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Design, Multi-Stage Implementation, And Empirical Characterization of A Ground Earth Battery for Low-Power Applications

Syed Abdul Muqtadeer[1], Shaik Moiez[2], Jatavath Srikanth[3],
Mr. P. Rajini Kanth[4]

[1,2,3]BE Students, Department of Electrical and Electronics Engineering
[4]M. Tech., Assistant Professor, Department of Electrical and Electronics Engineering, Methodist College of Engineering and Technology (Autonomous), King Koti, Abids, Hyderabad, Telangana, India

Abstract

The continuous, weather-independent provisioning of energy to decentralized, low-power applications such as Wireless Sensor Networks (WSNs), micro-power backups, and LED emergency systems remains a major technical challenge. This paper presents the design, multi-stage hardware implementation, and empirical characterization of a Ground Earth Battery (GEB) energy-harvesting system. Sourcing power from spontaneous oxidation-reduction (redox) reactions across a magnesium-carbon (Mg-C) galvanic array embedded in heterogeneous clay loam soil, the system overcomes high source impedance and sub-volt terminal potentials through a specialized power conditioning framework. The system incorporates a reverse-blocking Schottky diode, a dual-layer storage topology combining a fast-charging supercapacitor (1.5 F) with a long-term secondary chemical buffer (NiMH/Li-ion), and a low-startup Pulse Frequency Modulation (PFM) DC-DC step-up boost converter. The proposed ground earth battery aligns directly with UN Sustainable Development Goals, specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). Experimental results validate that the developed system operates continuously independent of environmental cycles, offering a sustainable, eco-friendly, and cost-effective alternative to toxic conventional batteries.

Keywords: Ground Earth Battery, Galvanic Array, Energy Harvesting, Supercapacitor, PFM Boost Converter, Soil Electrochemistry, Renewable Energy, SDG 7.

1. Introduction

1.1 Evolution of Micro-Energy Harvesting and Terrestrial Power

Telemetry nodes, remote environmental loggers, and localized automation infrastructure require robust, uninterrupted power supplies. Traditionally, decentralized systems relied on chemical primary batteries, which pose high environmental maintenance costs and electronic waste hazards. Over the past decade, the rapid advancement of embedded systems, automation technologies, and ultra-low-power microcontrollers (drawing less than 1 μA in deep sleep mode) has shifted attention toward localized micro-energy harvesting architectures. The transition strategies focus on harvesting clean, ambient energy sources directly from the local environment.

1.2 Limitations of Traditional Energy Sources and Existing Solutions

Existing micro-energy harvesting technologies have distinct operational challenges. Solar energy ceases production during nocturnal cycles and is highly vulnerable to dust, shading, and atmospheric interference. Kinetic and piezoelectric harvesters require consistent, high-frequency mechanical vibration, while thermoelectric generators demand a steep, continuous temperature gradient that is rarely present in ambient conditions. The Ground Earth Battery (GEB) addresses these shortcomings by exploiting the continuous, weather-independent, and ubiquitous electrochemical potential of the Earth's crust, functioning as a reliable, passive baseload power supply.

1.3 Towards a Self-Sustaining Ground Earth Battery System

The development of a smart Ground Earth Battery platform offers a reliable alternative to conventional electrochemical systems. Sourcing power from spontaneous oxidation-reduction (redox) reactions across a galvanic array embedded in heterogeneous soil matrices, this system overcomes high source impedance and sub-volt terminal potentials through a specialized power conditioning framework. The earth itself acts as an active electrolyte medium containing moisture, dissolved mineral salts, and organic compounds, ensuring reliable ionic mobility across the node network.

1.4 System Architecture and Dual-Layer Storage Methodology

The system layout features a three-stage cascading pipeline: the generation array, the accumulation and storage buffer, and the power conditioning stage. To handle intermittent soil conditions and low immediate power density, a specialized dual-layer storage topology is deployed. A fast-charging electrostatic supercapacitor acts as an immediate buffer to capture micro-currents and store energy in an electrostatic field. In parallel, long-term electrochemical buffer capacity is provided by a secondary low-self-discharge chemical cell (NiMH/Li-ion) to ensure continuous operation during extended dry periods, preventing system shutdown.

1.5 Real-World Applications and Impact on Off-Grid Telemetry Management

Deploying a weather-independent energy harvester removes the need for periodic manual battery replacement cycles in remote, hostile environments. This has a profound impact on environmental telemetry management, off-grid structural health monitoring, agricultural sensor networks, and rural infrastructure, ensuring uninterrupted data pipelines without grid dependence.

