re:3D GigabotX 2 XLT 900 Power Assessment at JIFX 26-3

Continuous Waveform Measurement
during Printing Operations

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1 Executive Summary

Every aspect of the printer's electrical operation over the 24.8-hour assessment window is consistent with **standard, best-practice engineering** — controlled, zero-cross-aligned switching of the main heater; tight regulator-driven duty cycling; smooth motion-side current through the internal DC bus; clean supply within ANSI C84.1 Range A for >99 % of the window; and per-part energy in the expected band for the machine class. **No observable operational concerns**: peak current ≈ 10.8 A on a 20 A circuit, with substantial headroom. The current channel has been bench-calibrated against a calibration-grade DMM (see *Measurement Notes*); all figures throughout reflect that calibration.

Headline findings:

- **The printer operates in five distinguishable modes**, inferred from the AC power signature. The structure is a cross-product of *heater state* (off-duty vs full-on pulse) and *motion state* (steppers / extruder de-energized vs energized), plus the idle baseline. The five labels below are used throughout the report:
  - **Idle** — ~52 W (controller, fans, no heaters and no motion)
  - **Heater off-duty, no motion** — ~210 W (inter-pulse level once heaters are cycling; no motion)
  - **Heater off-duty + motion** — ~300 W (same heater state, with steppers / extruder energized)
  - **Heater on-duty, no motion** — ~1.04 kW (heater fully on, sustained pre-heat ramp or a mid-print heater pulse with motion idle)
  - **Heater on-duty + motion** — ~1.19 kW (heater fully on with motion — the peak of a heater pulse)
- **Energy consumed over the measurement window: 4.08 kWh across 12 parts** — 1 long part in Session 1 (1.09 kWh over 139 min) and 11 shorter parts in Session 2 (mean 0.27 kWh, range 0.087–0.74 kWh; 2.99 kWh total). A part is defined as a continuous active stretch separated from the next by a return to idle; Session 1's count carries a single caveat from a ~32 s data gap at 18:41 PDT (see *Session Power Profiles*).
- **Peak draw ≈ 1.30 kW** at the heated bed during a heater pulse. Peak RMS current ≈ 10.8 A on a 20 A circuit; the running RMS over longer windows stays well under 11 A, with substantial headroom. The pellet extruder's hopper / barrel heaters reach the AC inlet through the printer's internal AC-DC supply, so they appear as a smoothly-varying base load rather than stacking with the bed-heater pulses (see *Load Disaggregation*).
- **Voltage held within ANSI C84.1 Range A for >99 % of the window**, with the deepest heater-pulse transient briefly dipping to 113.0 V (0.942 pu) — printer self-induced droop, not a supply-side event, and well above the 0.9 pu / 108 V sag threshold of IEEE Std 1159. Supply voltage 116–123 V (5th to 99th percentile), with the distribution split between a ~122 V state overnight and a ~119 V state during the day; **frequency exceptionally stable** at 60.008 Hz (mode); 99 % within 59.96–60.04 Hz.
- **Source impedance** at the supply outlet is ~**0.25 Ω** (Thevenin equivalent upstream of the printer's line cord, from a grid-state-conditioned V-vs-I analysis — see *Source Impedance* for the full derivation and why the simpler unconditioned regression overestimates it as ~0.37 Ω), giving a steady voltage droop of ~0.25 V per amp of additional draw.
- **The printer's AC-DC supply isolates motor switching from the AC inlet.** The NEMA 23 stepper drivers chop coil current via PWM on the printer's internal 24 VDC bus, and that switching is filtered

out before reaching the inlet. Motion activity therefore shows only as the smoothly-varying base-load lift in heater-on-duty mode, with no stepper-PWM spectral content upstream.

2 Introduction

EQ Systems Inc. ("EQ") assessed the U.S. Army-owned re:3D GigabotX 2 XLT 900 (manufactured by re:3D) at the **JIFX 26-3** event, hosted at the Naval Postgraduate School (NPS), 11–15 May 2026. The printer was sited in the hangar at **McMillan Airfield** — the NPS Field Laboratory inside **Camp Roberts**, the California National Guard training area near Paso Robles, CA. McMillan Airfield is **grid-connected** for the duration of the event — not running on generator power — so the supply discussed throughout this report is the utility feed delivered to the airfield's hangar circuits, and ultimately to the outlet the printer is plugged into.

EQ delivers measurement and analytics services under the **Energy Quotient™** product platform, which comprises:

- **EQ Wave™** — a continuous-waveform measurement unit (WMU) installed on the printer's 120 VAC supply, sampling voltage and current at 32 000 samples per second. The raw stream is what we call **CPOW** (continuous point-on-wave); the unit also computes power-monitor (**PMon**) aggregates once every 12 line cycles (5 Hz at the 60 Hz nominal frequency).
- **EQ Coherence™** — data acquisition, storage, and filtering of the Wave streams.
- **EQ Syntropy™** — physics-grounded analytics and agentic AI; the cognition layer of the platform. Syntropy accesses Coherence's APIs and additionally subscribes to live CPOW data.

Methodology check. This assessment infers the printer's behavior from a single AC-inlet measurement, with no internal-machine telemetry. The initial analysis drew on the AC-inlet data, re:3D's public product pages, and general power-engineering knowledge. re:3D's engineering team has since reviewed it and corrected two inferences:

1. **The hopper / barrel heater is DC-driven**, not AC. The small steady draw we initially attributed to an AC barrel heater on PID hold is in fact the AC-DC supply feeding the hopper heater on the printer's internal DC bus.
2. **The current channel was found to be mis-scaled.** Our JIFX field kit paired a 200 A primary, 100 mA secondary metering-class CT with the Wave's internal *differential* burden — a configuration we had not previously bench-characterized — against firmware whose `CT_DIV` was written for a single-burden output. We addressed this within two weeks of the event: procured a calibration-grade DMM, built a bench calibration rig, and calibrated both the current and voltage channels of the Wave against the reference. Every figure in this report reflects the resulting back-correction; see *Measurement Notes* for the calibration record.

The remaining named loads and components in this report match re:3D's design as confirmed in that review.

The deployment exercised the EQ workflow under the conditions JIFX is designed to produce. The program's **Failure = Learning** tenet runs the field week as a rapid iteration loop in which surfacing gaps and adapting in real time is the value, not a failure mode. JIFX is sponsored by the U.S. Department of Defense's Office of the Under Secretary of Defense for Research & Engineering (OUSD R&E) and NavalX, runs on roughly even private-industry and government participation, and is documented as a strategic entry point into the defense market for early-stage dual-use technology, with alumni maturing into acquisitions across analytics, defense aerospace, and power electronics.[1]

The v0.2 draft of this report, with all underlying data capture, was delivered to re:3D for engineering review within 72 hours of the event. That review surfaced the CT-burden mis-scaling described above; the correction (bench-calibration of both channels against a calibration-grade DMM plus back-correction of every figure) closed two weeks from the v0.2 hand-off and is the basis for this revision. Most of that two weeks was calendar time required by other business; the bench-cal work itself was 6–8 hours — roughly half setup and rigging, half measurement and analysis.

By comparison, commercial third-party power-quality assessments typically run on multi-week to multi-month timelines; IEEE Std 1159-2019 (*IEEE Recommended Practice for Monitoring Electric Power Quality*) frames the monitoring window alone at one to several weeks for facility surveys. **CPOW collapses that envelope by preserving every sample of voltage and current at the inlet.** Any follow-on question — harmonic analysis, alternate disaggregation, new operating modes, partner-driven re-scoping — runs against the existing field dataset without re-deploying. The CPOW record also carries its own forensic context: traditional event-triggered or RMS-aggregating meters routinely omit sub-cycle transients, slow-onset anomalies, and events that did not cross the trigger threshold — gaps that CPOW captures by design.

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[1] Book, A. (2025). *The Impact of the Joint Interagency Field Experimentation Program on Small Business Success.* SYM-AM-25-315, Twenty-Second Annual Acquisition Research Symposium, Naval Postgraduate School. `https://hdl.handle.net/10945/73785`. Acquired alumni include Splunk (Cisco, $28,B); Aurora Flight Sciences (Boeing); and Protonex (Ballard Power Systems, fuel-cell power electronics) — compiled from Table 1 of the same publication.

3 Deployment and Data

Deployment specifics that ground the results in this report are summarized in Table 1.

Table 1: Deployment specifics.

Item	Value
Site	hangar at McMillan Airfield, Camp Roberts (NPS Field Laboratory), near Paso Robles, CA — JIFX 26-3, 11–15 May 2026
Asset	**re:3D GigabotX 2 XLT 900** — large-format **FGF (fused-granulate fabrication)** printer fed by plastic pellets / chips / flakes through a hopper, dual pellet extruder, ∼900 mm Z build height (U.S. Army property; manufactured and operated at the event by re:3D)
Sensor	EQ Wave WMU — Wave v1.1 hardware, configured in single-phase mode on a 120 VAC outlet
Sample rate	32 ksps CPOW; PMon aggregates every 12 line cycles (5 Hz at 60 Hz nominal)
Measurement bandwidth	8 kHz (133rd harmonic of a 60 Hz grid, well beyond the 50th-harmonic envelope used in IEEE 519)
Window analyzed	2026-05-12 16:39 PDT → 2026-05-13 17:25 PDT (∼24.8 h)
Sessions	Session 1 — *Single 139-min print* (1 part), 16:39–18:58 PDT (12 May). Session 2 — *Eleven-part run*, 09:17–17:20 PDT (13 May)
Channels populated	VA, IA (single-phase 120 V outlet); other channels unused
Data captured	32 ksps CPOW continuous over the 24.8 h window — 2.86 billion samples per channel, 5.7 billion CPOW samples across the V and I channels. PMon 5 Hz records — 446 k records carrying 8 metrics each (RMS V/I, active P, fundamental RMS V/I, fundamental P/Q, frequency). Full CPOW + PMon archives are retained on EQ-hosted storage and available for further analysis.

3.1 Measurement Notes

Post-event calibration against a Siglent SDM3065X-SC reference (6½-digit DMM) surfaced a 2× over-read in the current channel and a ~1% residual in the voltage channel. Both corrections are applied throughout this report.

Measurement reference plane. Voltage and current are both sensed at the EQ Wave's current-measurement line splitter, which sits between the supply outlet and the printer's line cord (Figure 1). All voltage values in this report — including the source-impedance results in *Source Impedance* — are referenced to

Figure 1: EQ Wave v1.1 install at JIFX 26-3, McMillan hangar. The Intellimeter CT (upper left) is clamped around the line conductor exposed by the measurement line splitter. The L/N terminals power the Wave (~2.5 W); L and N are jumpered to V1 and V0 for voltage sensing. Optical-fiber uplink active (both indicator LEDs green).

that point; the drop across the printer's own line cord is downstream of the measurement and not included.

