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Design, Modeling and Seasonal Power Yield Comparison of a Radio Frequency Energy Harvester for Wireless Sensor Nodes

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ABSTRACT

A Radio-Frequency (RF) energy harvesting system for continuous operation in tropical environments is presented and evaluated. A detailed MATLAB/Simulink model was developed to analyze the performance of the RF energy harvester under seasonally varying ambient RF conditions. Monthly simulations were conducted to assess DC–DC output power, power management output, load power, conversion efficiency, and daily harvested energy. The results show a consistent power hierarchy in which the DC–DC converter output exceeds the regulated and load powers due to conversion and control losses. The system maintains a nearly constant efficiency of approximately 49.64% throughout the year, indicating stable power conditioning. Seasonal variations in harvested energy are primarily governed by changes in RF propagation conditions, with dry-season months achieving daily harvested energy above 3.4 mWh, while peak rainy-season conditions yield a minimum of approximately 2.99 mWh. Despite an 18 - 20% variation between best-case and worst-case months, the system consistently delivers usable power to the load. These results confirm the suitability of the proposed RF energy harvesting system for year-round deployment in tropical environments and for powering low-energy wireless sensor nodes.

Keywords: RF energy harvesting, Wireless Sensor Networks, Ambient RF energy, Power management system, Tropical Climate

1. INTRODUCTION

Industry 4.0 promises that cyber physical systems composed of cloud computing and Internet of Things (IoT) technologies will be used for environmental monitoring and enhancing decision-making capabilities (Alexander et al., 2021). We are in the era of IoT where sensors such as temperature sensors (Ramakrishnan et al., 2016), proximity sensors (Servent et al., 2017), ultrasonic sensors (Li et al., 2018), gas sensors (Yamazoe, 2005; Song et al., 2017) are widely distributed for environmental or industrial monitoring (Akhondi et al., 2010; Bhuiyan et al., 2012, Kelly et al., 2013; Kandris et al., 2020; Souad & Awatef, 2022), military applications (Jaigirdar et al., 2011). To realize this vision, it requires the deployment of wireless sensor networks (Annapureddy et al., 2018).

Wireless Sensor Networks (WSNs) are large number of static sensor nodes with limited processing and power capabilities that are deployed in a distributed manner and communicate over unreliable, short-range radio links or gateway (Baronti et al., 2007; Shaikh et al., 2013). WSNs have continued to undergo rapid advancement in various areas like military, environmental monitoring and disaster management, transportation, flora and fauna, health, security, energy, industry, smart homes, and other commercial purposes (Gupta & Kumar, 2013; Onuekwusi et al., 2015). A WSNs is comprised of nodes which may amount from a few to several hundreds or even thousands, where each node is connected to one sensor (Apurva, 2022). Each sensor node consists of a sensing unit, processing unit,

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communication unit, power supply unit usually a battery or some form of energy harvester, and optionally a positioning and mobility system (Obbo, 2022).

Despite the widespread applications and significant benefits of WSNs, it is well-known that one of the major challenges faced with WSNs is limited energy supply to sensor node (Shaikh et al., 2015; Ahmad et al., 2019; Iftikhar et al., 2021; Divyanshu et al., 2024). The key requirement of a WSNs is that it should be autonomous, operate for a particular time, and require little maintenance which can be costly and inconvenient depending on the number of nodes and the application itself which could necessitate nodes with limited accessibility (Panatik et al., 2016). The major existing energy source used by sensor nodes is battery, but many problems are associated with batteries (Raquib et al., 2016). First, severe weather conditions may break down the batteries, resulting in chemical leakages that can cause various environmental problems (Tiliute, 2007). Secondly, batteries are insufficient in providing enough energy for long term applications, which lead to inconvenient frequent charging or replacement (Penella et al., 2009; Katrina et al., 2021). Finally, for WSNs deployed in inaccessible areas, the replacement or recharge of depleted batteries is not feasible, so the device must be designed to ensure that the energy provided by battery is enough for the system's entire anticipated lifecycle (Sichitiu & Dutta, 2005; Abd Aziz et al., 2012). Of course, a possibility is to use higher capacity batteries to ensure the required energy constraints are met, but this result in increased size for the device that is often not acceptable (Marco, 2021).

