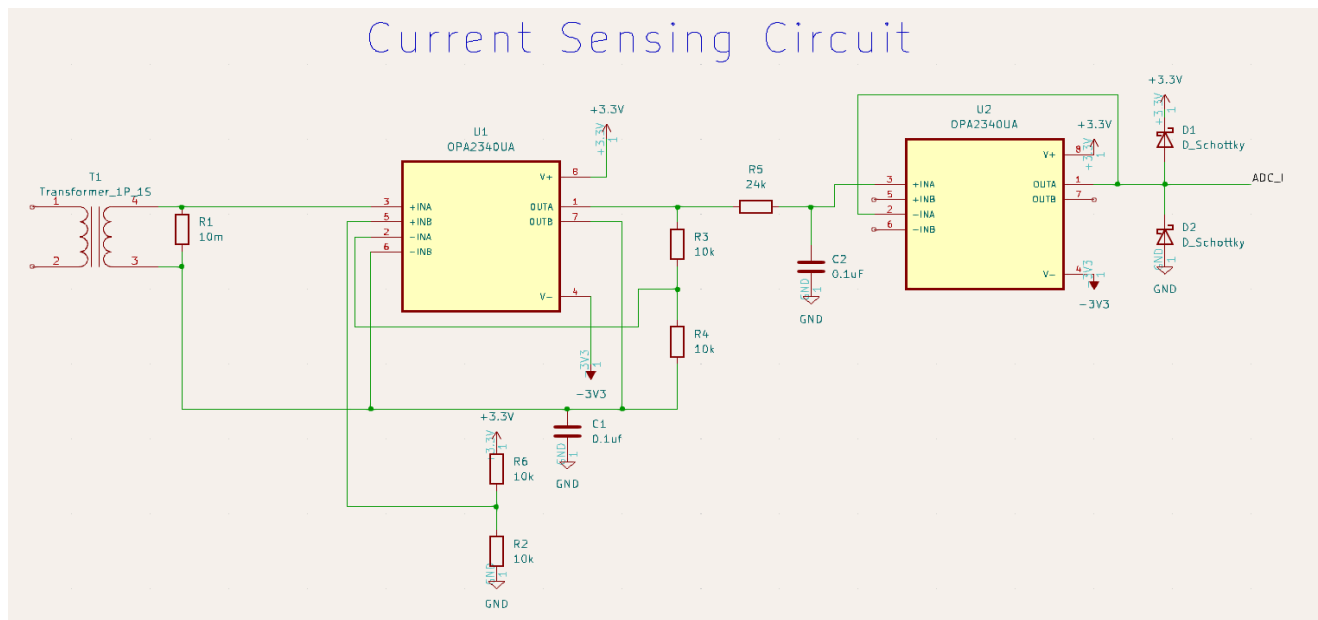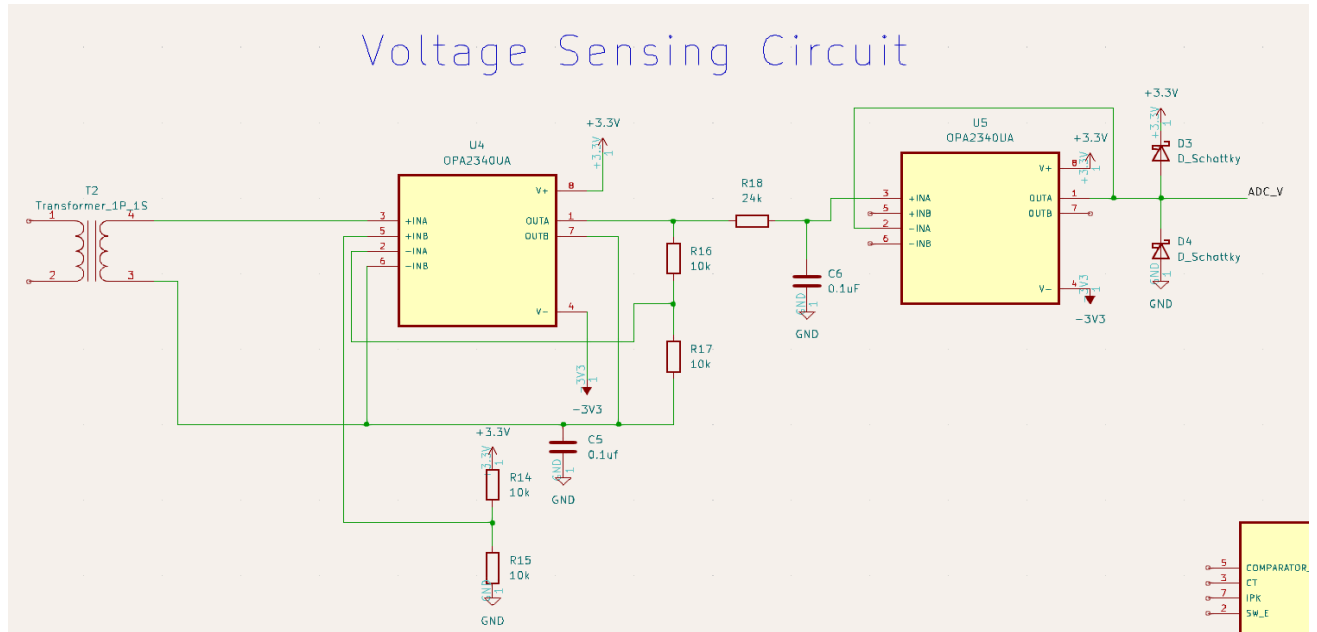

Figure 1: Current Sensing Circuit

Figure 2: Voltage Sensing Circuit

Requirement	Verification
1. Voltage and current circuits bring voltage and current into an acceptable range for the internal ESP32 ADC input such that it does not damage the device.	1a. Once our measuring circuits are connected to the load, and the components are connected to the power source, we will use the oscilloscope multimeter to measure the current, which should be 40mA ± 15mA, and the voltage, which should be 3.3V ± 0.3V.
2. Our measuring circuits should not significantly modify or change the values of voltage and current when bringing these values to a safe range for our ESP32.	2a. After recording data while operating our device we will compare the measured power and power factor to the actual values, and the percent error should be within 15%

Controller Subsystem:
- This subsystem consists of the ESP32 microcontroller itself as well as its connections to other subsystems. It will perform the processing of data and will interface with the SD card module and time series database via wifi. It will also be programmed via USB with a USB to UART module which is then sent to the ESP32.

Figure 3: Microcontroller Connections and USB to UART Connections

Requirement	Verification
1. Data inputs are received and the power and power factor are calculated.	1a. This will be verified through viewing the data sent to the server and seeing if any values are there, it should not be N/A or zeros.

Data Storage System:
- The ESP32 will act as the central microcontroller of our project measuring the values of the inputs received. It will routinely store and deliver data to the SD card via the SD card

