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Quick self-start and minimum power-loss management circuit for impact-type micro wind piezoelectric energy harvesters

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ABSTRACT

This paper proposes a new minimum power-loss management circuit with a quick self-start function, for effective power use from an impact-type micro wind piezoelectric energy harvester. The free tip of the piezoelectric cantilever harvester is excited by a miniaturized wind blade. A smart power management strategy is required for efficient saving and use of the energy generated from the random natured and small scaled wind. We propose a new small scale power management circuit composed of three sub-circuits. First, we have taken a resistive impedance matching strategy because the transient response of the harvester vibrates at the natural frequency and the corresponding impedance is almost time invariant. Second, we have designed a wake-up circuit with quick self-start function, for the timely activation from sleep mode. When the circuit detects the input energy, it rapidly self-starts, adaptively controls the operation mode, and charges load battery. Lastly, an overvoltage protection circuit with sleep function is designed for effective power storage. Measurement results demonstrate that the start-up time is approximately 1 ms for a wind speed of 1.5 m/s and that the maximum efficiency of the proposed circuit is 77% for a wind speed of 3.5 m/s. A commercial wireless sensor is successfully powered with the proposed energy harvesting system, demonstrating its potential application to the Internet of Things.

1. Introduction

Wind energy is a widely available ambient energy source, and the conversion of micro wind energy into electrical energy with a piezoelectric energy harvester (PEH) is a promising power supply method for the Internet of Things [1–3]. A number of studies investigated a resonance-type PEH which generates maximum power when the excitation frequency is equal to its natural frequency [4–6]. However, the randomly changing wind velocity makes it difficult to provide the excitation frequency close to the PEH's natural frequency. Also, the impedance of the resonance-type PEH is time-variant. In order to track the optimum impedance value and realize high-efficiency power transformation, it requires a complex circuit in real world applications [11–13].

The characteristics of the electrical energy generated by an impact-type PEH are different from those generated by a resonance-type PEH. That is, an impact-type PEH vibrates at the natural frequency after impact regardless of wind speed [7–10] even at a low cut-in speed [1]. This vibration characteristic enables the fixed impedance [14], and the circuit can be simplified to reduce the circuit power consumption and improve the efficiency of the energy harvesting system [1].

A wake-up circuit is another important issue for practicability of EH technology. In our previous study [15], a low-power management circuit (PMC) with sleep mode was designed for an impact-type PEH, considering the intermittent excitation in real world applications. However, this circuit could not be operated once the battery is fully drained. Some wake-up circuits with self-start have been proposed to power the oscillator for resonance-type PEH circuit, when the load batteries are completely drained [16–18]. One of the most common start-up methods is the use of a linear regulator to power the management circuit, which charges the load batteries until the batteries can power the entire circuit [5,19]. However, if large output capacitors between 2.2–100 μF are required for stability, the response time (including start-up time and stop time) of the most commercial linear regulator is much longer than the energy generation period when an intermittent excitation source is considered. This makes the commercial linear regulator inefficient. In this paper, a low-power management circuit for an impact-type PEH is proposed for realizing a self-powered system that can operate even when the battery is completely drained.

A wake-up circuit is designed to speed-up the start and convert into the PMC operation mode. A small capacitor in the wake-up

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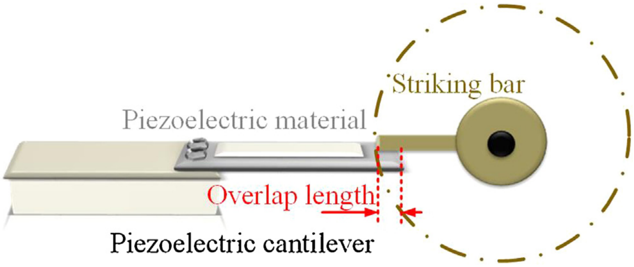

Fig. 1. Impact-type PEH schematic.

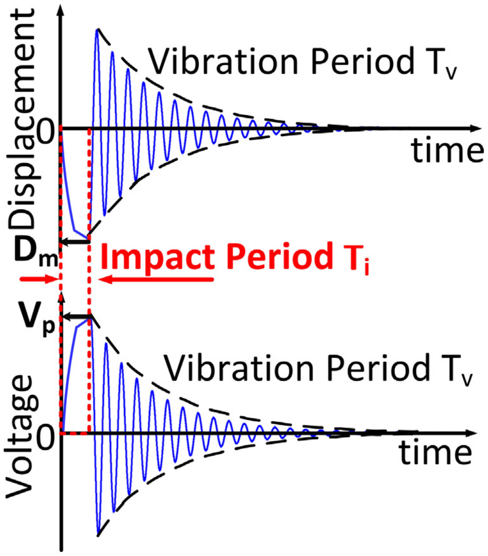

Fig. 2. Impact-type PEH displacement and open-circuit voltage.

circuit stores a minor portion of the input energy to power the PMC when there is input energy, and the PMC can enter the sleep mode for energy conservation when there is no input energy. This wake-up circuit not only enables self-start, but also switches the operation modes of the circuit. Compared to the previous wake-up circuit [15], the proposed circuit is simplified, composed of passive components, with negligible power loss in the sleep mode. In addition, an overvoltage protection circuit is proposed to prevent damage to the load device.