Though the energy efficiency and expected lifetime of WSNs has increased over the last few years due to sensor and software optimizations, lightweight communication protocols, and low-power radio transceivers, energy supply remains a major challenge with WSNs (Keh et al., 2011; Prauzek et al., 2018; Zhou et al., 2019; Wang et al., 2019).

Energy harvesting has emerged as a promising solution to address the energy constraints in WSNs (Choudhary et al., 2020; Fadoua & Adil, 2022; Hussain et al., 2024; Muhammad et al., 2025). By capturing energy from the environment and external sources and converting it into electrical energy, sensor nodes can potentially achieve a sustainable power supply (Jaspreet et al., 2023).

2. METHODOLOGY

2.1 Experimental Data Collection

Accurate characterization of ambient RF power density is fundamental to realistic performance evaluation of RF energy harvesting systems. This study relies on site-specific, long-term measurements to capture the true variability of 2.4 GHz signals in an urban tropical environment.

Measurements were conducted at the Electrical and Electronics Engineering Laboratory, Federal University of Petroleum Resources Effurun (FUPRE), Effurun, Delta State, Nigeria (geographical coordinates: approximately 5.65°N, 5.62°E). The laboratory is situated in a semi-urban academic campus with moderate RF activity from nearby Wi-Fi access points, Bluetooth and microwave devices.

Data collection spanned from January 1, 2025 to December 31, 2025, covering a full calendar year representative of the dry and rainy season.

A MESTEK EMF02R EMF Meter was used to measure Power density (µW/cm²) which was recorded at 20-minute intervals over 24 hours per day, resulting in 72 samples per day and 26,280 total measurements across the year.

2.2 System Architecture

The architecture of the Radio-frequency harvester is given in Figure 1. It consists of the radio-frequency harvester, impedance matching circuit, rectifier/voltage multiplier, buck DC-

DC converter, Maximum power point tracking (MPPT) controller, power management system, battery storage and a wireless sensor node.

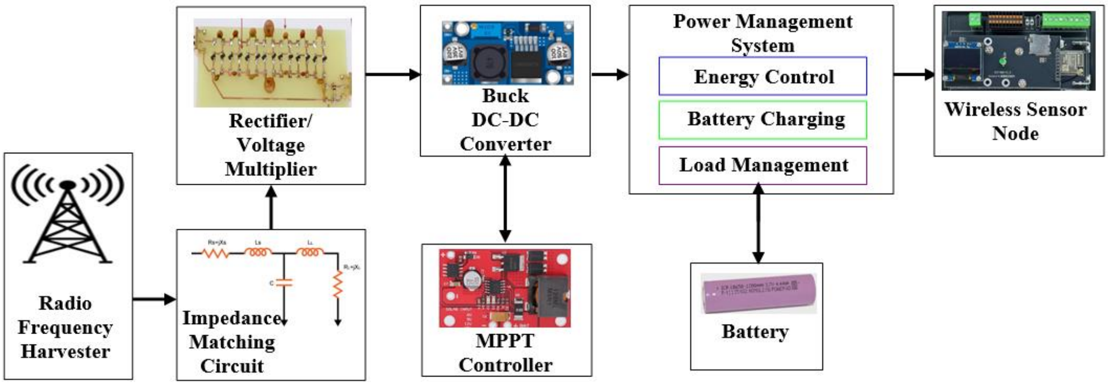

Figure 1: Architecture of the Radio-frequency harvester

The radio-frequency harvester (antenna) captures the ambient RF signal from the environment and then feds into the impedance matching circuit that maximizes energy transfer from the antenna (50Ω source) to the rectifier (load) by matching their impedances. The rectifier/voltage multiplier circuit converts the alternating current (AC) from the impedance matching circuit to direct current (DC) and the buck DC-DC converter efficiently steps down the high-voltage, low-current rectified into a stable, lower-voltage DC output suitable for powering low-power IoT devices. The MPPT changes the duty circle of the buck to ensure that the source always delivers maximum possible power, while the power management system (PMS) controls battery charging, manages energy flow and load management.