module and onto a time series database(TSDB). The microcontroller will send MQTT messages, then the TSDB will ingest the data which will allow data analysis and visualization.

Requirement	Verification
1. Data will be uploaded onto a time series database(TSDB) through MQTT protocol at least 4 times an hour.	1a. After 15 minutes of operation we will access the server to see if our first batch of data has been stored.
2. Voltage, current, and power will be recorded 10 times a second.	2a. Using a timestamp on each data measurement, we will observe if the interval is 0.1 seconds between samples by checking the server.
3. Data will be stored and maintained for 5 years. The local memory storage will need to hold 96 hours of data.	3a. After 96 hours, we will verify that the oldest data points are 96 hours old. Data stored on the cloud is managed by cloud providers so we can only apply settings to retain data for 5 years.

Display System:
- The display system will include an LCD display and a TV display. It will connect to the LCD using 2 GPIO pins, and to the TV display which will display data through a website. The LCD display will show immediate data in terms of voltage, current, and power. The cloud data will be displayed on the TV of the ECEB lobby where further visualizations and analysis of power usage over a larger time frame will be shown.

Requirement	Verification
1. Display measurements and data on LCD.	1a. Once our device has collected its first set of data it should be visible on the LCD screen and correspond to the data.
2. Display measurements and data onto a TV.	2a. Once our device has collected its first set of data it should be visible on the TV and correspond to the data.

