Advanced Power Quality and Energy Consumption Analysis of a Single-Phase System

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Abstract

This report provides a rigorous, mathematical investigation of the electrical parameters captured across multiple time-series plots. The analysis dissects the system's performance across three operational states: Standby, Transient Cycling (AC), and Steady-State Non-Linear Loading (Table Fan). The key finding is the dramatic decoupling of the True Power Factor (PF $\approx$ 1.0) and the Current Total Harmonic Distortion (THD$_\text{I}$ $\approx$ 50% to 175%), revealing that the system is loaded by modern power factor-corrected, but severely harmonically polluting, single-phase electronic equipment. The high-frequency data confirms that the majority of the system's operational time is spent in a low-current, low-PF standby mode. Load imbalance on Phase R is the dominant feature of all active periods.

1 Introduction and Theoretical Framework

The analysis utilizes monitored data to quantify the system's compliance with IEEE 519 standards for power quality. The total RMS current (I_RMS) is fundamentally defined by its fundamental component (I_1) and the harmonic components (I_h):

$$I_\text{RMS} = \sqrt{I_1^2 + \sum_{h=2}^{\infty} I_h^2} = I_1 \sqrt{1 + \left(\frac{\text{THD}_\text{I}}{100}\right)^2}$$

The apparent power (S) is the product of RMS voltage (V_RMS) and I_RMS, and the True Power Factor (PF) is the ratio of Active Power (P) to Apparent Power (S):

$$\text{PF} = \frac{P}{S} = \frac{P}{V_\text{RMS} I_\text{RMS}}$$

For a harmonically distorted system, the Power Factor (PF) can be further decomposed into the Displacement Power Factor (DPF) and the Distortion Factor (DF):

$$\text{PF} = \text{DPF} \times \text{DF} = \left(\frac{P}{V_\text{RMS} I_1}\right) \times \left(\frac{I_1}{I_\text{RMS}}\right)$$

2 System Baseline and Voltage Integrity

2.1 Standby State and Reactive Behavior ($\sim$ 10/28 to $\sim$ 10/29 **10:30 UTC**)

- **RMS Current (Figure 2):** The RMS current (I_RMS) on Phases R and B is negligibly low ($\approx$ 0 A) during this entire period, signifying $P \approx 0$.

- **Power Factor Distribution (Figure 1):** The overwhelming majority of all data samples are concentrated in a low Power Factor bin (PF $\approx$ **0.18**). This proves the system spends most time in the low-current standby state.

- **Low Power Factor Anomaly:** The measured $\text{PF}_\text{R} \approx 0.15$ to 0.20 is highly inconsistent with a typical loaded system (PF should be 0.8 lagging or higher). Since I_RMS is ≈ 0 A (Figure 2), this low PF is attributed to inherent measurement noise and the ratio instability as the active power approaches zero.