2.3 Modeling of a Radio-Frequency Energy Harvesting system

2.3.1 Modeling the 2.4 GHz Microstrip Antenna

The antenna is mathematically represented as a Thevenin equivalent circuit consisting of a voltage source (Vant) and an internal impedance (Rant) as shown in Figure 2.

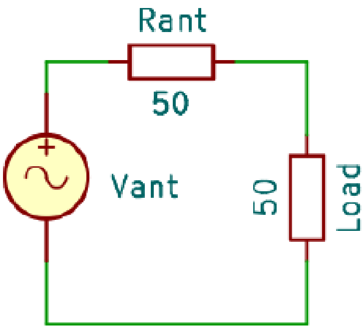

Figure 2: Equivalent circuit of an antenna

The power received from the transmitter on the antenna of the receiver is calculated using the effective antenna area A_{eff} (Serdijn et al., 2014) as:

$$Aeff = \frac{P_{av}}{S} \qquad (1)$$

Where, A_{eff} is antenna's effective area, P_{av} is power delivered to the antenna, and S is power density of the wave incident to the antenna.

If the load impedance is equal to the characteristic impedance of the antenna as shown in Figure 2, the maximum possible power transfer from the antenna to the load is equal according to (Flowers, 1909) as:

$$max\ (P_{load}) = \frac{V_{ant}^2}{4R_{ant}} \tag{2}$$

When free space is assumed together with a perfectly matched lossless antenna, the power available in the circuit is described by the Friis equation (Serdijn et al., 2014) as:

$$P_{av} = A_{eff}S = (\frac{\lambda}{4\pi D})^2 D_{RX}P_{EIRP} \tag{3}$$

where, d is antenna's directivity, $(\frac{\lambda}{4\pi D})^2$ is free-space equation, D_{RX} is maximum antenna directivity, and P_{EIRP} is effective radiated power.

Practically, the Friis equation shows how much power reaches a receiving antenna from a transmitting antenna over a given distance in free space and is given as:

$$P_r = P_t G_t G_r (\frac{\lambda}{4\pi D})^2 \tag{4}$$

2.3.2 Modeling the Impedance Matching Circuit

The impedance matching circuit maximizes transfer by achieving proper impedance between antenna and rectifier from transmission line theory minimizing reflections. Referencing P_r from Equation (4) the matched power is given as:

$$P_{match} = P_r(1-|\ \Gamma\ |^2) \tag{5}$$

where the reflection coefficient $\Gamma = (Z_{re}c_t - Z_a*)/(Z_{re}c_t + Z_a*)$, Z_a is the antenna impedance normally 50 Ω, and $Z_{re}c_t$ is the nonlinear rectifier input impedance.

2.3.3 Modeling the Rectifier/Multiplier Circuit

The rectifier employs Schottky diodes whose I-V characteristic follows the Shockley equation derived from drift-diffusion theory. For low-level RF signals, each diode acts as a half-wave rectifier with threshold voltage V_{th} is approximately 0.28 V. Using P_{match} from Equation (5), the single-stage rectified power is give as:

$$P_{rect,1} = \eta_{rect}P_{match} \tag{6}$$

Where η_{rect} = 0.4 to 0.7 reflecting threshold losses V_{th} around 0.3 volts.

The two-stage Greinacher multiplier cascades (Cockcroft-Walton) doublers to elevate voltage use each stage adding approximately twice the peak radio frequency voltage minus drops from diode. The multistage output voltage is given as:

$$V_{dc} = N(V_{rf,peak} - 2V_{th}) \tag{7}$$

Where N is the number stages, $V_{rf,peak} = \sqrt{(2\ P_{match}\ R_{ant})}$ with R_{ant} = 50 ohms yielding $P_{rect,N} = V^2_{dc} / R_{load}$ adjusted for load.

