

Verdigris Signals

Predicting Failure Through Power Anomalies

From Reactive Alarms to Proactive Reliability in Hyperscale Facilities

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Abstract

Legacy BMS/EPMS paradigms rely on threshold crossings after conditions are already severe at slow telemetry intervals—creating alert fatigue, missing precursor signatures, and delaying action until faults mature. Verdigris Signals introduces a fundamentally different approach: **the first system to scale waveform intelligence across platforms, context, and portfolios.**

By learning from high-frequency electrical features sampled at 8 kHz, Signals reveals patterns and precursors that conventional FDD frameworks cannot see. This deep waveform intelligence establishes ground truth datasets, enabling both direct detection of novel features and predictive inference when only coarser telemetry is available.

Beyond single-point anomalies, Signals folds multi-layered anomalies together across systems such as HVAC, UPS, and power distribution to validate faults and reduce false positives at scale. This paper focuses on three exemplar waveform-derived symptoms: (S1) current harmonic deviations (3rd–25th), (S2) rising voltage total harmonic distortion (THD_V), and (S3) voltage sags with cycle-to-cycle jitter and phase-offset anomalies. We derive the metrics, provide detection logic, quantify latency and confidence, and show how advisories reduce unplanned outages, avoid truck-rolls, and justify CapEx with evidence.

Why Thresholds Fail at Scale

Conventional monitoring aggregates to 1–60-second intervals and raises alarms when values exceed static limits (e.g., Vrms low, temperature high, breaker trip). This reactive model obscures precursors, overloads teams with noisy alarms, and delays intervention until faults have already matured. Predictive failure through power anomalies reverses the logic: infer equipment stress from its electrical fingerprints—harmonics, interharmonics, jitter, and phase behavior—then guide targeted actions while there's still time to prevent outages.

At portfolio scale, these limitations compound: rule-based thresholds trigger cascades of alarms across sites and systems, creating fatigue without improving reliability. Signals reverses this logic. Instead of waiting for thresholds to be breached, it interprets the electrical fingerprints of stress—harmonics, interharmonics, jitter, and phase behavior—at their earliest appearance. Combined with context across HVAC, UPS, and power distribution, these fingerprints are folded into validated advisories that reduce false positives and highlight actionable risks while there is still time to prevent outages.

What Signals Is (and Isn't)

Signals is an electrical-intelligence layer that learns the dynamic language of a facility's power. It integrates deep waveform visibility and advanced analytical models to translate raw electrical signatures into validated, actionable advisories.

Core capabilities include:

- 8 kHz waveform sampling with harmonic bins to the 25th (IEC 61000-4-7)
- Phase-Locked Loop (PLL) synchronization for precise phase alignment
- Discrete-Time and Fast Fourier Transform (DTFT/FFT) for spectral decomposition
- Computed features including THD_V, THD_I, Vrms sags, zero-crossing jitter, phase angle drift, and event rates
- Statistically engineered features such as variance ratios, correlation metrics, and normalized derivatives that characterize relationships across multiple waveform dimensions.

What Signals isn't: It is not another threshold engine or after-the-fact rule set. It doesn't generate more alarms — it folds anomalies together, suppresses noise, and delivers validated advisories.

Deployment: On-prem delivery is sub-second for operations; cloud advisory is seconds to minutes for fleet analytics and CapEx planning. Integration is two-way with EPMS/BMS/CMMS/ITSM (e.g., ServiceNow) ensures Signals reduces rather than adds to alert fatigue, opening targeted tickets with evidence and deep links for validation.

Measurement & Metrics (IEEE/IEC-consistent)

Signals builds on established harmonic and power quality standards, but applies them at a higher resolution (8 kHz windows) to surface features that traditional systems overlook. Metrics are organized into three categories:

1. Harmonic Content:

- Total Harmonic Distortion

$$THD_V = 100\% \cdot \frac{\sqrt{\sum_{h=2}^H V_h^2}}{V_1}$$

THD_V is computed against the fundamental RMS voltage V_1 ; bins follow IEC 61000-4-7. THD_I is computed analogously.

