PhD Forum Abstract: Knowledge From Noise: EMI-Guided Power Monitoring

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ABSTRACT

Server-level power monitoring is essential for efficient data center management. However, high expense of individual power meter for each server has hindered widespread adoption, resulting in a concentration on UPS and cluster-level monitoring in most data centers. We introduce an innovative and cost-effective power monitoring method, which utilizes a single sensor to derive power consumption data from all servers by tapping into the conducted electromagnetic interference (EMI) emitted by server power supplies. This enables the measurement of power consumption through non-invasive single-point voltage measurements. Our approach, tested with a set of ten servers from two different brands, can estimate individual server power with less than ~7% mean absolute error.

1 INTRODUCTION

The essence of effective data center power management lies within the power monitoring system, providing invaluable insights to optimize data center operations. A pivotal aspect is the intricate server-level power monitoring. This real-time scrutiny of server power consumption facilitates advanced methodologies like power capping and idle power reduction [1]. It also aids in efficient cooling management through load balancing and pinpointing potential server hotspots [1]. Moreover, detailed power monitoring plays a critical role in averting data center outages stemming from overloading and identifying malicious server activities initiated by attackers.

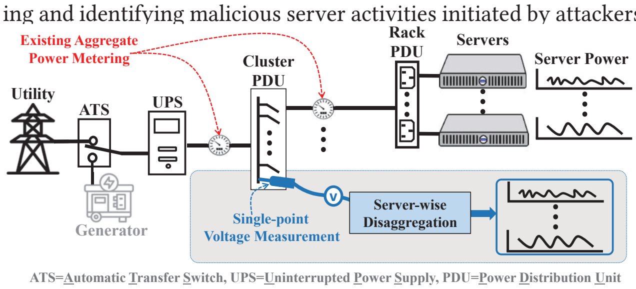

Figure 1: Overview of EMI-driven server power monitoring.

2 LIMITATIONS OF CURRENT SOLUTIONS

In typical data center environments, server-level power monitoring is infrequent due to its high costs, except for prominent IT companies like Facebook [1]. Current monitoring practices predominantly concentrate on UPS and cluster-level data, as integrating onboard power monitoring into servers proves costly [1], often leading to significant cost escalations. Another obstacle lies in the inability to monitor power consumption in tenant server racks within colocation data centers. Colocation data centers [1], constituting a significant portion of the market, offer shared solutions where tenants manage their servers, while the data center operator oversees infrastructure. However, the operator lacks access to tenant server racks, hindering the deployment of server-level power monitoring.

3 RELATED WORK

Dedicated hardware [1] provides accurate power metering but requires significant investment to achieve server-level metering in data centers. Conversely, software-based solutions generate power models using data from diverse sources, which are cost-effective but necessitate access to server performance counters [1], restricting their applicability in multi-tenant colocation data centers. Moreover, software-based power monitoring entails intrusive offline training, posing challenges for real-time implementation. Unlike related research, such as [2] which estimates total data center power using voltage side-channels, our project emphasizes on estimating server-level power metering. In contrast to [3], which similarly utilizes voltage measurements but centers on residential environments with fewer signal sources to track household appliance activity, our project depicted in Fig. 1 focuses on commercial data center environments with numerous servers.

4 BACKGROUND

A server's power supply (Fig. 2) converts 100-240V AC power into regulated DC voltage for internal components. The process initiates with an EMI filter to remove frequency components surpassing 150kHz, followed by a rectifier converting AC into pulsating DC voltage (unipolar half-sine waves). Subsequently, a power factor correction (PFC) stage boosts this DC voltage to 380V, which is then lowered to 12V for internal components via a DC-to-DC converter.

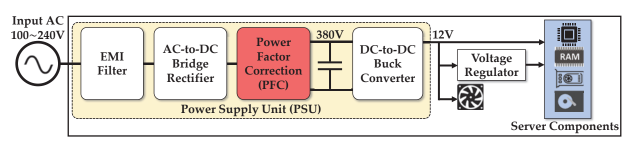

Figure 2: PFC (highlighted in red) with server components.

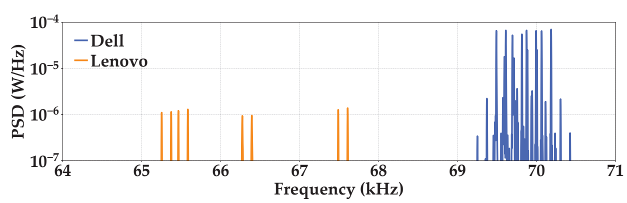

Figure 3: Server EMI in frequency domain.

The PFC circuit improves the power factor by preventing harmonic generation from distorted current waveforms. A commonly employed boost-type PFC comprises an inductor, diode, MOSFET switch, and a control circuit for pulse width modulation (PWM). The control circuit swiftly toggles the MOSFET on/off at a high frequency (PFC switching frequency), inducing current ripples. These ripples are manipulated to align with a reference waveform by regulating the MOSFET's on/off durations, resulting in high-frequency ripples. As the input current traverses the data center

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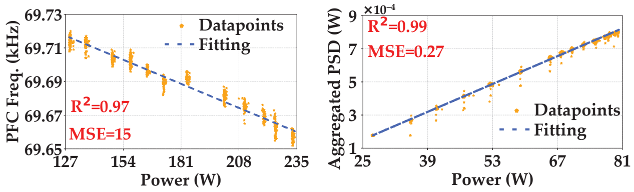


(a) Dell (b) Lenovo

Figure 4: (a) Power vs PFC frequency relation of a Dell server. (b) Power vs. aggregated PSD relation of a Lenovo server.

power network, voltage ripples arise due to line voltage drops in accordance with Ohm's Law. Importantly, these ripples occur at a much higher frequency(f_p) (40-100kHz) than the 50/60Hz(f_0) grid frequency, easily detectable in power network voltage readings with the help of oscilloscope and high pass filter. Fig. 3 illustrates the power spectrum density (PSD) of voltage measurements at a nearby power outlet of six Dell PowerEdge and 4 Lenovo ThinkSystem servers equipped with PFC. From the FFT, we identify the PFC EMI frequency f_p and Power Spectral Density (PSD) of PFC EMI (each server has two prominent EMI spikes at $f_p \pm f_0$).

