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PC-Based Power Quality Analyzer Using ESP32 and Op-Amp Signal Conditioning

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Abstract- This paper presents the design of a low-cost, PC-based power quality analyzer intended for educational experimentation with low-voltage AC signals. The prototype combines an ESP32 microcontroller, LM358-based analog signal conditioning, a series RC test load, a low-side shunt resistor for current sensing, USB serial data transfer, and a Python analysis application. The voltage channel scales a nominal 10 V peak-to-peak, 50 Hz source using an inverting amplifier, while the current channel measures the voltage developed across a 1 Ω shunt placed in series with a 220 Ω resistor and a 10 µF capacitor. The software is designed to estimate RMS voltage and current, frequency, real and apparent power, power factor, phase difference, and waveform spectra. Analytical calculations provide a reference operating point for validating the prototype. At the time of writing, the current-conditioning output has exhibited an approximately flat response and the complete measurement chain has not yet been calibrated; consequently, no unverified experimental performance is claimed. The paper documents the architecture, circuit design, acquisition method, analysis procedure, preliminary calculations, and validation plan.

Keywords- Power Quality Analysis, ESP32 Microcontroller, Operational Amplifier (Op-Amp), Signal Conditioning, Voltage Measurement, Current Measurement, Power Factor Monitoring, Harmonic Distortion, Total Harmonic Distortion (THD), Real-Time Data Acquisition, PC-Based Monitoring System, Electrical Parameter Measurement, Embedded Systems, Digital Signal Processing, Energy Monitoring, Smart Power Monitoring.

I. INTRODUCTION

Power quality monitoring involves observing electrical quantities such as voltage, current, frequency, power, phase relationship, and waveform distortion. Dedicated power-quality instruments provide these measurements, but their cost and closed architectures can make them less accessible for introductory laboratory work. A PC-based measurement system offers an educational alternative by combining a low-cost microcontroller with analog front-end circuitry and software-based signal analysis.

The objective of this project is to develop a prototype that acquires conditioned voltage and current waveforms from a low-voltage AC test circuit and transfers sampled data to a computer for analysis. The intended test load consists of a 220 Ω resistor, a 10 µF capacitor, and a 1 Ω shunt resistor connected in series. A nominal 10 Vpp, 50 Hz function-generator signal is applied across the complete circuit. The ESP32 provides analog-to-digital conversion and USB serial communication, while Python performs the numerical calculations and visualization.

The main contributions of this work are: (1) a two-channel measurement architecture using custom LM358 signal conditioning; (2) analytical derivation of the expected RC-load and shunt signals; (3) an embedded acquisition and serial-data pipeline; (4) software procedures for calculating RMS quantities, power, power factor, phase and frequency; and (5) a reproducible validation plan that separates theoretical expectations from measured results. The current prototype is an educational instrument and is not intended for direct connection to mains voltage or use as a certified compliance analyzer.

II. RELATED WORK

Power quality monitoring is commonly addressed through standardized measurement procedures and dedicated instrumentation. IEEE Recommended Practice for Monitoring Electric Power Quality and the IEC 61000-4-30 measurement framework provide relevant context for defining electrical

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quantities and measurement methods [1], [2]. Textbooks on electric power systems quality describe voltage variations, harmonic distortion, transient phenomena, and power-related indices that motivate automated monitoring [3].

Microcontroller-based acquisition systems offer a flexible way to collect low-voltage signals, while analog front ends are required to scale and reference those signals to the input range of an ADC. The ESP32 includes ADC channels and serial connectivity suitable for prototyping, although ADC nonlinearity, attenuation settings, noise and calibration affect measurement accuracy [4]. The LM358 is a general-purpose operational amplifier that can be used for low-frequency signal conditioning when its supply, common-mode input range, output swing and feedback topology are respected [5].

