Power Meter

ECE 445 Design Document - Fall 2024

Project #18

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1 Introduction

1.1 Problem

Factories all over the world require a clean, consistent output of power delivery in order to function optimally. Most countries in the world, especially those in Latin America, suffer from constant blackouts. In an industrial setting, these blackouts are a big risk to manufacturing, any downtime can mean hours of wasted labor and thousands of dollars lost. PowerBox Technology works to prevent this industrial downtime by isolating factories from the grid. While having the factory connected to a battery power system, PowerBox Technology's Power Management Software can predict faults in the grid and keep the batteries constantly charged.

The Power Management Software requires high-precision data from the factory's power consumption. This data is processed through a Power Meter. Our solution is to create a Power Meter that will provide the Power Management Software with all the data readings from the factory's loads. This data includes real power, apparent power, reactive power, and per phase current/voltage readings that fall within a 1.41% and 1% error respectively. This solution is crucial to PowerBox Technology's mission as it will provide the data needed to allow the software to maximize energy costs, predict faults, and keep the factory running regardless of the status of the grid. Unlike other industrial systems which rely on less precise data or monitoring, our power meter is integrated directly with the factory's power infrastructure. This means that we will be able to deliver real-time, high-precision measurements ensuring reliability.

Even a one-second loss of power can cause hours of downtime spent in recalibration. This is why, unlike common systems where backup power may only kick in after the power goes out in the factory, the power meter within the PowerBox ecosystem will provide the data required to keep the machines running no matter what the external conditions are.

1.2 Visual Aid

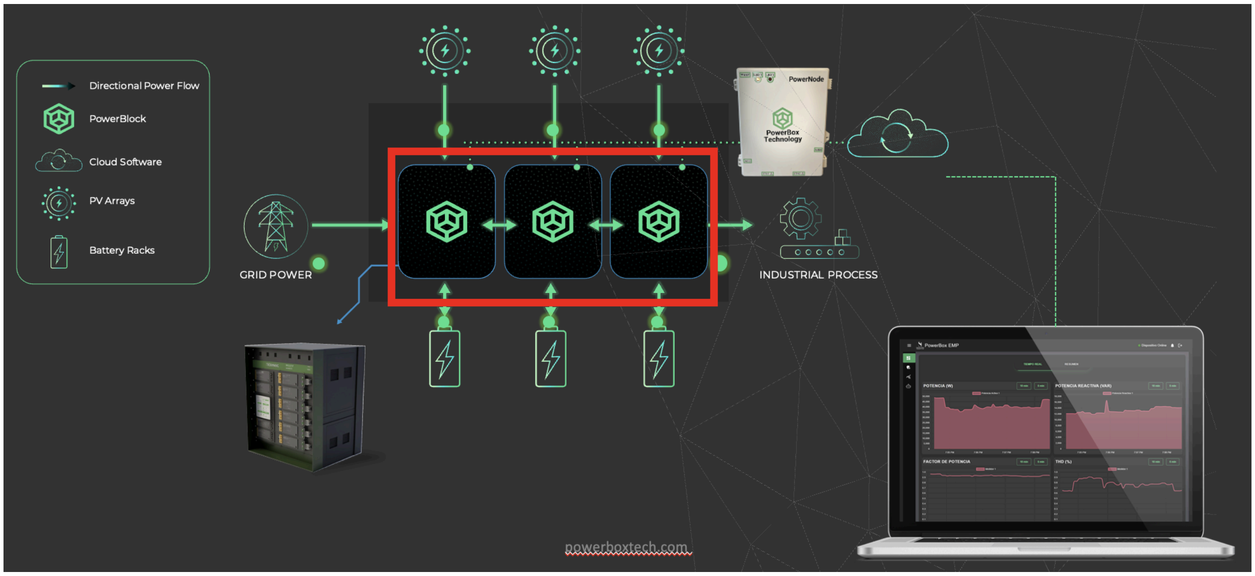

Figure 1. PowerBox Technology helps modernize factories' electrical systems through the PowerBox Energy System. This is a diagram of what the company does as a whole. The PowerBlock (inside red borders) is what the company works on.