- **Current channel — sensor configuration and calibration**: an Intellimeter-brand metering-class CT (200 A primary, 100 mA secondary) terminated on the EQ Wave's built-in **2 × 2.74 Ω differential burden resistors** (0.1% tolerance, 25 ppm/°C; 5.48 Ω total across the pair). The CT is external; the burden pair is internal to the Wave, across the differential current input ahead of the analog-to-digital converter (ADC). EQ's standard sensor for assessment work is the **ACCU-CT 0750 series** split-core CT (Continental Control Systems / Socomec, ±0.75% accuracy 1–120%, IEEE C57.13 class 1.2, with a factory-installed 333 mV output — plug-and-play into the Wave's standard input); the JIFX field kit carried the Intellimeter against the differential-burden internals, which is what prompted the post-event bench cal below.
  - **Post-event bench calibration (2026-05-28).** The CT + burden pairing was bench-calibrated against the Siglent SDM3065X-SC (factory-calibrated by Siglent on 2025-09-17, ~8 months prior to the bench cal) at a 9.96 A reference current (5-minute paired capture, 280 samples on a 1-

  Hz grid). The empirical correction has two components: (1) a **2× topology correction** (k = 0.5) — the firmware divider was written for a single-burden output, so against the differential burden in hardware the Wave reports 2× the true current as a baseline; and (2) a **residual gain trim** (k = 0.98564, ~1.4% below unity) absorbing CT non-linearity at ~5% of full scale and ADC gain/offset — comparable to the voltage channel's 0.99030 gain trim. The paired-ratio std on the combined factor is ~0.01%, reference-limited at this precision. The voltage channel was bench-calibrated against the same reference across 75 / 100 / 120 V and shows a clean $\mathbf{k_{voltage} = 0.99030}$ gain trim with no detectable non-linearity. Both corrections are applied throughout this report.
  - The 200 A primary is heavily oversized for a ~11 A peak load (operating at ~5.5% of the primary range), which trades off resolution. The EQ Wave's 24-bit ADC delivers approximately **16 bits ENOB** (effective number of bits — the practical noise-limited resolution), which against the 200 A primary range gives a current resolution of ~3 mA, or ~0.4 W at nominal 120 V. The ~25 W heater-pulse variation discussed in *Main Heater Switching* below sits roughly 60× above that floor.
- **Field validation channel.** Our JIFX field kit did not include a clamp-on current meter for independent in-field cross-check on the current channel, and the printer's outlet did not permit safe in-line measurement with a benchtop meter. As a result, the burden-pairing mis-scaling was not caught on-site and was instead identified during post-event bench calibration. A Fluke 376 FC clamp-on current meter is on order so that future engagements include an independent in-field cross-check on the current channel.

4 Session Power Profiles and Energy Budget

This section is the per-part energy budget — energy consumed and peak power demand per part across the run.

The printer falls back to a ~52 W idle between parts (Figure 2 and Figure 3). We define a **part** here as a continuous active stretch where P stays above ~125 W — each return to idle ends a part and the next active stretch starts a new one. By this definition we count **1 part** in Session 1 and **11 parts** in Session 2.

The Session 1 part count carries one caveat: a ~32 s data gap at 18:41 PDT (two short recorder restarts in quick succession) sits inside the single 139-min active window. If the printer briefly dropped to idle during that gap, what we count as one 1.09 kWh part may actually have been two smaller parts back-to-back. The AC measurement alone cannot resolve it; internal printer data was not used in this report.

Table 2 lists the per-part energy budget; Table 3 aggregates by session.

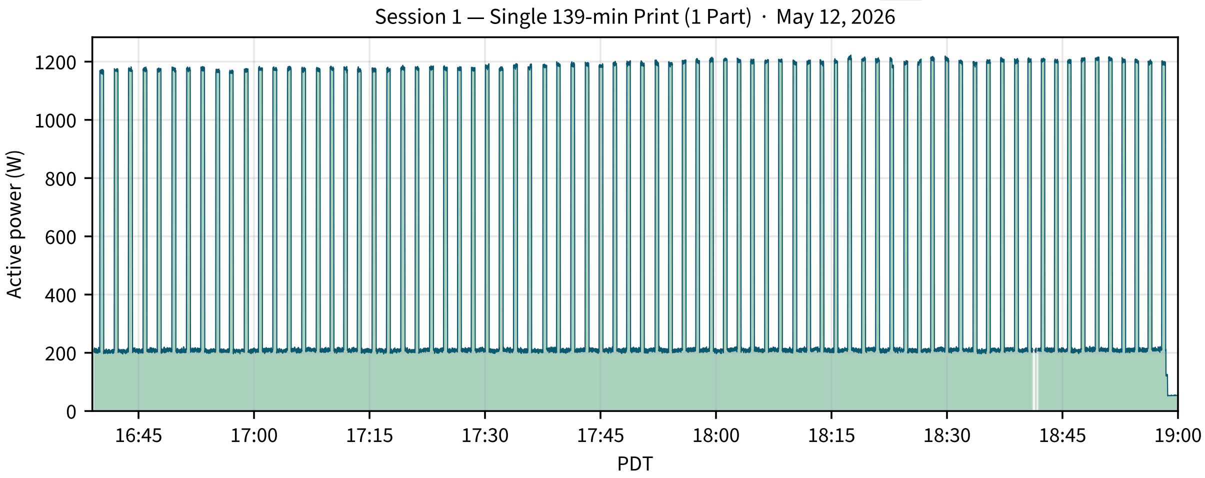


Figure 2: Session 1 active-power profile (single 139-minute print). A break in the trace is a data gap (recorder restart) spanned by a dotted connector, not a return to idle.

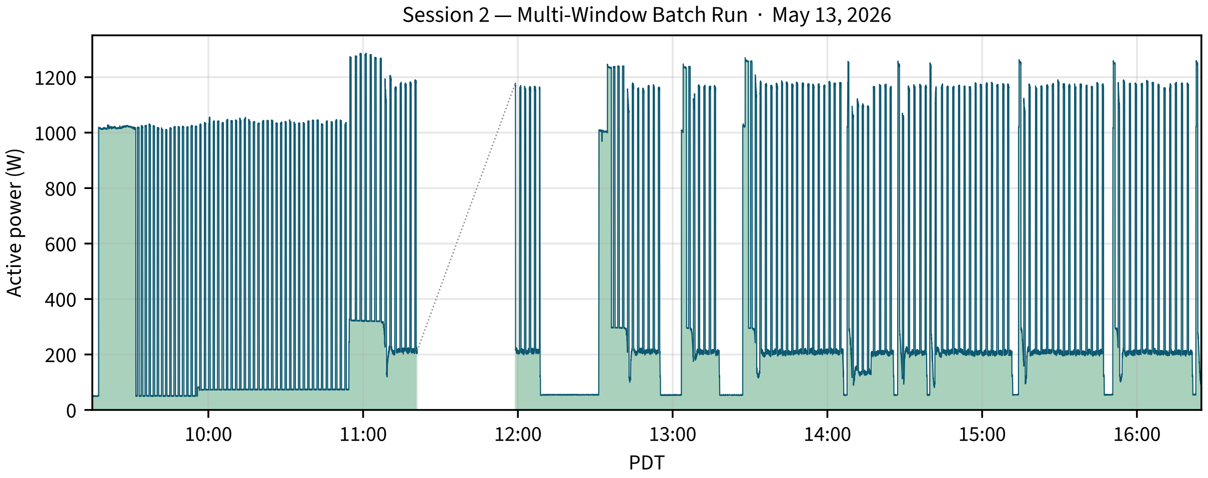


Figure 3: Session 2 active-power profile (eleven-part run). Breaks in the trace are data gaps (recorder restarts) spanned by a dotted connector, not returns to idle.

Table 2: Per-part energy budget.

Part	Start (PDT)	End (PDT)	Duration	Peak	**Energy**
S1-P1	05-12 16:39	05-12 18:58	139.4 min	1.22 kW	**1.09 kWh**
S2-P1	05-13 09:17	05-13 09:36	18.5 min	1.03 kW	0.28 kWh
S2-P2	05-13 10:54	05-13 12:08	74.1 min	1.29 kW	**0.74 kWh**
S2-P3	05-13 12:31	05-13 12:55	23.7 min	1.25 kW	0.24 kWh
S2-P4	05-13 13:03	05-13 13:18	14.6 min	1.25 kW	0.13 kWh
S2-P5	05-13 13:27	05-13 14:06	39.1 min	1.27 kW	0.31 kWh
S2-P6	05-13 14:07	05-13 14:25	18.1 min	1.26 kW	0.13 kWh
S2-P7	05-13 14:27	05-13 14:38	11.4 min	1.26 kW	0.09 kWh
S2-P8	05-13 14:39	05-13 15:11	32.1 min	1.25 kW	0.22 kWh
S2-P9	05-13 15:14	05-13 15:47	33.2 min	1.26 kW	0.24 kWh
S2-P10	05-13 15:50	05-13 16:21	30.9 min	1.26 kW	0.22 kWh
S2-P11	05-13 16:22	05-13 17:20	58.1 min	1.26 kW	0.39 kWh

Table 3: Session totals.

Session	Parts	Total active	**Total energy**	Mean per part	Largest part
1	1	139.4 min	**1.09 kWh**	1.09 kWh	1.09 kWh
2	11	353.8 min	**2.99 kWh**	0.27 kWh	0.74 kWh
Cumulative	**12**	**493.2 min**	**4.08 kWh**	0.34 kWh	1.09 kWh

Session 1's single part dominated both duration and energy. Session 2 is a sequence of 11 shorter parts separated by returns to idle (one ~78-min idle stretch clearly delimits the morning's first part from the rest of the run; subsequent idle stretches are 1–9 min and appear to be quick part-to-part turnarounds). Per-part energy spans 0.087–1.09 kWh — a factor of ~12 across the captured population.

5 Grid Supply

This section characterizes the McMillan hangar supply against ANSI C84.1 (voltage, frequency, and stability), and quantifies the local source impedance at the printer's outlet.

The printer was monitored on the McMillan Airfield hangar's 120 VAC single-phase service (grid-connected as noted in *Introduction*). Power to the hangar is fed from the main breaker at Building 3.

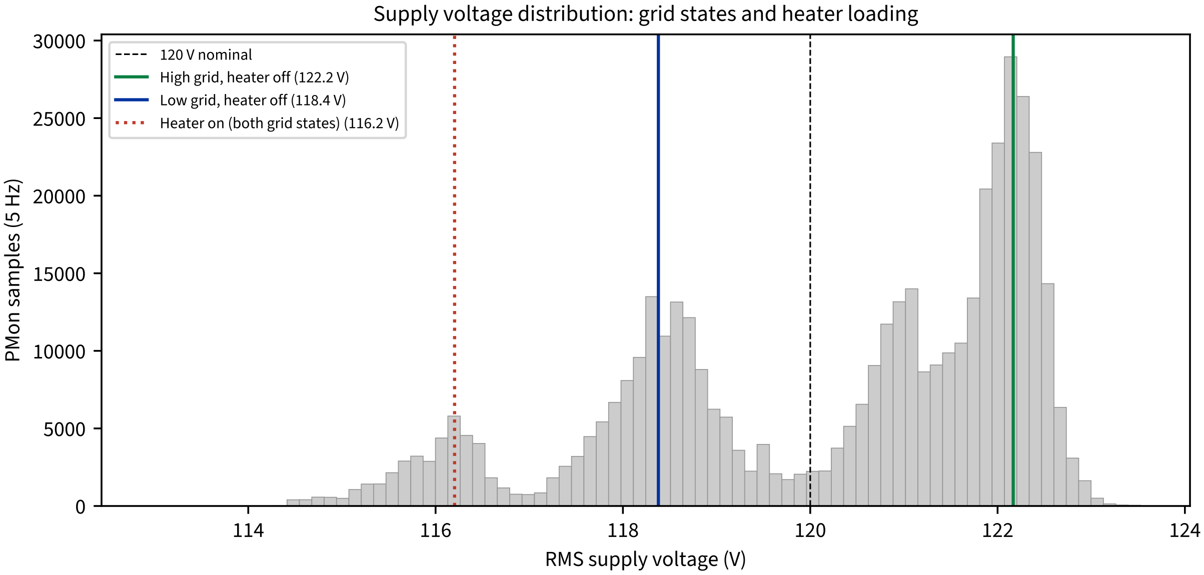


Figure 4: Supply voltage distribution over the analysis window, shown across the full ANSI C84.1 Range A envelope (114–126 V) for direct comparison to the standard.