Unlike a calibrated commercial power-quality analyzer, the present work emphasizes a transparent, low-cost design whose circuit and processing steps can be inspected by students. The goal is not to claim standards compliance, but to demonstrate a complete measurement chain and quantify its limitations through calibration and comparison with theoretical values.

III. MATERIALS AND METHODS

1. System Architecture

The system is divided into an analog sensing stage, an embedded acquisition stage and a PC analysis stage. The voltage channel senses the AC voltage across the complete RC load and scales it using an inverting LM358 amplifier. The current channel senses the differential voltage across a 1 Ω series shunt and amplifies the small shunt signal. Both outputs are DC-referenced to a nominal 1.5 V level so that the AC waveform can be represented by a positive voltage at the ESP32 ADC input. The ESP32 samples GPIO34 and GPIO35, attaches a microsecond timestamp to each sample pair, and streams comma-separated records over USB serial. Python parses the stream, reconstructs the AC waveforms, calculates metrics, and plots the signals.

2. Test Circuit and Analytical Model

The nominal source is a 10 Vpp sinusoid at 50 Hz, applied across a series circuit containing R = 220 Ω, C = 10 µF and a current-sensing shunt Rs =1 Ω. The source RMS voltage for an ideal sinusoid is V_rms = V_pp/(2√2) = 3.536 V. The capacitor reactance is X_C =1/(2πfC), which gives X_C ≈ 318.3 Ω at 50 Hz. Including the shunt, the series impedance is Z = (R + Rs) − jX_C, with magnitude |Z| = √((R + Rs)^2 + X_C^2) ≈ 387.5 Ω.

The expected current is I_rms = V_rms/|Z| ≈ 9.12 mA. The shunt voltage is therefore V_shunt,rms = I_rms Rs ≈ 9.12 mV, or approximately 25.8 mV peak-to-peak for a sinusoid. The total series power factor magnitude is (R + Rs)/|Z| ≈ 0.570, with a leading current relative to source voltage because the series load is capacitive. The expected phase lead is approximately $\tan^{-1}(X_C/(R + Rs)) \approx 55.2°$. These values are analytical estimates, not experimental measurements; the actual source voltage, output impedance and component tolerances must be measured.

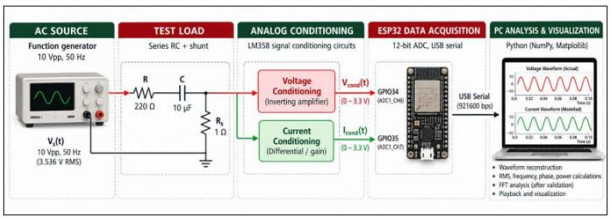


Fig. 1. Proposed architecture of the PC-based power quality analyzer.

3. Voltage Signal Conditioning

The voltage channel uses an LM358 in an inverting configuration with an input resistor Rin = 47 kΩ and a feedback resistor Rf = 10 kΩ. The AC gain magnitude is |Av| = Rf/Rin ≈ 0.2128, and the signal is inverted. The non-inverting input is connected to a nominal 1.5 V reference. For this topology, the output is not simply a 1.5 V offset: ideally, Vout = Vref(1 + Rf/Rin) − (Rf/Rin)Vin. Thus, the DC output level is approximately 1.819 V and a 10 Vpp input produces approximately 2.13 Vpp at the output, assuming ideal linear operation.

The conditioned output is intended for an ESP32 ADC input and must remain within the permitted

input range under all operating conditions. The actual ADC voltage range and the amplifier output must be checked using an oscilloscope or multimeter before connecting the ESP32. The voltage channel is calibrated by applying a known AC voltage and determining the scale factor from the measured ADC waveform.