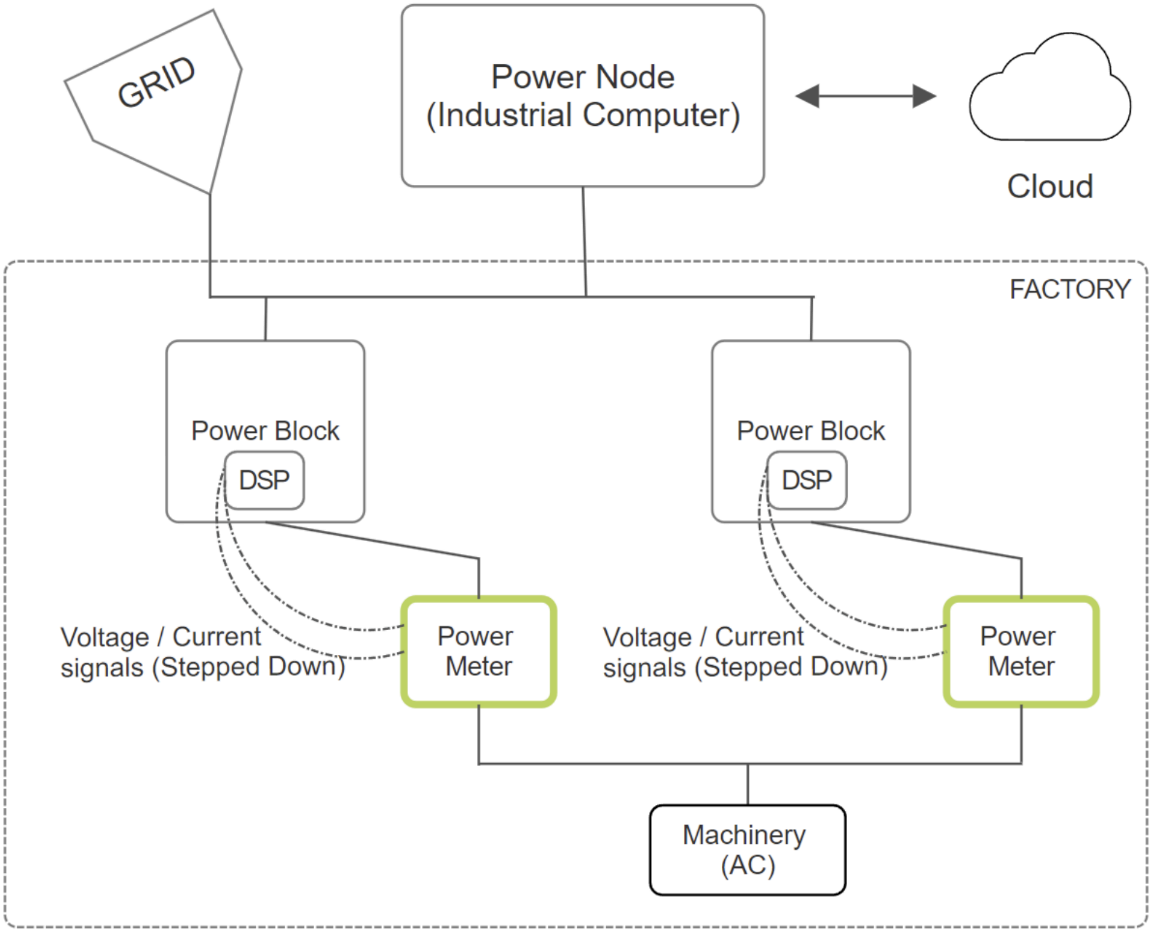

Figure 2. This is a visual representation of how our power meter fits into the system. The power meter is outlined in green and is between the power block and the machinery.

1.3 High-Level Requirements List

To consider our project successful, our power meter must fulfill the following:

1. Our Power Meter will output analog current and voltage that have been stepped down from the three-phase high voltage and current to the digital signal processor, with a tolerance of ±1% of the true values.
2. Our Power Meter will display the per-phase voltage and current readings of the system.

