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MICROPOWER ENERGY HARVESTING SYSTEMS: OPPORTUNITIES AND CHALLENGES

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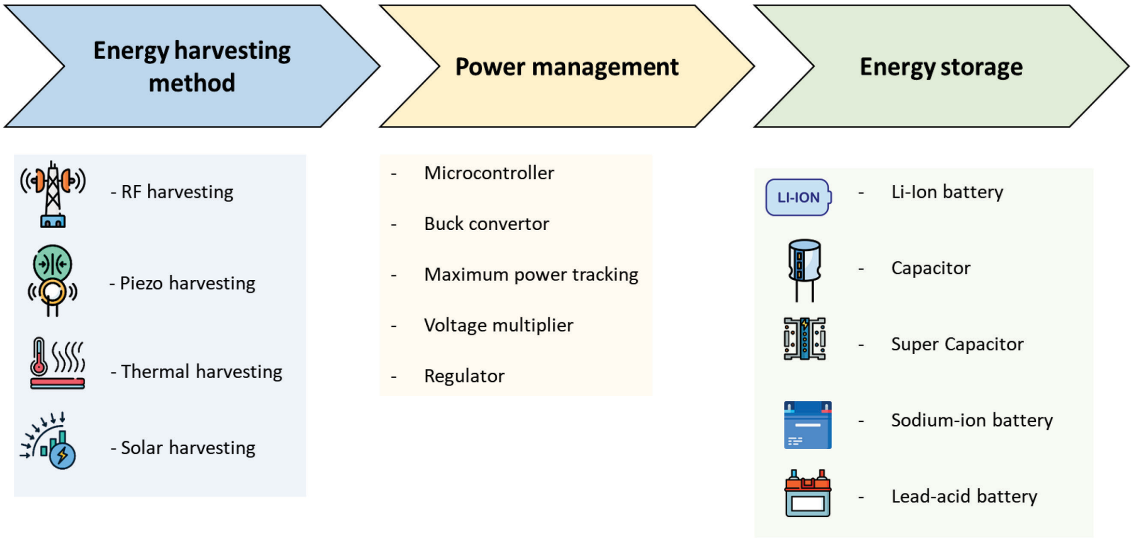
Abstract
Most of the review works on micropower energy harvesting systems concentrate on the energy harvesting device (transducer) while its integration with power management and energy storage systems is not further assessed. Therefore, this paper aims to give a complete overview of recent developments in self-sustainable systems concentrating on three fundamental types of ambient energy sources – piezoelectric, radiofrequency and thermoelectric sources. Relevant scientific works are reviewed in terms of transducer type, power management and energy storage in order to evaluate the system's capabilities to meet the power demand of low power electronic devices such as wireless sensors, wearable electronics, biomedical devices, etc.

Keywords: micropower energy harvesting systems, power management, energy storage, piezoelectric, radiofrequency, thermoelectric, self-sustainable systems

INTRODUCTION

Energy harvesting generally refers to the process of capturing and converting ambient or waste energy into electrical energy. There are many ambient or waste energy sources such as light, heat, vibration, electromagnetic (EM), radiofrquency EM, and piezo. The generated power can be stored in batteries for later use or used to power devices such as wireless sensor networks, portable electronics, Internet of Things (IoT) devices, micro electro-mechanical systems. The main challenge for these electronic devices are batteries which are not capable of delivering long term power thus leading to inconvenient frequent charging or replacement. Therefore one alternative solution to this problem is the so called self-sustainable technology, which incorporates energy harvesting system, power management and energy storage (see Figure 1). This study aims to give an overview of the last achievements in the field of micropower energy harvesting systems and is divided into sections which describe the following energy harvesting methods: piezoelectric, radiofrequency (RF) and thermoelectric. Each section represents



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a review of relevant literature on the corresponding energy harvesting method including power management and energy storage techniques.