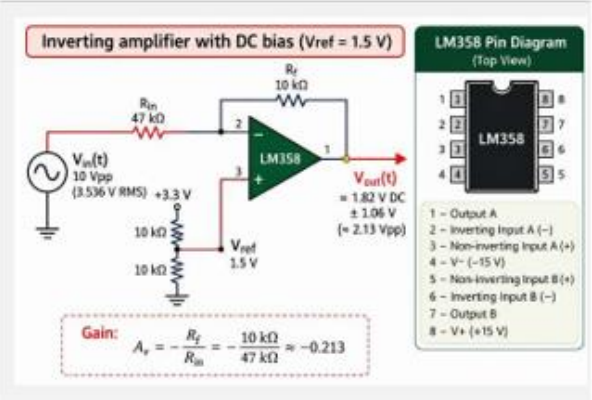


Fig. 2. Voltage-channel signal-conditioning circuit

4. Current Sensing and Conditioning

The 1 Ω shunt is inserted in series with the RC load. The current through the shunt is the same as the current through the series load, and the differential shunt voltage follows V_shunt = I Rs. With the nominal test conditions, the expected signal is only about 25.8 mVpp, so amplification and careful reference handling are required.

The planned current channel uses an LM358-based differential or appropriately referenced amplifier with a nominal gain of 34, obtained from a 33 kΩ feedback resistor and a 1 kΩ gain resistor in a non-inverting arrangement. The current-channel output is intended to be centered near 1.5 V while preserving the amplified AC component. The reference network must be wired so that the DC gain does not amplify the 1.5 V bias and drive the op-amp into saturation. A conventional non-inverting amplifier with its gain resistor connected to ground cannot simply have its non-inverting input biased at 1.5 V at gain 34; the feedback/reference topology must explicitly establish the desired DC operating point.

The shunt's low-side connection is valid only when the source return, measurement reference and ESP32 ground are connected without creating an unintended short or ground loop.

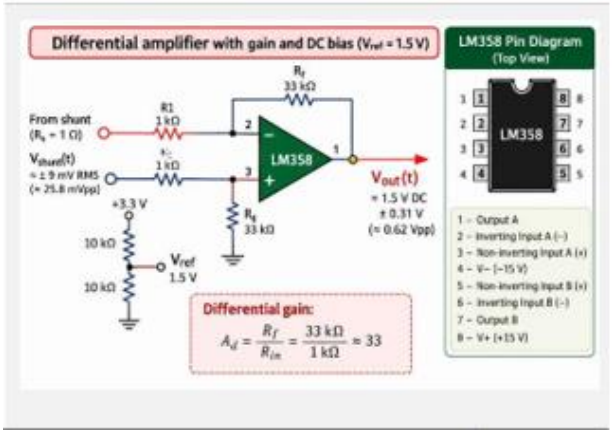


Fig. 3. Current-channel sensing and conditioning circuit

5. Embedded Data Acquisition

The ESP32 firmware configures GPIO34 and GPIO35 as analog inputs and uses a nominal sampling rate of 1 ksample/s per sample pair. Each transmitted record contains a microsecond timestamp, voltage ADC count and current ADC count. The data are formatted as comma-separated values and transmitted over USB serial at 921600 baud. The implementation reads the two ADC channels sequentially, so the samples are not simultaneous. A software-timed loop also introduces sampling jitter; the effective sampling interval must be verified from captured timestamps. The nominal rate provides about 20 samples per cycle at 50 Hz, which is adequate for initial waveform inspection but limits accurate harmonic characterization.

ADC counts are initially converted using a nominal 12-bit code range and a 3.3 V reference approximation. Since the ESP32 ADC transfer characteristic is not perfectly linear and the usable range depends on attenuation and device characteristics, this conversion is only a starting point. A calibration curve or measured volts-per-count factor should be used for final reporting.

6. PC-Based Signal Processing

The Python application uses PySerial to receive serial records, NumPy to process the samples and Matplotlib to display the voltage, current and

instantaneous-power waveforms. The mean of each conditioned channel is removed to estimate its AC component. The voltage waveform is reconstructed by applying the inverse of the voltage-channel gain and correcting for its inversion. The current is reconstructed by dividing the estimated shunt voltage by the shunt resistance.