- Inter-harmonic Distortion:

$$IHD = 100\% \cdot \frac{\sqrt{\sum_{f \notin f_1} V_h^2}}{V_1}$$

Captures non-integer spectral content; particularly relevant for motor drives and UPS switching sidebands. Mechanical resonance of motorloads through a Variable Frequency Drive (VFD) can manifest as IHD.

2. Dynamic Stress Indicators

- Voltage Sags:

$$V_{rms}(t) < (1 - \alpha) \cdot V_{nom} \text{ for } \Delta t \geq t_{min}$$

Detects deviations against ITI/CBEMA ride-through envelopes.

- Cycle-to-Cycle Variability:

$$\alpha_t^2 = Var(\tau_n), \Delta\phi = \phi v(t) - \phi i(t)$$

Jitter and phase drift that precede instability

3. Multivariate Anomaly Detection

- Statistical Difference

$$S(x) = (x - \mu)^T \Sigma^{-1} (x - \mu)$$

Mahalanobis distance for identifying correlated deviations across multiple features.

- Autoencoders

Highly effective for identifying anomalous patterns in specific equipment or categories by comparing current behavior against learned baselines of normal operation. Since each asset behaves differently depending on its environment and load conditions, autoencoders can significantly reduce noise and false alerts by learning the distinct behavioral patterns of target equipment—something conventional threshold-based alerts cannot achieve.

For nonlinear feature interactions, autoencoder architectures can be trained on baseline waveform data to reconstruct expected patterns. Elevated reconstruction error highlights deviations from normal operation, complementing distance-based methods.

- Isolation Forest

Tree-based anomaly methods such as Isolation Forest are well-suited for multivariate waveform features in high dimensions, isolating rare behaviors without assumptions about Gaussian structure. These methods provide interpretability at scale, highlighting which features most contribute to anomalies.

Standards context

These metrics are consistent with IEEE 519 (harmonic limits by ISC/IL), IEC 61000-4-7 (harmonic bins), IEC 61000-4-30 (power quality measurement methods), and ITI/CBEMA ride-through envelopes.

Why This Matters

By combining these metrics with 8 kHz visibility and anomaly folding, Signals moves beyond compliance reporting. It transforms standards-based measurements into predictive signatures that reduce false positives and expose failure precursors invisible to threshold monitoring.

Three High-Value Symptoms & Preventable Outcomes

S1 — Current Harmonic Deviations (3rd–25th; emphasis on 5th/7th)

Nonlinear loads such as VFDs and rectifiers exhibit characteristic harmonic fingerprints. In 6-pulse rectifiers, rising 5th and 7th harmonic magnitudes are strong precursors of capacitor degradation and diode imbalance. Signals detects these trends at sub-cycle precision, identifying deviations far before threshold-based alarms are triggered.

(Eq. 5). On-prem detection triggers 8 kHz windows on edges or jitter spikes, computes bins to 25th, and raises an Advisory when persistent, trending, or IHD sidebands emerge.

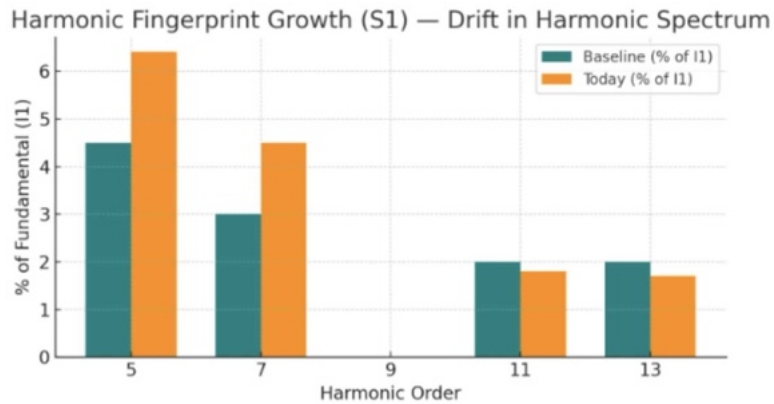


Figure: Harmonic Fingerprint Growth (S1)