PIEZOELECTRIC ENERGY HARVESTING

Piezoelectricity was first identified by Jacques and Pierre Curie in 1880 on specific crystals such as quartz, and Rochelle salt. Experiments showed that applying mechanical stress to any material with piezoelectric properties, an electric charge is generated, thus leading to polarization and voltage. This is known as the direct piezoelectric effect. On the other hand, Lippman in 1881 showed that applying an electric field on a piezoelectric material could lead to mechanical deformation – the converse piezoelectric effect.

Since the piezoelectric transducers have the greatest energy density and more flexibility in terms of incorporating into existing devices, piezoelectric materials are well applied and studied both theoretically and experimentally as energy transducers in micropower energy harvesting systems

Table 1 summarizes recent developments in the field of piezoelectric energy harvesting. Linjuan Yan et al. [1] shows a complete application of self-powered wireless sensor using an integrated piezoelectric transducer on a representative composite structure - a smart composite reduced-model car. Based on an optimized self-powered SSHI circuit (Synchronized Switch Harvesting on Inductor circuit), the authors managed to harvest up to 40 µW on a resistive load 3 MΩ for a linear velocity of 12.5 km/h. This generated power is enough to power a wireless temperature sensor which sends data each 60 s. Road traffic represents another source of energy which can be harvested using piezoelectric sensors. Vehicle’s kinetic energy is converted into electrical potential via piezoelectric transducers. Cheng Chen et al. [2] demonstrated an innovative roadway energy harvesting system which is capable of

Table 1. *Piezoelectric energy harvesting systems.*

Study	Year	Energy harvesting + Power management + Energy storage	Wear abale techn	IoT	RFID	Self-powered sensor	Biomedical devices	Portable electronics	Energy harvesting	Power management	Energy storage
[1]	2023	Piezoelectric + SSHI + Full Wave Voltage Doubler + Capacitor				•			Output power 40 µW	Synchronized Switch Harvesting on Inductor circuit (SSHI)	2 x 470 µF capacitors
[2]	2021	Piezoelectric + 12V DC battery				•			15.37J/(m.pass.lane)	-	12 V DC battery
[3]	2022	Piezoelectric + DB107, LTC3588-1(rectifier + buck convertor) + Capacitor				•			RMS voltage of 25 V, and RMS power of 60 -131 µW under the rotating speed range 600 ÷ 1200 rpm	DB107, LTC3588-1(rectifier + buck convertor)	Capacitor
[4]	2023	Piezoelectric + capacitor				•			Max 511 mW (average 24.5 mW) at harmonic excitation 21 Hz and 0.7 RMS g; Max 568 mW (average 7.3 mW) are generated under a measured railway track vibration signal.	-	Electrolytic capacitor 22mF
[5]	2022	Piezoelectric + capacitor				•			73µW at (4 ÷ 10Hz)	-	Capacitor 470µF

achieving energy density as high as 15.37 J/(m.pass.lane) based on the open circuit voltage measurements in road tests.

In study [3] an energy harvesting system is presented which converts the rotational energy from rotating machines. The proposed energy harvester is capable of supplying power to sensors and detection of bearing fault. It was showed that a single piezoelectric section of the energy harvester can generate RMS voltage of 25 V and RMS power of 60 ÷ 131 μW under the rotating speed range from 600 to 1200 rpm.

Study [4] has shown high-power, robust piezo stack energy harvesting system for powering wireless sensor networks in rail systems. Experimental results from prototype testing provide evidence for high-power output of the energy harvester and its ability to power a wireless sensor. A maximum power of 511 mW and an average power of 24.5 mW are achieved at a harmonic excitation with 21 Hz and 0.7 RMS (Root Mean Square) g.

In work [5] a power supply system for a wireless sensor network node monitoring the bogie parameters of railroad wagons is proposed. Usually the problems during monitoring these parameters are associated with the harsh environment and the lack of power supply. At typical car vibration frequencies (4 ÷ 10 Hz), the system is able to generate 73 μW. The node was used to measure the temperature of the bearings and axle box in the bogie of a freight car.