5.1 Voltage and Frequency Envelope

Voltage held within 116–123 V (5th to 99th percentile) (Figure 4). Frequency held within **59.96–60.04 Hz** for 98 % of samples and never strayed beyond 59.84–60.09 Hz (Figure 5). Neither metric ever exceeded the steady-state limits of **ANSI C84.1 Range A**, the U.S. standard envelope for acceptable voltage: ±5 % of nominal, i.e. **114–126 V** on a 120 V service.

The voltage distribution is multimodal (Figure 4). Its two tall peaks are the supply with the heater off, at the two levels the feed visits over a day: near **122 V** overnight and near **119 V** during the day (the diurnal shift examined in *Source Impedance* below). When the heater is on, its current pulls the supply down through the source impedance into a third, lower cluster near 117 V. The cross-product of grid state and heater state gives four conceptual modes, but only three appear in the capture: the printer was off during the deepest overnight high (Session 1 ended 18:58 PDT, before the grid finished rising), so the heater-on + high-baseline mode is absent. The two heater-off modes resolve at the values above (near 122 V overnight, near 119 V daytime), and all observed heater-on samples sit in the 119–121 V baseline range Session 1 reached and cluster near 117 V after the local-Z droop.

The supply held within ANSI C84.1 Range A for >99 % of the window, with a single brief dip to **113.0 V** (0.942 pu) at the deepest heater-bed-on transient discussed in *Source Impedance* below — printer self-induced droop, not a supply-side event. IEEE Std 1159 uses 0.9 pu / 10 % as the threshold that defines a voltage sag (108 V on 120 V nominal); the supply stays comfortably well above that.

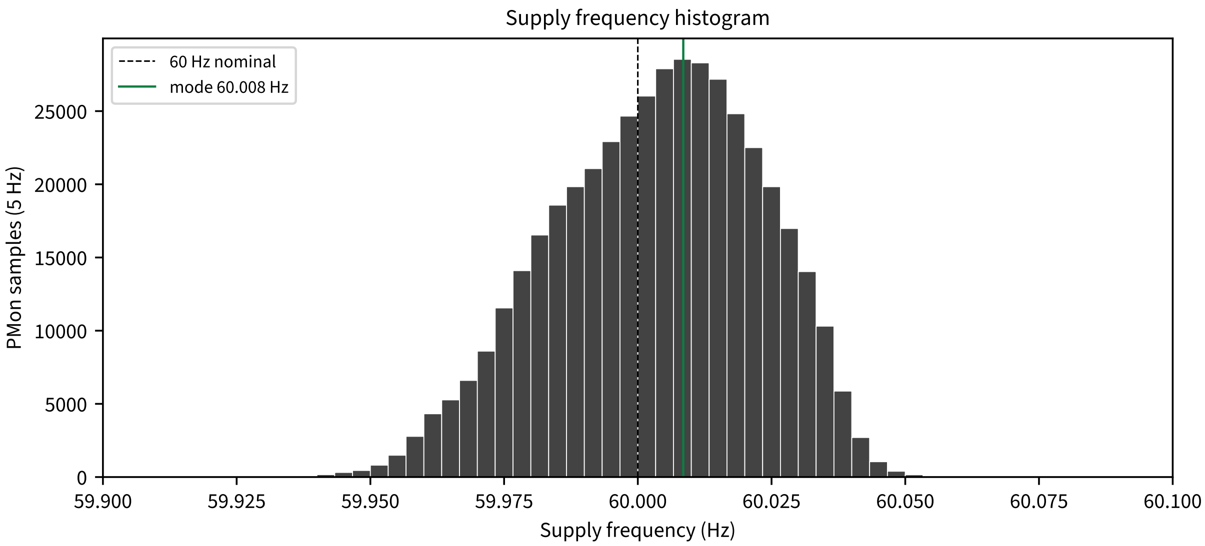


Figure 5: Supply frequency distribution over the analysis window.

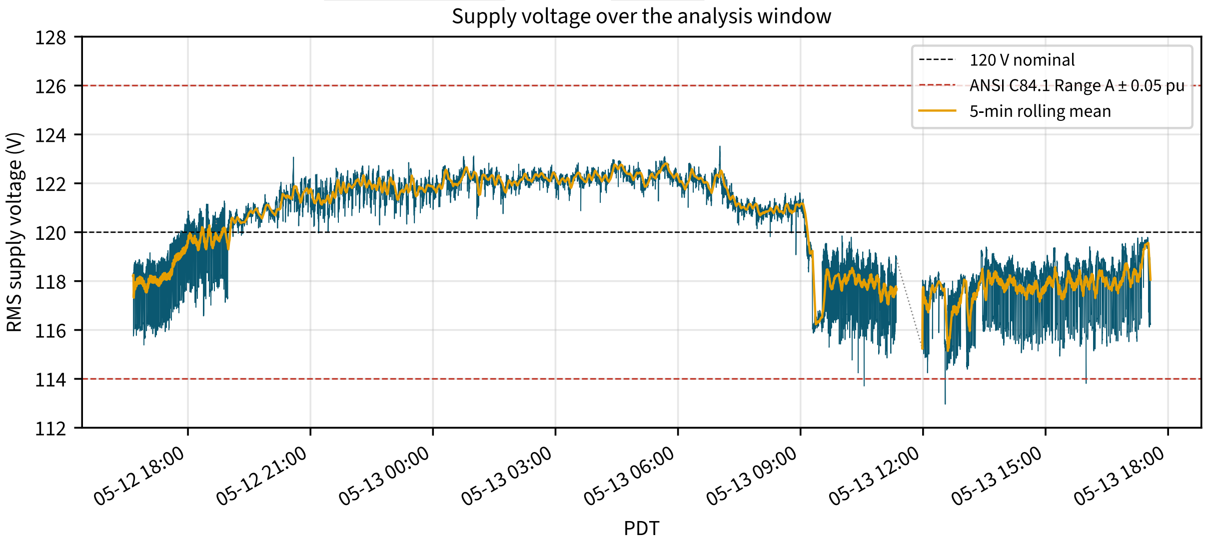


Figure 6: Supply voltage over the analysis window — 5 Hz PMon series (blue) and 5-minute rolling mean (green). Dashed red lines mark ANSI C84.1 Range A (120 V ± 0.05 pu).

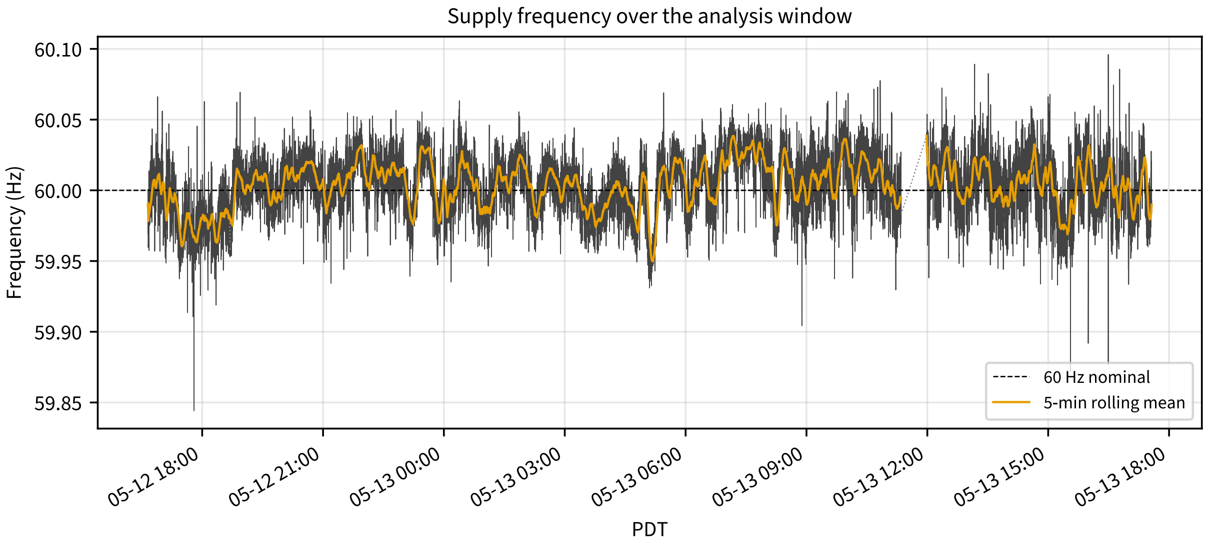


Figure 7: Supply frequency over the analysis window — 5 Hz PMon series (grey) and 5-minute rolling mean (green).

5.2 Voltage and Frequency Over Time

The full 24.8 h time series shows the supply was steady throughout — not just on average.

The voltage record (Figure 6) sits between 116–123 V (5th to 99th percentile), with the visible droops corresponding to the printer's heater pulses (recoveries are immediate when the heater opens). The 5-min rolling mean wanders smoothly over a ~1.5 V range, consistent with aggregate-feeder-load drift; nothing appears to be a discrete voltage event.

The frequency record (Figure 7) is unremarkable in the best sense: it sits on 60 Hz, with the 5-minute rolling mean wandering by no more than ~30 mHz peak-to-peak over the 24.8-hour window, and shows the small-scale "tic" pattern characteristic of a healthy AC interconnect responding to aggregate load. Brief excursions to 59.85 Hz and 60.09 Hz are isolated single-sample outliers on the 5 Hz PMon series — 4 samples below 59.90 Hz across the whole window, each surrounded immediately by normal readings.