2.3.4 Modeling the DC – DC buck converter

The DC – DC converter typically a boostk type elevates the low rectified voltage to battery levels using inductor-based switching from energy storage principles. Reusing $P_{rect,4}$ from the extension of equation (6) the output power is given as:

$$P_{conv} = \eta_{dc-dc}P_{rect,4} \tag{8}$$

with η_{dc-dc} 0 = .7 to 0.85 for low-input ICs

The DC to DC converter now utilizes a buck topology to step down the high rectified voltage to the battery charging level using inductor-based switching from energy storage principles with duty cycle D < 1. Reusing $P_{rect,4}$ from Equation (6) and applying volt-second balance on the inductor as in solar buck models the output power is revised and given as:

$$P_{conv} = \eta_{buck}P_{rect,4} \tag{9}$$

With η_{buck} 0.85 to 0.95 for low-power synchronous or diode-based buck converters operating at frequencies of 100 KHz to 1 MHz to minimize quiescent losses while stepping down from 4 V – 8 V to 3 V - 4.2 V suitable for battery charging.

2.3.5 Modeling the Maximum Power Point Tracking Circuit

Maximum power point tracking for radio frequency adapts perturbation and observation methods to tune DC-DC converter duty for peak rectification efficiency from optimization theory. Referencing P_{conv} from Equation (9) the algorithm perturbs a control variable like varactor capacitance and observes power change given as:

$$\Delta \mathrm{P} = P_k - P_{k-1} \tag{10}$$

If $P_k - P_{k-1} > 0$: $x_{k+1} = x_k + \Delta x$ (increment perturbation), $x_{k+1} = x_k - \Delta x$ (decrement perturbation) achieving an efficiency $\eta_{MPPT} > 95$ %, where P_k is harvested power at iteration k, P_{k-1} is harvested power at iteration k-1, Δx is perturbation step (duty cycle, load or control variable).

2.3.6 Modeling the Power Management System

The power management system regulates flow with protection thresholds from control logic. Reusing P_{conv} from Equation (9) the managed power is give as:

$$P_{pms} = \eta_{pms} P_{conv} \tag{11}$$

with η_{pms} 0.98 including overvoltage cutoff at 4.5 V.

2.3.7 Modeling the Battery Storage

Battery storage charges electrochemically with efficiency for low-rate inputs. Reusing P_{pms} from equation (11) stored power is given as (3.38):

$$P_{stored} = \eta_{charge} P_{pms} \tag{12}$$

η_{charge} 0.98 for lithium at nanoampere rates.

2.3.8 Modeling the Wireless Sensor Node

The wireless sensor node load draws intermittently modeled as duty-cycled resistance. Reusing P_{stored} from Equation (12) system efficiency is Equation (3.39):

$$\eta_{system} = P_{stored} / P_r \tag{13}$$

cascading efficiencies typically 20 % to 50 % end-to-end.

