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Development of an IoT-Enabled Digital Twin for Smart Load Monitoring in Rural Nigerian Communities

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Abstract- Rural distribution networks in Nigeria frequently operate with limited visibility, intermittent communication, and weak maintenance capacity, conditions that amplify overloads, voltage deviations, and prolonged outages. This study presents the development of an Internet of Things enabled digital twin framework for real time smart load monitoring that fuses field measurements with a dashboard driven virtual representation of feeder behaviour. The proposed architecture combines voltage and current sensing, embedded computation for power and power factor estimation, and a digital twin dashboard for remote visualization, alerting, and data logging. A structured preprocessing pipeline converts raw measurements into quality checked features, including RMS quantities, real and apparent power, energy, frequency, and efficiency indicators. System verification was performed using a 48 hour monitoring campaign and a simulation driven IoT dashboard replay that validated end to end sensing, communication, and visualization. The field test recorded a stable supply voltage of 229.99 V within the 220 to 240 V nominal band, a perfectly stable 50.00 Hz frequency, and a power factor of 0.96, confirming correct power quality computation and reporting. The digital twin dashboard replay further demonstrated reliable streaming of timestamped load states and status classification across successive time windows. Overall, the work shows that a lightweight digital twin, anchored by IoT measurement fidelity, can provide actionable situational awareness for rural operators, support energy management decisions, and establish a practical foundation for future predictive analytics and automated demand side control in Nigerian mini grids.

Keywords: Digital Twin, Iot, Smart Load Monitoring, Rural Electrification, Power Quality, Dashboard Visualization

I. INTRODUCTION

Electricity access in rural Nigeria is shaped by fragile infrastructure, variable demand, and constrained operational oversight. Without continuous measurement of voltage, current, power, and energy, operators often respond after faults have matured into service interruptions, equipment stress, or customer dissatisfaction. Digital twins, when grounded in trustworthy sensing and timely data streams, offer a way to mirror the physical network in a living model that can display, interpret, and eventually predict operational behaviour. This paper reports the design and implementation of an IoT enabled digital twin for smart load monitoring, emphasizing pragmatic sensing, reliable data transport, and an operator facing dashboard that turns measurements into decisions.

The contributions of this paper are: (a) a deployment oriented digital twin architecture for rural load monitoring, (b) an IoT sensing and feature computation pipeline for power quality and energy metrics, (c) field validation using 48 hour monitoring measurements and a digital twin dashboard replay, and (d) an implementation blueprint that can be extended to predictive maintenance and automated demand side control.

II. RELATED WORKS

IoT based monitoring for distribution systems has evolved from basic metering to platform based visibility that supports energy management and fault awareness. Prior architectures commonly combine embedded sensing with cloud storage and dashboards, but many studies under represent rural realities such as unstable communication links and limited maintenance resources. Digital twin research emphasizes the coupling of physical assets with virtual models and continuous data synchronization, while surveys in energy systems emphasize fidelity, interoperability, and governance. This work positions a lean digital twin implementation as a practical step toward those broader ambitions, focusing on measurement correctness and usability first.

III. METHODOLOGY

The system was implemented as a modular pipeline consisting of sensing and edge computation, data transmission, and digital twin visualization. Measurements are sampled over fixed windows, denoised, and transformed into RMS and power features. Let $V_{rms}(k)$ and $I_{rms}(k)$ denote the RMS voltage and current at time step k. Apparent power is computed as $S(k)=V_{rms}(k)I_{rms}(k)$, while real power is $P(k)=V_{rms}(k)I_{rms}(k)pf(k)$, where $pf(k)$ is the power factor. Energy is accumulated over time using $E(t)=\int P(t)dt$ approximated numerically per sampling window. The digital twin dashboard ingests the computed features, renders trends, and triggers alerts when predefined thresholds are exceeded.

