

ECE 445
SENIOR DESIGN LABORATORY
PROJECT PROPOSAL

Power Quality Monitor and Submeter System

Team 30

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Abstract

This document is an extension of our RFA with extra quantitative details, concrete project goals, and more in-depth considerations. We will cover our project's motivation, design, requirements, ethics, and safety.

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1. Introduction

In this section, we explain the problem that we are attempting to solve, and we highlight its relevance in the field of power electronics today. We also illustrate our solution to the problem, along with a visual aid and our high-level requirements so that others can understand our planning and design process.

1.1 Problem

In the rapidly evolving field of power electronics and energy technologies, maintaining consistent and high-quality power distribution and energy usage is critical for residential and commercial buildings. Using submeters can help create energy savings, lower operating costs, increase building efficiency and reliability, and improve occupant comfort. However, devices today have several drawbacks. They can be cost-inefficient, complex to operate and to read, and they may lack real-time insights. Additionally, they may not employ any or sufficient power quality monitoring, which is critical for ensuring that electric devices can safely use the power source. These shortcomings can lead to difficulty in meeting recent sustainability efforts, and as such, an innovative solution is needed.

For example, a common residential electrical submetering product is from Byram Labs. It's a single phase submeter that costs \$420, doesn't provide prior electrical usage data, doesn't provide a way to perform data analysis, and doesn't monitor power quality or notify owners of poor power quality for the following metrics: large voltage changes/irregularities, power outages, harmonic disturbances. This can cause many problems, especially for large commercial applications such as hospitals. In Japan, there was a study done on 13 pieces of medical equipment and found that voltage dips caused 7 devices to stop for about 0.5 seconds, which caused some of the 7 devices to start an automatic reboot. Without having the electrical submeter also measure for power quality, medical equipment could get damaged or patients could suffer from ineffective medical care.

1.2 Solution

For our project, we'd like to design and construct an improved device that monitors power quality and acts as a submeter to its loads – a device that is cost-effective, has high-fidelity data acquisition, and operates with an intuitive user interface LCD screen. Our project will solve the problems listed above by combining a power quality monitor along with a submeter in a cost-effective manner that stores real-time data and loads the data to a database that can be accessed through a website. The website would also allow users to be alerted of power quality issues, provide access to prior data, and showcase voltage and power waveforms.

Over the course of the build process, we will produce a prototype that analyzes voltage, current, and power from an outlet and examines the power usage of a connected load. To do this, the device will connect into an outlet, step down voltage and current to be sensed proportionally with ICs, and send measurements through the microcontroller to the database. The control unit of the device will be powered by a converter circuit with a linear regulator, and in backup cases, with a battery subsystem. We will encase all circuitry and hardware within a box that has an LCD display on the front to display data for the load (which during building and testing will likely be in the form of a power resistor). Upon final testing and troubleshooting, we aim to demonstrate the capabilities of this product by using a power outlet at the ECEB and connecting a phone charger as the load.

1.3 Visual Aid



Figure 1: Visual of our system

1.4 High-Level Requirements

For our project to be considered successful, there are various high-level criteria that must be met. Our device should be able to perform the following tasks:

- I. Sample a single-phase input for its voltage and current (with a high level of accuracy, tentatively within 10%, which can be checked with a wattmeter).
- II. Use a microcontroller to process the voltage and current samples and calculate apparent and real power. Store data points onto an SD card (once every second) and to a cloud

database (once every 10 seconds). Instantaneous waveforms will also be displayed on a screen.

- III. Notify the user (in a timely fashion, tentatively within 5 seconds) of any disturbances in measurements outside of a set tolerance (tentatively 5%) and of any failures.

More detailed subsystem requirements can be found in Section 2.3. As a stretch goal, we hope to implement measurement and notification of total harmonic distortion (THD).

