

SINGLE-PHASE AC POWER ANALYZER PROJECT PROPOSAL

By

Isaac Herink

Jeffrey Pohlman

Joseph Kim

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TA: Eric Tang

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Abstract

This project presents the design, considerations, and implementation of a portable, microcontroller-based single-phase AC power analyzer. The system samples isolated voltage and current waveforms and computes RMS voltage, RMS current, real power, and power factor in real time. Signal conditioning circuits scale and bias the waveforms for ADC acquisition, and embedded firmware performs time-synchronized sampling and numerical computation. Measurement results are transmitted over USB to an external display interface. The device is designed to provide low-cost power analysis suitable for laboratory and educational environments.

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1. Introduction

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 Visual Aid

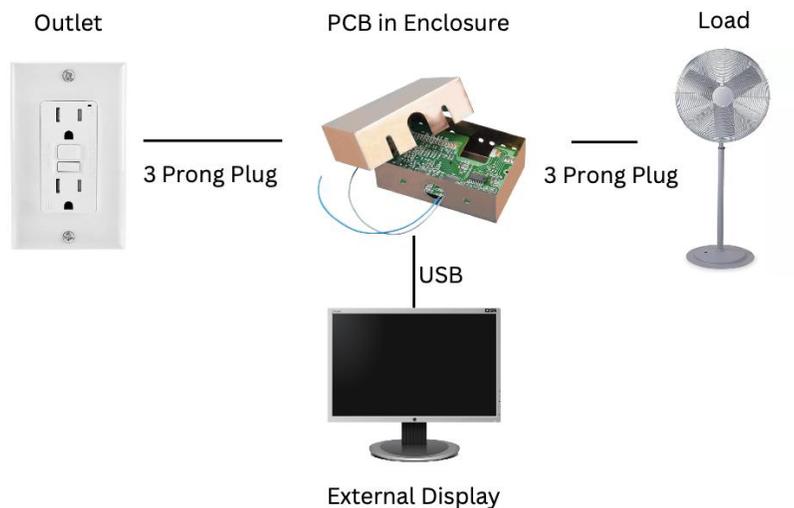


Figure 1 Pictorial representation of project

1.4 High Level Requirements

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.

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.

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.