3. Our Power Meter is able to accurately calculate the system's real, reactive, and apparent power from the stepped-down voltage and current, with a tolerance of ±1.41% of the true values.
4. Our Power Meter is able to consistently transmit the power data to the Power Node, with a maximum of 5 seconds as the delay in propagation.

2 Design

2.1 Block Diagram

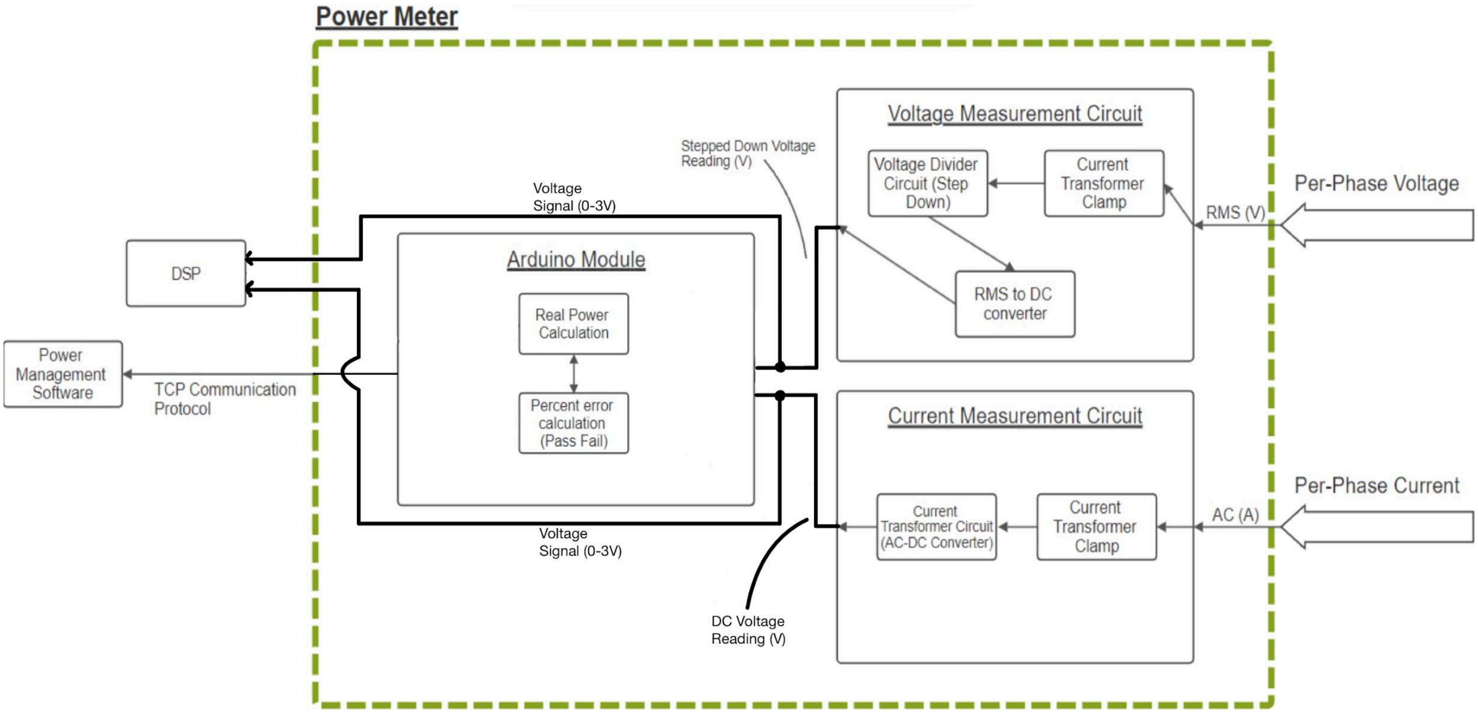

Figure 3. Power Meter Block Diagram

Our design for the Power Meter consists of three subsystems that work together to measure and communicate essential power data in an industrial setting. The RMS Voltage Measurement Circuit steps down and measures the three-phase voltage output from the inverter, ensuring safe and accurate voltage levels for further processing. Simultaneously, the AC Current Measurement Circuit uses current transformers to monitor and step down the high current levels. These stepped-down measurements contribute to the calculation of real power, reactive power, and apparent power. The Power Calculation Subsystem, controlled by an Arduino module, computes the power values from the stepped-down voltage and current signals and ensures that the data is reliable by performing error checks. This data is then transmitted via Modbus TCP for secure and reliable communication with the Power Node, allowing real-time monitoring and data storage for power management.