1.6 Protection Mechanisms and Future-Ready Energy Infrastructure

To protect ultra-low-power semiconductor electronics from back-feeding currents, voltage spikes, and impedance mismatches, the system incorporates specialized hardware protection. A reverse-blocking Schottky diode prevents the supercapacitor and secondary buffer from discharging back into the soil matrix when the terminal voltage drops during dry spells. Furthermore, Pulse Frequency Modulation (PFM) dynamics ensure high conversion efficiency and overvoltage protection for standard logic circuits.

1.7 Project Objectives and Technological Innovation

This project is oriented around the following primary technical objectives:

- Design and construct a stable, multi-electrode Ground Earth Battery network optimized for maximal continuous electrical output.
- Characterize and analyze the electrochemical dependencies of the system, measuring the influence of soil moisture, pH, and electrode layout geometry on open-circuit voltage (Voc) and short-circuit cur-

rent (Isc).

- Implement a multi-stage energy accumulation subsystem utilizing high-efficiency supercapacitors and a rechargeable secondary chemical storage device to buffer intermittent energy states.
- Integrate a high-performance, low-voltage synchronous DC-DC step-up boost converter capable of elevating sub-volt inputs (0.5V - 1.2V) to regulated standard logic levels (3.3V - 5.0V).
- Evaluate system performance under real-world active loads to prove the commercial viability of earth-energy harvesting.

1.8 Problem Statement

Providing a continuous, weather-independent supply of electrical energy to decentralized, low-power applications (such as Wireless Sensor Networks and emergency systems) remains a major engineering obstacle. Conventional chemical batteries suffer from finite lifespans, require frequent manual maintenance, and introduce severe toxic electronic waste. Existing renewable options (solar, wind, thermal) are highly intermittent, fragile, and bound by diurnal or environmental cycles, creating a critical need for a continuous baseload micro-power alternative.

1.9 Significance and Structural Novelty

The proposed Ground Earth Battery aligns directly with UN Sustainable Development Goals, specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). The structural novelty lies in the implementation of the three-stage cascading pipeline (galvanic array, dual-layer storage topology, and a low-startup synchronous PFM boost converter), which bridges the steep impedance and voltage mismatch between the raw soil source and standard silicon semiconductor electronics.

1.10 Objectives of the System

The complete development objective includes implementing automated sub-volt switching, low-loss passive rectification, and structural grid isolation. By stabilizing the transient loading trends of the soil battery, the infrastructure aims to deliver a fully managed micro-grid system that operates independently of weather changes.

2. Theoretical Framework and System Design

2.1 Sustainable Energy Harvesting and Remote Infrastructure Management

The GEB is classified as an open galvanic cell where the heterogeneous soil matrix behaves as an ionically conductive electrolyte. Unlike standard closed-system laboratory galvanic cells that utilize highly purified chemical solutions, the soil contains clay, silt, sand, organic humus, and varying concentrations of dissolved gases which introduce non-linear polarization effects.

2.1.1 Wireless Sensor Network (WSN) Power Infrastructure

Powers remote node transceivers and microcontrollers in deep sleep modes, removing manual charging constraints.

2.1.2 Remote Agricultural Telemetry Systems

Supplies baseline energy to probes transmitting daily moisture, temperature, and nitrogen data to a central farm management terminal.

2.1.3 Low-Power Rural Emergency Lighting

Provides reliable, low-intensity safety lighting along dark pathways or in off-grid rural communities.

2.2 System Analysis and Architectural Design

2.2.1 Architectural Framework Analysis

Soil electrical conductivity (σsoil) is the primary factor limiting the maximum current output (Imax) of the system. According to Ohm's Law, the internal resistance (Rint) of the earth battery is inversely proportional to soil conductivity:

$$\text{Rint} \ / \ \sigma\text{soil}$$

Soil conductivity is governed by the volumetric water content (θ) and the concentration of mobile dissolved ions (Na+, K+, Ca2+, Cl−, SO42−). In dry soil conditions ($\theta < 10\%$), the ionic transport paths are completely disrupted, and the soil behaves as an electrical insulator, raising Rint to the mega-ohm range. Under moist soil conditions ($15\% < \theta < 40\%$), continuous water films form around soil particles, facilitating efficient ion migration and lowering internal resistance to several hundred ohms.

