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Physics Procedia 70 (2015) 1017 – 1021

Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

Electrical Interfacing Circuit Discussion of Galloping-Based Piezoelectric Energy Harvester

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Abstract

The equivalent circuit and electrical interfacing circuit of a galloping-based piezoelectric flag energy harvester is discussed and the nonlinear synchronized switching technique is used to increase the power. Energy harvesting from ambient is highly focused and by using a cantilever beam to convert the vibration energy is the most popular topics. Except using cantilever beam, piezoelectric flag or plate converted the flow energy has been widely invested. As the interfacing circuit is the important design part to increase the power output, in this paper, several interfacing circuit including standard DC approach, SSHI technique and transformer-based SSHI technique are proposed and compared. Simulations and experimental results show the optimal interfacing circuit in piezoelectric flow energy harvester

Peer-review under responsibility of the Scientific Committee of ICU 2015

Keywords: Piezoelectric, Energy harvesting, intefacing circuit, galloping-based

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1. Introduction

During past decade, energy harvesting from ambient environment to be the small alternative energy source becomes the most popular topic. Wireless sensor networks (WSN) is one of the most suitable applications to powered by energy harvesting devices. The lifetime of the battery becomes the problem for the WSN and the energy harvesting devices can harvest energy from the surrounding environment to be the power source to extend the battery lifetime or even to be the permanent energy source is the ultimate object [1-2]. Piezoelectric materials are

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Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.212

robust, high quality factor and high power density and to be the one of the most popular and useful energy conversion materials. The host structure of the classical piezoelectric energy harvester is the cantilever beam due to its simplicity and high efficiency [3-7]. Except vibrating-based energy harvester, Wind force is also a good candidate to be the external energy force. O. Doaré, and S. Michelin propose the energy harvesting fluttering flexible plates in axial flow composed of many piezoelectric patches [8]. Comparing to the fluttering flexible plates, galloping-based energy harvester is another type of wind-driven energy harvesting [9-10]. The schematic of galloping piezoelectric energy harvest is shown in Fig 1.

In classical cantilever beam based energy harvester, a nonlinear switching technique, the synchronized switching harvesting on inductor (SSHI) technique is a very successful and efficient technique to boost the piezoelectric output power [11-15]. In real energy harvesting applications, there should be no external energy to supply the switches and the self-powered synchronized switching technique is proposed by using the velocity control technique [7].

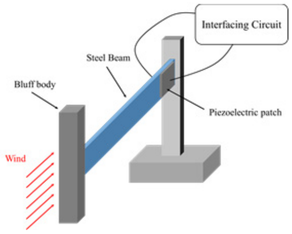


Fig. 1. Schematic of galloping piezoelectric energy harvesting (GPEH).

In this study, three classical interfacing circuits used in vibrating-based energy harvester are compared to be used in galloping-based energy harvester. Fig 2(a) shows the simple model of piezoelectric patch and the basic standard DC approach interface, Fig 2(b) shows the series-SSHI interface and the Fig 2(c) shows the transformer-based technique called optimized synchronous electric charge extraction (OSECE). In the next, a equivalent circuit of galloping piezoelectric energy harvester (GPEH) will be considered and combined with these three interfacing circuits. The experiments will be compared to the simulation results (MATLAB+PSIM software) to show the performance of these three interfacing circuits in galloping-based applications.

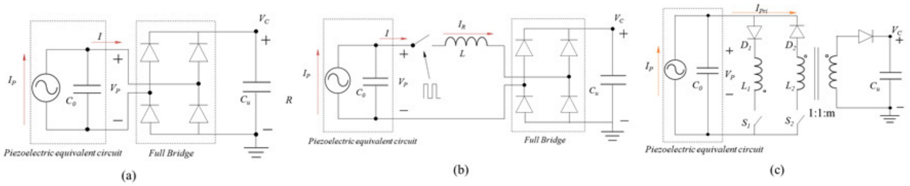


Fig. 2. (a) Standard DC approach (b) Series-SSHI interfacing circuit (c) Optimized synchronous electric charge extraction (OSECE).

2. Theoretical analysis and equivalent model

Galloping-based energy harvester is composed of a bluff body placed at the tip of an elastic cantilever beam and piezoelectric patch placed at the fixed end of the beam. Considering the lumped parameter model and piezoelectric equations, the governing equations of the GPEH can be written as equation (1) [9].

$$\begin{cases} M\ddot{x}(L_b,t) + D\dot{x}(L_b,t) + K^E x(L_b,t) + \alpha V_P(t) = F_Z(t) \\ F_Z(t) = \dfrac{1}{2}\rho_a h L_{tip} U^2 C_{Fz} \\ I(t) = \alpha \dot{x}(L_b,t) - C_0 \dot{V}_P(t) \end{cases} \tag{1}$$

Where M, K^E, and D represent the effective mass, spring and damper of the system. $F_Z(t)$, $V_P(t)$, $I(t)$ and $x(L_b, t)$ refer to external aerodynamic force, piezoelectric terminal voltage, piezoelectric output current and the displacement of the system. α and C_0 are the piezoelectric force-voltage coefficient and the clamped capacitor of the piezoelectric patch. L_b is the length of the cantilever beam, ρ_a is the air density, h is the edge length of the square section, L_{tip} is the length of the bluff body and U is wind speed. C_{Fz} is the total aerodynamic force coefficient and is a function of the angle of attack. In order to use the governing equation into equivalent circuit model, the aerodynamic force can be further written as equation (2)

$$-\frac{1}{2}\rho_a h L_{tip} U^2 \left[\sum_{i=1,2,\ldots} Ai \left(\frac{\dot{x}(t)}{U} + \beta \frac{V_C(t)}{K^E} \right)^i \right] \tag{2}$$

