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Energy harvesting: State-of-the-art

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ABSTRACT

This paper presents a brief history of energy harvesting for low-power systems followed by a review of the state-of-the-art of energy harvesting techniques, power conversion, power management, and battery charging. The advances in energy harvesting from vibration, thermal, and RF sources are reviewed as well as power management techniques. Examples of discrete form implementation and integrated form implementation using microelectromechanical systems (MEMS) and CMOS microelectronic processes are also given. The comparison between the reviewed works concludes this paper.

1. Introduction

Energy (or power) harvesting or (scavenging) is without any doubt a very attractive technique for a wide variety of self-powered micro-systems. Examples of such systems are wireless sensors, biomedical implants, military monitoring devices, structure-embedded instrumentation, remote weather station, calculators, watches, Bluetooth headsets. Recently, Nokia announced it is developing a mobile prototype that could harvest energy from ambient radio waves emitted from mobile antennas, TV masts and other sources [1–6].

Energy harvesting has become of a growing interest in the last few years and research report number has kept increasing for the last decade. The scope of this paper is to provide the research community with an update of the state-of-the-art of energy harvesting from vibration, thermal, and RF sources. The principle of energy harvesting approaches can be found in Ref. [7].

In the following, we list the energy harvesting sources (Section 2), a brief history of energy scavenging (Section 3), state-of-the-art based on the review of several recently published papers (Section 4) and Conclusion.

2. Energy harvesting sources

Even though macro-energy harvesting has been around for centuries in the form of windmills, watermills and passive solar power systems, etc., they are not game changers for electronic designers whose mission in life is to snip the wires – including power cords and even battery powered systems where the perpetual device is the ultimate design goal [8]. Progress in ultra-low-power microelectronic technology with the advance in micro-energy Harvesting makes the number of battery charging cycles the main limit towards the perpetual self-powered device.

Towards this mission, and to meet the design community's long march to ultra-low-power technology, we can identify several micro-energy harvesting sources:

– Motion, vibration or mechanical energy: floors, stairs, object's movement, transfer energy from the engine to the battery during braking, etc. The electromechanical transducer can be electromagnetic [9], electrostatic [10], or piezoelectric [11,12].
– Electromagnetic (RF): Base stations, wireless internet, satellite communication, radio, TV, digital multimedia broadcasting, etc. One must not confuse between electromagnetic energy source and electromagnetic transducer. In some articles, electromagnetic generator is used for electromagnetic transducer.
– Thermal.
– Momentum generated by radioactive reactions into electrical energy.
– Pressure gradients.
– Micro water flow (e.g. faucet).
– Solar and light.
– Biological.

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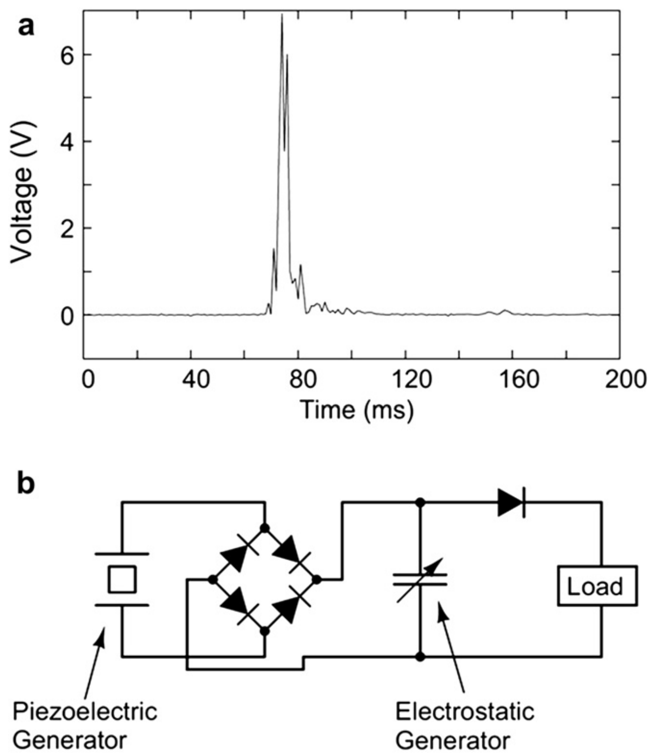

Fig. 1. (a) Piezoelectric generator voltage versus time after rectification for a single impact applied to the generator, (b) Schematic diagram of the connections between the piezoelectric film and the electrostatic generators. The diodes are Schottky type with forward voltage drop near 0.33 V [24].