2 Design

2.1 Block Diagram

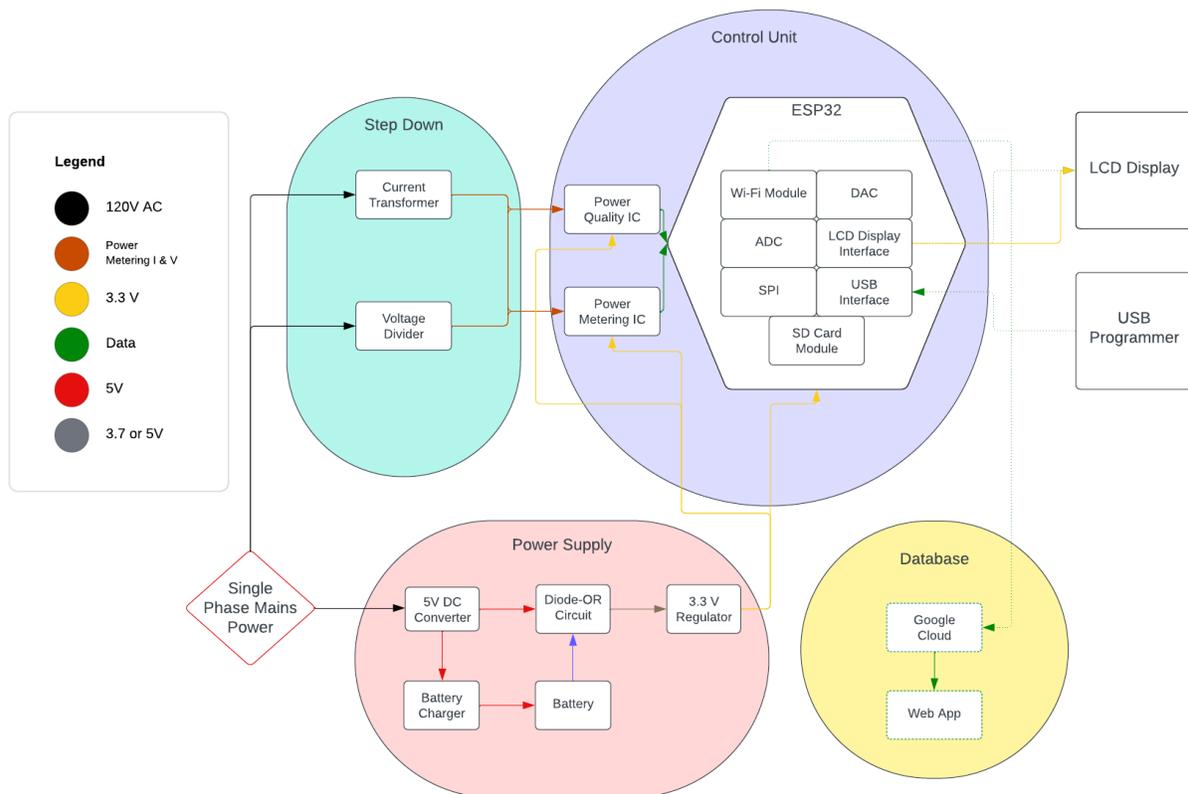


Figure 2: Block Diagram

2.2 Subsystem Overview

Our design is separated into 4 subsystems that implement hardware and software tools.

2.2.1 Power Supply

The Power Supply Subsystem handles powering our entire unit. It is either taking power from the wall directly and converting it into a 3.3V DC signal that will power our Control Unit while simultaneously charging our backup battery, or (in the event of a power failure) it will use a battery to power our control unit.

2.2.2 Step Down

The IC chips we are planning on using are not rated to withstand the voltage and current coming directly from the wall, instead we will set up a current transformer and a voltage divider circuit to step down the current and voltage to pass to our ICs for measuring.