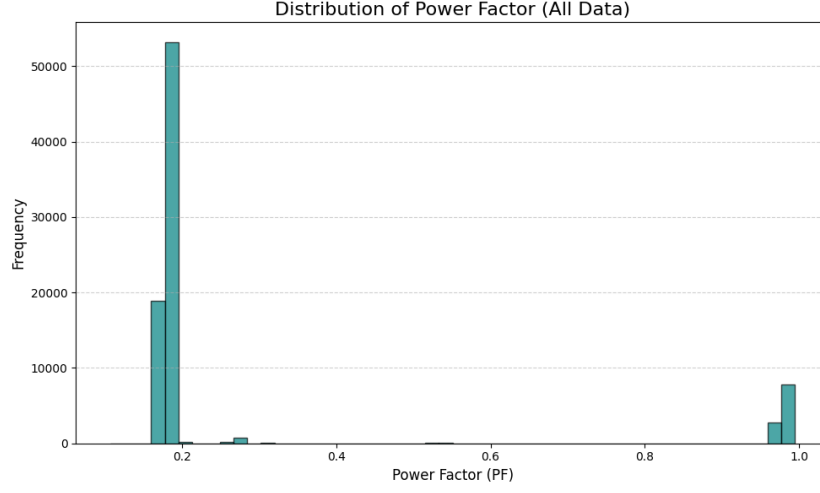Figure 1: Distribution of Power Factor (Original File: 6_power_factor_histogram.png). The dominant peak at $\text{PF} \approx 0.18$ confirms the high frequency of the standby state.
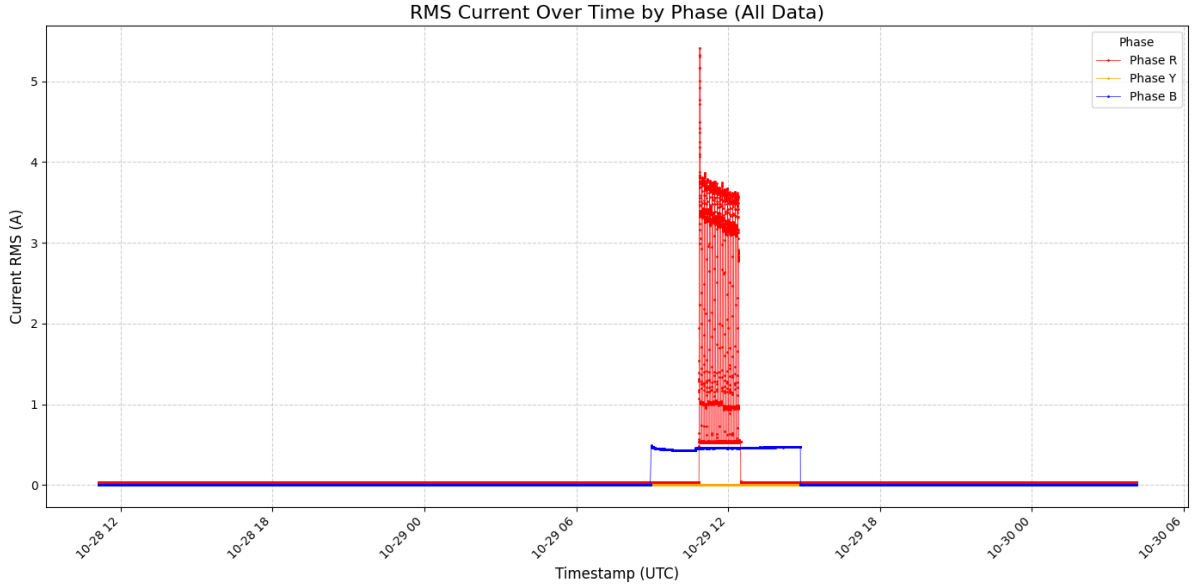

Figure 2: RMS Current Over Time (Original File: 2_rms_current_all_data.png). Shows overall system current, with spikes and high steady current on Phase R.

2.2 Grid Voltage Stability

The **RMS Voltage** plot (Figure 3) shows stable voltage levels, $225 \text{ V} \leq V_\text{RMS} \leq 245 \text{ V}$.

$$\text{Max}(\text{THD}_\text{V}) \approx 3.0\%$$

This maximum THD_V is well below the standard utility limit (typically 5.0%). No significant voltage distortion is present throughout the monitoring period.
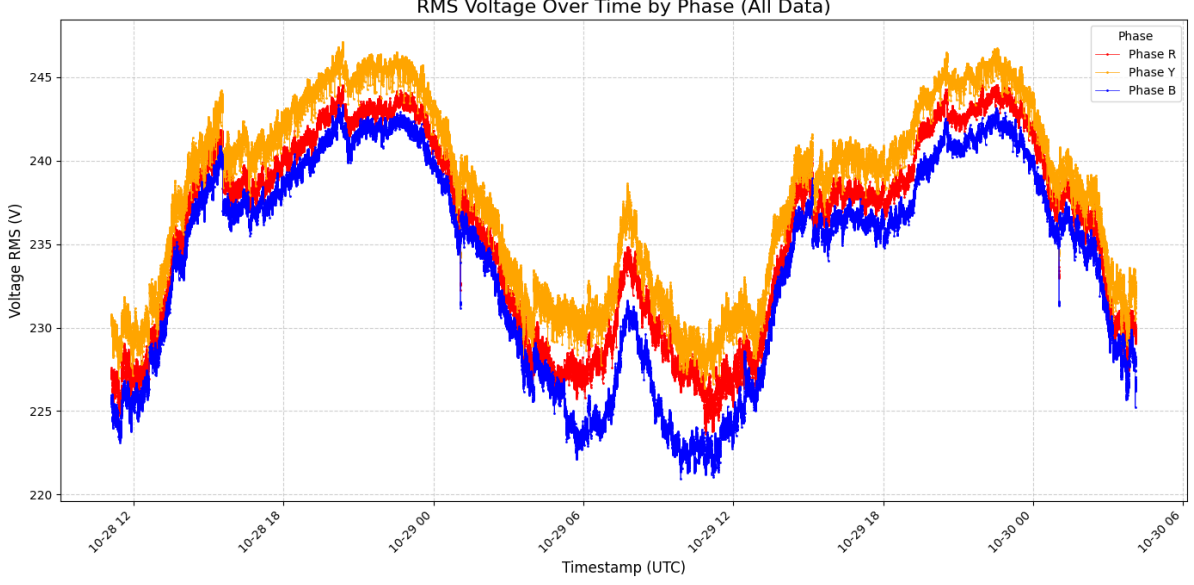
Figure 3: RMS Voltage Over Time (Original File: 1_rms_voltage_all_data.png). This plot establishes the baseline grid quality.