Worked example (rectifier input to UPS battery): baseline THD_I=8% with I₅=4.5% I₁, I₇=3% I₁; today THD_I=9% with I₅=6.4% I₁, I₇=4.5% for 15 minutes at stable temperature. Rising I_{rms} ($\propto I_{rms}^2$), along with frequency shift to impending diode bridge timing issue.

Preventable outcomes:

- Proactively replace or service the UPS rectifier module before catastrophic failure.
- Avoid unexpected downtime during a transfer event when the UPS is relied upon.
- Maintain power quality for downstream IT loads without unplanned service interruption.

S2 — Voltage THD Rising

Rising THD_V reflects system-level nonlinearity or resonance—overloaded PDUs, capacitive/inductive interactions, or rectifier behavior reflecting back onto the bus. Sustained elevation can prematurely heat transformers/PDU buses and destabilize protection. While rising voltage THD can be observed at the panel or bus level, actionable insights often come from comparing upstream and downstream current THD. Signals applies THD_V trending with persistence checks and dominant order analysis to distinguish resonance from benign load growth.

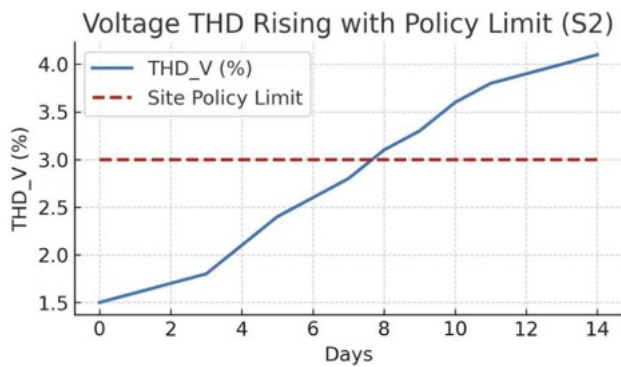


Figure: Voltage THD Rising with Policy Limit (S2)

Example (PDU resonance): THD_V rises from 1.5% to 4.0% in 14 days with oscillatory 5th growth near compressor starts.

Advisory: “Voltage distortion rising on PDU-07 (5th dominant). Likely resonance with load profile.

Recommendation: verify PFC/filter tuning, balance phases, evaluate detuned filters.

Preventable outcomes:

- Avoid nuisance breaker trips and hot bus runs.
- Prevent protection mis-operations.
- Support CapEx justification for harmonic filters with measured drift and quantified losses.

S3 — Voltage Sags, Cycle-to-Cycle Jitter, Phase-Offset Anomalies

Repeated sags with abnormal jitter (zero-cross variance) and phase offset indicate loose terminations, high-impedance faults, or intermittent load events (e.g., large motor inrush, STS events).

Signals combines sag magnitude/duration, jitter, and phase offset into a signature vector, compares against ITI/CBEMA ride-through envelopes for impact tiering, and correlates events with equipment schedules to separate root causes from load-driven variability.

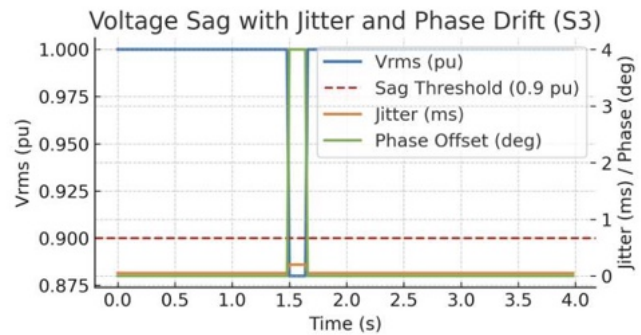


Figure: Voltage Sag with Jitter and Phase Drift (S3)

From Signals to Action — Architecture & Latency

Sensing & Triggers

Signals begins at the edge, capturing voltage and current at 8 kHz in short, triggered windows. Triggers include load edges, sag flags, jitter spikes, or a periodic sampling cadence to ensure coverage. These high-resolution captures form the raw electrical fingerprint from which novel features are derived.