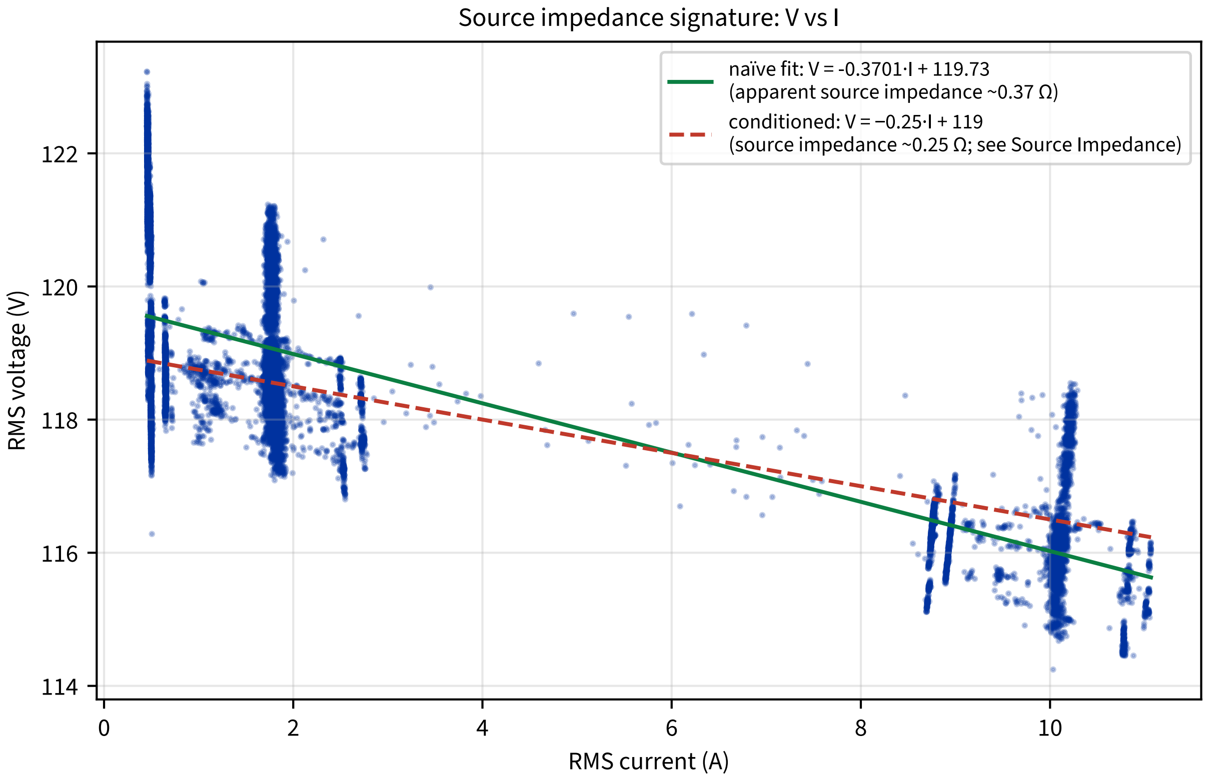


Figure 8: RMS supply voltage at the printer's outlet plotted against RMS load current. The dashed red line is the conditioned **~0.25 Ω source impedance**, anchored at the daytime grid baseline (~119 V at I ≈ 0) — visually, it traces the constant-droop pattern between vertical clusters at the same baseline V. The green line is the naïve unconditioned fit, shown for reference only; its slope is upward-biased because heater-on samples concentrate in the lower-baseline grid state.

5.3 Source Impedance

Source impedance is how much the printer's own current draw sags its own outlet voltage. It sets electrical headroom and bounds whether the printer will disturb its own operation or sensitive equipment on the same feed. Separating that local contribution from upstream-grid variation — and at sites with longer feeders, weaker grids, or microgrid topologies, from utility-regulator action as well — is what CPOW enables once the analytics pipeline is in place; a single-point RMS log conflates them. For mission-critical equipment on a deployable circuit, that decomposition matters: sustained overvoltage above ANSI C84.1 Range A ages capacitive filters, surge-protective devices, insulation, and voltage-rated semiconductors.

Source impedance is the slope dV/dI under fixed baseline conditions. Because the underlying grid baseline drifts independently — with upstream feeder loading, not with printer draw — fitting V against I directly across a multi-hour record conflates two distinct effects: the baseline shifting through the day, and the printer's own droop. The right method holds the baseline constant: for each heater-on PMon sample ($P > 0.75$ kW), pair it with a local baseline V drawn from the median of heater-off samples ($P < 0.4$ kW) within ±30 s, so the only thing varying between the paired V's is the printer's own current draw. That conditioning collapses the relationship to a **constant ~2.5 V droop at the ~10 A heater-on draw across the 118.5–121 V baseline range the printer actually saw**, i.e. **~0.25 Ω of source impedance** at the supply outlet (Thevenin equivalent upstream of the printer's line cord; reference plane defined in *Measurement Notes*). Across all 40,303 heater-on samples successfully paired this way, the per-sample Z is tightly clustered (median 0.251 Ω, IQR [0.243, 0.269], 95 % bootstrap CI on the median [0.251, 0.251] Ω). The dashed red line in Figure 8 traces this slope; visually, it matches the constant-droop pattern between vertical clusters at the same baseline V. The dominant contributors to this value are the extension cord and surge protector in front of the Wave; the utility-side network is a smaller share. A naïve unconditioned fit (green line) overstates the impedance to ~0.37 Ω by conflating the two effects.

Filtering the 5 Hz record to heater-off samples ($P < 400$ W) removes the printer's own contribution and exposes the upstream voltage directly. Two distinct grid states emerge (Figure 9): the supply ran near **122 V** overnight (held from the late afternoon of 12 May into the early hours of 13 May) and near **119 V** during the day, roughly 2.7 V apart. The transition is gradual — a five-hour climb through the evening of 12 May, a two-hour fall on the morning of 13 May, with the knee near 09:00 PDT and no apparent sub-second tap steps. The shape points to **feeder loading**: aggregate daytime load across Camp Roberts and the surrounding Paso Robles / San Miguel area depresses the voltage, then drops off overnight and the voltage recovers. Extended captures later in the deployment reinforce this: the daytime level ran several volts lower again on 14 May, tracking that day's feeder loading rather than a fixed schedule. In every case the supply stayed within ANSI C84.1 Range A.

Figure 9 also overlays the **heater-on samples** (red): while the bed heater draws, the printer's own current pulls the measured voltage several volts below the unloaded grid level through the ~0.25 Ω local source impedance. That is the printer acting on its own supply, not a grid event, and it is the mechanism behind the lower-voltage cluster in the histogram of *Voltage and Frequency Envelope*. This also explains the vertical scatter in Figure 8: roughly two-thirds of the spread at fixed I is the overnight / daytime offset rather than fine-grained feeder noise.

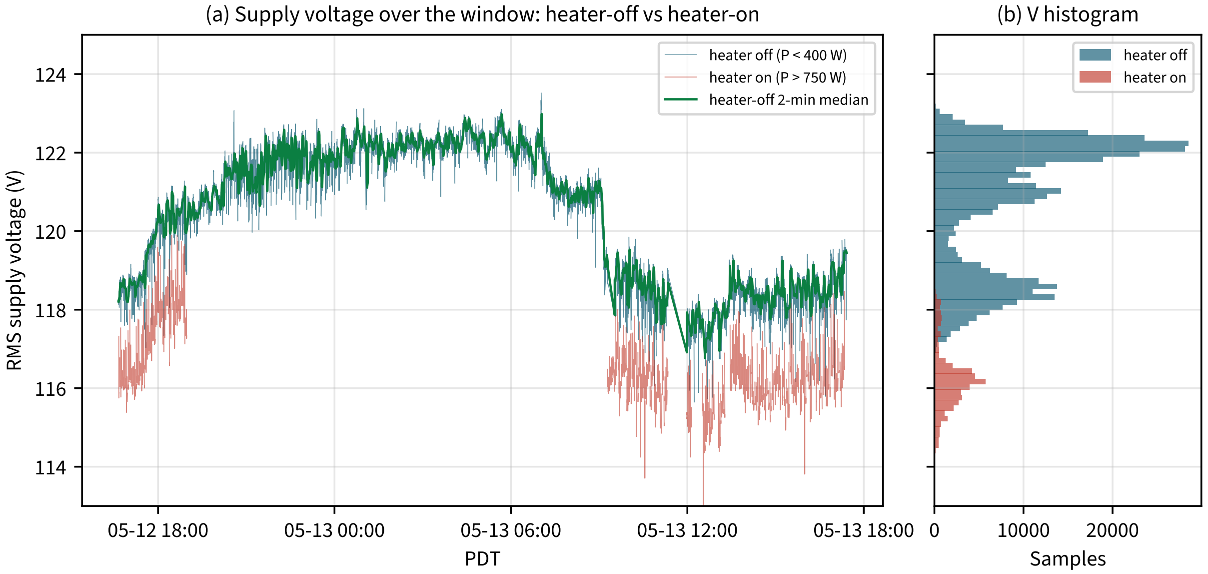


Figure 9: Supply voltage at the printer's outlet, heater-off (blue) versus heater-on (red). (a) Time-series at 5 Hz: the heater-off trace shows the slow diurnal grid swing, while heater-on samples sit several volts lower. (b) Histograms of the same samples: heater-off is bimodal, resolving the two grid states, while heater-on is pulled down by the source-impedance droop.

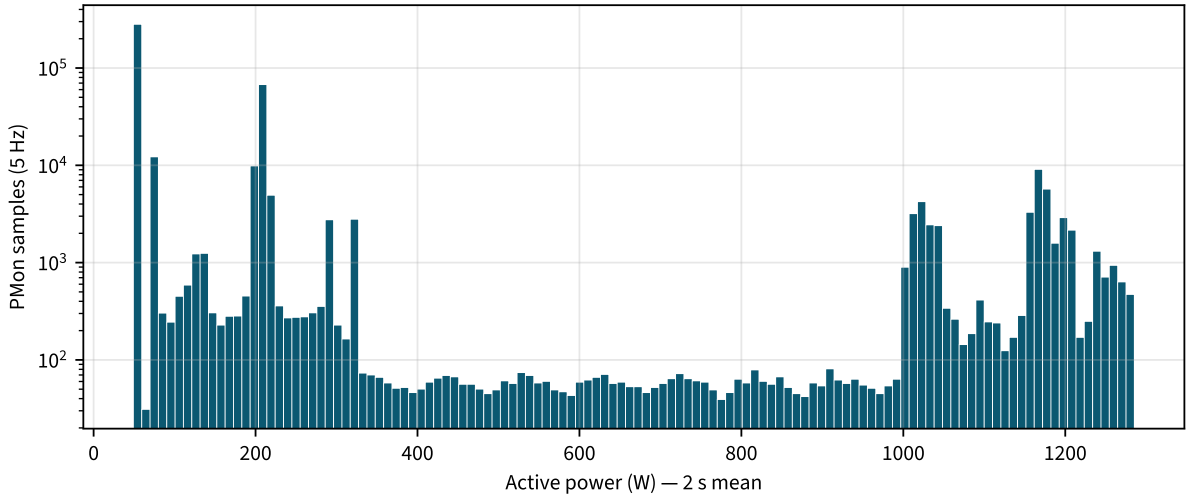
6 Load Disaggregation

A single sensor at the wall sees only the total draw, but the printer is comprised of several individual loads (heaters, motors, controller). Separating that total into recognizable operating modes lets us attribute energy and flag anything abnormal without adding instrumentation within the machine.

We locate the printer's discrete power levels from a kernel-density estimate (KDE) of the load-level distribution rather than a raw histogram, whose apparent peaks shift with bin width and placement. The KDE is bin-independent and smooths sampling noise, so each operating mode resolves as a distinct peak. The structure of those peaks (Figure 10) reflects the cross-product of *heater state* (off-duty vs full-on) and *motion state* (no motion vs steppers/extruder energized), plus the standalone idle baseline. The 210 W off-duty / no-motion peak is the sharpest in the distribution — when both regulators are settled and no motion is happening, there is little for the load to vary. The four heater-or-motion-engaged peaks are broader because regulator on-time, mid-cycle voltage variation, and motion-current draw all modulate the instantaneous power.

These five modes account for most of the time the printer spent at any P level during the measurement window. Stepper-driver PWM does not show up as distinct spectral content at the AC inlet (see *Implications for re:3D* and *Stepper-Energization Check* for the underlying reasons and the natural follow-on instrumentation); the steppers appear here only as the smoothly-varying base-load lift in the heater-on-duty + motion mode.