2.2.3 Control Unit

This block is where our sensors, microcontroller, and display will connect. The ICs used in this block are the ADE953 and ADE9430, they are the Power Metering and Power Quality Monitoring IC respectively. They have inputs of scaled current and voltage which is then converted into digital signals by the onboard ADC. The output from our step down subsystem is taken by our measurement ICs and then, using the SPI Communication Protocol built into the ICs (the SCLK, MISO, MOSI, and CS pins), the data is sent to the microcontroller. This data is then sent to the Database from the ESP32 through an established HTTP connection that sends "POST" requests. These requests have SQL "INSERT INTO" statements which insert data into the Google Cloud database. The microcontroller also powers the measurement ICs from the 3.3V pin. The ESP32 also powers the LCD display via the 3.3V pin as well. The communication protocol we aim to use to display information on the display is the I2C protocol, compared to SPI, I2C is a 2 wire protocol rather than a 4 wire protocol, it is also slower than SPI, so we won't have to worry about displaying data at a faster rate than we collect it.

2.2.4 Database

The database subsystem is a full-stack web application that displays graph data, specifically the voltage and current of the power outlet and the load. The web app also notifies the user when there are disturbances or failures with the power outlet voltage or current in real-time so that a building manager or electrician can fix the problem as early as possible. The data is received by the Google Cloud MySQL database through an HTTP connection from the ESP32. The backend is written in JavaScript using Node.js and Express.js to create a server and send HTTP requests to and from the frontend and the database. The frontend is written in JavaScript as well by using

React.js to create an interactive web application. To create real-time graphs, we will use websockets and the Chart.js library, which allows us to read and plot data.

2.3 Subsystem Requirements

In addition to high level criteria for success, each subsystem of our project has specific requirements to ensure the accurate and safe operation of our device.

2.3.1 Power Supply

The power supply unit will need to interface between the mains power to provide power to our control unit. Specifically, the regulator will need to provide 3.3 V to the microcontroller. This unit must operate continuously for at least 24 hours, and in the event of a power failure, it must automatically switch to battery power. This battery must be able to be safely recharged when needed. The battery we plan on using is a LiFePo 18650 battery rated for 3.7 V nominally.

2.3.2 Step Down

The current and voltage transformers must step down 120 V ac from the mains to a level that will not damage the current and voltage sensing (ICs). This unit will need to have absolutely minimal power loss across it so as to obtain the most accurate measurements at the sensors. It should also have a built-in margin of safety; that is, it should not step down to exactly the chips' rated values, but instead leave room for some error without blowing the ICs.

2.3.3 Control Unit

In the control unit, the measurements from the voltage and current sensing ICs must scale proportionally to the real values within a high degree of accuracy. The control unit will use these values to calculate accurate values for real and apparent power, and send measurements to the SD card once per second. Measurements will also be uploaded to the Google Cloud Database via the Wifi module once every fifteen minutes. Finally, measurements will be used to display real-time waveforms on an LCD display.

2.3.4 Database

The requirements for this system are the following: data will be sent from the ESP32 to the database once every 10 seconds, measurements stored in the database will be compiled and presented to the user in an understandable and concise fashion through a web app. The web app will have notifications for any notable disturbances or failures within 5 seconds. Lastly, up to 8 GB worth of data will be stored in the Google Cloud database.

2.4 Tolerance Analysis

For our design, we believe the most challenging portion will be the battery charging circuit. We expect there to be two portions of this circuit: the first is the actual battery charger, and the second will be a boost circuit to ensure that our battery voltage is at 5 V, so that after our voltage regulator when we are using battery power to operate our system, it operates as expected. Working from a Circuit Digest Post¹ we observe the circuit schematic shown in Figure 2.