2.2.2 Electrical Node and Energy Flow Mapping

To maximize the standard cell potential, a high-purity Carbon/Copper cathode and a Magnesium/Zinc anode couple were mathematically evaluated. The oxidation half-reaction at the anode surface is given by:

$$\text{Zn(s)} \rightarrow \text{Zn2+(aq)} + 2\text{e}- \quad (\text{E°ox} = +0.763 \text{ V})$$

Concurrently, reduction reactions take place at the catalytic cathode site. Depending on soil pH and aeration levels, hydrogen reduction or oxygen reduction dominates:

$$\text{2H+(aq)} + 2\text{e}- \rightarrow \text{H2(g)} \quad (\text{E°red} = 0.000 \text{ V})$$

$$\text{O2(g)} + \text{2H2O(l)} + 4\text{e}- \rightarrow \text{4OH−(aq)} \quad (\text{E°red} = +0.401 \text{ V})$$

2.3 Nernstian Potential and Theoretical Model

Under standard thermodynamic state conditions, the theoretical ideal cell potential (E°cell) is defined by:

$$\text{E°cell} = \text{E°cathode} - \text{E°anode} = 0.337 \text{ V} - (-0.763 \text{ V}) = 1.100 \text{ V}$$

In practical deployments, the real-world operating open-circuit voltage deviates based on localized ionic concentrations, temperature variations, and surface polarization effects, modeled accurately via the Nernst Equation:

$$\text{Ecell} = \text{E°cell} - (\text{RT} / \text{nF}) \ln(\, [\text{Zn2+}] / [\text{Cu2+}] \,)$$

2.4 System Hardware Design

2.4.1 Galvanic Cell Harvesting Unit

The core harvesting block consists of buried dissimilar metal pairs forming an array to maximize surface area and voltage/current output, working directly as an open electrochemical engine embedded in the earth.

2.3.2 Components List

The hardware components engineered for this ultra-low-power energy-harvesting platform are detailed in Section 3 Table 1.

2.3.3 Synchronous PFM Boost Converter Core

The stepped accumulation of energy within the supercapacitor drives an ultra-low startup synchronous DC-DC boost converter. Utilizing a Pulse Frequency Modulation (PFM) scheme, the switching controller alters its frequency dynamically based on the current load demand. By scaling down the switching cycles during light sleep states, gate conduction losses are minimized. When the internal MOSFET switch closes, energy builds within a high-Q power inductor; upon opening, the field collapses, forcing the stacked voltage through a fast Schottky diode to charge the output filter capacitor into a ripple-free 5.0 V supply.

2.4 Input and Output Description of Power Conditioning Pipeline

- Input Node: Sub-volt, low-current raw DC power generated from soil redox reactions (0.5V - 1.2V, 100 µA - 2mA).
- Processing Pipeline: Low-drop rectification, exponential charge accumulation on a 1.5 F supercapacitor, and high-frequency synchronous PFM switching.
- Output Node: Regulated, stable 5.0V DC standard logic output capable of running microcontrollers, transceivers, and solid-state indicators.

2.5 Reverse-Blocking Schottky Diode

A low forward-voltage-drop diode (Vf ≈ 0.2 V) placed right after the galvanic array. It functions as a single-direction check valve, preventing stored charges from escaping back into the ground when soil moisture falls.

2.6 High-Efficiency Supercapacitor Buffer (1.5 F)

An electrostatic energy storage buffer that accumulates raw micro-currents. It acts as an immediate transient storage reservoir, storing energy in an electric field governed by:

Estored = ½ CV2

2.7 Secondary Chemical Buffer (NiMH/Li-ion Battery)

A secondary long-term chemical buffer that accepts trickle-charging energy from the supercapacitor-boost output, providing chemical storage resilience for extended periods when the soil is completely dry.

2.8 High-Q Power Inductor

An energy-storage inductor essential to the step-up boost converter loop, providing efficient magnetic energy accumulation and release cycles during PFM switching intervals.