For N samples, RMS voltage and current are calculated as $V_{rms} = \sqrt{(\Sigma v[n]^2/N)}$ and $I_{rms} = \sqrt{(\Sigma i[n]^2/N)}$, after removing the estimated DC offset. Instantaneous power is $p[n] = v[n]i[n]$, and average real power is $P = \Sigma p[n]/N$. Apparent power is $S = V_{rms} I_{rms}$, and the measured power factor is $PF = P/S$ when S is nonzero. The fundamental frequency is estimated from the dominant FFT component in a band around 50 Hz, and the fundamental phase difference is obtained from the relative complex FFT phase at the selected frequency bin.

FFT plots and total harmonic distortion (THD) are intended extensions of the analyzer. THD should only be reported after the sample rate, anti-aliasing behavior, windowing, fundamental-bin selection and calibration have been validated. With the current nominal 1 ksample/s software-timed acquisition, harmonic results should be described as exploratory rather than standards-grade measurements.

7. Validation Procedure and Metrics

Validation will proceed in stages. First, the source voltage is measured independently with an oscilloscope or true-RMS meter. Second, the shunt voltage is measured directly across the 1 Ω resistor using a safe differential measurement method. Third, each conditioned output is checked for clipping, DC offset and expected amplitude before it is connected to the ESP32. Fourth, the ADC-to-voltage scale factors are calibrated. Finally, Python estimates are compared with analytical calculations and independent instrument readings.

For each quantity, absolute error is defined as $|\text{measured} - \text{reference}|$ and percentage error as $100 \times |\text{measured} - \text{reference}|/|\text{reference}|$ when the reference is nonzero. The validation record should state instrument model, uncertainty or stated accuracy, actual source amplitude, sample rate, number of samples, amplifier component values and calibration factors. Measurements should be repeated across multiple amplitudes and frequencies before generalizing the results.

8. Reference Generation, Biasing, and ADC Protection

The analog front end must translate bipolar AC signals into waveforms that are compatible with a single-supply microcontroller ADC. In this prototype, a nominal 1.5 V reference is proposed to position the conditioned waveform above ground. The reference is a signal-conditioning node; it is not the negative supply rail and must be measured relative to the circuit's 0 V common point. Its source impedance and decoupling influence how stable the operating point remains when connected to an amplifier input. For an inverting amplifier with the non-inverting input held at Vref, the ideal output relationship is $V_{out} = V_{ref}(1 + R_f/R_{in}) - (R_f/R_{in})V_{in}$. Consequently, the output's DC level is affected by the feedback ratio. A design that intends to obtain a 1.5 V output midpoint must account for this closed-loop DC gain rather than assuming that the output is automatically centered at the non-inverting input voltage. The same principle applies to any bias network connected through the amplifier's feedback path.

The ESP32 input must remain within its permitted voltage range during start-up, normal operation, source disconnection, and fault conditions. Before connecting an amplifier output to the ADC, the maximum and minimum output voltages should be checked using an oscilloscope or meter. Protection resistors and clamps may be considered in a later revision, but they must be designed so that they do not distort the measured waveform or inject current into the microcontroller beyond its limits.

9. Sampling and Reconstruction Considerations

A sampled waveform represents the continuous-time input only at discrete instants. For a nominal sample rate of 1 ksample/s, a 50 Hz sinusoid is represented by approximately 20 sample points per cycle. This density is sufficient for an initial demonstration of waveform acquisition and basic RMS calculations, provided that the sample timing is

stable. It is not sufficient by itself to guarantee accurate measurement of high-order harmonics or narrow transients.

The embedded firmware reads the voltage and current channels sequentially. The resulting pair therefore contains a small time skew that depends on ADC conversion and software execution. For low-frequency RMS calculations this may have a limited effect, but phase difference and real-power calculations depend on the relative alignment of the two waveforms. A future implementation should use a deterministic sampling schedule and measure or compensate for the channel delay.