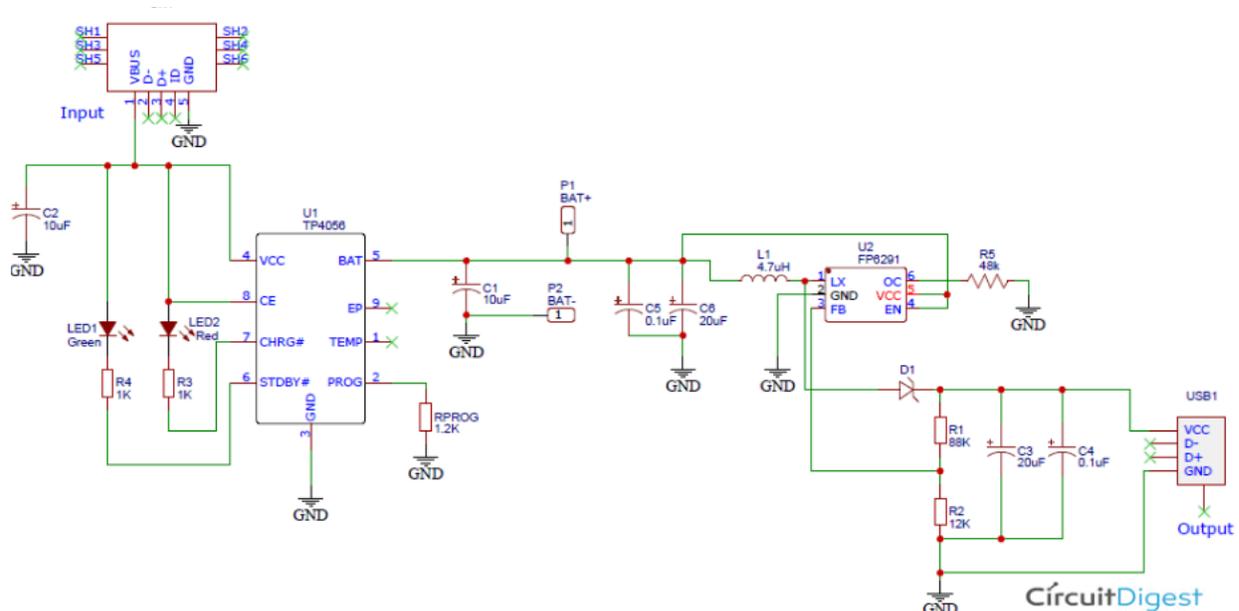


Figure 3: Battery Charge and Boost Circuit

However, instead of a TP4056 as our charging IC, we will be using a TI BQ25638 as our IC since it is intended for LiFePO batteries, which is the chemistry we intend to use. We will also change the boost IC to a MT3608 rather than a FP6291 Boost Converter IC since the MT3608 is rated for higher input voltages and higher output currents based on their datasheets^{2,3}. This gives us more flexibility to push more current when the ESP 32 draws more power. Essentially the problem we want to confirm we are solving is that our system can run at full load when being powered just by a battery. Based on this⁴ forum post, each GPIO pin is rated for 40 mA, ideally they draw 20 mA for efficiency. When all pins are being used and all modules on an ESP32 are running (Wi-Fi, Bluetooth, etc) it is estimated that there is a total load of 250 mA. Another source says that the chip could draw more than 800 mA of current when doing transmissions over bluetooth and Wi-Fi. We could reduce this number of active pins and thus the total power draw by using a multiplexer to decide which pins to power rather than having them all be powered, we could also code pragmatically and not allow different types of transmissions at the same time. However, for the sake of the tolerance analysis we will use the 800 mA value and double it to 1.6 A just to get a sense of the true worst case power draw.

$$\text{Given: } V_{ESP} = 3.3V, I_{max} = 1.6A, P_{max} \sim 5.28W$$

We need to check what the max load our boost converter can handle. Our MT3608 IC calculates V_{out} by the following ($V_{ref} = 0.6V$)

$$V_{out} = V_{ref} \times \left(1 + \frac{R_1}{R_2}\right)$$

If we want our V_{out} to be 5V then R_1/R_2 will be 7.33 Ω . This is a feasible ratio and can be achieved. Also assuming a 18650 LiFePO4 battery rated for 3.7V. We can also calculate the duty cycle necessary to boost the voltage to 5V. This calculated value must be less than 0.9 (D_{max})

$$V_{out} = \frac{V_{in}}{1-D} \Rightarrow 5 = \frac{3.7}{1-D} \Rightarrow D = 1 - 0.74 = 0.26 < D_{max}$$