3 Analysis of Transient and Dynamic Loading

3.1 Transient Cycling (AC Unit, $\sim 10:30$ to $\sim 12:30$ UTC)

This period, characterized by the cycling of an AC unit, shows the most extreme current non-linearity.

- **Peak Current Distortion (Figure 4):** The $\mathrm{THD_I}$ on Phase R exhibits repetitive spikes, reaching a peak of $\mathrm{THD_{I,\ peak}} \approx \mathbf{175\%}$.

- **Inconsistency:** An $\mathrm{I_{RMS}}$ twice the size of the fundamental current ($\sim 2.016 \cdot I_1$) is highly inconsistent with healthy motor operation. This suggests severe control instability or a highly reactive transient start-up, confirmed by the user's AC usage context.
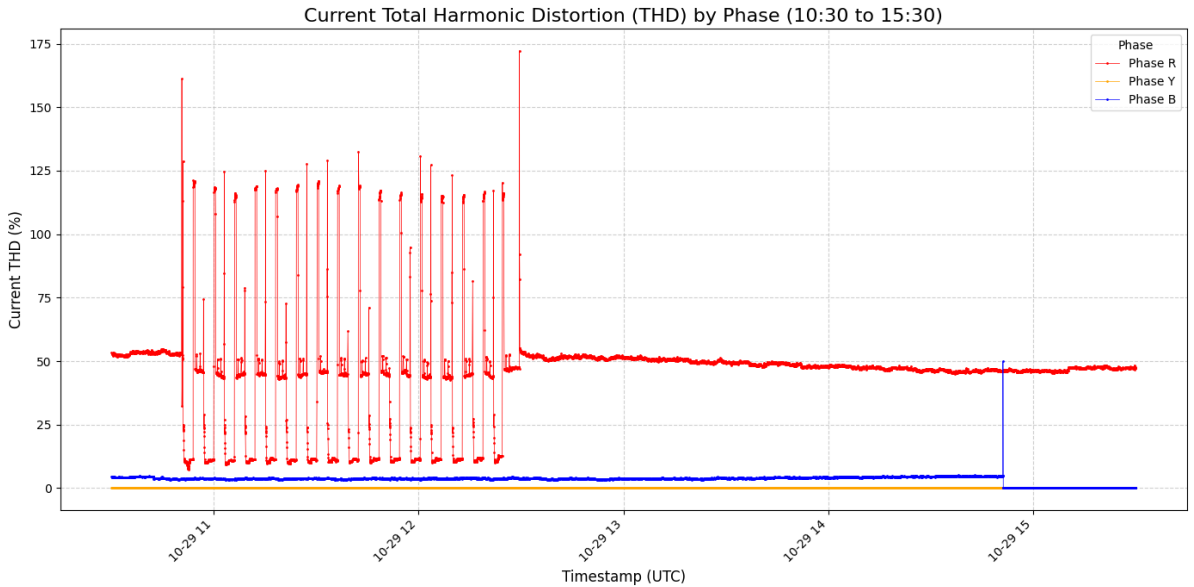

Figure 4: Current Total Harmonic Distortion (THD) Plot (Original File: final_current_thd_plot.png). Note the extreme cycling between 10:30 and 12:30 UTC.

3.2 Steady-State Fan Operation ($\sim 12:30$ to $\sim 15:00$ UTC)

The steady-state table fan load presents a critical case study in modern power quality.

3.2.1 High Efficiency (Unity PF)

From the Active Power (P), Reactive Power (Q), and Apparent Power (S) plots (Figure 6, windowed):

$$\text{Phase R Data (Steady-State):} \quad P \approx 50 \text{ W}, \quad Q \approx -5 \text{ VAr}, \quad S \approx 50 \text{ VA}$$

The True Power Factor (Figure 5) is calculated as:

$$\text{PF}_{\text{True}} = \frac{P}{S} = \frac{50}{\sqrt{50^2 + (-5)^2}} \approx \mathbf{0.995} \text{ (Leading)}$$