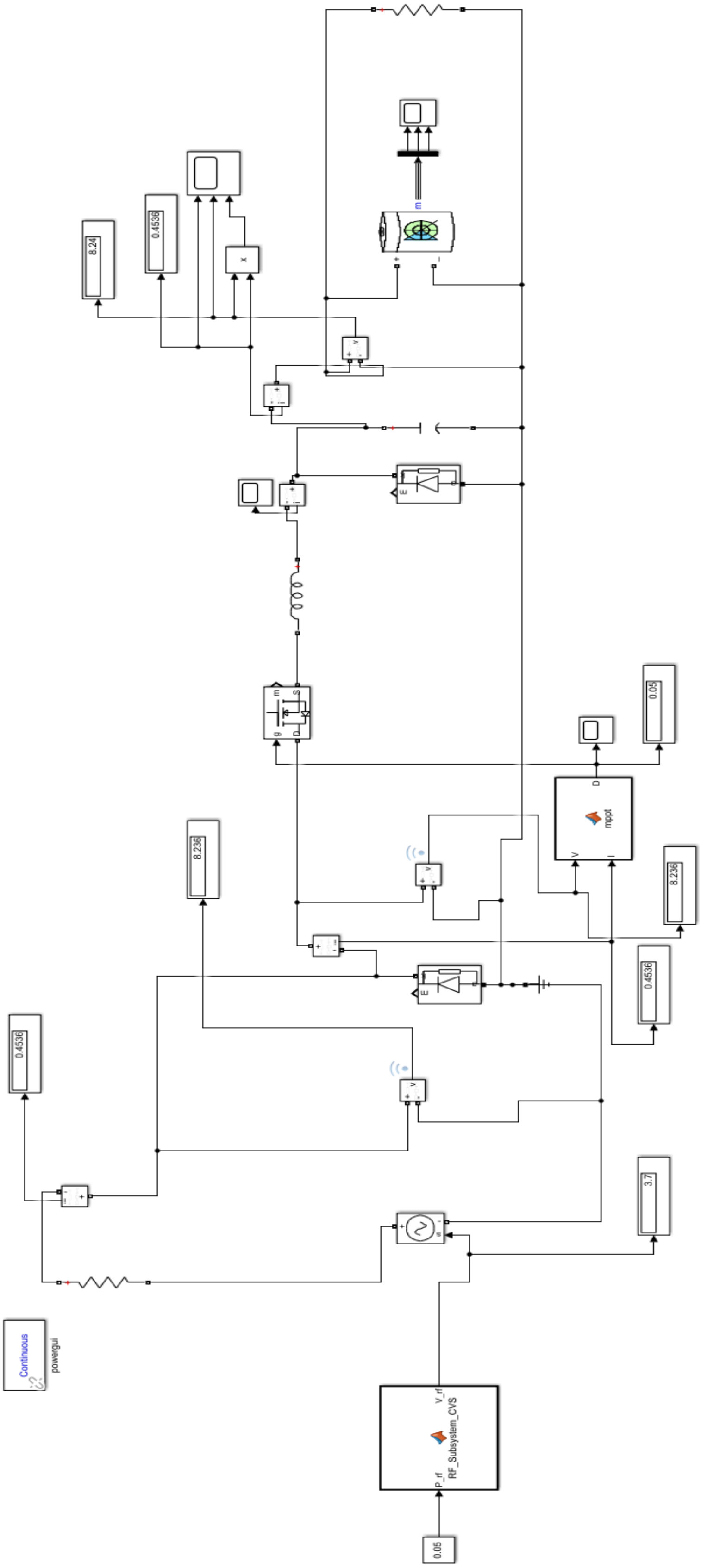

Figure 3: Simulink Model of the Radio Frequency Energy Harvesting System

3. RESULTS AND DISCUSSION

Figure 4(a)-4(d) respectively presents the comparative monthly performance of the proposed RF energy harvesting system, including the DC-DC converter output, power management system (PMS) output, load power, and daily harvested energy over a full annual cycle. In all months, a consistent power order is observed, where the DC-DC output exceeds the PMS output and the load power, reflecting expected conversion and regulation losses. Notably, the system efficiency remains nearly constant at approximately 49.64% throughout the year, indicating that the internal power conditioning stages are stable and largely independent of seasonal variations.

Seasonal changes in harvested energy are therefore governed primarily by variations in ambient RF energy availability. The highest average power levels and daily harvested energy (exceeding 3.4 mWh/day) occur during the dry-season months, when low humidity and minimal rainfall favor RF propagation. Under these conditions, reduced atmospheric attenuation allows higher RF power density to reach the receiving antenna, resulting in increased DC-DC, PMS, and load power.

As the system transitions into the rainy season, a gradual reduction in harvested power is observed. Increased atmospheric moisture, rainfall, and cloud cover introduce RF absorption, scattering, and multipath fading, leading to lower DC-DC output and corresponding reductions at the PMS and load. The minimum daily harvested energy of approximately 2.99 mWh/day occurs during the peak rainy period. Despite these adverse conditions, the system continues to deliver stable power to the load, demonstrating effective regulation and robustness against environmental variability.

Overall, the annual results reveal an energy variation of approximately 18-20% between the best and worst months, while maintaining constant efficiency. This confirms that system performance is limited by environmental RF propagation rather than electronic inefficiencies, validating the suitability of the proposed RF energy harvesting system for year-round operation in humid tropical environments and for powering low-energy wireless sensor nodes.