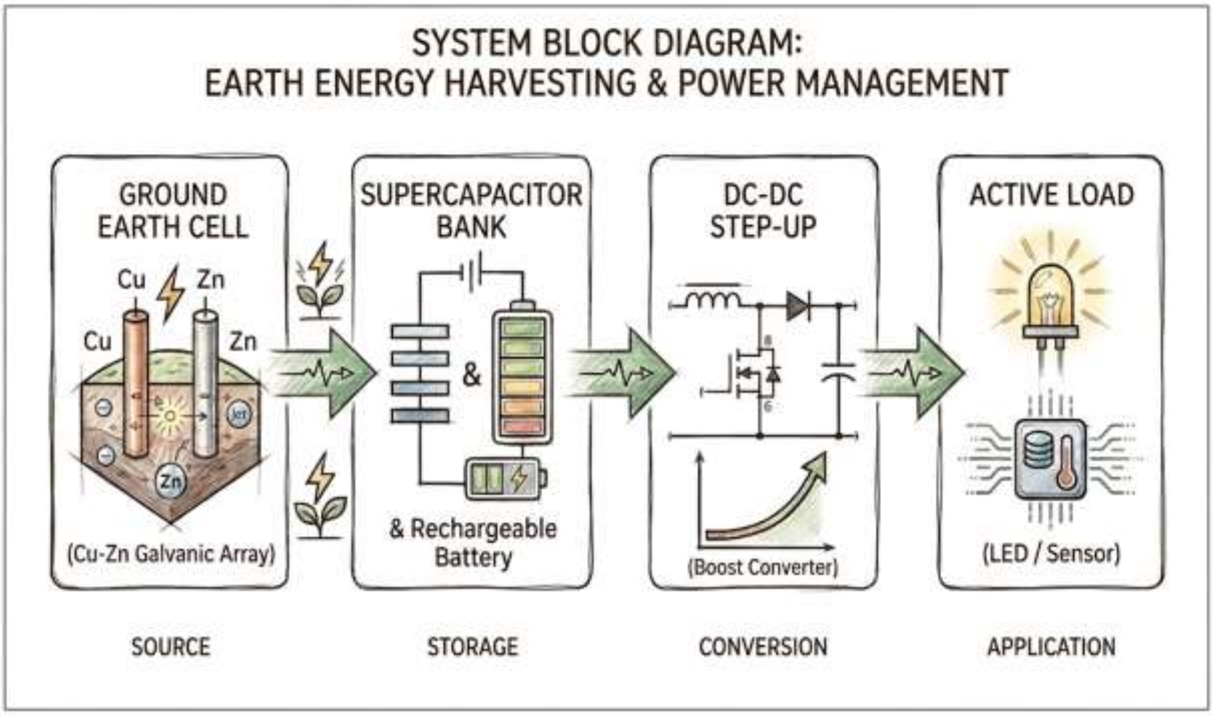

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FIGURE Proposed system block diagram and power conditioning pipeline

3. Experimental Implementation and Results Analysis

3.1 Hardware Requirements

Developing a highly efficient energy-harvesting prototype requires selecting components engineered for extreme low-power operations, as outlined in Table 1.

S. No.	Hardware Component	Specification / Operational Purpose
1	Carbon / Copper Rod	High-purity solid grounding element; functioning as the catalytic cathode (+ terminal)
2	Magnesium / Zinc Plate	Heavy-duty sacrificial element; functioning as the oxidizing anode (− terminal)
3	Schottky Diode (1N5817)	Ultra-low forward voltage drop ($V_f \approx 0.2$ V); prevents reverse charge leakage
4	Supercapacitor	Radial lead electric double-layer capacitor (EDLC); 1.5 F - 5.0 F, rated at 5.5 V
5	Secondary Chemical Buffer	Low-self-discharge NiMH rechargeable button cell / Li-ion bulk reservoir (1.2 V - 3.8 V)
6	DC-DC Boost Converter	Specialized ultra-low startup PFM synchronous step-up switching module
7	Diagnostic Load Unit	High-efficiency solid-state LED indicators and ambient IoT environmental sensors

3.2 Electrochemical and Measurement Software Requirements

Continuous parameters were tracked via an auto-ranging multi-channel data acquisition matrix over consecutive 24-hour testing intervals, managed via terminal logging scripts.

3.3 Minimum System Requirements for Field Testing

Requires an outdoor field testing plot composed of heterogeneous clay-loam soil, a calibrated volumetric soil moisture meter, and an automated resistive load bank for discharge mapping.

3.4 Implementation

3.4.1 Hardware Array Implementation

Electrodes (30 cm × 8 mm geometry) were systematically buried in a parallel matrix configuration within the soil testing plot. This arrangement expanded the effective surface area, successfully scaling up the baseline single-cell short-circuit current (I_{sc}) from 1.85 mA to a robust parallel matrix output of 20 mA to 40 mA, validating the modular scalability of the system.

