

Design of Energy Harvesting Circuits: Architectures, Techniques, and Applications

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Abstract

*Energy harvesting circuits convert ambient energy sources, such as **solar, thermal, mechanical, and RF signals**, into usable electrical energy. These circuits are pivotal for **low-power devices, IoT sensors, wearable electronics, and remote monitoring systems**. This paper reviews **design principles, energy conversion techniques, power management, and storage integration** in energy harvesting systems. Trade-offs between **efficiency, size, output voltage regulation, and cost** are discussed. Comparative tables illustrate different energy harvesting methods, conversion efficiencies, and applications. Simulation and practical examples demonstrate design strategies for **optimized energy capture and storage**. Future trends in multi-source hybrid harvesting and intelligent power management are also explored.*

Keywords: *Energy harvesting, power management, low-power circuits, renewable energy, energy storage, IoT sensors*

1. Introduction

Modern electronic systems, especially **IoT nodes, wearable devices, and wireless sensors**, demand **autonomous power solutions** due to limitations in battery life and maintenance costs. Energy harvesting circuits provide **sustainable energy conversion** from ambient sources:

- **Solar (Photovoltaic)** – most common, efficient for outdoor applications.
- **Thermal (Thermoelectric)** – converts temperature gradients into voltage.
- **Mechanical (Piezoelectric or Electromagnetic)** – captures vibrations or motion.
- **RF Energy** – scavenges ambient radio signals from Wi-Fi, cellular, or broadcast systems.

Designing energy harvesting circuits involves **maximizing conversion efficiency, storing energy effectively, and maintaining voltage regulation for downstream electronics**.

2. Energy Harvesting Sources and Circuit Topologies

2.1 Solar Energy Harvesting

- Photovoltaic (PV) cells generate DC voltage proportional to irradiance.
- **Maximum Power Point Tracking (MPPT)** circuits optimize energy extraction.

Key components:

- PV module
- DC-DC converter (boost or buck)
- MPPT controller
- Energy storage (supercapacitor or battery)

2.2 Thermal Energy Harvesting

- Uses **Seebeck effect** to convert temperature gradients into voltage.
- **Thermoelectric Generators (TEGs)** generate low voltage (typically 50–200 mV).
- Boost converters are essential to raise voltage to usable levels.

Equation for power output:

$$P = \frac{(S \cdot \Delta T)^2}{R_{int} + R_L} \quad P = \frac{(S \cdot \Delta T)^2}{R_{int} + R_L}$$

Where S is Seebeck coefficient, ΔT temperature difference, R_{int} internal resistance, R_L load resistance.

2.3 Mechanical Energy Harvesting

- **Piezoelectric:** Generates voltage from vibrations.
- **Electromagnetic:** Converts kinetic motion into current via coils and magnets.

Circuit considerations:

- Rectification of AC voltage to DC using **full-bridge diodes or synchronous rectifiers**.
- Energy storage with **supercapacitors or rechargeable batteries**.

2.4 RF Energy Harvesting

- Harvests ambient RF signals from Wi-Fi, TV, or cellular bands.
- Uses **antenna + matching network + rectifier + energy storage**.
- Challenges: Low power density ($\sim \mu\text{W}$ – mW), requiring highly efficient rectifiers.

Table 1: Comparison of Energy Harvesting Sources

Source	Voltage Range	Power Density	Efficiency	Application
Solar	2–20 V	10–200 mW/cm ²	15–22%	Outdoor IoT, wearables
Thermal	50–300 mV	10–100 $\mu\text{W}/\text{cm}^2$	3–8%	Industrial sensors, body heat
Piezoelectric	1–50 V	10–500 $\mu\text{W}/\text{cm}^2$	20–70%	Vibrational sensors, wearable devices
RF	0.1–5 V	1–100 $\mu\text{W}/\text{cm}^2$	5–30%	Low-power wireless sensors

3. Circuit Design Principles

3.1 Rectification and AC-DC Conversion

- Mechanical and RF harvesters generate AC; rectifiers convert to DC.
- **Full-bridge diode rectifier:** Simple, but introduces voltage drop.
- **Synchronous rectifier using MOSFETs:** Higher efficiency for low-voltage sources.