Another classification scheme may consider who or what provides the energy for conversion: the first kind is called the human energy source. The energy is provided by the activity of human beings or animals. The second kind is the energy harvesting source that gets its energy from the environment [13,14].

The power transferred to a load is limited by the availability of the raw energy, and the efficiency of the transducer and the conversion circuit.

The discontinuous nature of energy harvesting has consequences on the way the electronic devices powered by energy harvesting are operated. In principle, we can distinguish two situations:

1. The power consumption of the device is lower than the average harvested power. In this case, the electronic device may operate continuously.
2. The power consumption of the device is greater than the average harvested power. The operation must be discontinuous, and the time between operations depends on the stored energy of the device [13].

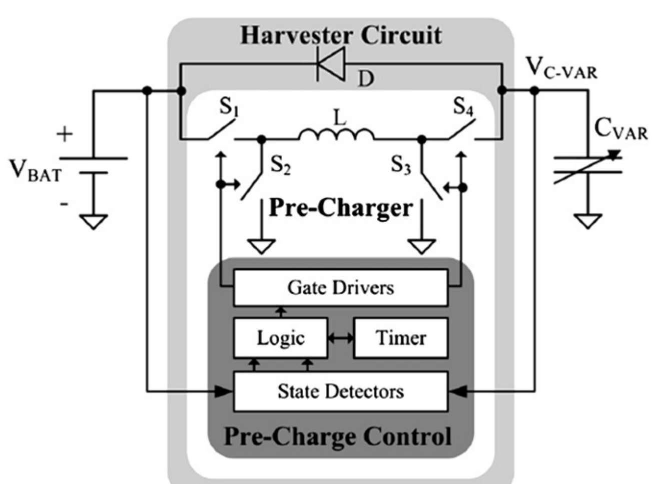

Fig. 2. Energy harvesting and battery-charging system proposed by Torres et al. [1].

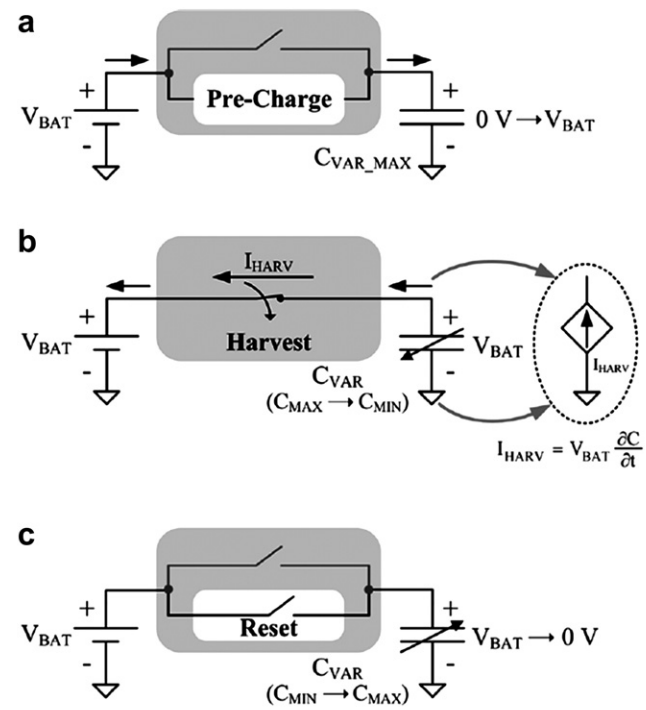

Fig. 3. Three steps to harvest energy: (a) Battery pre-charges the capacitor, (b) vibrations cause capacitance value to decrease and energy is harvested into the battery, and (c) reset [1].

3. History

The first observation of harvesting energy in form of current from natural source was in 1826. Thomas Johann Seebeck found that a current would flow in a closed circuit made of two dissimilar metals when they are maintained at different temperatures [15,16]. For the following three decades, the basic thermoelectric effects were explored and understood macroscopically, and their

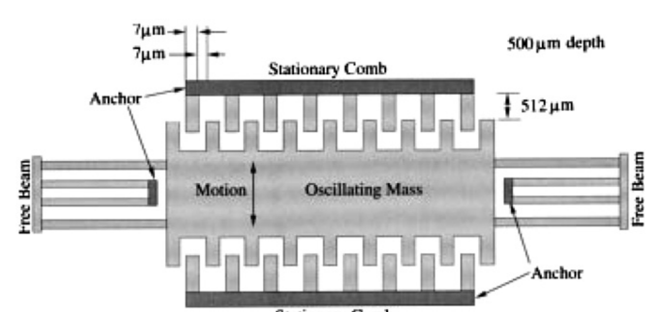

Fig. 4. A complete harvesting cycle [1].