2.2 Functional Overview & Block Diagram Requirements

2.2.1 AC Current Measurement Circuit Subsystem

The current on one of the phases will be measured with a current transformer. The current transformer is used to accurately monitor the current while not damaging the equipment with the high current flow. It does this by stepping down the current according to the turns ratio. The output of the AC current measurement circuit and the RMS voltage measurement circuit will be used to calculate the real power, reactive power, and apparent power. The circuit will also step down the current and output three analog signals to the digital signal processor. The current transformer is given in this project, but we will have to set the current limits. We will include circuitry that will ensure that the stepped-down values are clean and accurate.

The current transformer will step down the current to the range applicable to the current sensing circuit and the circuit will output voltage as an analog signal. This analog signal will be sent to the DSP. To convert the AC current signal to a DC output, a shunt resistor on the secondary will be placed and an operational amplifier will be used to get the voltage output. The voltage output should be relative to the current. The stepped-down AC signal from the current transformer will also be sent to the Arduino to calculate the real, reactive, and apparent power. A current shunt monitor IC (INA138) will be used to get the output voltage signal.

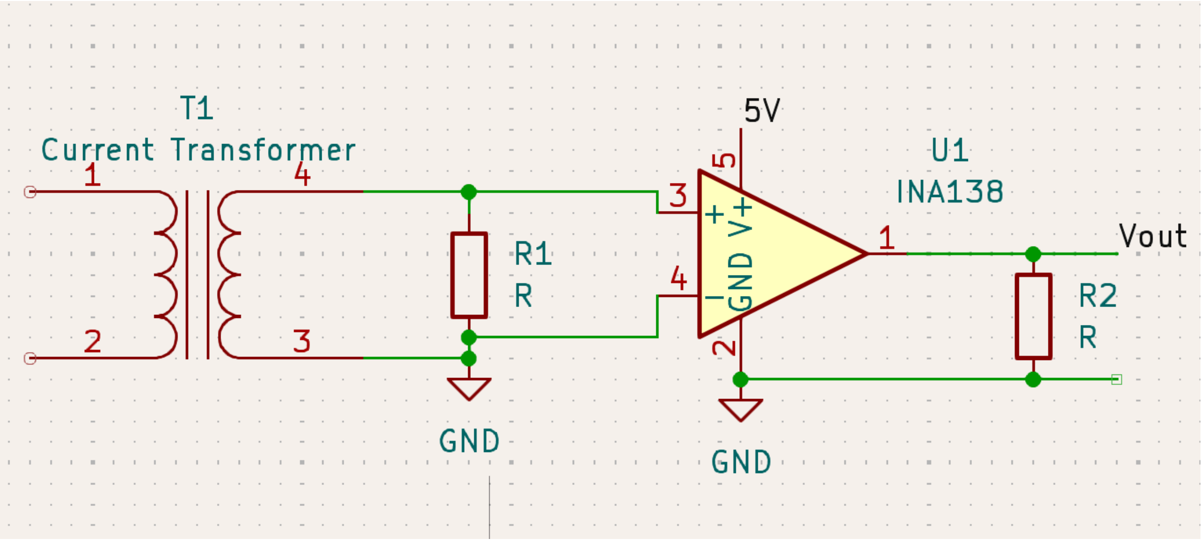

Figure 4. A sample of what the circuit will look like with the IC. The shunt resistor (R1) will be connected across the secondary side of the current transformer.[8]