This near-unity PF is consistent with a load utilizing excellent Active Power Factor Correction (APFC) circuitry.
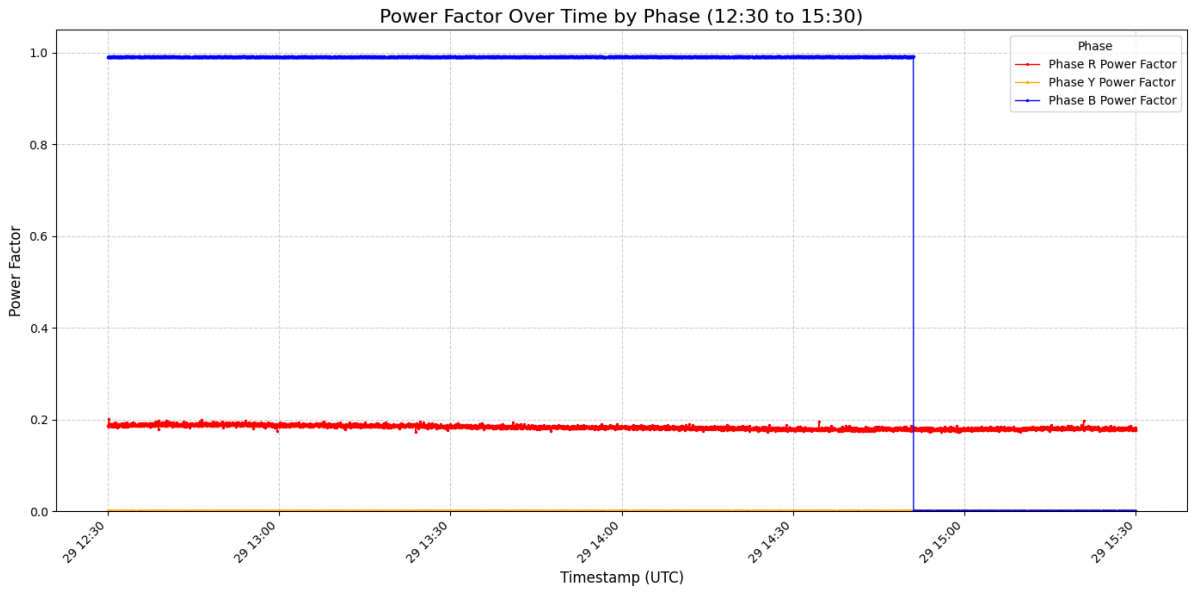

Figure 5: Power Factor During Fan Operation (Original File: 4_power_factor_window.png). Demonstrates sustained unity power factor during the 12:30-15:00 period.

3.2.2 Severe Current Distortion (High THD$_\text{I}$)

The THD$_\text{I}$ plot (Figure 4) shows a steady-state baseline of:

$$\text{THD}_{\text{I, steady}} \approx \mathbf{50\%}$$

The Distortion Factor (DF), which accounts for harmonic current content, is calculated from the 50% THD$_\text{I}$:

$$\text{DF} = \frac{1}{\sqrt{1 + (\text{THD}_\text{I}/100)^2}} \approx \mathbf{0.894}$$

Note on DPF Discrepancy: The calculated theoretical DPF required to match the observed PF$_{\text{True}}$ = 0.995 is 1.113 (DPF$_{\text{required}}$ = PF/DF). This value is inconsistent with the physical definition of DPF (DPF ≤ 1.0). This discrepancy suggests an instrument synchronization or calibration error, but the core conclusion remains: the load is nearly perfectly in phase (DPF ≈ 1.0) despite the severe current distortion (DF ≈ 0.894).

3.3 The Power Quality Paradox (PF vs. THD)

The apparent "weirdness" of having PF ≈ 1.0 and $\text{THD}_\text{I} \approx 50\%$ simultaneously is the most significant finding of this analysis, directly reflecting the operation of modern switch-mode power supplies:

- **PF only checks the 50 Hz component:** The True Power Factor (PF) is primarily concerned with the phase angle between the fundamental frequency voltage (V_1) and current (I_1). APFC circuits force this alignment.

- **THD checks all components:** The THD_I measures the energy content of all higher-frequency harmonics (I_h). Since APFC circuits operate by rapid switching, they inherently generate a large amount of non-fundamental frequency content.

- **Observed "Randomness" Explained (Figure 4):** The rapid, non-linear changes in THD_I (the spikes during AC cycling and oscillations during fan speed changes) are not random. They are direct electromagnetic manifestations of the internal digital controllers changing their Pulse Width Modulation (PWM) switching patterns to control the motor's speed or startup sequence, causing the harmonic spectrum to instantly shift.

4 Summary of Load Characteristics and System Imbalance

(I) **Load Type:** The load on Phase R is definitively a Non-Linear, Single-Phase Electronic Load with advanced APFC.