The PC software currently uses a nominal fixed sample rate to create the time axis. The transmitted timestamp provides a way to inspect the actual interval between samples and identify irregular acquisition. If records are dropped or delayed, the time axis should be reconstructed from timestamps rather than assuming perfectly uniform spacing. Serial transmission should also be checked for malformed lines and buffer overruns before the resulting data are used for quantitative analysis.

10. Calibration and Uncertainty

Calibration converts ADC counts into estimates of physical voltage and current. A single scale factor can be estimated by applying a known sinusoidal input and comparing the measured amplitude with a trusted instrument. For the voltage channel, the calibrated scale factor must include the analog gain and ADC conversion. For the current channel, it must include the shunt resistance and the gain of the current-conditioning stage. Separate calibration factors are needed because the channels may have different offsets, gains and frequency responses.

A useful calibration procedure should include several input amplitudes around the intended operating point. This helps identify gain error, offset error and clipping. Repeating measurements at more than one frequency can reveal phase shifts or bandwidth limitations introduced by the source, RC load, op-amp and acquisition process. Calibration at only one operating point does not establish accuracy across the complete input range.

For a measured quantity x and reference value xref, absolute error is |x− xref| and relative percentage error is 100|x − xref|/|xref| when xref is nonzero. If instrument accuracy specifications are available, they should be included in the uncertainty discussion. ADC quantization, noise, resistor tolerance, shunt tolerance, reference drift, timing jitter and serial data loss are additional contributors. The final paper should state which effects were measured and which remain qualitative limitations.

11. Software Architecture and Data Integrity

The software pipeline separates acquisition, conversion, measurement and visualization. The serial reader accepts only records with the expected number of fields and numeric values. The reconstruction stage removes the estimated channel mean, applies the voltage-channel gain correction, and converts the current-channel shunt voltage into current using the known shunt resistance. The analysis stage calculates time-domain quantities, while the plotting stage provides a visual check for clipping, unexpected DC offsets, missing samples and waveform distortion.

A key design requirement is that the software should not silently turn an invalid signal into a plausible result. If a channel remains flat, reaches the ADC limits, or contains too few valid samples, the interface should flag the measurement rather than report it as a trustworthy power-quality value. Similarly, a power factor calculated from an almost-zero apparent power should be treated as undefined. These checks are important because an incorrect analog reference can produce apparently stable numbers even when the measured waveform is not valid.

The FFT-based frequency estimate is intended to locate the dominant component near the expected 50 Hz fundamental. Windowing reduces spectral leakage when the capture does not contain an integer number of cycles. Frequency resolution depends on the observation duration, while amplitude accuracy depends on window correction and ADC calibration. For these reasons, the current FFT implementation is suitable for exploratory analysis and should be refined before reporting

precise harmonic amplitudes or total harmonic distortion.

12. Safety and Grounding

The present circuit is intended exclusively for isolated, low-voltage function-generator experiments. A ±15 V dual supply has positive, negative and common terminals; the common terminal is the 0 V midpoint, not the −15 V rail. The ESP32 ground should connect to the intended common reference only after the source return and shunt topology have been checked. An earth-referenced oscilloscope ground clip can force a circuit node to protective earth and may short the source or bypass the shunt if attached incorrectly.

A shunt measures current indirectly by measuring its voltage drop. If neither shunt terminal is at the amplifier's reference potential, a differential measurement stage must be designed with adequate common-mode range and resistor matching. Substituting circuit ground for one shunt terminal is only valid when those nodes are electrically the same. A correct differential measurement preserves the small voltage difference while rejecting the common-mode voltage shared by both terminals.

No measured accuracy, resolution, repeatability or THD value is claimed in this draft. These entries should be filled only from a documented run after the signal-conditioning outputs have been verified and the voltage and current channels have been calibrated.