2. Design

2.1 Block Diagram

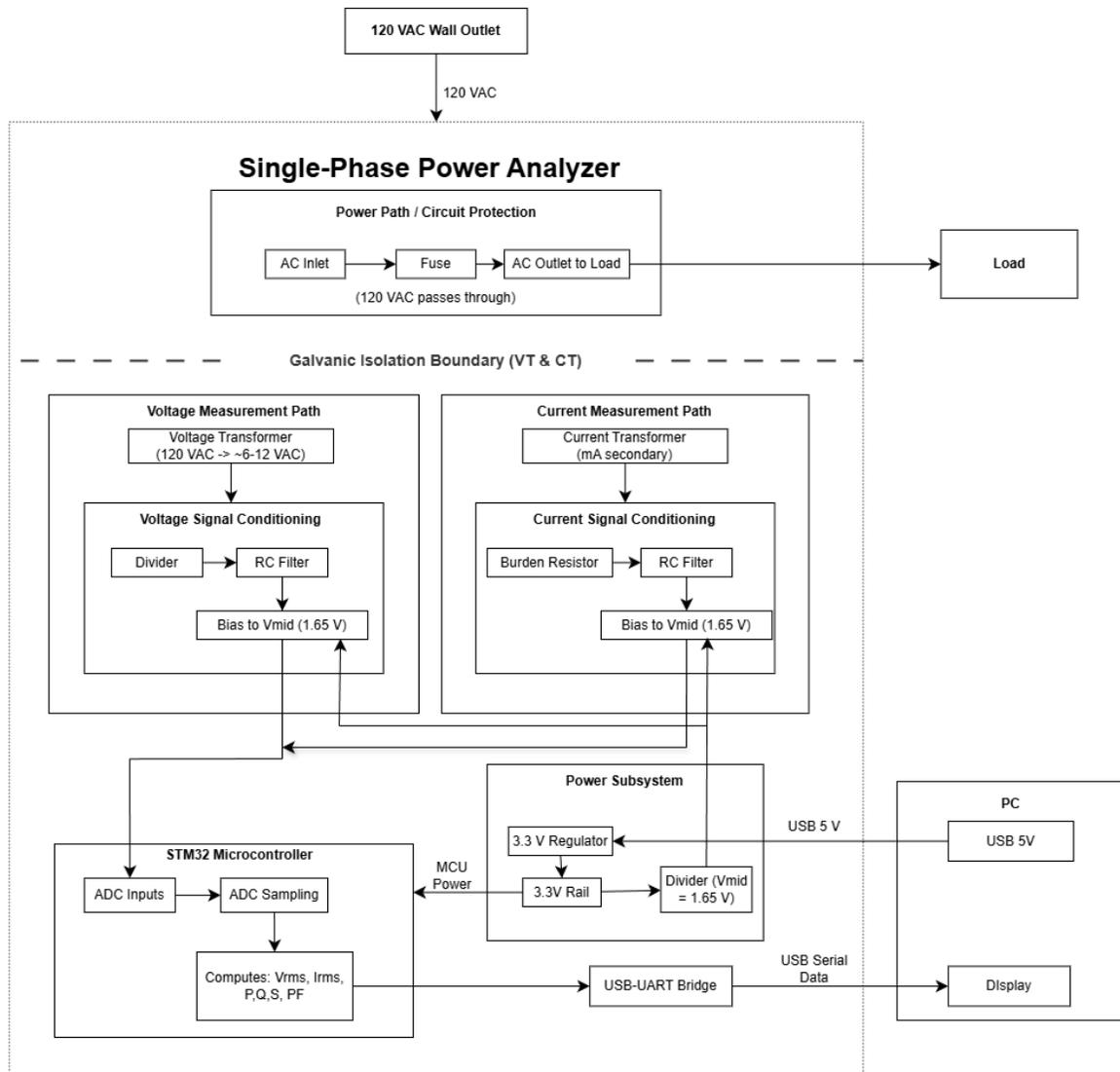


Figure 2 Block Diagram with each subsystem

2.2 Power Path / Circuit Protection Subsystem

The power path subsystem design ensures a secure connection between the AC inlet and the load. It will also maintain electrical isolation of high and low voltage. In case of a load short circuit or internal wiring failure, we will place a series fuse on the hot line to prevent overcurrent conditions. This fuse will be placed after the AC inlet, but before the voltage sensing and the load.

2.2.1 Power Path / Circuit Protection Subsystem Requirements

The power path/circuit protection subsystem shall satisfy the following requirements:

- Secure connection between the load and inlet.
- Maintain electrical and physical isolation of high and low voltage.
- Provide protection in case of a fault in the design or the load.

Failure to meet these requirements would result in safety hazards and no power flow.

2.3 Voltage Measurement Subsystem

The voltage measurement subsystem is responsible for taking accurate, isolated voltage readings from the line to neutral. To do this, we need to use a step-down transformer to convert the high voltage to low voltage. We will need to consider accuracy tolerances and rating of our transformer to ensure accurate RMS voltage readings. This transformer will be a PCB mounted transformer, so we will have to ensure that there is enough creepage between the high voltage side and the low voltage side on the PCB.

2.3.1 Voltage Measurement Subsystem

The voltage measurement subsystem shall satisfy the following requirements:

- Isolate high voltage from low voltage.
- Does not affect the load input.
- Accurately describes input RMS voltage.
- Steps voltage down from 120VAC to 6-12VAC, 6VA.
- Transformer creepage of at least 5mm on PCB.

2.4 Current Measurement Subsystem

The current measurement subsystem is responsible for taking accurate, isolated current readings from the line. We will do this by using an isolated current transformer and a burden resistor to turn the current into a readable voltage waveform. We will need to consider how the tolerance of the resistor and CT affects our RMS current readings.

2.4.1 Current Measurement Subsystem Requirements

The current measurement subsystem shall satisfy the following requirements:

- Make isolated current measurements.
- Does not affect the load input.
- Accurately describes input RMS current.
- 5A to 5mA Current Transformer.
- Current from CT is turned into a voltage waveform.
- Burden resistor tolerance

2.5 Analog Signal Conditioning Subsystem

The analog signal conditioning subsystem scales, filters, protects, and level-shifts the voltage and current sensing signals to meet the input requirements of the 0–3.3 V ADC while maintaining waveform integrity for accurate RMS current/voltage, real power, and power factor calculations.

For the voltage conditioning, we will be using the transformers secondary as an input to a voltage divider, into a series capacitor, into a DC bias circuit, into an RC low-pass filter, then finally outputs to the ADC input.