Tolerance Analysis:

Power Supply

- Due to noise sensitivity in analog components we decided to use a low noise linear regulator to supply the power for these devices in order to maintain their accuracy
- The rechargeable battery will provide 24 hours of power after being disconnected from the initial source with a 10% margin of error

Voltage Sensing Circuit

- When inputting a 206V 60Hz voltage, our transformer steps down the voltage to an RMS value of 2.5576 Vrms. The RMS value before stepping down is 146.29 Vrms. This leads us to a step down ratio, Vout/Vin, of 0.017483. The stepped down voltage is then passed through a non inverting amplifier with gain Vout = Vin(1 + R2/R1) - (R2/R1)1.65. After this we pass the signal through an RC low pass filter and finally through another op amp to act as a buffer before finally sending the data to the ADC on the ESP-32. The Vrms value at the ADC is 2.5233. Taking this to the ratio we found when the voltage transform occurred, (2.5233/0.0017483) yields us a Vrms of 144.328. This Vrms value is only 1.3% off the original voltage value that is passed in. This was done in testing in LTSpice, and we are able to conclude that our measurement of the Voltage will be within +- 1.5% of the actual value.
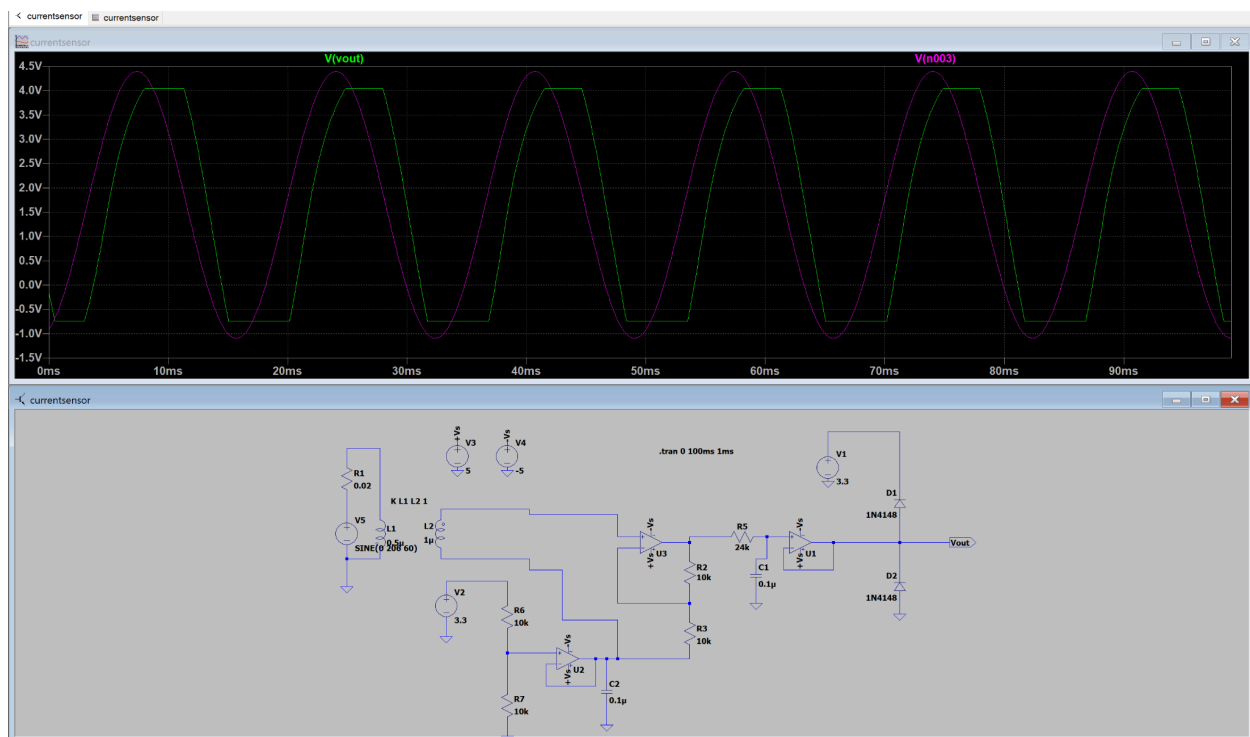

Figure 4: Voltage After Transformer and before ADC

Data Storage

- MQTT Protocol will cover connection instability issues we encounter, but we can set an alarm system that sends notifications when data has not been ingested for an hour if the meter stops sending data.

Cost and Schedule

Cost-Analysis:

Our costs include the labor and the sum of our parts, as we do not plan on using any external services such as the machine shop. Assuming an hourly rate of $40/hour, and given 11 weeks, estimating the time spent being on average 5 to 6 hours a week, we use the provided formula to get $40/hour * 2.5 * 55 hours = $6600 per individual, meaning the entire labor cost would be $19800. Adding the sum of our parts gets us to a total cost of $19800+$93.72 = $19893.72.