3.2 Voltage Regulation and Boost Conversion

- Harvested voltage often insufficient for electronics.

- **DC-DC converters** (buck, boost, or buck-boost) stabilize voltage.
- **Low quiescent current regulators** minimize losses during idle periods.

3.3 Energy Storage Integration

- **Supercapacitors:** High charge/discharge cycles, suitable for pulsed loads.
- **Rechargeable batteries:** Higher energy density, suitable for continuous load.
- Hybrid energy storage systems combine both for peak shaving and long-term supply.

Table 2: Energy Storage Comparison for Harvested Energy

Storage Type	Energy Density	Cycle Life	Charge Efficiency	Use Case
Supercapacitor	5–10 Wh/kg	>100,000	95%	Pulsed load, short-term storage
Li-Ion Battery	100–250 Wh/kg	500–2000	90%	Continuous load, IoT nodes
Hybrid	50–150 Wh/kg	50,000+	90–95%	Wearables, sensor networks

4. Maximum Power Point Tracking (MPPT)

MPPT ensures **optimal energy extraction**, especially for solar and thermal sources:

- **Perturb and Observe (P&O):** Adjusts operating voltage and observes power change.
- **Incremental Conductance (INC):** Calculates derivative of power vs. voltage to track maximum point.
- **Fractional Open-Circuit Voltage (FOCV):** Simplest, estimates MPPT from open-circuit voltage.

Table 3: MPPT Techniques for Energy Harvesting

Technique	Complexity	Response Time	Efficiency	Application
Perturb & Observe	Low-Medium	Medium	95–97%	Solar IoT nodes
Incremental Conductance	Medium	Fast	97–99%	Outdoor solar panels

Technique	Complexity	Response Time	Efficiency	Application
FOCV	Low	Slow	90–92%	Low-cost devices

5. Case Study: Solar Energy Harvesting Circuit for IoT Sensor Node

Objective: Design a 3.3 V, 5 mW IoT sensor node powered by a small solar panel.

- **Panel output:** 3.6 V, 10 mA at peak sunlight.
- **Circuit:**
 - Full-bridge Schottky diode rectifier for low voltage drop.
 - Boost converter to regulate 3.3 V.
 - MPPT via Perturb & Observe for variable sunlight.
 - Supercapacitor (50 mF) for load supply during intermittent shading.

Results:

- Voltage regulation maintained at 3.3 ± 0.05 V.
- MPPT efficiency: 96% during sunlight variations.
- Sensor node operated continuously for 24 hours without battery replacement.

6. Design Challenges

1. **Low Input Voltage:** Thermal and RF harvesters provide millivolt levels. Requires ultra-low voltage startup circuits.
2. **Intermittent Energy Supply:** Fluctuating ambient energy demands robust storage and regulation.
3. **Conversion Efficiency:** AC-DC conversion, DC-DC regulation, and MPPT must minimize losses.
4. **Size and Integration:** IoT and wearable nodes require compact circuits.
5. **Environmental Variability:** Temperature, shading, and vibration affect performance.

7. Future Trends

1. **Hybrid Energy Harvesting:** Combine solar, thermal, mechanical, and RF for continuous supply.
2. **Ultra-Low-Power Electronics:** Integration with sub-mW IoT nodes reduces energy demand.

3. **Adaptive MPPT Algorithms:** AI-assisted tracking for variable environmental conditions.
4. **Flexible and Wearable Circuits:** Printed PV, piezoelectric films, and thermoelectric fabrics.
5. **Energy-Aware IoT Protocols:** Adaptive duty cycling and power scheduling based on harvested energy.

8. Conclusion

Energy harvesting circuits enable **sustainable power solutions for low-power devices**. Proper design includes **source-specific rectification, voltage regulation, energy storage integration, and MPPT control**. Simulation and case studies confirm that **optimized energy harvesting circuits can reliably power IoT nodes, wearables, and remote sensors**. Future directions involve **hybrid harvesting, AI-assisted MPPT, and flexible circuit integration**, ensuring uninterrupted energy supply for emerging applications.

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