Table 1. AC Measurement Circuit Subsystem – Requirements & Verification

Requirements	**Verification**
The subsystem should be able to measure the AC current with an error percentage of ±1%	● A true RMS meter will be connected to check the RMS current from the inverter. ● The RMS meter can be set up in the lab and it can be tuned to show the accurate current measurement. ● Knowing the current transformer ratio, the RMS current calculated on the Arduino can be compared with the value from the true RMS meter.
The current should be stepped down to a suitable value for the current sensor circuit to operate.	● If the current transformer ratio is 1000:1 and a 100A current is applied to the primary, the stepped down current should be 0.1A. ● A current probe can be used to check the output current of the current transformer. ● The value from the current probe can be verified if it is around 0.1A, considering the error component of the current transformer.
The subsystem should be able to send analog signals to the DSP and the Arduino.	● The analog dc voltage to the DSP and Arduino should be the same signal. ● The voltage to the DSP and the Arduino can be

Requirements	Verification
	measured with a multimeter or voltage probe. - This value can be compared with the theoretical value we expect from the output of the AC measurement circuit. - The DSP module and the Arduino should receive a DC voltage that corresponds to the current value.

2.2.2 RMS Voltage Measurement Circuit Subsystem

The RMS voltage measurement circuit uses the inverter's output to measure the system's three-phase voltage. The output of this module and the AC current measurement circuit will be used to calculate the Arduino module's real power, reactive power, and apparent power.

The voltage measurement circuit functions the following way: Through the use of the Current transformer clamps, we can read the per-phase RMS voltage of an inverter. This RMS voltage is then passed through a voltage divider circuit. Through the use of a simple voltage circuit, we can step down our voltage to a value that can be manipulated, processed, and calculated by the Arduino module. Arduinos can read a maximum analog voltage of 5V. The voltage divider circuit should look similar to the following schematic [12]:

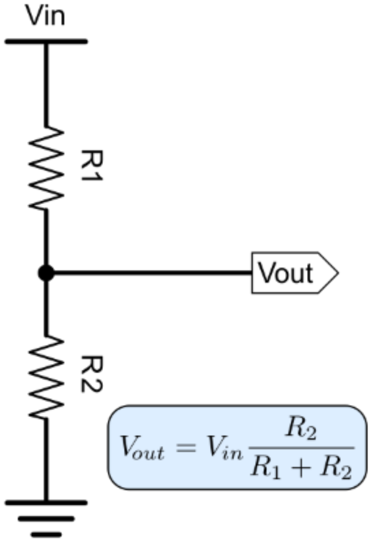

Figure 5. Voltage Divider Circuit Schematic

The output of the voltage divider circuit fractionizes the value of the RMS voltage. This value is then passed onto an AD737 chip [11]. The AD737 works to convert the RMS voltage into a simple DC voltage. The importance of working with DC voltage is that its stability can be used to easily measure the power values that will be calculated in the Arduino module as there is no fluctuation and the power factor will not be an issue. The stepped-down DC voltage that is outputted from the AD737 is then sent over to the Arduino's voltage read pin to be processed and stored. This is the main ingredient to be used in the power calculations.

Table 2. RMS Voltage Measurement Circuit Subsystem – Requirements & Verification

Requirements	**Verification**
The subsystem should output a DC voltage reading with an error of ±1% or better as per IEC standards.	Refer to the ideal voltage delivery values of the inverter as rated by the manufacturer for comparison. Calculate the step-down voltage value of this ideal voltage output using a basic voltage divider equation (Vout = Vin(R2/(R1+R2))). Call this Vout the Expected Value and use the resistances shown in the schematic. Use a multimeter to read the actual DC voltage output and apply the percent error equation found in pt. 2.3.1.
The voltage value should be stepped down to a value that can be interpreted and calculated by the Arduino module (0-3V).	A multimeter is used to read the output voltage of the voltage divider circuit. The user verifies that this value is no lower than 0 or greater than 3 volts. For further verification, the user can use the previously mentioned voltage divider equation to calculate the inverter's output voltage. Where Vout is the recorded, stepped-down voltage, R1 and R2 are the voltage divider resistances, and Vin is the inverter's output voltage. Finding this value and comparing it to the inverter's output voltage rating proves the functionality of the voltage divider circuit.
The subsystem should be able to send analog signals to the DSP.	The DSP module should receive three analog signals from the subsystem. One phase would send one signal. The DSP module should receive a DC voltage that corresponds to the current value. This can be manually tested through the use of a multimeter, the test passes if

Requirements	Verification
	the values are within (0-3V).