Models & Confidence

Each asset or bus is assigned an unsupervised baseline that adapts with seasonal factors. Change-point detection highlights drifts in THD and harmonic vectors, while confidence scores combine:

- Statistical anomaly measures (Eq. 5),
- Persistence across time windows, and
- Causal context from related assets.

The result is not just an anomaly, but a validated signal with quantified reliability.

Delivery & Integration

Advisories are generated along **two** time horizons:

- **On-premise, sub-second** for operational response during live events.
- **Cloud, seconds–minutes** for fleet analytics, persistence checks, and CapEx impact assessment.

Two-way integration with EPMS, BMS, CMMS, and ITSM platforms (including ServiceNow) ensures that advisories reduce rather than add to alarm volume. Signals suppresses redundant noise, opens precise tickets with supporting evidence, and deep-links to waveform snapshots for validation.

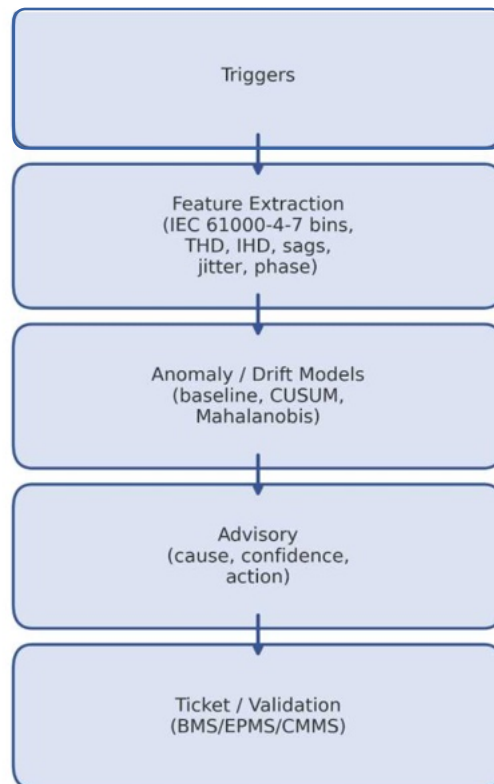


Figure: Signals Processing Pipeline (Triggers → Advisory → Ticket)

Quantitative Impact (KPIs & Formulas)

Signals performance can be evaluated through measurable KPIs that connect detection quality to business outcomes.

6.1 Noise Reduction

$$\text{Noise Reduction} = 1 - \frac{A_1}{A_0}$$

- A_0 : alarms generated under conventional thresholds.
- A_1 : advisories generated by Signals.

Target: >50% reduction in non-actionable alarms, achieved by replacing noisy threshold crossings with a smaller number of high-value advisories.

6.2 Risk Reduction

$$\Delta \text{Risk} = p_{\text{before}} \cdot C_{\text{incident}} - p_{\text{after}} \cdot C_{\text{incident}}$$

- p_{before} , p_{after} : incident probabilities before/after Signals deployment.
- C_{incident} : average cost of an unplanned outage.

Signals reduce unplanned outage probability by surfacing precursor signatures earlier.

6.3 OPEX Savings

$$\text{OPEX Savings} = N_{\text{avoided}} \cdot C_{\text{truckroll}}$$

- N_{avoided} : number of avoided site dispatches.
- $C_{\text{truckroll}}$: cost per truck-roll, estimated at \$2–5k including labor and opportunity cost.