Back to the total current draw. If we take our assumed battery and look online⁵ we see that the minimum current draw of this size battery is 5A. Looking at the datasheet we see that the minimum efficiency of the converter at this voltage is around 80%. Meaning that 80% of the power consumed is delivered at worst.

$$\begin{aligned} P_{in} &= 3.7V * 5A = 18.5W \Rightarrow \\ P_{delivered} &= 18.5(0.8) = 14.8W \Rightarrow I_{out} = \frac{P_{delivered}}{V_{out}} \\ &= 2.96A \end{aligned}$$

We have confirmed that we are capable of delivering the necessary power to the load. Now we can use this to understand how long our battery will last. Again referencing the battery inventory website we see that the battery capacity is 3400 mAh. If we assume an average current draw of 300 mA, meaning that all our pins are powered plus some arbitrary amount of current to account for larger draw due to transmissions.

$$3400/300 = 11.3 \text{ hrs}$$

We can expect our system to operate on battery power alone for up to 11.3 hours. We are not enthusiastic about this number but we feel that if we add more cells in parallel and add a protection IC perhaps we could elongate the time for which our system stays on.

Another system tolerance we could have considered would've been a timing analysis for all the components in the control unit and ensuring that all signals sent will be received properly. We felt this would be unnecessary since all data is passed through SPI which is standardized, and any functions within IC's that need to be clocked can be synchronized to the clock generated on the ESP32 Chip, and since the generated clock is generated by the digital device we can ensure

that the rate at which data is sent is not faster than the rate at which the microcontroller can process it as the only digital device amongst analog devices.

3 Ethics and Safety

In terms of ethics, we do foresee a few ethical issues that could arise during the development of our project as well as the misuse of our prototype. For example, during the development of our project, we could have poor teamwork, alienate group members, or stop participating in the project. Additionally, we could reference the designs of other submeters or power quality monitors on the market. In terms of the misuse of our prototype, the data that is collected is private data for the users and must be protected. There are people that could try to access other people's data, which is a violation of laws and regulations.

Our group is committed to maintaining the highest ethical standards throughout the course of this project by following the IEEE Code of Ethics, such as upholding the highest standards of integrity, treating everyone equally and with respect, and making sure that the Code of Ethics is followed by the entire group. We will avoid these ethical breaches and follow the aforementioned Code of Ethics through the following:

1. We've set up a group chat through iMessage where we have consistently communicated our schedules, when we can work, and what we plan to work on. This has allowed us to split the workload well and finish our work on time while ensuring high quality. We have also set up a Google Drive folder for all our ECE 445 documents so that we can stay organized and stay on the same page.
2. We will hold each other accountable to make sure all of the work we do is of high quality and is original. If questions or uncertainties arise, we will make sure to contact and consult with experts in the field such as Surya (our TA), Professors, Machine Shop Technicians, or Jack Blevins.
3. We will have our website be password protected so that it becomes significantly harder to breach private data. If we were to take this to market, we would look to have other privacy measures in place as well such as encryption.

In terms of the safety regulations for this project, we have identified the following risks: lithium-ion batteries, as well as the voltage and current transformers since we will step down the voltage and current. To combat these issues, we have talked to Jason and Surya, both being TAs in ECE 445, to identify a workaround for the lithium-ion batteries. They suggested using LiFePO batteries since the chemistry in the battery is less likely to cause a fire or other safety hazards. Additionally, we will mark the device as a potential safety hazard that shouldn't be used by a minor without an adult present. Lastly, we will use adequate lab safety equipment such as safety goggles during the construction of the project to ensure that we are safe.

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