Name	Cost	Quantity	Part #	Manufacturer	Link
SD Card Module	$5.20	1	DFR0229	DFRobot	SD Card Module
Voltage Transformer	$12.02	1	VPL10-500	Triad Magnetics	Voltage Transformer
Buck Converter	$1.20	1	MC34063AP	Texas Instruments	Buck Converter
Current Transformer	$26.00	1	CTF-5RL-0400	AcuAmp	Current Transformer
Backup battery circuit	$4.20	1	TPS3620-50DGKT	Texas Instruments	Backup battery circuit
Linear Regulator	$1.51	1	LP38798	Texas Instruments	Linear Regulator
ESP32 (Microcontroller)	$2.68	1	ESP32-WROOM-32E-H4	Espressif Systems	ESP32
LCD Display	$3.66	1	LCD 1602	UNIVERSAL-SOLDER Electronics	LCD
Micro SD Card	$9.98	1	SP128GBSTXDU3V20AB	SP Silicon Power	MicroSD Card
12V Rechargeable Battery	$19.99	1	WKA12-7F	Mighty Max Battery	Battery
Op Amp OPA2340UA	$1.819 (each)	4	OPA2340UA	Texas Instruments	Op Amp

Other parts shown in the schematics such as resistors, diodes, capacitors, transistors and switches will be retrieved from the ECE service shop.

Schedule:

Week	Tasks	Person
2/29	Finish Design Document	Everyone
	Project Proposal regrade	Everyone
2/26	Simulate measuring subsystem and confirm functionality	Aleksai, Jonathan
	Begin to order parts	Everyone
	Finish initial PCB layout for PCB review	Everyone
	Research cloud solutions for data storage/website hosting/MQTT broker	Mike
3/4	First round Order of PCB	Everyone
	Simulate MQTT publish and subscribe with example data and ingest into a Time series DB	Mike
	Write code to interface with LCD display	Jonathan
	Work on code used to calculate power measurements on ESP32	Aleksai
3/11	Spring Break	Spring Break
3/18	Second Round Order of PCB	Everyone
	Assemble current and voltage measuring circuits	Jonathan, Aleksai
	Build backend of website ● API calls/structure	Mike

	● SQL queries	
	Set up web server for website hosting	Mike
3/25	Third Round order of PCB	Everyone
	Test and verify if data is being stored onto SD card	Aleksai
	Test current and voltage measuring circuits	Jonathan
	Connect TSDB, backend, and sample MQTT and get it to display sample data on a website (very rough data)	Mike
4/1	Fourth Round order of PCB	Everyone
	Debug any areas/subsystems which are not meeting required verification	Aleksai, Jonathan
	Upload data from the SD card to the cloud through MQTT publish	Mike
	Ingest legitimate data from the meter and display onto the website	Mike
4/8	Fifth Round order of PCB	Everyone
	Add data visualizations on the website	Aleksai, Mike
	Display the website onto TV of the ECEB	Jonathan, Mike
4/15	Prepare for Mock Demo	Everyone
4/22	Final Demo	Everyone
	Prepare for Mock Presentation	Everyone

4/19	Final Presentation	Everyone
	Complete Final Paper	Everyone
	Turn in lab notebook	Everyone

Discussion of Ethics and Safety:

With regards to safety we are going to need to take into consideration the CAT Rating. This relates to safety equipment ratings needed when handling different types of electrical devices or systems, which can pose a danger in the event of arc flashes[1]. Our device is a CAT II rating as it will be attached to a single-phase AC load. Ideally we would need to take into account arc flashes and sudden harmonics in the power grid which could cause irregularities when measuring voltage and current.

We will make sure that the data presented is allowed to be public, and that displayed values are not manipulated. This falls under maintaining integrity aspect of the IEEE code of ethics by not lying about our results to improve perceived accuracy [2]. When handling potentially private data we must take the proper precautionary methods to make sure that this data is not shared, which is why we will only display public data on to the TV's [3].

References

[1] N. Fire and N. Fire, *NFPA 70E*. National Fire Protection Association (NFPA), 2004.
[2] IEEE Code of Ethics. (n.d.). https://www.ieee.org/about/corporate/governance/p7-8.html
[3] "IEEE SA - IEEE 7002-2022," IEEE Standards Association.
https://standards.ieee.org/ieee/7002/6898/