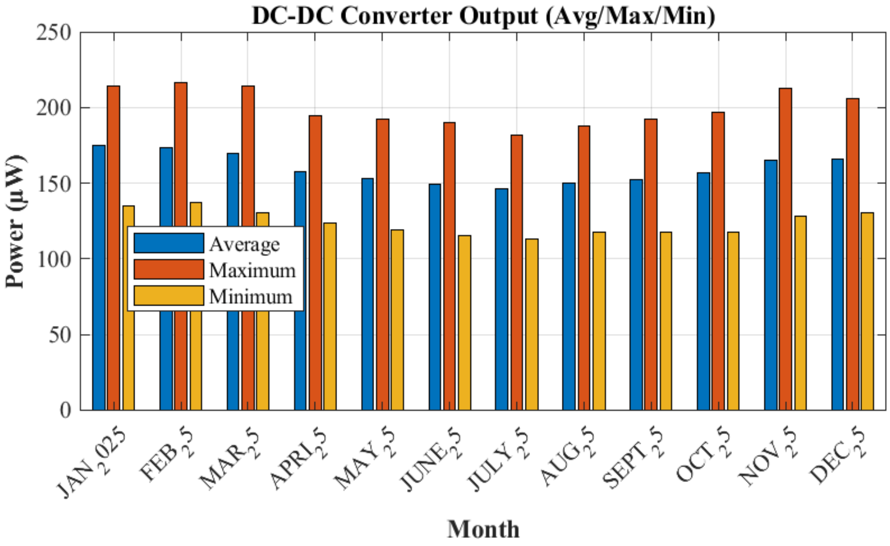

Figure 4(a): Comparative monthly performance of the proposed RF energy harvesting system

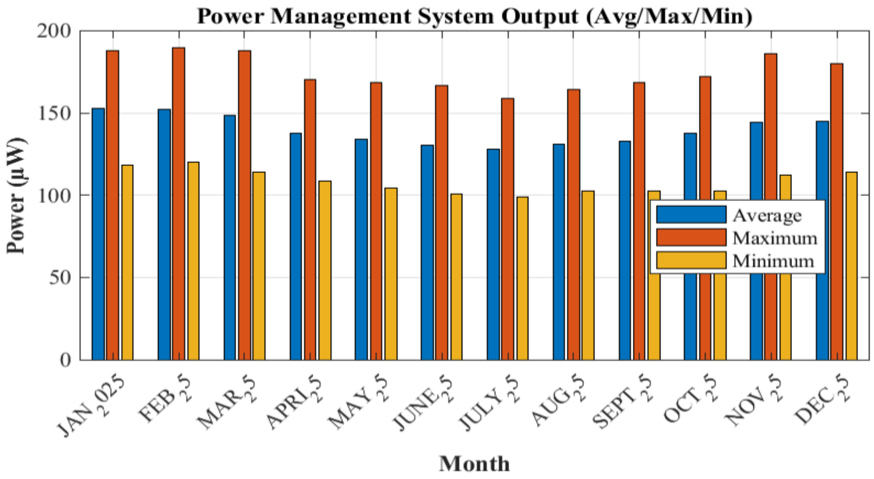

Figure 4(b): Comparative monthly performance of the proposed RF energy harvesting system