2.2.3 Power Calculation Subsystem

The Power Calculation Subsystem is responsible for calculating and recording real power, reactive power, and apparent power. This subsystem interfaces with the Voltage Measurement Circuit and Current Measurement Circuit, receiving stepped-down analog signals representing the voltage and current. These signals are processed by the Arduino microcontroller, which performs the necessary power calculations and ensures that the data is accurately communicated to the Power Node. The Arduino board, acting as the central controller, processes the signals to compute real power using the formula $P = V \times I \times cos(\phi)$, reactive power as $Q = V \times I \times sin(\phi)$, and apparent power as $S = V \times I$, where ϕ represents the phase angle between the voltage and the current. These results are stored in memory registers for further use, and the power data is transmitted to the Power Node for monitoring and analysis.

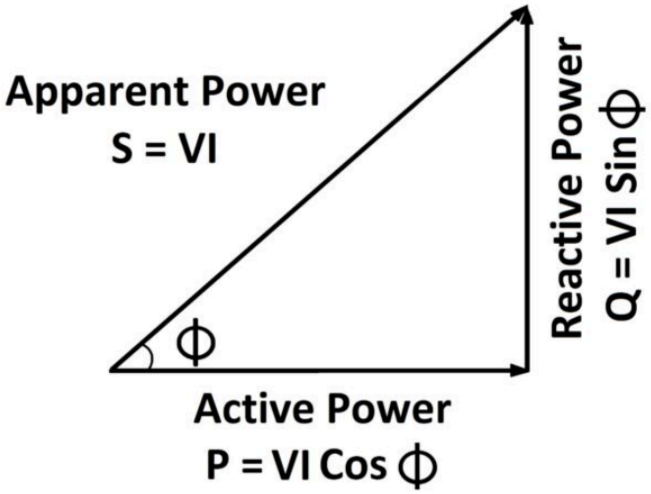

Figure 7. Relationships Between Apparent, Active, and Reactive Powers

The Arduino microcontroller was chosen due to its compatibility with analog-to-digital conversion, low power consumption, and ease of integration with industrial communication protocols. Its processing capability is sufficient to handle real-time power calculations, while its memory allows for storing power data. The choice of Modbus TCP as the communication protocol ensures reliable, industry-standard transmission of data. Modbus TCP is widely used in industrial settings, offering a robust solution for transmitting data in high-interference environments. The Ethernet shield attached to the Arduino allows the system to function as a Modbus TCP server, sending power data as requested by the Power Node.

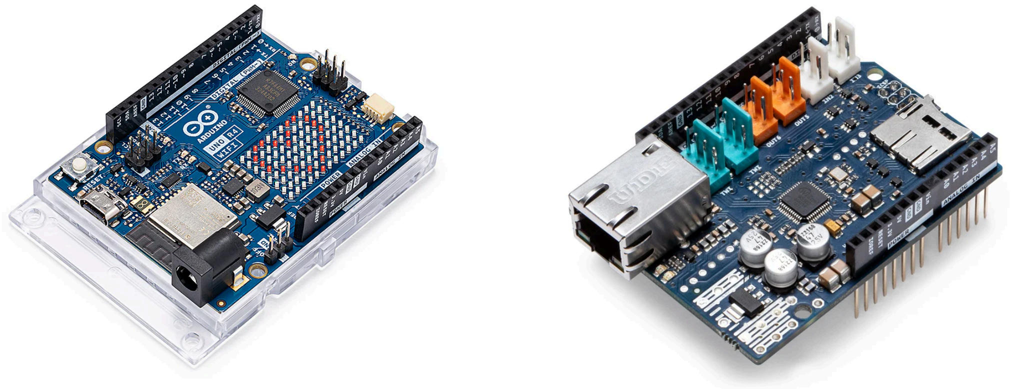

Figure 8. Arduino® UNO R4 WiFi[9] and Arduino Ethernet Shield 2[10]

The Power Calculation Subsystem interfaces with the voltage and current measurement circuits via analog signals. It receives the stepped-down voltage and current readings from these circuits and processes them to compute power values. The Arduino then transmits the calculated power data to the Power Node, which acts as an industrial PC that handles power management, over a Modbus TCP connection, ensuring that the data is stored and distributed to other servers for further analysis. The data communication is designed to occur at regular intervals, ensuring real-time power monitoring.