(a) Load-level histogram



(b) Five operating modes: heater state × motion state

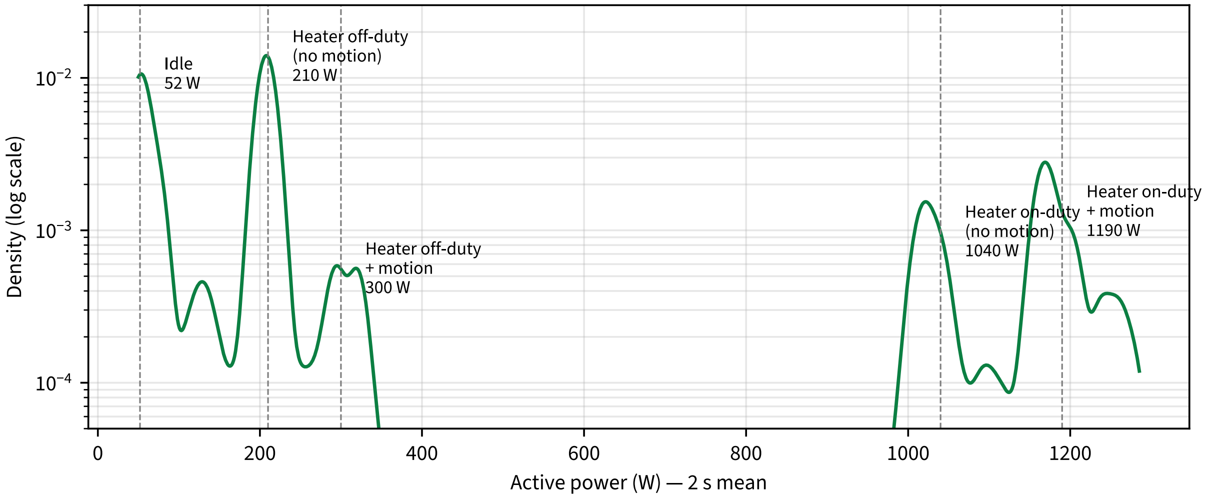


Figure 10: (a) Load-level histogram on a log y-scale; (b) the same data smoothed into a log-y kernel-density estimate (KDE) with the five inferred operating modes overlaid at the visible peaks.

Table 4: Operating modes: power signatures and likely composition.

Inferred mode	Power signature	Likely composition
Idle	∼52 W, flat	Single-board computer + MCU-based controller, touchscreen panel, cooling fans, stepper holding currents at the idle setpoint; no heaters energized and no motion.
Heater off-duty, no motion	∼210 W, sharp peak	The inter-pulse level once heaters are regulating: idle baseline plus a small steady draw (per re:3D, this is the AC-DC supply feeding the hopper heater on the printer's internal DC bus, not an AC-line heater). No motion — the tight peak comes from there being little variability when steppers / extruder are de-energized.
Heater off-duty + motion	∼300 W	Same heater state as above, with NEMA 23 steppers and the extruder drive energized. The ∼90 W lift over the off-duty level is the stepper-drive current drawn through the 24 VDC bus.
Heater on-duty, no motion	∼1.04 kW	Bed (and/or extruder) heater drawing full power, no concurrent motion. Appears in two operating contexts: (i) the sustained pre-heat ramp at the start of a print (best example is part S2-P1: 18.5 min at mean 1.02 kW, essentially flat near peak), and (ii) the ∼30 s on-pulse of the duty cycle when motion happens to be off.
Heater on-duty + motion	∼1.19 kW	Bed heater drawing full power with steppers/extruder energized — the peak of a heater pulse. The ∼150 W lift over the heater-on / no-motion level is the stepper-drive current drawn through the 24 VDC bus.

6.1 Main Heater Switching

The bed heater is the printer's largest load; the way its controller cycles drives both the energy use and the current peaks the circuit sees. Modern thermostatic controllers drive zero-cross-switched solid-state relays (SSRs) so each switching event happens at a line-voltage zero crossing — this minimizes di/dt and thermal stress on the SSR's semiconductor switching element and avoids the wideband transient that a random-phase switch would inject onto the supply. A healthy thermostatic cycle therefore has a characteristic shape; this section confirms the printer's matches it.

The dominant ~1 kW resistive load is pulsed by the printer's controller in a slow ~2 min period with ~30 s on-pulses — characteristic of a high-thermal-mass thermostatic regulator. The signature fits a heated build platform (large area, slow time constant) more naturally than a barrel zone (which typically holds at temperature with smaller modulation while polymer is flowing); the two cannot be distinguished from the AC inlet alone — re:3D can confirm.

Within heater-on-duty stretches the heater runs in a slow on/off pattern consistent with a regulator (PID or tight-hysteresis thermostat — both produce this signature) driving a zero-cross-switched solid-state relay (SSR) or equivalent solid-state switch, not fast PWM. Table 5 summarizes the duty-cycle statistics from the 5 Hz PMon trace (with "heater on" defined as P > 0.75 kW).

Table 5: Bed-heater on/off statistics (5 Hz PMon; heater-on defined as P > 0.75 kW).

Metric	Value
On-time	~29 s (median); tightly clustered, p95 = 32 s
Period (rise-to-rise)	~112 s (median); p25–p75 107–125 s
Duty cycle	**~26 %** (mean on / mean period)
On-fraction over all active windows	34 %

This is the textbook slow-switching behavior for a large-thermal-mass heated bed regulating to set-point: long thermal time-constant ⇒ ~2-minute on/off period, with ~30 s heater pulses.

6.1.1 Peak heater power tracks grid voltage

A finer-grain observation that fell out of the duty analysis: the heater-on peak power is not exactly constant from pulse to pulse — it varies by ~25 W (peak-to-peak) across the 77 heater pulses in Session 1, while the inter-pulse baseline (~225 W average) is essentially flat. The two behaviors have different physical origins:

- The **heater is a nearly-resistive AC-line load**, switched onto the 120 VAC supply by an SSR — its power obeys $P = V^2 / R$, so a change in supply voltage shows up directly as a $2 \cdot \Delta V / V$ change in heater-on power. Across the 77 pulses, the pre-pulse supply voltage varied 118.2–121.0 V (std 0.85 V) and the peak power varied 1188–1240 W (std 14 W). Pearson correlation between pre-pulse V and pulse P_peak is **0.965** — high enough to consider this the definitive explanation. The empirical slope is **16 W/V**, against a V^2/R prediction of **18 W/V** at the no-motion R operating point; the small shortfall (~10 %) matches what the local source impedance (~0.25 Ω) does to V while the heater is conducting (V droops further, partly cancelling the upstream swing). No feedstock-flow, ambient-temperature, or element- temperature-coefficient term is needed to fit the data.
- The **baseline (~225 W) is dominated by the switched-mode power supply (SMPS)** — the printer's internal AC-DC supply regulates its DC output bus, so when AC voltage shifts the AC current adjusts to keep DC power roughly constant. This makes the controller-and-fans baseline far less sensitive to grid voltage than the heater is.

The ~25 W variance on the heater peak power is, to high confidence, the V^2/R physics of the resistive heater responding to upstream grid voltage variation. Most likely cause of the V variation: other loads on the same JIFX feeder coming and going.

6.1.2 Heater resistance from the heater-on sub-clusters

A second, independent read on the heater comes from the mean V over mean I within each heater-on sub-cluster of the load-level distribution (Figure 10). With the heater at stable temperature the printer's terminals satisfy V_outlet = R_heater · I_heater, so the cluster centroid is a direct measurement of R_heater.

From the data:

- **Heater on-duty, no motion**: $\langle V\rangle/\langle I\rangle$ = **13.2 Ω** — the equivalent resistance of the main heater alone (at operating temperature, plus the small steady controller-PSU load).
- **Heater on-duty + motion**: $\langle V\rangle/\langle I\rangle$ = **11.5 Ω** — lower because the motion-side current (~1.5 A) adds in parallel without raising the heater's own V. The ~1.7 Ω drop is the additional conductance contributed by the stepper drives on the internal DC bus.

The 13.2 Ω heater resistance is consistent with the earlier V^2/R prediction: at the nominal 120 V supply, $P = V^2/R = 14400 / 13.2 \approx 1.09$ kW, which is the observed peak in the heater-on-duty no-motion mode.

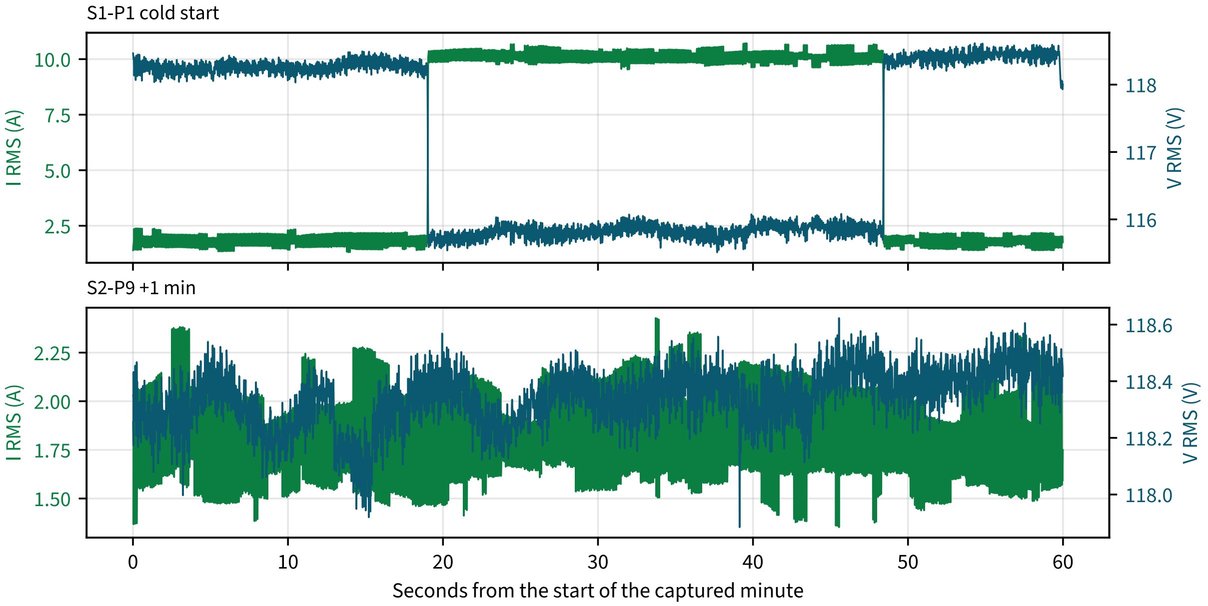


Figure 11: CPOW minutes capturing clean heater on/off transitions, cycle-by-cycle RMS. **Top:** S1-P1 cold start. **Bottom:** S2-P9 +1 min the next day — pulse envelope and timing repeat to well under 1 %.

7 Waveform Character and Harmonics

Harmonics are current or voltage content aside from the clean 60 Hz sine wave. They are intrinsic to certain loads — a rectifier-fed AC-DC supply naturally draws harmonic-rich current to deliver DC power — but in excess they heat conductors disproportionately, can nuisance-trip protective devices, and may interact with system resonances. The distortion the printer draws and the distortion already on the supply here are both small and well within the accepted limit (IEEE 519), so neither the printer nor the JIFX feed is a power-quality concern. The rest of this section is the supporting evidence.

