Sensors and Actuators A 216 (2014) 106–115

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Self-powered nonlinear harvesting circuit with a mechanical switch structure for a bistable generator with stoppers

Weiqun Liu[a,*], Fabien Formosa[a], Adrien Badel[a], Yipeng Wu[a], Amen Agbossou[b]

[a] Laboratoire SYMME, Université de Savoie, 74944 Annecy le Vieux, France
[b] Laboratoire LOCIE, Université de Savoie, 73011 Chambery, France

ARTICLE INFO

Article history:
Received 2 February 2014
Received in revised form 25 April 2014
Accepted 26 April 2014
Available online 23 May 2014

Keywords:
Energy harvesting
Bistable oscillator
Wideband
Self-powered
Nonlinear
Mechanical switches

ABSTRACT

Energy harvesting is considered as one of the most promising solution for the power supply of autonomous sensor systems. Two main properties are required: self-powered ability and wideband operation. This article proposes a new self-powered bistable generator which is composed of three parts: the self-powered OSECE (Optimized Synchronous Electric Charge Extraction) circuit, the BSM (buckled-spring-mass) oscillator and two stoppers. The combination of the BSM oscillator and the stoppers allows wideband harvesting capability and the self-powered OSECE circuit with mechanical switches ensures high harvested power and autonomous features. A model of this novel generator is detailed and experimentally validated. As an incremental innovation, better performance is obtained for this new generator compared with the original BSM generator with the standard circuit (without stoppers and mechanical switches). Discussions and optimizations are performed to find the optimal parameters and fully investigate the performance of the proposed generator. It shows that introducing the stoppers and the self-powered OSECE circuit using mechanical switches can substantially enhance the harvested power with moderate additional complexity.

1. Introduction

Advances in wireless technologies and low power electronics accelerate the development of autonomous sensors, which are useful for environment control and monitoring, emergency response or healthcare monitoring. In many applications, these devices would take advantage of embedded autonomous power sources which would increase their lifetime especially. Energy harvesting [1] is a promising solution to fulfill this goal. Scavenging energy from the environment vibration is a realistic approach since vibrations exist in many application domains. A lot of VEHs (vibration energy harvesters) have been developed using piezoelectric, electromagnetic and electrostatic mechanisms [2–6].

A typical VEH includes two parts: an energy extraction circuit and a mechanical oscillator. For piezoelectric energy harvesting applications, a simple extraction circuit which will be latter referred as standard circuit is a full-bridge rectifier followed by a smoothing capacitor to transfer the harvested energy to the functional electronics parts (sensor, wireless transmission etc) [7]. In order to optimize the harvested power, many nonlinear switching harvesting techniques have been developed, such as SSHI (Synchronized Switching Harvesting on an Inductor) [8,11], SECE (Synchronous Electric Charge Extraction) [9] and OSECE (Optimized Synchronous Electric Charge Extraction) techniques [10]. These nonlinear techniques make use of inductors and switches to enhance the extracted power from the piezoelectric material. The performances are significantly improved compared to the standard circuit, in the case of low electromechanical coupling coefficient especially [11–13]. Moreover, low load impedance dependence is achieved in the case of the SECE [9,12] and the OSECE circuits [10].

Self-powered is a key issue for these techniques. Realizations for these nonlinear harvesting strategies are investigated to fulfill the autonomous requirement of the generator: Lallart et al. [14] developed a PKD (peak detector) circuit for the SSHI circuit while Liang and Liao [15] analyzed and discussed it in details. Some other self-powered approaches such as zero-crossing detector [16] and digital control technique [17] were also proposed. A similar PKD was developed for the OSECE circuit by Wu et al. [18]. These self-powered techniques take advantages of additional electronic or transduction components to detect the proper voltage extreme and drive the electronic switches accordingly. Recently, Giusa et al. [19] proposed a new approach of RMSHI (Random Mechanical Switching Harvesting on Inductor) based on the SSHI technique using mechanical switches. It needs less electronic parts and shows a

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[*] Corresponding author. Tel.: +33450096543.
E-mail address: weiqun.liu@univ-savoie.fr (W. Liu).

http://dx.doi.org/10.1016/j.sna.2014.04.040
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Table 1
Parameters of one APA120S component.

Definition	Symbol	Value
Stiffness	K_p	0.195 N/μm
Capacitance	C_p	1.15 μF
Piezoelectric force factor	α_p	0.13 N/V

zero voltage threshold. However, it is difficult for the mechanical switches to be closed and opened at the proper time to obtain high harvested power. Wu et al. [39] successfully used stoppers as mechanical switches for the OSECE circuit on a piezoelectric cantilever beam.

Parallel developments have been performed on the mechanical oscillator. An important issue is the increase of the operating bandwidth [20]. Nonlinear mechanical behavior has been investigated as a potential solution for this problem [21–23]. Among the variety, the bistable behavior attracts a lot of interests because of its simplicity and good performance. Many prototypes have been developed such as cantilever beams with tip magnets [24], hair bundle structures [25], BSM (buckled-spring-mass) structures [26], buckled beams [27] and plates [28], and other magnets based architectures [29–31]. The performance improvement and broadband property of the bistable generator have been assessed for white noise [24,26] and for sweeps excitations [26,31]. Introducing stoppers to a linear structure to design a piece-wise oscillator can also allow the bandwidth to be extended [32–36]. The hardening effect of the stopper was investigated by Soliman et al. [32] and Liu et al. [33,34]. The frequency up-converting effect of the harvester with stoppers is studied by Ashraf et al. [35].