Table 3. Power Calculation Subsystem – Requirements & Verification

Requirements	**Verification**
The subsystem should calculate real, reactive, and apparent power with an error of ±1.41% or better as per IEC standards.	● Connect multimeters to the output of the current and voltage circuits and note down the values ● Manually calculate the real, reactive, and apparent power with the current and voltage. ● Compare the manually calculated data with the values calculated by the subsystem and ensure they are the same.
The subsystem should record power data in registers for access by other software modules.	● Load the power meter with a known source and a true RMS meter. ● Use a serial monitor to verify that the power data is properly stored in Arduino registers. ● Access the data and export it to a CSV file to verify.
The subsystem should transmit power data using Modbus TCP.	● Set up a Modbus TCP client on a laptop ● Connect the Arduino to the same network using an Ethernet shield. ● Request real, reactive, and apparent power data from the Arduino. ● Compare the transmitted values with the known power data stored in the Arduino registers and verify that the data transmitted are received within 5 seconds.

2.3 Tolerance Analysis

Some critical aspects that are needed to define the successful completion of the project are the accuracy of the measurement circuits, power calculation, and data transmission. Every one of these aspects is to meet the accuracy standards imposed by the IEC. As per the IEC's standards, all current, voltage, and power measures should fall within an error margin of ±1%. This tolerance analysis will quantify the worst-case scenarios and will ensure that our design can handle those conditions without exceeding the determined error margins.

2.3.1 Voltage and Current Measurement Circuits

The voltage and current measurement circuits work to step down the values read from the three-phase inverter to levels appropriate for analog signal processing. These values must all follow a percent error accuracy of ±1% as per the IEC's accuracy standard. The percent error margin of both the voltage and current measurements can be calculated using the following equation:

$$E = \left(\frac{V_{\text{measured}} - V_{\text{actual}}}{V_{\text{actual}}} \right) \times 100$$

In this equation, the values of "V" can be either the voltage or current readings. Measured Values are the ones that are recorded when the fixture is run. Actual Values are the values that are expected based on the known parameters.

To prevent the worst-case scenario, we can calculate the maximum allowable voltage / current deviation and compare this to our recorded values as well. We can do this by multiplying our actual value by 1%. For example, if our expected value is 500V, we multiply it by .01 which gives us a value of 5V. This means that the range of allowable measured values is from 495V -

505V. Again, the same equation can be applied to current readings. If our actual current is 50A, then our range of allowable measured values is from 49.5A to 50.5A.

The stepped-down values thus require high precision. This means that interference and fluctuations will be mitigated with filtering and regulating circuitry.

2.3.2 Power Calculation

Real Power will be calculated using the following formula:

$$P = V_{\text{rms}} \times I_{\text{rms}} \times \cos(\theta)$$

Where Vrms and Irms are the measured values. Cos(theta) is the Power Factor.

To find the percent error of the Real power, we use the following equation:

$$E_P = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \times 100$$

In this equation, the Delta values are the maximum allowable voltage / current error deviations previously calculated, while the I and V are the expected current and voltage values.

If we assume that the error for both our current and voltage values are at their 1% maximum, the percent error value for Real Power will be different.

$$E_P = \sqrt{(0.01)^2 + (0.01)^2} \times 100 = \sqrt{0.0002} \times 100 \approx 1.41\%$$

This means that our maximum percent error value for Real Power will always be at a maximum of ±1.41%.