Two parts of the printer set the waveform shape. The **heated bed is a plain resistor**, so when it is switched onto the line it draws a clean sine wave with essentially no harmonics of its own. The **controller's power supply (PSU)** is an AC-to-DC converter, a rectifier feeding switching electronics, and like all such supplies it pulls current in brief pulses near each voltage peak, which is what creates harmonics. The printer therefore looks cleanest while the heater is on, because the large resistive load dominates and dilutes the PSU's contribution, and most distorted while the heater is off and only the PSU is drawing. Neither state is a problem; the modest distortion present comes from the PSU, not the resistive heater and not the grid.

Across the captured intervals the **voltage waveform is clean** — no notching, no inverter signature, consistent with a utility-quality feed. The **current waveform** is near-sinusoidal when the heater is engaged (resistive load) and is distorted by the controller's power-supply unit (PSU) when the heater is off (Figure 16) — a near-sinusoidal envelope with diode-commutation notches at the zero crossings and a crest factor of ~2.1 against the 1.41 of a clean sinusoid. The 60-Hz fundamental dominates throughout, with the expected odd-harmonic-dominant pattern (Figure 13 and Figure 14; visi-

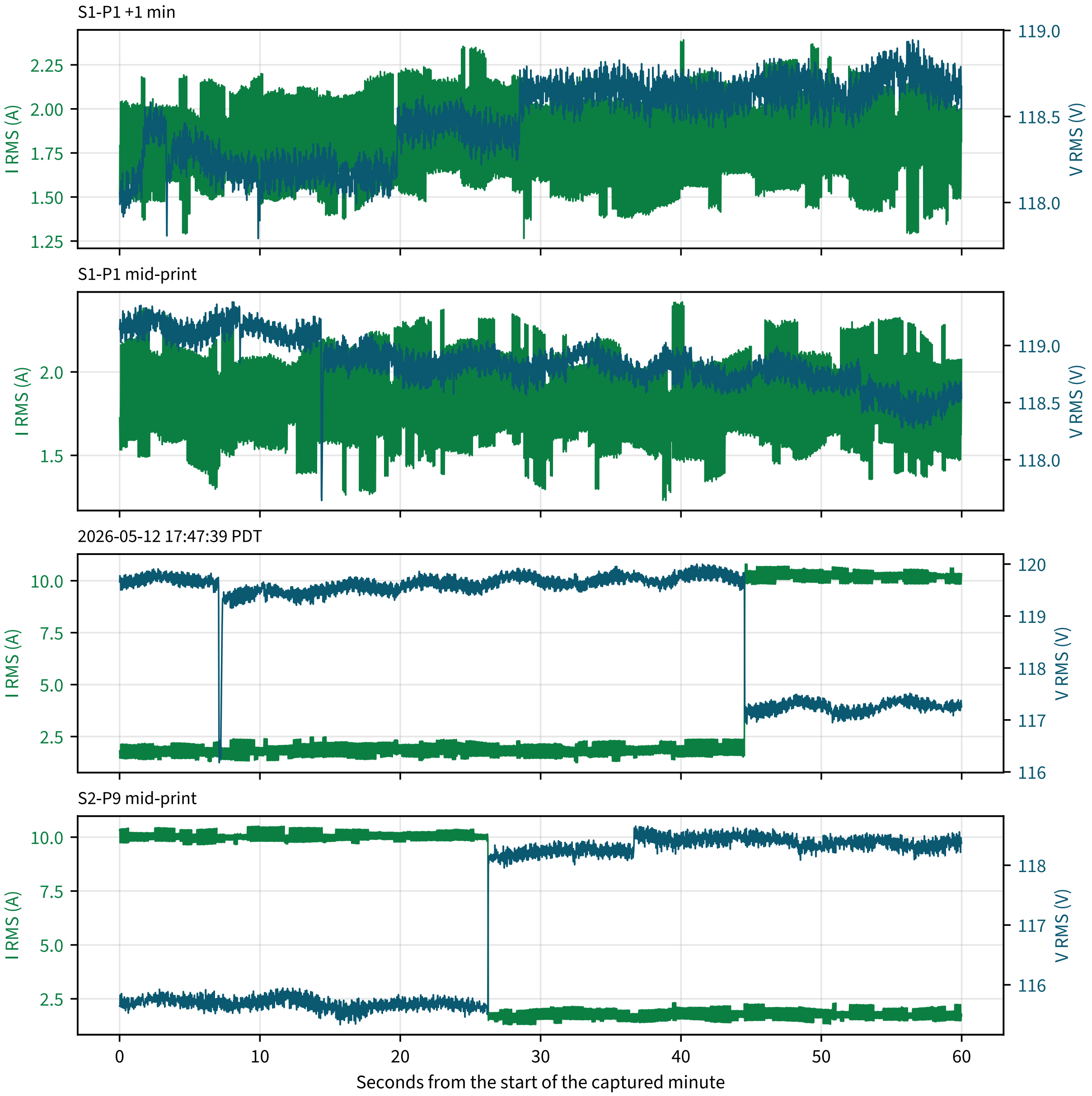


Figure 12: CPOW minutes from within heater-on-duty stretches, cycle-by-cycle RMS. **Top:** S1-P1 +1 min (duty pattern established). **Middle:** S1-P1 mid-print. **Bottom:** S2-P9 mid-print — Session 2's signature matches Session 1 across the ~17 h gap.

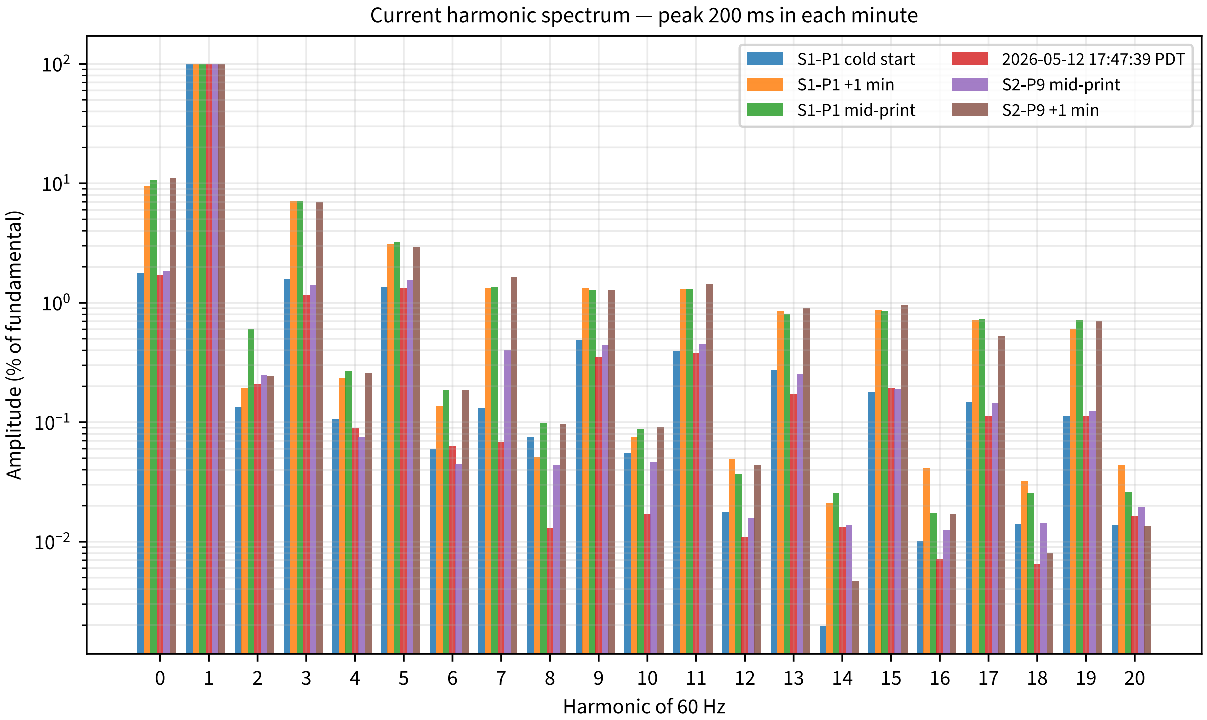


Figure 13: Current harmonic content (% of fundamental) at the peak 200 ms within each of the six captured CPOW windows.

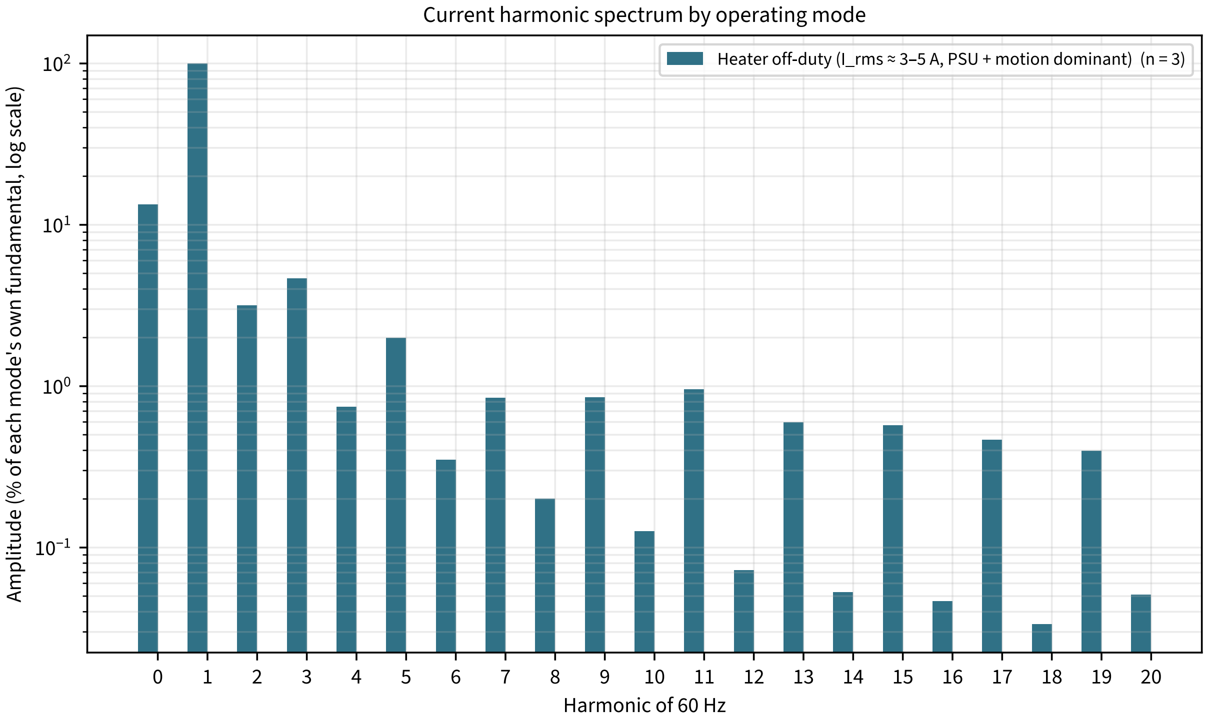


Figure 14: Harmonic content regrouped by operating mode (pooled across six captured CPOW windows), log-y.