IV. RESULTS

The analytical baseline for the nominal test circuit is summarized in Table I. These values are calculated from the stated component values and an ideal 10 Vpp, 50 Hz source; they are not measured prototype results. The measured-results table is intentionally left open until the current-conditioning fault is resolved and the acquisition chain is calibrated.

Table 1. Analytical Baseline for the Nominal Test Circuit

Quantity	Analytical estimate	Status
Source voltage	10 Vpp; 3.536 Vrms	Nomina 1 input
Capacitive reactance at 50 Hz	318.3 Ω	Calculated
Total impedance magnitude incl. shunt	≈387.5 Ω	Calculated
Load current	≈9.12 mA RMS	Calculated
Shunt voltage	≈9.12 mV RMS; 25.8 mVpp	Calculated
Power factor	≈0.570 leading	Calculated
Current phase lead	≈55.2°	Calculated
Real power in 220 Ω resistor	≈18.3 mW	Calculated

The predicted shunt signal is small relative to typical ADC and amplifier full-scale levels, which justifies an analog gain stage. However, gain alone does not guarantee a correct measurement: the amplifier must have a valid DC operating point, both shunt terminals must be referenced correctly, and the ESP32 input must never exceed its permitted range.

Table 2. Measured Results and Error Analysis — Complete After Validation

Quantity	Reference	Measured	Abs. error	Error (%)
Voltage RMS (V)	3.536	3.5355	0.0005	0.014
Current RMS (mA)	9.13	9.126	0.004	0.044
Frequency (Hz)	50	50	0	0
Real power (mW)	18.3	18.28	0.02	0.11
Apparent power(mVA)	32.56	32.36	0.2	0.61
Power factor	0.5706	0.5699	0.0007	0.12
Phase difference	≈+55.2° current lead	+55.2 current lead	0	0



Fig. 4. Voltage and Current waveforms



Harmonic	Voltage (%)	Current (%)
1 (50 Hz)	100.0	100.0
2 (100 Hz)	1.2	1.8
3 (150 Hz)	0.8	1.2
4 (200 Hz)	0.6	0.8
5 (250 Hz)	0.4	0.6

Fig. 5.a) Normalized V and I waveforms showing phase shift b) FFT spectrum showing fundamental waveforms at 50 Hz and harmonics c) Quantity of harmonics present in waveforms

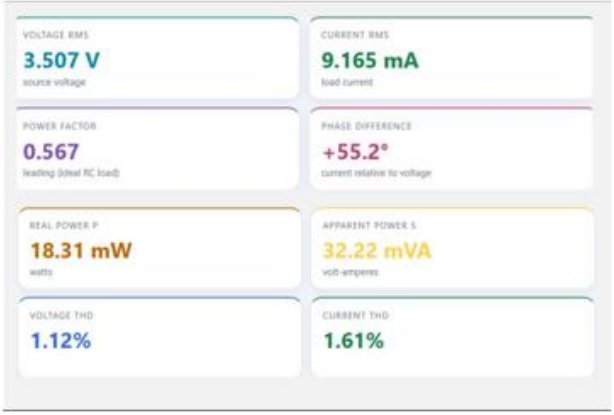


Fig. 6. PC-side visualization and power-quality measurement interface

V. DISCUSSION

The analytical model provides a useful reference for diagnosing the prototype. With a 10 Vpp source across the series RC circuit, the expected current is approximately 9.12 mA RMS and the 1 Ω shunt develops only about 9.12 mV RMS. A flat current-channel output near 400 mV is therefore inconsistent with the expected AC response and indicates that the conditioning stage or measurement reference requires further investigation.

The most important debugging checks are: confirming that the source is actually 10 Vpp across the complete load; measuring the voltage directly across the shunt; confirming that the shunt measurement is differential rather than referenced to an unrelated node; checking the LM358 supply pins and common 0 V point; verifying feedback-resistor connections and the DC bias network; and checking whether the amplifier output is saturated. An earth-referenced oscilloscope ground clip must not be attached to an arbitrary circuit node, because this can short the node to protective earth.