3 Cost and Schedule

3.1 Cost Analysis

The total cost for parts as seen below in Figure x before shipping is \$85.41. With another 9.00% in sales tax and \$2 shipping fee for each part, this brings the total cost before labor to \$103.10. We can expect a salary of around \$50 per hour. So, the labor cost would be $\$50/hr \times 15\ hrs/week \times 10\ weeks = \$7500$ per partner in the project. Accounting for all three partners would give us $\$7500 \times 3 = \$22500$ as the total labor cost. Adding the parts cost and the labor cost, we have the total cost of \$22603.10.

Table 4. List of Items and Cost

Name	**Manufacturer**	**Quantity**	**Price**	**Link**
INA138	Texas Instruments	1	\$1.12	Link
Current Transformer[1]	Smappee	1	-	Link
UNO R4 WiFi	Arduino	1	\$27.50	Link
Ethernet Shield 2	Arduino	1	\$29.80	Link
AD 737	Texas Instruments	1	\$13.00	Link
Resistor Kit (1000 pcs)	Bojack	1	\$13.99	Link

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[1] A current transformer would be provided in the lab. This is a sample of what type of current transformer we would be using.

3.2 Schedule

Table 5. List of Items and Cost

Week	**Task**	**Person**
October 7 - October 13	Design Review	Everyone
	Research more on the parts planning to use	Everyone
	Start a design for PCB review	Everyone
October 14 - October 20	Consult with Oscar and his team on the design	Everyone
	Start ordering parts	Everyone
October 21 - October 27	Unit test with available parts	Everyone
	Finish PCB design for 2nd round of PCBWay orders (October 22)	Arisa & Abraham
	Start learning software for the Arduino and Power Node	Frank
October 28 - November 3	Test PCB	Arisa & Abraham
	Finish programming the Arduino	Frank
November 3 - November 10	Test PCB	Arisa & Abraham
	Finish revised PCB design for 4th round of PCBWay orders (November 4)	Arisa & Abraham
	Test code with Arduino	Frank
November 11 - November 17	Finish final PCB design for 5th round of PCBWay orders (November 12)	Arisa & Abraham

	Test communication protocol to transmit data	Frank
November 18 - November 24	Integrated tests	Everyone
	Mock demo	Everyone
November 25 - December 1	Thanksgiving Break!!	Everyone
December 2 - December 8	Final demo	Everyone
	Mock presentation	Everyone
December 9 - December 15	Final presentation	Everyone
	Turn in final paper	Everyone
	Lab checkout	Everyone

4 Ethics and Safety

One ethical issue involves the responsibility to design and implement a safe and reliable system, as outlined in the IEEE Code's principles of prioritizing the safety, health, and welfare of the public.[3] The potential misuse of our power meter, such as improper installation, could lead to inaccurate power measurements or electrical hazards, causing harm to operators or damaging equipment. To prevent such incidents, we will conduct comprehensive testing and documentation to ensure that users are well-informed and can operate the power meter safely. Safety concerns that involve high voltages are also important. We will follow established safety standards at the PowerBox Technology lab, which provide guidelines and training that we have already done to protect against electrical shock, fire, and equipment damage.

The main code of conduct followed when working with power is the OSHA. When working with any type of equipment in a lab, it is important to keep the space clean and clear of obstructions. The floor of the workspace should be clear, dry, and free of hazards such as sharp objects, leaks, water, etc. The workspace should be inspected and maintained regularly.[4]

Another important issue for working with high-voltage equipment is personal protective equipment (PPE). Training should be done on when and how the PPE should be used.[5] There should be appropriate eye, face, head, foot, and hand protection worn while working. More specifically, the PPE we will be using is the electrical protective equipment. The design and electrical requirements of the electrical protective equipment should be met.[6]

When there is an emergency, there should be an emergency plan for the lab. The safety exit should not be blocked and must be unlocked.[7] Since we are working in the POETS Research and Development Center, we will be following their emergency plan. If the emergency plan is changed, we need to be responsible for learning the new action plan as necessary.

Finally, we will be designing and implementing systems that are robust and secure and avoid harm to others according to the ACM code of conduct.[2] We will prioritize the well-being of the people while doing the project. Work will be divided according to our areas of expertise. If things exceed our knowledge, we should consult with a professional to ensure our project runs smoothly.[1]

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