5 EXPERIMENTAL VALIDATION

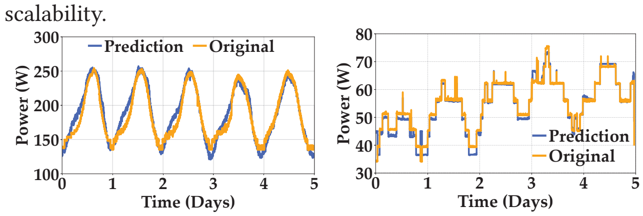
Within Power Factor Correction (PFC), the input voltage shapes the current into a sinusoidal waveform. Despite the voltage remaining constant (e.g., approximately 120V in the U.S.), the current must adapt proportionally to server power while preserving this form. For instance, a 100W server generates a PFC current waveform twice as tall as a 50W server. Consequently, PFC switching adjusts to these power fluctuations, albeit the specifics vary based on the proprietary designs of server power supply manufacturers. According to our experiments with Dell and Lenovo servers, PFC control typically responds to power variations in two manners: by modifying the switching frequency (FM-PFC, observed in Dell servers) and by adjusting the amplitudes of high-frequency ripples (AM-PFC, observed in Lenovo servers) as illustrated in Fig. 4.

6 EMI-GUIDED POWER MONITORING

Our experiments, involving a Dell and a Lenovo server (Fig. 4), demonstrate that conducted Electromagnetic Interference (EMI) signals can reveal a server's power consumption. Hence, in a multi-server setting, EMI-based power monitoring fundamentally entails the isolation of each server's EMI signatures from the voltage data. This is accomplished by leveraging the notion of frequency-domain orthogonality, leading our algorithm to primarily function in the frequency domain. Our power monitoring algorithm encompasses three pivotal stages: (1) Identify the EMI spikes of each server (2) Track the PFC frequency of each server over time (3) EMI-to-power models to calculate the power consumption of each server.

7 RESULTS

We utilize a cluster comprising six Dell PowerEdge R640 servers and four Lenovo ThinkSystem SR250 rack servers. To evaluate server power fluctuations, we expose them to diverse workloads by applying stress to different numbers of CPU cores. In this context, we concentrate on the outcomes obtained from one Dell server and one Lenovo server throughout a span of five days, as depicted in Fig. 5. These results indicate a mean absolute percentage error of approximately less than ~7%. Currently we are developing a prototype which can cost below 20 USD to monitor the servers. Also we are developing a simulation program to test our algorithm's scalability.



(a) Dell#1 (b) Lenovo#1

Figure 5: Predicted Power vs Original Power

8 OTHER ONGOING WORK

The growing adoption of residential distributed energy resources (DERs) introduces more uncertain variability in power grid operation. More importantly, the residential DERs (solar panel) operate behind customers' energy meters, and therefore, the utility cannot "directly" monitor them. Prior approaches to enable visibility into behind-the-meter (BTM) DERs either depend on estimations or require intrusive instrumentation on the customer side. To address the critical need for direct real-time monitoring of DERs, we propose a novel approach (Fig. 6) for utility-side direct real-time monitoring of residential DERs. We utilize high-frequency (> 10kHz) conducted EMI (Fig. 7) from residential DERs' grid-tied inverters (from power supply) to monitor their power generation. The U.S. power grid

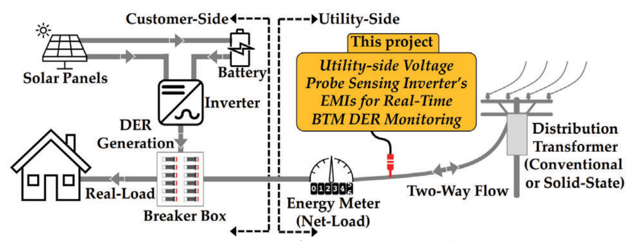
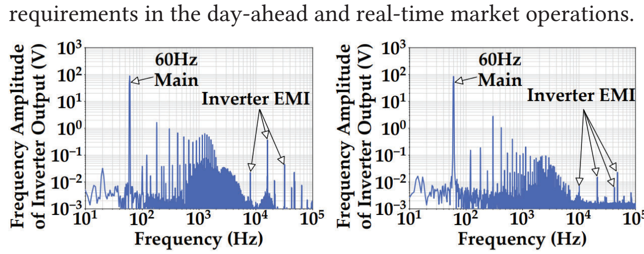


Figure 6: : Overview of our proposed approach.

has been evolving over the years with the growing electrification of buildings and vehicles and an increasing number of grid-connected storage devices altering the load types and profiles. Monitoring variable DERs will improve the electricity market participation, where accurate forecasting is critical for determining reserve and ramping requirements in the day-ahead and real-time market operations.



(a) SMA Sunny Boy (b) Enphase IQ7

Figure 7: FFT of the output voltage of two different inverters.

9 BIO

The author is 5th year PhD student and the graduation timeline is 2025, May. The name of the supervisor is Mohammad Atiqul Islam.

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