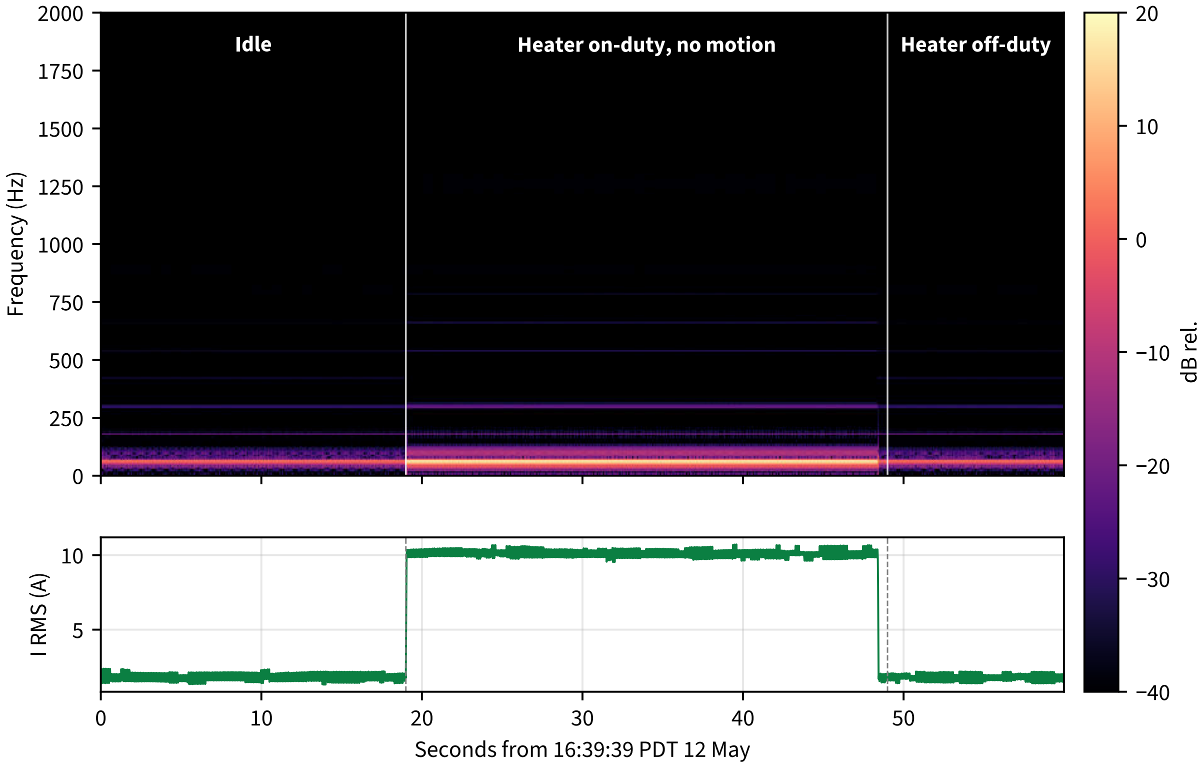
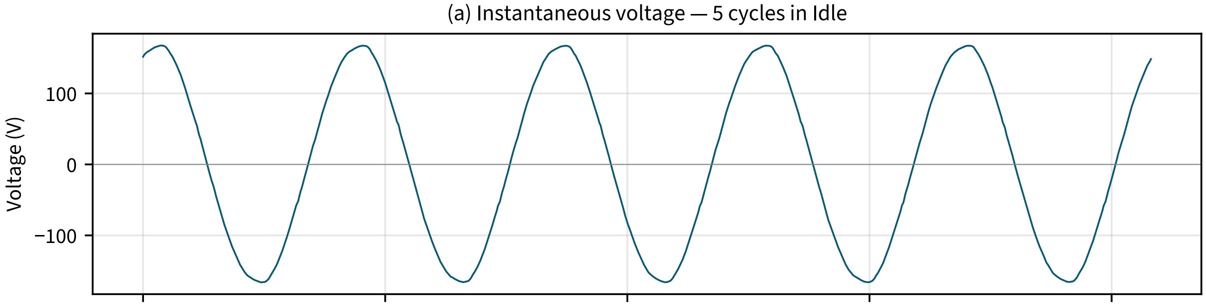


Figure 15: Current spectrogram (0–2 kHz) across the S1-P1 cold-start capture, with cycle-by-cycle I RMS overlaid. Three operating modes sweep through one 60-s window.


(a) Instantaneous voltage — 5 cycles in Idle

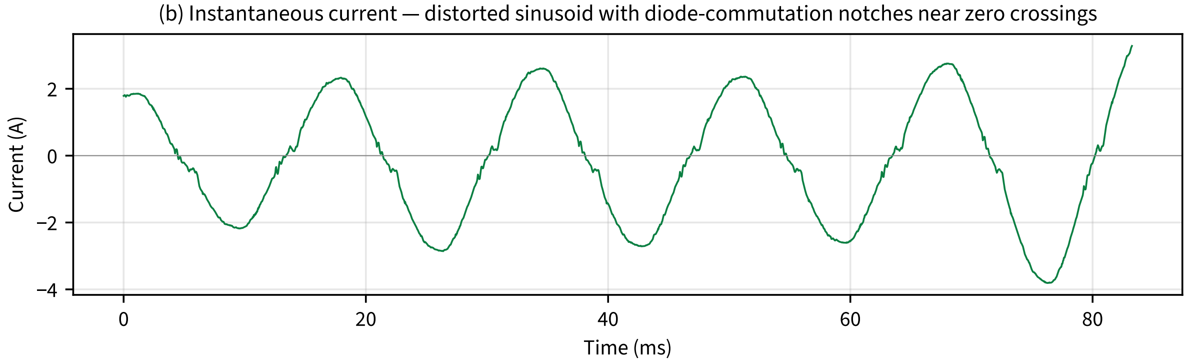

(b) Instantaneous current — distorted sinusoid with diode-commutation notches near zero crossings

Figure 16: Five-cycle V(t) and I(t) inside an Idle stretch — the current shape that drives the higher Current THD reported below.

ble bands at 180, 300, 420 Hz; even harmonics negligible). The spectrogram (Figure 15) shows nothing above ~700 Hz — no PWM, no inverter switching, no switching transients.

Total Harmonic Distortion (THD_F, IEEE convention, computed on 1-second segments across all six captured CPOW windows) is summarized in Table 6.

Table 6: Voltage and current THD over six captured CPOW windows.

Metric	Mean	Median	p95	Max
Voltage THD	1.5 %	1.5 %	1.8 %	1.8 %
Current THD	7.2 %	8.3 %	8.6 %	8.7 %

Voltage THD is well below the 5 % limit set by IEEE 519 for utility voltage at the point of common coupling — the supply is clean. Current THD sits at the typical level for a small switching-supply load. It is lower during heater-on minutes (the resistive heater draws near-sinusoidal current and dilutes the distortion) and higher during low-load minutes when the controller's PSU sets the waveform shape.

During the heater-engaged segments the current is essentially clean-fundamental (<2 % 3rd harmonic). During low-load PSU-only segments the 3rd, 5th, and 7th harmonics (Figure 14) rise to 7 %, 3 %, and 1 % respectively — typical of a small rectifier-capacitor switching power supply, and not a concern. (The first-minute bed-heater turn-on transient is examined in detail in *Heater Switch-On* below.)

7.1 Power Factor

Table 7 summarizes power factor (PF = real power / apparent power) per operating mode, computed from PMon aggregates over the full 24.8-hour window.

Table 7: Power factor by operating mode (PMon aggregates over the 24.8-hour window).

Operating mode	P (W)	I_{RMS} (A)	S (VA)	PF
Idle	50	0.46	56	**0.90**
Heater off-duty, no motion	208	1.78	211	**0.98**
Heater off-duty + motion	295	2.53	299	**0.99**
Heater on-duty, no motion	1,024	8.78	1,021	**~1.00**
Heater on-duty + motion	1,174	10.12	1,174	**~1.00**

The pattern is what the harmonic signature predicts. The bed heater is a resistive load switched at zero crossings, so when it dominates the draw the printer presents **unity PF** to the supply. When the heater is off and the load is just the AC-DC supply (with the DC hopper-heater bus, controller, fans, and possibly motion downstream), the power factor drops modestly — to about 0.98 at the heater-off-duty levels and to 0.90 at idle. That degradation is **distortion-PF**, not displacement-PF: the AC-DC stage draws current in narrow peak-clipped pulses that contain harmonic content (the same 3rd / 5th / 7th signature in the harmonics table above), and at light loads those pulses dominate the RMS-current denominator without contributing to real power.

For deployment planning, the implication is benign. The printer draws under 0.5 A RMS at idle, so even a PF of 0.90 corresponds to negligible apparent-only loading — under 6 VA of reactive / distortion content. When real work happens (heater pulses), PF is unity and apparent power equals real power. A generator or microgrid sizing exercise can use the real-power numbers in *Session Power Profiles and Energy Budget* directly, without an apparent-power derating.

8 Heater Switching Transition — Health Check

Every time the heater switches on, the switching device (a solid-state relay) takes the stress. A failing or mis-firing switch shows up first as inrush, arcing, or half-cycle asymmetry at that instant, well before it fails outright; this section is a preventive look at that moment.

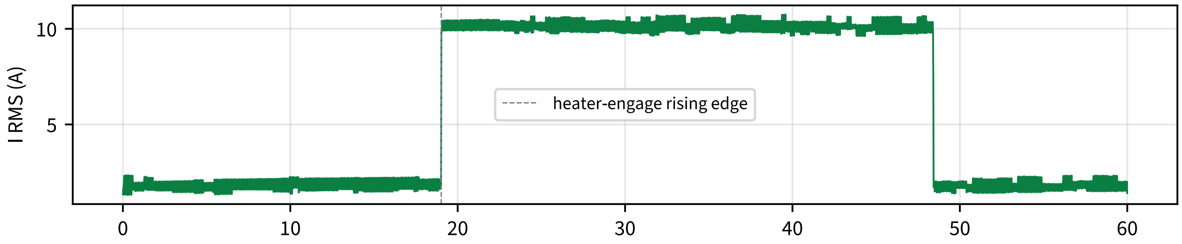
We used the first bed-heater engagement of Session 1 to inspect the **switching transition itself**. The 32-ksps CPOW record around the rising edge can reveal several distinct conditions that would warrant attention if present:

- **Inrush dynamics** — a fast current spike or oscillation beyond steady-state, characteristic of a non-resistive load (motor, transformer, incandescent filament). Not expected for a heated bed but worth confirming.
- **Zero-cross switching** — whether the SSR/TRIAC closes the heater at the AC zero crossing (clean, low-EMI commutation) or fires mid-cycle (which would inject a step in the current and add high-frequency content to the line).
- **Slow ramp-in** — a longer current rise than the controller-soft-start would explain, which can indicate a switch that is slow to commit or a regulator out of tune.
- **Switching time constant or notching** — a brief non-sinusoidal region around the rising edge that flags the switch's transition region (commutation, contact bounce, or early-degradation modes that show as heat / arcing dwell).
- **Wear or heating indicators in the switch element** — asymmetric on/off behavior between half-cycles, persistent DC offset, or drift of the zero-cross alignment over multiple switching events.