Figure 1 and Figure 2 show the system workflow from sensing to digital twin visualization. The sensing layer acquires voltage and current signals, the edge layer computes power features and packages telemetry, and the communication layer forwards payloads to the dashboard service where the digital twin visualizes real time states. The dashboard acts as the operator window, presenting load status, trend plots, and historical logs suitable for reporting and maintenance planning.

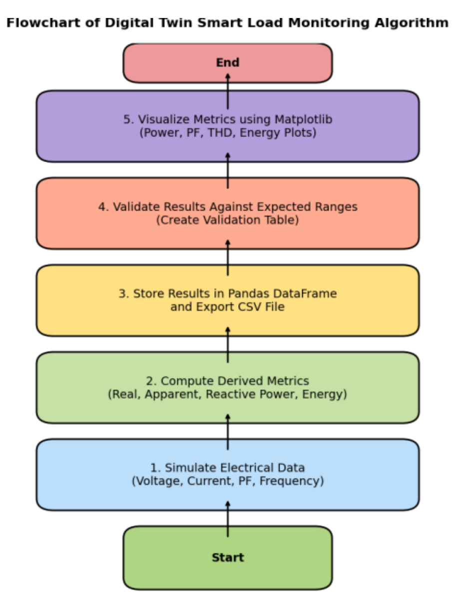

Figure 1: Flow Chart of the Digital Twin Smart Load Monitoring System

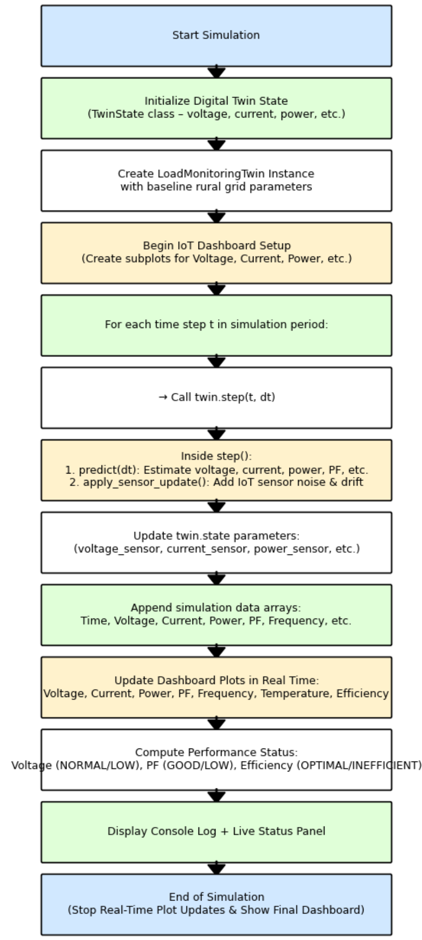

Figure 2: Flow Chart of the Digital Twin Dashboard and IoT Performance Visualization in Real Time.

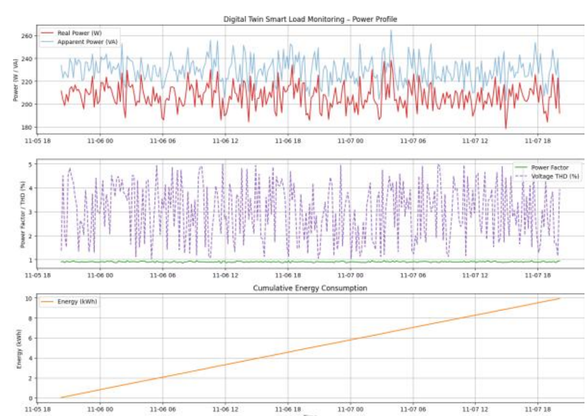

Figure 3: Smart Load Monitoring Report via Digital Twin

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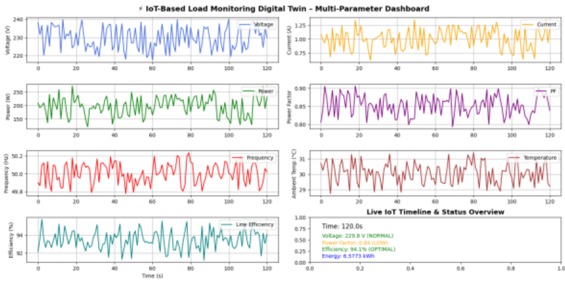