In this paper, a self-powered approach with a new mechanical switch structure is proposed specially for the BSM generator and the OSECE circuit which can provide high performance and low impedance dependence property for a wide load range. Furthermore, the switching strategy of the OSECE technique is simple which makes it suitable to replace the electronic approach by a mechanical one. Using mechanical switches, less electronic components are to be used and the electronic energy loss is expected to be reduced. This self-powered approach is applied to a new structure BSMOS (BSM Oscillator with Stoppers). It aims at capitalizing on the advantages of the two nonlinear techniques (bistability and stoppers) at the same time. The purposes of the stoppers, explained in Section 2, are dual: to obtain a broader bandwidth than the BSM oscillator alone and to be part of the self-powered approach. Besides, the stoppers provide limitations of the structure displacement when over-high excited, and can therefore prevent potential damages. As a result, a self-powered bistable harvester with wider bandwidth can be achieved. The performance of this self-powered BSMOS structure is studied theoretically and validated experimentally. Results are compared with the BSM generator using standard circuit (Table 1).

2. Model and principle

2.1. BSMOS structure

As shown in Fig. 1, the proposed BSMOS structure includes three parts: a BSM oscillator, a mechanical switch structure and two stoppers. The BSM oscillator is composed of two piezoelectric components and a central inertial mass connected with flexible hinges. The piezoelectric materials are electrically connected in series.

To realize an autonomous harvester, a double-pole, single-throw mechanical switch structure is introduced into the BSM oscillator. An electrode support is fixed between the flexible hinge and one of the piezoelectric components and follows the rotational motion of the latter. Two separated copper electrodes (the center electrode and the side electrode) are carved. When the moving electrodes part swings with the hinge, the static electrode part is electrically connected to the moving center electrode when the mass cross the zero position and to the moving side electrode when the mass arrives at a given positive or negative displacement. By doing this, the electrical connection is made on and off alternately and the electrodes act as synchronized switches. Moreover, two identical elastic stoppers are symmetrically arranged at the two sides of the mass. When the displacement is large enough to let the mass contact a stopper, the additional stiffness from the stopper presents a more obvious hardening effect than the single BSM oscillator. Then the bandwidth can be increased in some excitation cases. Fig. 1b and Table 2 define the parameters of the system. In order to get a clear view of the structure configuration, the mechanical switch items are removed in Fig. 1b.

Table 2
Definitions of the system parameters.

Definition	Symbol	Value
Inertial mass	M	42 g
Horizontal distance between two adjacent hinge centers	L	33 mm
Total structural stiffness	K	0.39 N/μm
Mechanical damping	μ_0	0.42 N/(m s)
Elastic constant of the stoppers (stiffness)	K_s	2334 N/m
Distance between the stoppers and the center	d	1.85 mm
Damping induced by the stoppers	μ_s	1.91 N/(m s)
Additionally and serially connected capacitance	C_a	0.208 μF
Total system capacitance	C_0	0.154 μF
System piezoelectric force factor	α	0.034 N/V
Initial buckled position	x_0	1.3 mm
Transformer turn ratio	m	0.94

The mechanical potential energy of the BSM oscillator is written as:

$$U_b = \frac{K}{2}\Delta l^2 + 4\times\frac{1}{2}K_\theta\theta^2 = \frac{K}{2}\left(l_0 - \sqrt{L^2+x^2}\right)^2 + 2K_\theta\frac{x^2}{L^2} \tag{1}$$

where K_θ is the rotational stiffness of the flexible hinge and l_0 represents the natural longitudinal length between the rotary centers of two adjacent hinges.

From a modeling point of view, two springs are used to account for the stoppers. As the inertial mass bumps against the stoppers, it is approximated as an elastic collision between the mass and the springs. With the mass of the stoppers neglected, only the potential due to the deformation of the stoppers is taken into account:

$$U_s = \frac{1}{2}K_s(x-d)^2H(x-d) + \frac{1}{2}K_s(x+d)^2H(-x-d) \tag{2}$$

where $H(x)$ is the Heaviside function. After the stoppers reach the maximum deforemation, the mass rebounds under the restoring action of the stoppers.

Then the total potential energy of the BSMOS structure $U = U_b + U_s$ is plotted and compared with the BSM oscillator in Fig. 2. It is clear that the stoppers bring supplementary stiffness to the BSM oscillator as the potential increases more quickly when the displacement is larger than the stopper position d. Neglecting the mass of the hinges, the mechanical structure and piezoelectric components, the kinetic energy of the system is:

$$T = \frac{1}{2}M\dot{x}^2 \tag{3}$$

Applying the Euler–Lagrange approach to the device:

$$\frac{\partial}{\partial t}\left(\frac{\partial(T-U)}{\partial\dot{x}}\right) - \frac{\partial(T-U)}{\partial x} = M\gamma - \alpha V_p\frac{x}{L} - \mu_0\dot{x} - \mu_s\dot{x}(H(x-d) + H(-x-d)) \tag{4}$$