6.4 Return on Investment (ROI)

$$\text{ROI} = \frac{\text{Losses Avoided} + \text{Outages Avoided} + \text{OPEX Saved}}{\text{Program Cost}}$$

This aggregates avoided financial losses (from downtime), reduced unplanned outages, and OPEX savings from fewer truck-rolls, normalized by program cost.

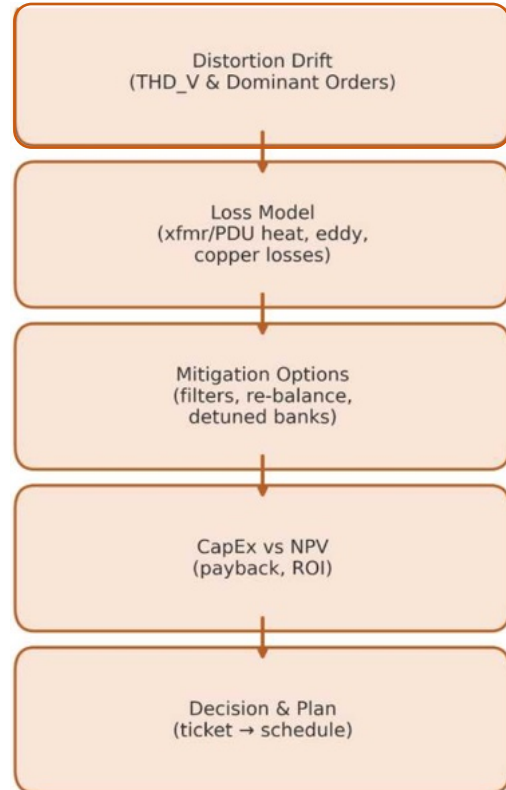


Figure: CapEx Justification Flow (Distortion → Loss → Mitigation → ROI)

Implementation Blueprint

(90 Days to Value)

Signals deployments are structured to deliver measurable outcomes within a single quarter. The blueprint ensures that value is demonstrated early while scaling toward broader integration.

Week 0–2 | Site Selection & Data Readiness

Select representative systems such as cooling equipment, PDUs, and clean-power buses. Confirm readiness for 8 kHz waveform triggers, synchronized clocks, and consistent asset naming. This foundation ensures that baseline learning and event correlation will be accurate.

Week 3–6 | Baseline & Policy

Establish unsupervised baselines for each asset. Define site-specific policies for THD_V, THD_I, and sag detection thresholds. Align ticket templates in CMMS/ITSM so that advisories are actionable from the start.

Week 7–10 | Symptoms to Advisories

Enable core symptom detection (S1, S2, S3). Tune persistence and slope thresholds to distinguish transients from actionable precursors. Integrate two-way with EPMS, BMS, and CMMS platforms, and pilot alarm suppression to prove that Signals reduces noise rather than adding to it.

Week 11–13 | Prove-Out & CapEx Evidence

Measure before-and-after alarm volumes, outage precursors, and avoided interventions. Generate CapEx evidence packs that tie advisories to filter tuning, retermination programs, or VFD maintenance. These artifacts provide both operational proof and financial justification for scaling.

Limitations & Roadmap

Scope

Signals currently applies to AC power systems. DC-link behavior is inferred indirectly through harmonic and phase features on the AC side. Direct DC monitoring is on the roadmap to expand applicability to rectifier and battery subsystems.

Coverage

Waveform analysis today extends to harmonic bins through the 25th order, consistent with IEC 61000-4-7. Interharmonics are computed but not yet formalized as a first-class symptom. The roadmap prioritizes expansion into interharmonic distortion (IHD) to capture sidebands from UPS and motor drive switching, extending coverage beyond conventional PQ metrics.

Latency

On-premise detection delivers sub-second advisories for operational response. Cloud advisories run in seconds to minutes to validate persistence and context across sites. Some fleet-scale policy rules currently run hourly, with roadmap improvements aimed at tightening feedback loops for enterprise-wide monitoring.