RADIOFREQUENCY ENERGY HARVESTING

Radiofrequency (RF) is another emerging low energy harvesting technology due to its self-sustainable strategy. It can offer limitless energy supply and install in remote areas to power micro/small scale technologies. Table 2 shows an overview of recent studies on RF-energy harvesting systems (RF-EH).

In [6] a new RF-EH system for Wireless Sensor Network (WSN) is proposed. The system consists of two different monitored architectures and switch circuits controlled by the input power. One architecture is more adapted to high input powers and the other to low input powers. The measured DC power supplied by the first architecture is 288.8 μW at the effective distance of 72 m and 39.2 μW at 122 m. The DC power supplied by the second architecture is 660 μW at the effective distance of 45m and 3.2 μW at 122 m. The maximum measured DC power of 5.12 mW is achieved at the effective distance of 22 m from the relay antenna. The proposed RF-EH system has feeding possibility of many sensors such as gas sensors, image sensors, pressure sensors, biomedical sensors and temperature sensors. In study [7] a self-powered wireless sensor node is proposed based on RF-EH and management combined design method. The proposed WSN can achieve self-powered operation at a distance of 13.5 m from a 27 dBm RF energy source. In [8] the development of an ambient RF powered IoT wireless sensor system is reported. It is demonstrated that the system is capable of sensing temperature, pressure and humidity and wirelessly transmit these signals to a central server with a duty cycle of approximately 15 minutes, when the background ambient RF signals are as low as − 28.6 dBm at 950 MHz. Important goal when designing an energy harvesting circuit is to realize high power conversion ratio (PCE). In study [9] a square-wave approximation technique was introduced to analyze common circuit topologies for RF CMOS rectifiers for energy harvesting applications. Rectifier design optimization techniques are possible based on this simplified method. In study [10] a compact RF-EH-WSN consisting of antenna rectifier, energy management circuit and load has been proposed. This system can achieve self-powered operation at a distance of 13.4 m from RF source. The maximum RF-to-DC conversion efficiency is 52 % at 7 dBm input power. Moreover, an adaptive energy management algorithm has been proposed, which adjusts the system operating mode according to the RF energy input intensity. A multichannel RF-EH system operated at

***Table 2.** RF energy harvesting systems.*

Study	Year	Energy harvesting + Power manegement + Energy storage	Wearabale technologies	IoT	RFID	Self-powered sensor networks	Biomedical devices	Portable electronics	Energy harvesting	Power management	Energy storage
[6]	2022	RF				•			First architecture: 288.8 µW at the effective distance of 72 m and 39.2 µW at 122 m Second architecture: 660 µW at the effective distance of 45 m and 3.2 µW at 122m. Max 5.12 µW at 22 m.	–-	-
[7]	2023	RF + Impedance matching and Rectifier and PMIC + Capacitor				•			-10 dBm(100 µW) at a distance of 13.5 m and radiation intensity of 4 µW/cm2	PMIC: TI BQ25504 Schottky diodes: SMS7630-079LF Buck chip: TI TPS62840	Capacitor 100 µF
[8]	2022	RF + PMU + supercapacitor				•			-	TI BQ25570	Supercapacitor 42 mH
[9]	2022	RF	•	•	•	•			10-Stage Dickson Multiplier 65nm: approx. 25 µW (-2dB input power and 4V output Voltage)	-	-
[10]	2023	RF + PMIC and buck convertor + capacitor				•			–-	PMIC(TI BQ25504 RGTT) + Buck convertor(TI TPS62840)	Capacitor 100 µF
[11]	2022	RF + PMU				•	•		approx. 423 µW at 0 dBm input power	-	-

single frequency (2.4 GHz) which can produce output power of ~ 423 µW at a peak PCE of 21.5 % has been presented in [11].