This paper is organized as follows: Section 2 analyzes the output characteristics of the impact-type PEH and proposes a corresponding low-power PMC with self-start and sleep mode. Section 3 presents the experimental results, demonstrating the excellence of the proposed control function and ascertaining its application as a wireless sensor power supply. The conclusions are made in Section 4.

2. Impact-type micro wind piezoelectric energy harvester circuit design

The impact-type PEH presented in [1] consists of a rotary striking bar and a piezoelectric cantilever, as shown in Fig. 1. The time response of this PEH can be divided into two parts, as depicted in Fig. 2. During the impact period, T_i, the bar strikes the piezoelectric cantilever and they remain contacted until the free end of the cantilever reaches a maximum displacement. During this period, the behavior of the piezoelectric cantilever is non-resonant. The vibration period, T_v, starts right after the striking bar leaves the cantilever. The cantilever then vibrates at its natural frequency, regardless of the impact condition during T_i [20]. T_v is defined as the time interval from the end of impact period to the point when the peak of V_p is less than 1 V, and T_w is the total generation period $(=T_i+T_{v,})$ as shown in Fig. 2. This is a critical advantage of the impact-type PEHs that makes the corresponding circuit design simple. We design the circuit model that utilizes the vibration period only (T_v) which is considerably longer than T_i.

2.1. Impact-type PEH equivalent circuit

This section explains an equivalent circuit design for the impact-type PEH. The equivalent circuit of a piezoelectric material is shown in Fig. 3(a); the series impedance can be expressed as in Eq. (1).

$$\mathrm{Zseries} = \mathrm{RS} + \mathrm{j}(\mathrm{XLs} - \mathrm{XCs}) \tag{1}$$

As discussed above, an impact-type PEH always generates power at the PEH natural frequency. When the PEH generates power at its natural frequency, the reactance (X) of the inductance (L_s) and capacitance (C_s) are identical; hence, they cancel out each other and only the resistance (R_s) remains in the series impedance, or

$$\mathrm{XLs} = \mathrm{XCs}, \mathrm{Zseries} = \mathrm{RS}. \tag{2}$$

This characteristic enables its equivalent circuit simpler than that of the resonance-type PEH because the resonance-type PEH should consider varied excitation frequency in real applications. The circuit of the impact-type PEH is equivalent to a parallel RC circuit (resistance and capacitance) as shown in Fig. 3(b), and the impedance of the impact-type PEH can be expressed as Eq. (3), where ω is the resonant frequency of the PEH in radian, and Cp is the inherent capacitance of the PEH as shown in Fig. 3.

$$|Z_{impact-type}| = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + (\omega C_p)^2}} \tag{3}$$

2.2. Energy harvesting circuit with self-start and sleep mode

In order to realize an efficient self-powered system, an energy harvesting circuit with self-start and sleep mode is designed as depicted in Fig. 4. This circuit consists of: a full bridge rectifier for converting the AC voltage to DC; a buck-boost DC–DC switching converter for matching the resistance of the PEH; and a controller for generating a square wave to control the buck-boost DC–DC switching converter. This controller consists of: a wake-up circuit for controlling the operation mode of the energy harvesting circuit (self-start, sleep and active modes); an oscillator circuit for generating a square waveform to switch the DC–DC converter; and an overvoltage protection circuit for preventing overload.

2.2.1. Full bridge rectifier

The full bridge rectifier is used for converting the AC voltage generated by the impact-type PEH to DC voltage. The peak voltage generated by the impact-type PEH depends upon the impact strength, but is sufficiently large up to several tens of volts. Thus, the voltage drop on the diodes in the full bridge is not a concern [21]. Besides, the average current of the PEH is relatively small due to the large impedance of the piezoelectric material, so the rectifier power loss for the impact-type PEH is not significant.

2.2.2. Buck-boost DC–DC switching converter

A buck-boost DC–DC switching converter is used for matching the resistance of the impact-type PEH and the charge storage device. The inductor (L) and the switching frequency (f_s) of the converter is determined by the load requirement of the output ripple.