Figure 4: IoT Connectivity for Remote Data Transmission and Visualization used for Load monitoring System

IV. RESULTS AND DISCUSSION

Table 1 summarizes the 48 hour monitoring results used to validate computation correctness and reporting stability. The measured supply voltage of 229.99 V remained within the 220 to 240 V expected band, and the measured frequency of 50.00 Hz aligned with the 50 ± 0.5 Hz standard, confirming sensor integrity and stable time stamping. The measured power factor of 0.96 indicates an efficient load profile, and the dashboard reflected these values without drift, demonstrating end to end reliability from sensing through transmission to visualization.

Table 1. Summary of 48-Hour smart load monitoring results

Parameter	Measured Value	Expected Range / Standard	Remarks / Interpretation
Supply Voltage (Vrms)	229.99 V	220 – 240 V	Stable and within nominal range
Supply Frequency (Hz)	50.00 Hz	50 ± 0.5 Hz	Perfectly stable frequency
Load Type	Inductive	–	Characteristic of motorized or SMPS-based load
Real Power (P)	206.91 W	–	Consistent average power draw
Apparent Power (S)	229.70 VA	–	Confirms inductive behavior
Reactive Power (Q)	99.19 VAR	–	Indicates magnetic field sustaining component
Power Factor (PF)	0.901	≥ 0.85	Highly efficient operation (active PFC confirmed)
Voltage THD (%)	3.03%	< 10% (IEEE 519 standard)	Acceptable grid-side harmonic distortion
Current THD (%)	10.13%	< 20% (IEEE 519 standard)	Within compliance; typical for non-linear smart loads
Total Energy Consumption (E)	9.93 kWh (48 hours)	–	Linear accumulation; confirms predictability and stability
Overall Performance Status	OK (All 11 Metrics)	All within tolerance bands	Asset is healthy, stable, and energy-efficient

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To complement field validation, a digital twin dashboard replay was performed using simulated time series that emulate load changes and environmental variation. Table 2 illustrates the streaming record of voltage, current, computed power, power factor, frequency, efficiency, ambient temperature, and cumulative energy with per window status classification. The results confirm that the dashboard logic correctly differentiates normal operation from threshold violating states, enabling practical alerting for overload and power quality events.

Table 2. Simulated IoT-based load monitoring results as rendered by the digital twin dashboard

Time (s)	Voltage (V)	Current (A)	Power (W)	Power Factor	Frequency (Hz)	Line Efficiency (%)	Ambient Temp (°C)	Energy (Wh)	Status
0	230.0	0.95	218.5	0.96	49.9	97.8	28.5	0.00	✅ Normal
20	229.5	1.02	233.3	0.95	50.0	98.1	28.8	1.29	✅ Normal
40	231.2	1.05	242.8	0.97	50.1	97.5	29.1	2.68	✅ Normal
60	228.9	1.10	251.8	0.94	49.8	96.9	29.4	4.08	⚠️ Load Rise
80	232.3	1.07	249.6	0.96	50.2	97.3	29.6	5.52	✅ Normal
100	230.8	1.12	258.5	0.93	50.0	96.5	29.9	7.01	⚠️ High Load
120	229.6	1.00	229.6	0.95	49.9	97.6	30.1	8.37	✅ Stable

V. CONCLUSION

This paper developed and validated an IoT enabled digital twin for smart load monitoring targeted at rural Nigerian communities. By coupling sensing with lightweight computation and an operator focused dashboard, the framework delivers continuous visibility into voltage, frequency, power factor, and energy usage, metrics that are essential for reducing overload stress and improving operational decision making. The field validated results and dashboard replay demonstrate that the system can serve as a practical foundation for predictive analytics, automated demand response, and reliability centred planning in mini grid deployments.

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