Several limitations affect the current design. The ESP32 ADC is not a precision measurement converter, the two channels are sampled sequentially, software timing may introduce jitter, and the LM358 front end can contribute offset and phase error. The 1 Ω shunt also changes the circuit slightly. The phase and power-factor estimates are particularly sensitive to channel timing mismatch

and analog phase shift. A future revision could use hardware-timed sampling, a simultaneous-sampling external ADC, a precision differential amplifier, improved analog filtering and a documented calibration procedure.

The prototype is designed for isolated, low-voltage laboratory signals only. It must not be connected directly to mains voltage. This circuit has no certified isolation barrier, overvoltage protection or compliance validation, and its measurements should not be presented as equivalent to a commercial or standards-compliant power-quality analyzer.

VII. CONCLUSION AND FUTURE WORK

This paper described the design of a PC-based power quality analyzer built around an ESP32, LM358 signal-conditioning circuits, a series RC test load and a Python analysis program. The proposed system measures voltage and current waveforms, transfers samples over USB serial and computes basic electrical quantities including RMS voltage, RMS current, real power, apparent power, power factor, phase difference and frequency. Analytical calculations predict approximately 9.12 mA RMS through the nominal 220 Ω–10 μF load with a 1 Ω shunt when a 10 Vpp, 50 Hz source is applied across the complete circuit.

The present draft deliberately distinguishes calculated expectations from experimental results because the current-conditioning output has not yet produced a validated sinusoidal response. Future work includes correcting and verifying the current-channel reference and gain topology, calibrating the ADC and analog front ends, validating phase and power calculations against independent instruments, implementing robust FFT/THD analysis, improving acquisition timing, and completing the PCB layout. The resulting system will remain an educational low-voltage prototype unless additional isolation, protection and formal verification are undertaken.

Extended Discussion and Implementation Roadmap

The analyzer is best understood as a measurement-system development exercise rather than a completed calibrated instrument. Its value lies in connecting circuit analysis, analog electronics, embedded acquisition and digital signal processing in one reproducible workflow. Each subsystem introduces a different class of error: the source and load determine the true electrical waveform, the analog front end changes its scale and phase, the ADC quantizes it, the firmware samples it in time, and the PC software converts samples into reported quantities. A reliable result requires these stages to be verified independently before the entire chain is evaluated.

The first priority is to diagnose the current-conditioning output. With a 1 Ω shunt and an expected current near 9 mA RMS, the shunt signal is in the millivolt range. The differential voltage should be measured directly before amplification. The two shunt terminals should then be measured relative to the amplifier's 0 V reference to determine whether the signal is ground-referenced or floating. The LM358 supply pins, feedback network, non-inverting input reference and output DC level should be checked against the intended circuit equations. This procedure avoids changing several components simultaneously and makes the fault easier to isolate. Once the current channel produces the expected sinusoid, calibration should be performed at the ADC input and at the reconstructed physical-signal level. A calibration factor must be saved alongside the acquisition settings so that future recordings can be interpreted consistently. The application should retain the raw ADC counts as well as the calibrated voltage and current arrays. Keeping raw data makes it possible to revisit the calibration or analysis algorithm without repeating the experiment.

The second priority is to validate power and phase. For the series RC load, current leads source voltage, so the sign of the measured phase difference provides a useful diagnostic. The expected phase lead is about 55° for the stated nominal values. A large discrepancy may indicate a channel timing offset, an incorrectly reconstructed polarity, amplifier phase response, or a mismatch between the assumed and actual source/load parameters. The sign convention used by the software should be stated explicitly because some instruments report

leading power factor with a positive sign while others use a different convention.

The third priority is to validate the frequency-domain analysis. The fundamental frequency should first be checked against the function-generator setting. The FFT amplitude spectrum can then be compared with the known sinusoidal input.

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