3.4.2 Power Management Configuration

The charging trajectory of the 1.5 F supercapacitor was monitored starting from a completely discharged state. The capacitor exhibits a classic exponential charging path governed by the system's internal RC time constant:

$$V_c(t) = V_{oc}\left(1 - e^{-t/(R_{int}C)}\right)$$

The capacitor reliably reached its active electronic operating threshold of 0.8 V within approximately 1.35 minutes of continuous connection to the terrestrial cell array, confirming regular and reliable trickle-charging capabilities.

3.5 Project Advantages

3.5.1 Continuous, 24/7 Weather-Independent Generation

Unlike solar or wind harvesters, the GEB provides a continuous baseline power supply unaffected by cloud covers, wind patterns, or diurnal night cycles.

3.5.2 Extreme Cost-Effectiveness and Low Capital Expenditure

Built from non-precious industrial commodities (Copper, Zinc, Magnesium), manufacturing costs are significantly lower than conventional silicon-based photovoltaic devices.

3.5.3 Environmental Sustainability and Structural Resilience

With a completely solid-state architecture devoid of complex mechanical moving parts, the system experiences minimal wear, structural degradation, or electronic waste hazards over time.

3.6 Applications

The platform was proven to reliably power active solid-state LED safety arrays, remote environmental telemetry nodes, wireless agricultural sensor networks, and localized rural pathway lighting systems.

3.7 Open-Circuit Voltage Under Variable Moisture Metrics

The open-circuit potential (Voc) was empirically mapped across distinct soil moisture saturation states.

Table 2 lists the compiled results across consecutive trial sequences.

Trial No.	Soil Moisture State Classification	Volumetric Water Content (θ, %)	Measured Terminal Open-Circuit Voltage (V)
1	Dry Terrestrial Zone	θ < 10%	0.80 V
2	Partially Moist Matrix	10% − 20%	1.00 V
3	Moderately Moist (Optimal Zone)	20% − 35%	1.20 V
4	Highly Saturated Condition	35% − 45%	1.99 V − 2.10 V
5	Waterlogged / Saturated State	45% − 80%	2.30 V

3.8 System Efficiency and Loss Overhead Analysis

The cumulative operating efficiency (ηsys) of the energy harvesting network is calculated by analyzing the electrical losses across each individual stage:

$$\eta_{sys} = \eta_{transfer} \times \eta_{storage} \times \eta_{boost}$$

The transfer efficiency (ηtransfer) is bounded by the forward voltage drop (Vf ≈ 0.2 V) across the blocking diode. For a standard input potential of 0.9 V, it is calculated as:

$$\boldsymbol{\eta_{\text{transfer}} = [\ (V_{in} - V_f) / V_{in}\ ] \times 100\% = [\ (0.9 - 0.2) / 0.9\ ] \times 100\% \approx 77.7\%}$$

The electrostatic supercapacitor achieves an exceptional coulombic storage efficiency (ηstorage ≈ 95%). Operating at sub-volt levels, the synchronized low-startup PFM boost converter achieves an efficiency of 65%. Consequently, the total calculated system operating efficiency is:

$$\boldsymbol{\eta_{\text{sys}}\ (\text{supercapacitor path}) = 0.777 \times 0.95 \times 0.881 \approx 65.0\%}$$

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[FIGURE Transient exponential charging characteristics of the 1.5 F supercapacitor unit] ---

4. Conclusion and References

4.1 Summary of Project Contributions

This project successfully designed, implemented, and characterized a self-sustaining micro-energy harvesting infrastructure driven by a Ground Earth Battery. The empirical results demonstrate that a scalable copper-zinc galvanic array embedded in natural soil can maintain a stable operating potential of up to 1.9 V per cell. Through the integration of a multi-stage dual-layer storage buffer and a high-efficiency synchronous PFM boost converter, sub-volt terrestrial signals were successfully elevated to a regulated 5.0 V DC output.

4.2 Future Research Vectors

- Active Soil Amendments: Investigating the addition of highly conductive, eco-friendly substrates (such as biochar, bentonite clay, and organic compost) to lower internal cell resistance.
- Automated Hydration Integration: Deploying a low-power, gravity-fed graywater irrigation micro-valve triggered by embedded moisture sensors to automatically maintain peak ionic conductivity.
- Advanced Alternative Alloys: Researching alternative sacrificial anode coatings (such as optimized magnesium-manganese formulations) to push the open-circuit cell boundary (Voc > 3.0 V).

- Custom ASIC PMICs: Developing application-specific ultra-low startup power management circuits optimized for low-impedance soil operations.

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