THERMOELECTRIC ENERGY HARVESTING

Thermoelectric generators (TEG) are solid state energy harvesting devices which have the ability to convert thermal energy into electrical energy. They can be used to generate electric power in remote and hazardous environments, to power environmental micro-sensors and wireless sensor nodes, wearable biomedical IoT sensor nodes. A battery-free soil-monitoring sensor for agriculture is proposed using TEG in [12]. Field experiments showed that the developed device could harvest 100 ÷ 370 µW on average and drive a wireless microcontroller unit to perform soil monitoring In [13] Huang et al. showed the feasibility of TEGs to power wireless sensor nodes for forest monitoring. The TEG devices have used the temperature gradient between shallow soil and near ground air. In [14] a laboratory prototype of an autonomous power supply for WSN that employs ultra-low alternating temperature gradients has been developed. The WSN node on water pipes was chosen for design and prototyping. The low temperature gradient in his case arises between the concrete pipe surface and the surrounding air. The experiments confirmed that the thermoelectric harvester produces more than 0.5 ÷ 2 mW at a temperature difference of about 1 ÷ 2 K between the pipe calm wind speed of about 1 m/s.

Table 3. *TEG energy harvesting systems.*

Study	Year	Energy harvesting + Power manegement + Energy storage	Wearabale technologi	IoT	RFID	Self-powered sensor networks	Biomedical devices	Portable electronics	Energy harvesting	Power manage ment	Energy storage
[12]	2020	TEG				●			100 ÷ 370 μW	-	-
[13]	2019	TEG				●			Harbin - 3.7 mW(average 0.335 mW) Beijing - 2.3 mW(average 0.076 mW)	-	-
[14]	2022	TEG				●			0.5 ÷ 2 mW at ΔT of about 1–2 K	-	-
[15]	2018	TEG				●			Max 19.3 mW and 0.4V open circuit voltage	-	-
[16]	2022	TEG				●			1.09 ± 0.0002 W at a current of 0.187 ± 0.002 A	-	-
[17]	2018	TEG + PMIC-+ Capacitor					●		80 mV with a power density of 38 μW/cm	PIMC	Capacitor
[18]	2021	TEG + Voltage booster + Li-S battery					●		output voltage of 10 mV with output power of 83 μW and power density of 8.7 μW/cm	Voltage booster	Li-S battery
[19]	2023	FTEG + Energy management + supercapacitor	●						Flat state: output voltage of 89 mV and current of 3mA at ΔT=2K Bent state: output voltage of 167 mV and current of 1.9 mA at ΔT=4K	Energy manage ment	Super-capacitor

Another heat energy source is the waste heat produced by machines. Studies [15] and [16] investigate the feasibility of energy harvesting from railroad waste heat and atmospheric pressure plasma jet machine respectively.

Temperature differences between biological structures and ambient environment can be also regarded as heat energy source for the development of thermoelectric generators. Due to the fact that the human body represents a near-infinite source of thermal energy, TEGs are suitable for powering wearable electronics and sensors which monitor human health. Kim et al. [17] report on a TEG-powered electrocardiography sensor (ECG) to monitor abnormal heart activity. In study [18] glucose sensor powered by TEG, which can send the data vie NFC (Near Field Communication) for continuous glucose monitoring without external power, was proposed. Yang et al. [19] proposed a wearable health monitoring bracelet powered by body heat. The flexible thermoelectric generator (FTEG) converts the temperature difference between skin and ambient environment into electrical energy.

CONCLUSION

Despite the enormous achievements in the field of low power energy harvesting, there are still some issues which have to be overcome in future. The reviewed literature in this study shows that the proposed systems rarely achieve optimal performance out of the ideal operating conditions which represents a challenge when these conditions change in a real operating system. Furthermore, from the presented literature is evident that there are still a few studies which incorporate a full self-sustainable system including energy harvesting, power management and energy storage. Further research should be carried out in order to obtain integrated designs which incorporate a whole self-sustainable system.

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