Data Quality

Signals require accurate time synchronization and healthy channel telemetry. Built-in self-checks monitor sensor drift, channel continuity, and phase consistency to maintain data integrity. Future releases will expand automated self-healing, including re-baselining and redundant channel substitution.

Conclusion — From “Alarm After Break” to “Intervene Before Failure”

Conventional monitoring reacts only after thresholds are crossed, creating noise without preventing downtime. Signals reverses this model by elevating three high-value electrical symptoms—harmonic deviations, rising THD_V, and sag/jitter/phase anomalies—into validated, plain-language advisories delivered fast enough to change outcomes.

Operationally, Signals reduces nuisance alarms and accelerates targeted maintenance.

Financially, it avoids costly truck-rolls and justifies CapEx investments with evidence.

Strategically, it reduces the probability of unplanned outages and establishes a trusted foundation for predictive operations.

By moving from alarm after break to intervene before failure, Signals positions data center operators to not only manage today's risks but to build toward tomorrow's automated, resilient infrastructure.

References (indicative)

- IEEE Std 519-2014, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.
- IEC 61000-4-7, General Guide on Harmonics and Interharmonics Measurements and Instrumentation.
- IEC 61000-4-30, Testing and Measurement Techniques—Power Quality Measurement Methods.
- ITI (CBEMA) Curve, Voltage Tolerance Boundary for IT Equipment.
- ASHRAE, Thermal Guidelines for Data Processing Environments.

Appendix A — Advisory Template (Operator-Ready)

Title: “Voltage distortion rising on PDU-07 (5th dominant).”

What Signals sees: THD_V $\uparrow$ 1.5% $\rightarrow$ 4.0% in 14 days; 5th harmonic 2.8% $\rightarrow$ 5.1%; coincident with compressor starts. Likely cause: PDU resonance/filter detune; load unbalance contribution.

Confidence: High (0.84). First action: Verify PFC tuning; phase re-balance; evaluate detuned filters.

Evidence: Trend & spectra; links to BMS/EPMS points.

Ticket: ServiceNow incident #...; Owner: Power Ops; SLA: 72h.

Appendix B — Mini Worked Examples

B.1 Harmonic Drift $\rightarrow$ Motor/VFD Risk — THD_I 8% $\rightarrow$ 12%; I5 +4 pp. Inspect bearings; verify VFD cooling; schedule downtime.

B.2 THD_V Trend $\rightarrow$ Filter CapEx — THD_V 1.5% $\rightarrow$ 4.0%; 5th dominant; filter payback from avoided losses + reduced trip risk.

B.3 Sag + Jitter + Phase Offset $\rightarrow$ Loose Lug — Sag to 0.88 pu for 160 ms, $\Delta\phi=4^\circ$; re-terminate under planned window; no outage.

Jonathan Chu

Jonathan Chu is the cofounder and Chief Technology Officer of Verdigris, where he leads technology strategy and platform R&D to advance intelligent energy management for critical infrastructure. His work bridges machine learning, IoT, and power systems to make buildings and data centers smarter, more efficient, and more resilient.

Before founding Verdigris, Jonathan worked at IBM on advanced server research and at NetLogic Microsystems (acquired by Broadcom/Avago), developing high-performance computing and networking technologies. He holds a master's degree in Computer Engineering with a dual degree in Public Policy from Carnegie Mellon University.

Jonathan's career centers on transforming high-frequency energy data into actionable intelligence, helping organizations understand, predict, and optimize the flow of energy that powers the modern world.

Mike Mahedy

Mike has spent the last 20 years in and around the data center industry. At Apple he led the Global Data Center Automation and Tools, implementing Power Telemetry, Automation and Reporting across all of Apple's owned and leased DC's. More recently he led the Data Center Capacity Planning and Automation Team at Workday, streamlining hardware capacity signal to fulfillment in the DC.