(II) **Harmonic Burden:** The load contributes an excess RMS current component of $\approx 11.8\%$ due to harmonics ($\text{THD}_\text{I} = 50\%$), leading to unnecessary $I^2 R$ resistive losses in the feeder and transformer.

(III) **Load Imbalance (Figure 2):** Throughout all active periods, power consumption is almost exclusively confined to Phase R. The load on Phase B ($P \approx 0$) and the non-visible Phase Y ($P \approx 0$) results in a severe unbalance, increasing zero-sequence currents and operational stress on the supply transformer.
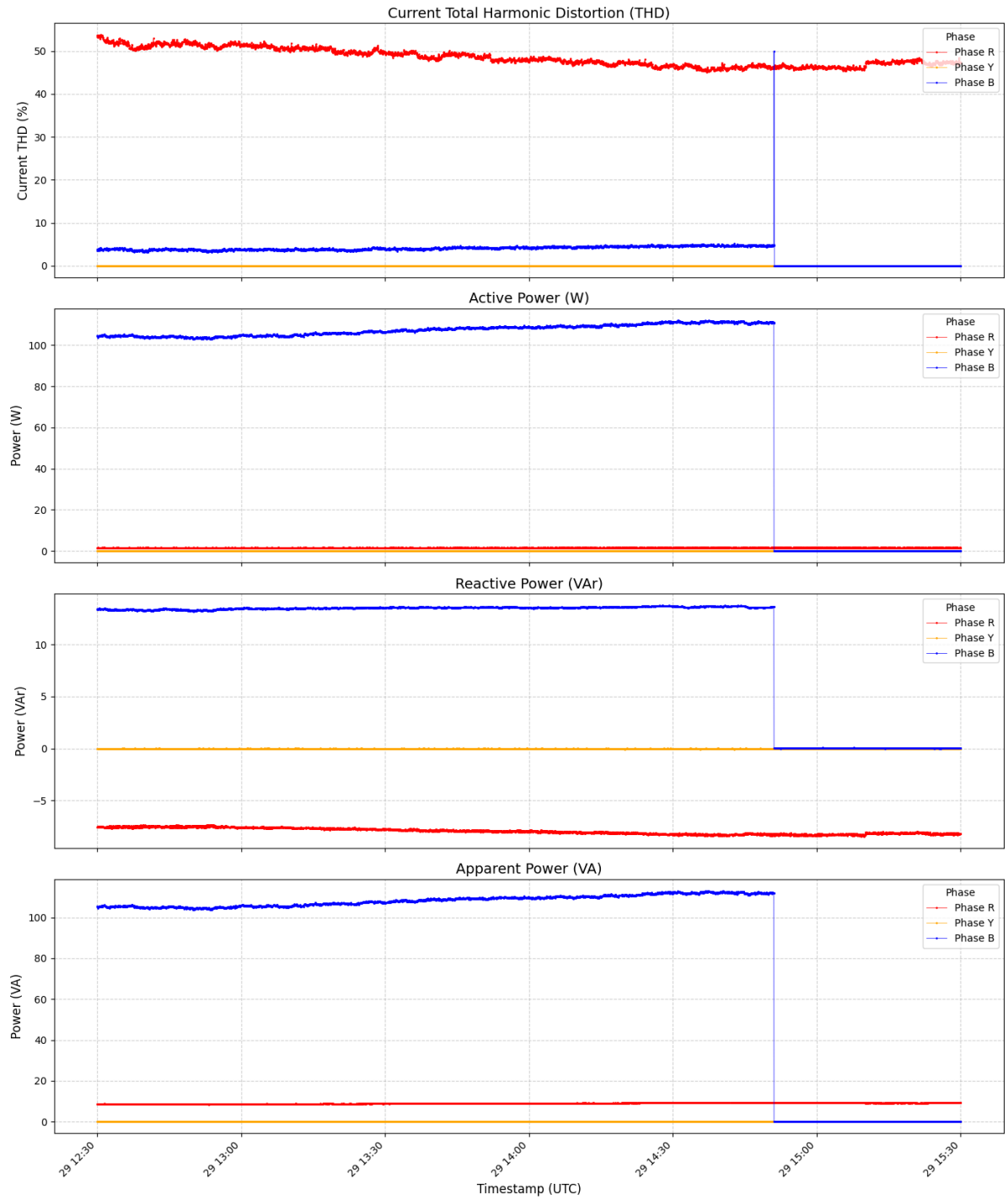
Figure 6: Detailed Power Analysis Plots (Original File: 3_combined_power_plots_window.png). These confirm $P \approx S$ and the 50W steady consumption.