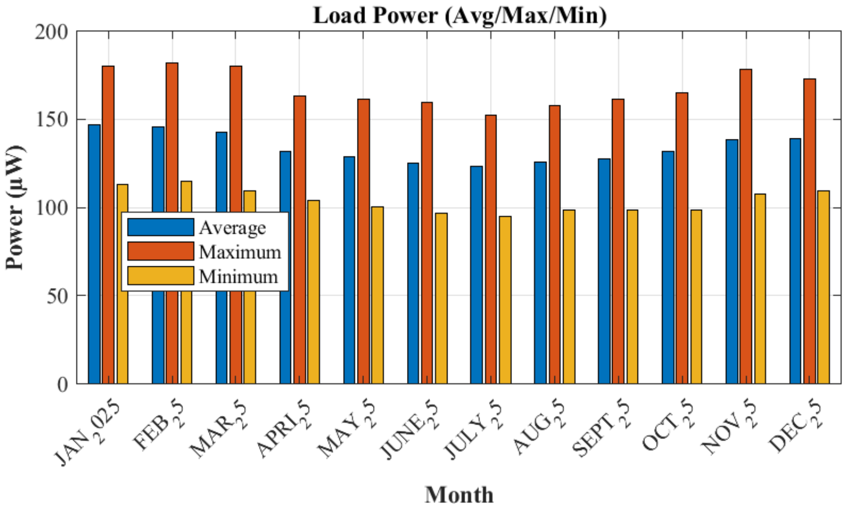

Figure 4(c): Comparative monthly performance of the proposed RF energy harvesting system

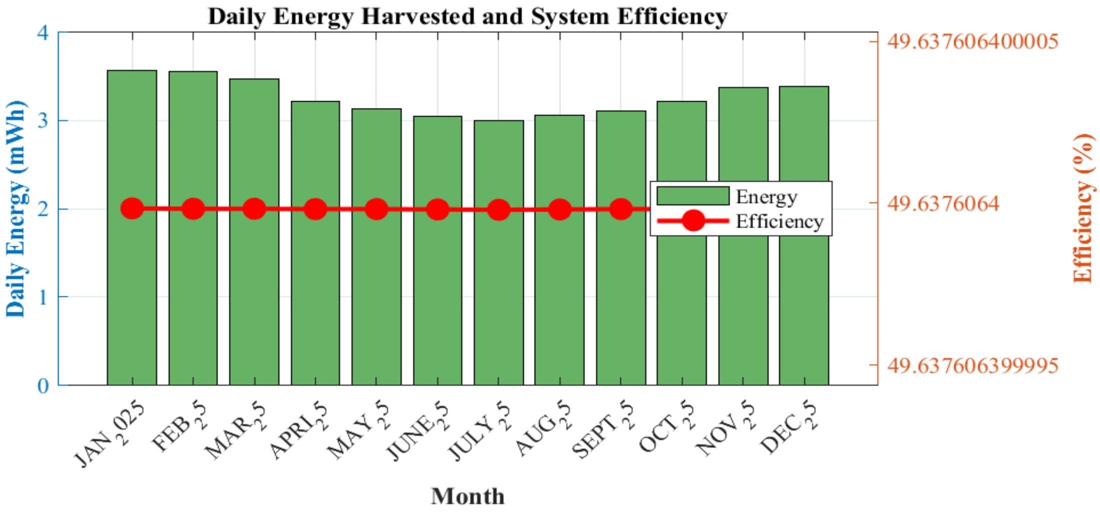

Figure 4(d): Comparative monthly performance of the proposed RF energy harvesting system

4. CONCLUSION

This study investigated the year-round performance of a proposed RF energy harvesting system using MATLAB/Simulink simulations, with particular emphasis on the influence of seasonal RF propagation conditions in a humid tropical environment. The results demonstrate a consistent power hierarchy across all months, in which the DC–DC converter output exceeds the power management system (PMS) output and the load power, reflecting expected conversion and regulation losses.

A key finding is the near-constant system efficiency of approximately 49.64% throughout the year, confirming the stability and robustness of the power conditioning architecture. Seasonal variations in harvested power and daily energy were shown to be driven primarily by changes in ambient RF energy availability rather than electronic inefficiencies. The system achieved its highest energy yield during dry-season months, with daily harvested energy exceeding 3.4 mWh/day, while the lowest performance occurred during peak rainy-season conditions, with a minimum of approximately 2.99 mWh/day. Despite this variation of about 18 - 20% between best- and worst-case months, the system maintained stable and usable power delivery to the load under all conditions.

Overall, the results validate the suitability of the proposed RF energy harvesting system for continuous, year-round operation in humid tropical environments. The demonstrated resilience to seasonal RF attenuation and the stable efficiency of the power management architecture make the system a viable power source for low-power wireless sensors, Internet-of-Things (IoT) nodes, and distributed monitoring applications where battery replacement is impractical. Future work may focus on experimental long-term field validation and adaptive impedance or frequency-selective techniques to further enhance harvested energy under adverse propagation conditions.

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