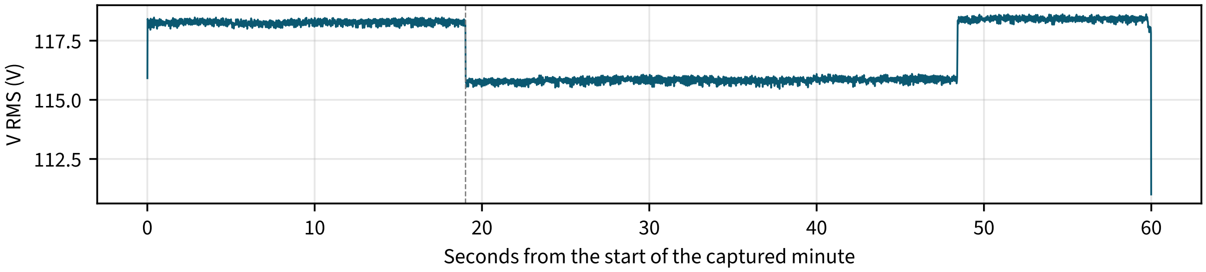
What we see in the data:

- The transition is **a clean on / off step**, not a transient (Figure 17, top). Cycle- RMS current rises monotonically from ~1.9 A to ~9.6 A over ~5 line cycles (~83 ms), with no overshoot. RMS voltage droops ~2 V during the on-phase, then recovers when the heater opens.
- At the instantaneous-sample level (Figure 17, bottom panels) the current remains sinusoidal throughout the rising edge — no fast spike, no DC offset, no ringing. The 5-cycle rise is consistent with the controller switching the heater on via an SSR or TRIAC with zero-cross synchronisation and a brief regulator ramp-in.
- **Peak instantaneous current ~15.5 A** is reached later in the heater-on interval and is simply the sinusoidal peak of the 9.6 A RMS current (15.5 / 9.6 ≈ 1.61, slightly above √2 — mild waveform distortion, not a transient).

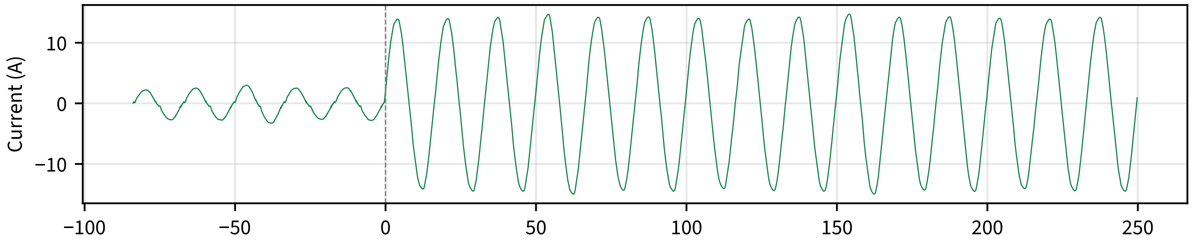
(a) Single-cycle RMS current (from CPOW) over the captured minute



(b) Single-cycle RMS voltage (from CPOW) over the captured minute



(c) Instantaneous current across the heater rising edge



(d) Instantaneous voltage across the heater rising edge

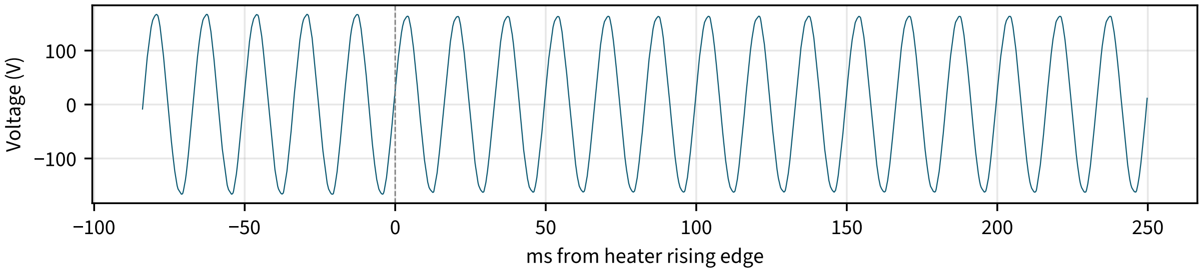


Figure 17: Heater switch-on at the start of Session 1. **Top:** cycle-by-cycle RMS over the captured minute. **Bottom:** 20-cycle instantaneous-sample zooms of current (left) and voltage (right) across the rising edge.

Conclusion: switching transition is healthy. No inrush spike, no slow ramp, no notching, no asymmetry — just a clean, zero-cross-aligned SSR closure onto a resistive heater that ramps to its steady-state RMS over ~5 line cycles. This validates the resistive-bed assumption that underlies the V^2/R correlation analysis above and the per-part energy budget, and shows the solid-state switch driving the main heater is operating cleanly with no sign of contact-region heating or degradation. The 20 A circuit faces only the steady-state heater current with no spike margin needed.

8.1 Stepper-Energization Check

Like the bed-heater switching above, stepper energization is a controlled-switching event whose signature reveals the health of the drive electronics. A dragging or faulting drive would pull abnormal current; confirming a clean, bounded draw is a quick way to verify the motion system is electrically healthy.

Stepper coils also have a small inrush when they are first energized: the chopper driver ramps current up to the holding setpoint over microseconds. A healthy driver bounds this sharply; an unhealthy one would show longer ramps, overshoot, or audible / electrical chatter.

From the AC inlet we cannot see per-step events directly: the chopper drivers run from the printer's internal DC bus, and the bulk capacitor on that bus low-pass-filters any microsecond-scale coil-current transient before it reaches the AC line. What we *can* see is **bulk** stepper energization — the change in steady-state base load when motors transition from de-energized to fully energized.

The captured CPOW windows happen to sit inside established operating modes rather than across a clean "before / after stepper energize" boundary, so the cleanest evidence is the mode-to-mode base-load difference reported in *Load Disaggregation*:

- Heater off-duty: **~210 W** with no motion; **~300 W** with steppers / extruder energized.
- Heater on-duty: **~1.04 kW** with no motion; **~1.19 kW** with steppers / extruder energized.

In both heater states the motion lift is **~90–150 W**, attributable to the NEMA 23 motion + extruder steppers drawing through the printer's internal 24 VDC bus. The transition itself is not captured in the six representative CPOW windows analyzed here, but the steady-state numbers are consistent with a healthy multi-motor load drawn through the AC-DC supply (no obvious extra current that would suggest a stuck coil or a driver in fault). A targeted re-extract from the full continuous CPOW record on the NAS could surface the energize event on request.

A definitive stepper-inrush check requires a DC-bus tap (the internal 24 VDC rail) at sub-millisecond resolution, where the per-step current ramp is visible directly.

9 Implications for re:3D

- **Per-part energy budget**: parts in this dataset span 0.087–1.09 kWh. At a representative California commercial tariff of $0.30 / kWh (typical for PG&E commercial-class service in the region after the 2026 rate redesign; residential is closer to $0.40 / kWh) that is roughly **$0.026–$0.33 per part** in energy cost. JIFX is grid- connected for this period; a generator-based deployment would carry several-times-higher equivalent-energy cost from fuel.
- **Circuit sizing**: peak ≈ **10.8 A** on a 20 A circuit (calibrated value; see *Measurement Notes*), with substantial headroom. A standard 20 A receptacle is sized comfortably for this printer; no need for a 30 A drop in typical deployment conditions.
- **Supply quality at JIFX**: the feed has been **clean** for the printer's purposes — wide-margin within ANSI C84.1, no sags below 0.9 pu, frequency tightly held. Local source impedance is ~**0.25 Ω** at the supply outlet (upstream of the printer's line cord, refined from the V-vs-I analysis under grid-state conditioning; see *Source Impedance*), so the printer itself causes a ~0.25 V/A voltage droop on its own supply.
- **Disaggregation at the AC inlet is partial.** Heater state changes resolve confidently. Per-motor stepper activity does not — the chopper drivers run from the printer's internal **24 VDC bus** (the GigabotX's enclosed switching supply, per re:3D's published specification), downstream of the AC-DC stage. The natural next instrumentation point for per-motor visibility is that DC rail directly.
- **What this report warrants.** The 24.8-hour record covers a complete cold-start print (Session 1), an 11-part run (Session 2), the heated bed's switching pattern, and a clean grid envelope. Nothing in the findings asks for additional data on its own. For follow-on work — e.g. tying per-part energy to g-code / layer count / material, or instrumenting the 24 VDC bus for per-motor diagnostics — scope and instrumentation can be agreed directly.

10 Methodology and Reproducibility

EQ analyzed the data in three layers:

1. **PMon parquets** (5 Hz aggregates) for session boundaries, voltage and frequency distributions, sag detection, and per-session energy integration. Bench-calibration corrections (V_TRIM = 0.99030, I_CORRECTION = 0.49282) applied per the analysis pipeline; active power and energy scaled by their product.
2. **CPOW parquets** (32 ksps continuous waveform) sampled at six representative 1-minute windows from the full 24.8 h CPOW record on the NAS — four from Session 1 (cold-start heater engagement at 16:39 PDT 12 May, established duty pattern at 16:40 PDT, mid-print references at 17:30 and 17:47 PDT) and two consecutive minutes from Session 2's part S2-P9 (15:35 and 15:36 PDT 13 May). Used for waveform character, harmonic content, and inrush dynamics.
3. **Kernel-density estimation** on the smoothed PMon P trace to detect steady-state load levels for disaggregation.

The analysis pipeline and intermediate per-part energy ledger are retained alongside the raw CPOW + PMon archives. EQ can re-run the analysis on extended data (additional sessions, post-event capture) and deliver an updated report on request.

10.1 Authoring Workflow

This report was produced under a tight feedback and iteration loop between AI-assisted analysis and the human engineer-author. The engineering tools and analyses developed here — the conditional V-vs-I impedance estimation, the duty-cycle / pulse-statistics characterization, the harmonic-mode decomposition, the inrush envelope analysis — are being integrated into **EQ Syntropy** for further automation, with the aim of delivering this depth of physics-grounded engineering analysis in near real time and on a continuous basis: to **detect, diagnose, and predict** power-system and equipment issues at the point of measurement, rather than after the fact.

10.2 Printer Specifications Referenced

Where this report names specific printer-side components (NEMA 23 stepper, single-board computer + MCU-based controller, 5/8” pellet extruder screw, 16:1 L/D ratio, 3–5 mm granule input, <270 °C melt range), values are taken from re:3D’s published product pages:

- *GigabotX 2 product page* — re3d.org/portfolio/gigabot-x/
- *GigabotX 2 XLT product page* — re3d.org/portfolio/gigabot-x-xlt/
- *GigabotX 2 tech specs* — shop.re3d.org/pages/gigabotx-2-tech-specs
- *Gigabot 24 V power supply* — shop.re3d.org/products/gigabot-24v-power-supply (source for the 24 V internal DC bus)

Heater wattages, AC-DC supply ratings, and stepper-driver model are not stated in the public product pages and are inferred from the measured power signature only.

11 Open Items and Caveats

This document is **v0.3 — DRAFT**. Final v1.0 release is gated on:

- **re:3D’s final sign-off on the remaining inferred identifications.** The bench-calibration corrections (voltage and current) are applied throughout this draft, and re:3D’s engineering review surfaced the hopper / barrel-heater-is-DC correction that is now also reflected. Any remaining flagged inferences (e.g. which specific heater drives the cycling pattern, exact PSU rating, stepper-driver model) will be confirmed or corrected in the v1.0 release.