For the current conditioning, we will be using the CT + burden resistor as an input to a series capacitor, into DC bias circuit, into a clamp diode protection circuit, into an RC filter, then finally outputs to the ADC input.

2.5.1 Analog Signal Conditioning Subsystem Requirements

The analog signal conditioning subsystem shall satisfy the following requirements:

- Both outputs referenced at $V_{mid} = 1.65 \text{ V}$.
- Minimize relative phase shift between voltage and current channels.
- Use 70-80% of the ADC range(0-3.3V) to prevent clipping.
- Limit bandwidth using low-pass filters to prevent aliasing during sampling.
- Provide input protection using series resistance and clamping diodes to prevent overvoltage at the ADC inputs.

2.6 Embedded Processing Subsystem

The Embedded Processing Subsystem is responsible for acquiring time-synchronized voltage and current measurements and computing electrical quantities in real time. This subsystem will be implemented using an STM32F303 microcontroller operating from a regulated 3.3 V supply.

This subsystem receives two analog input signals from the Voltage and Current Signal Conditioning subsystems. These signals are scaled and biased to fall within the 0-3.3 V ADC input range and are centered around a reference voltage ($V_{mid} = 1.65 \text{ V}$). The microcontroller samples both channels using timer-triggered dual ADC hardware to ensure consistent sampling intervals.

Samples are collected over a fixed-duration window corresponding to multiple cycles of the 60 Hz waveform. For each window, the firmware computes RMS voltage (V_{rms}), RMS current (I_{rms}), real power (P), and power factor (PF). Calibration constants are applied to convert ADC counting into physical voltage and current units.

Computed values are passed to the Communication Subsystem for transmission to the host PC.

2.6.1 Embedded Processing Subsystem Requirements

The Embedded Processing Subsystem shall satisfy the following quantitative requirements:

- The subsystem shall sample voltage and current channels at a minimum sample rate of 3 kHz to ensure adequate resolution of 60 Hz waveforms.
- Voltage and current samples shall be acquired using time-synchronized sampling with channel-to-channel timing difference less than 10 μ s.
- The ADC input range shall be limited to 0-3.3 V.
- The subsystem shall compute V_{rms} , I_{rms} , P, and PF over a window of at least 5 cycles of the 60 Hz waveform.
- The subsystem shall update computed measurement values at a minimum rate of 5 Hz.
- The subsystem shall apply calibration scaling factors to convert ADC counts into physical voltage and current units.
- The subsystem shall maintain computational error contributions below the levels specified in the high-level requirements.

Failure to meet these requirements would prevent accurate power measurement and the device will fail to meet overall system objectives.

2.7 Communication Subsystem

The Communication Subsystem provides real-time transmission of computed electrical measurements to a host PC. A CP2102N USB-to-UART bridge converts UART signals from the microcontroller into USB serial data.

The subsystem receives computed measurement values from the Embedded Processing Subsystem and transmits serial messages over USB at a fixed update rate. On the host side, a software application will parse through the incoming data and display V_{rms} , I_{rms} , P, and PF numerically.

This subsystem ensures that measured quantities are presented to the user in real time, satisfying the third high-level requirement.

2.7.1 Communication Subsystem Requirements

The Communication Subsystem shall satisfy the following quantitative requirements:

- The subsystem shall transmit computed measurement values to a host computer over USB using a UART-based serial protocol.
- The data transmission rate shall be sufficient to support a minimum update frequency of 5 Hz without data loss.
- UART communication shall operate at a baud rate sufficient to transmit all required values within each update interval.

- The subsystem shall ensure that the loss of communication does not affect measurement computation within the Embedded Processing Subsystem.

Failure to meet these requirements would prevent the real-time display of measurement data and compromise system functionality.

2.8 Board Power Subsystem

The Board Power Subsystem is responsible for converting raw USB 5V power into stable voltage that is used for onboard electronics as well as providing a mid-voltage reference at 1.65V.

Utilizing a USB interface, the system draws USB 5V power directly from a connected PC. Then, the onboard regulator steps down the 5V input to a stable 3.3V which will be provided to the STM32 microcontroller to be able to run its logic operations and code.

Next, a voltage divider will be used to create a mid-rail reference at 1.65V which would be able to offset AC signals into a positive range (0V to 3.3V) that the microcontroller's Analog-to-Digital Converter (ADC) can safely process.

2.8.1 Board Power Subsystem Requirements

The Board Power Subsystem shall satisfy the following quantitative requirements:

- The provided 3.3V using the regulator must maintain a steady output with minimal ripple to prevent noise from affecting ADC measurement accuracy.
- There must be sufficient current to power the MCU, isolated sensing circuits, and any peripheral displays.
- The voltage divider must use high precision resistors to ensure the 1.65V offset remains consistent.

2.9 Tolerance Analysis

The most critical performance requirement is accurate real power and power factor measurement. These quantities depend on time-aligned sampling of voltage and current. Any sampling delay introduces phase error, which directly affects computed real power and power factor.

The Embedded Processing Subsystem requires channel-to-channel sampling skew less than 10 μ s. The resulting phase error at 60 Hz is:

$$\phi_{error} = 2\pi f \Delta t = 2\pi(60)(10 \times 10^{-6}) = 0.00377 \text{ rad} \approx 0.216^\circ$$

Since power factor is the cosine of phase angle, a small phase error of 0.216° (0.00377 rad) produces at most a 0.0038 change in PF. This is much smaller than the allowed ± 0.10 PF error. Therefore, channel timing skew is not expected to limit PF or real power accuracy.

The system will sample at a minimum rate of 3 kHz. For a 60 Hz waveform, this gives:

$$\frac{3000}{60} = 50 \text{ samples per cycle}$$

Using at least 5 cycles per computation window yields 250 samples per update. With 50 samples per cycle and averaging over multiple cycles, the discrete summation closely approximates the continuous RMS integral. For a smooth sinusoid, the numerical error at this sampling density is well below 1%, which is well below our allowed tolerance.

The microcontroller uses a 12-bit ADC over a 0-3.3 V input range. The least significant bit (LSB) size is:

$$LSB = \frac{3.3V}{2^{12}} = \frac{3.3}{4096} = 0.806 \text{ mV}$$

The maximum quantization error is $\pm \frac{1}{2} LSB$:

$$\epsilon_q = \pm 0.403 \text{ mV}$$

The conditioned voltage and current waveforms are designed to have peak amplitudes on the order of 1-1.5 V. Using the conservative lower bound of 1 V peak amplitude, the worst-case relative amplitude error due to quantization is:

$$\frac{0.000403}{1.0} = 0.000403 = 0.040\%$$

For a 1.5 V peak amplitude:

$$\frac{0.000403}{1.5} = 0.000269 = 0.027\%$$

Thus, quantization contributes less than 0.05% relative error in amplitude, which is negligible compared to the required voltage and current accuracy specifications. Quantization error is therefore not expected to limit measurement performance.

Therefore, overall measurement accuracy is expected to be limited primarily by analog sensing tolerances (VT ratio error, CT ratio error, and resistor tolerances), rather than by embedded computation.

3. Ethics, safety and societal impact

Ethics

Regarding ethics, we will strive to adhere to the IEEE Code of Ethics. Specifically for our project, it is imperative to ensure the safety of not only our group, but the users that will be using our power analyzer. We will ensure to have the implementation of specific safety hardware, including fuses and surge protection, to prevent catastrophic failure or fire hazards during operation, as well as disclose and

warn about the high-voltage risks associated with 120V AC. Moreover, by designing a functional, low-cost tool, this project supports the IEEE goal of improving the understanding of technology, specifically by making power quality analysis more accessible for educational and laboratory environments.

Safety

Due to working with 120V AC mains provided by the wall outlet, it is essential to make sure that the high voltage portion of our project remains electrically isolated from the rest of the components and low voltage equipment such as the microcontroller. To alleviate the dangers associated with working with high voltage, we will make sure to test and simulate our ideas initially through LTSpice and calculations before physically implementing and working on them. Furthermore, to also make sure that the user is protected from touching any components or voltage, the entire system will be enclosed in a portable encasing that will prevent any possible exposure. Additionally, it is essential to make sure that this enclosure has proper soldering connections, insulation of wires, and galvanic isolation boundaries to prevent overheating, arcing from low to high voltage, and shock protection.

Societal Impact

The development of our project is to provide a low cost, but effective single phase AC power analyzer that would be able to fill the gap in both educational and personal use. Commercial power quality analyzers are expensive and are reserved for industry and specialized research institutions. Therefore, we hope to be able to provide a low cost-alternative that could be used in laboratory and teaching environments. Furthermore, we believe that tool could be utilized personally to, for example, check appliances or homemade projects to make sure that the correct amount of AC power is being provided. Overall, through this project, we hope to be able make a useful tool more accessible for everyone, while still being accurate and efficient.