Combining the governing equation (1) and aerodynamic force equation (2), the equivalent circuit modal of GPEH and three interfacing circuits in PSIM circuit simulator are shown in Fig. 3(a). The left hand parts are the equivalent circuit of GPEH modal and right hand parts are standard DC approach (STD), series-SSHI and OSECE circuits. The simulation results are plotted in 3D as shown in Fig. 3(b)(c)(d). As the compassion in classical vibration-based piezoelectric energy harvester (VPEH), the optimal load of the series-SSHI technique is smaller than STD. And the advantage of OSECE technique is the low-load depending effect, the optimal load range can be from 100 kΩ to 1 MΩ.

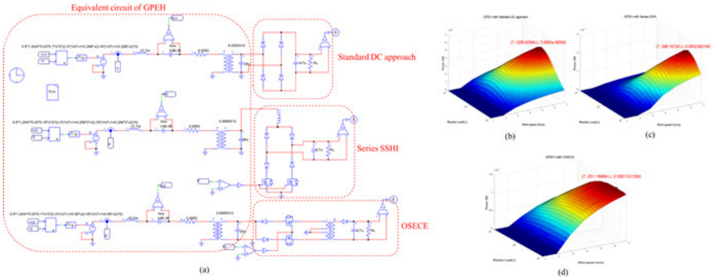


Fig. 3. Simulation setup in PSIM (a) and results (b)STD (c) Series-SSHI (d)OSECE.

3. Experimental results and discussion

Fig. 4 shows the experimental setup and photos. The wind source is driven by a fan (4184 NXH) and the wind speed U can be controlled by the driving voltage from 12-28 VDC. A laser vibrometer (LK-G152 and LK-G3001P, KEYENCE) is used to measure the tip displacement an anemometer is used to measure the wind speed U. Three interfacing circuits (Standard DC approach, Series-SSHI and OSECE) are made to compare the power output. The schematic circuits diagram are shown in Fig 1. The model of diodes used in the circuit are BAT48 and the voltage drop is around 0.22V. The model of transformer used in OSECE circuit is PT8SM.The turn's ratio is 1:1:2 and the inductance is around 10mH. The two switches used in OSECE circuit are two MOSFET. The model of N MOSFET is 2N7002 and the model of P MOSFET is NDS0610. The smooth capacitor is 4.7uF. The dimension and modal parameters are shown in Table1.

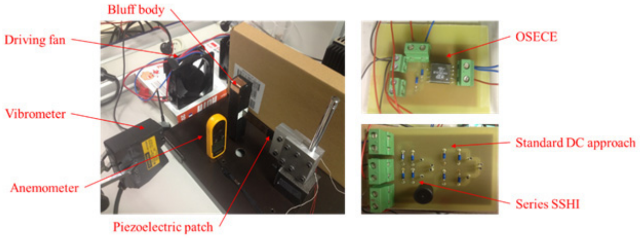
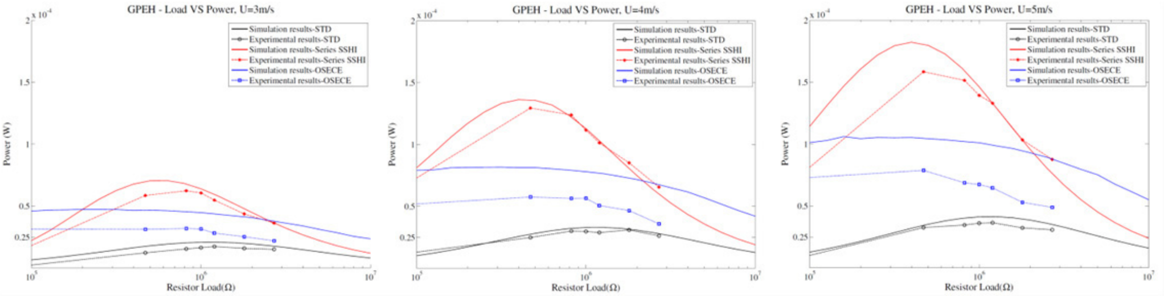


Fig. 4. Experimental setup and photos.

Table 1. Dimensions and modal parameters.

Symbol	Description	Value (units)
Steel beam	Length*width*thickness	120*20*0.5 (mm^3)
Piezoelectric patch (PZT)	Length*width*thickness	20*14*0.3 (mm^3)
bluff body	Length*width*thickness	100*30*30 (mm^3)
f^{op}	Short circuit resonant frequency	7.6 (Hz)
f^{sh}	Open circuit resonant frequency	7.57 (Hz)
k^2	Electromechanical coupling coefficient	0.0079
M	Mass	17.7 (g)
K^D	Equivalent stiffness when piezoelectric patch is in open circuit	40.36 (N/m)
K^E	Equivalent stiffness when piezoelectric patch is in short circuit	40.04 (N/m)
D	Damping coefficient	0.0052 (N/m/s)
α	Force-voltage factor	0.0000312 (N/V)
C_0	Clamped capacitance of piezoelectric patch	25 (nF)

The galloping piezoelectric energy harvesting device are connect to three interfacing circuit driven in different wind speed and tested in different resistor load. The experimental results for three wind speed U are shown in Fig 5. The black, blue and red curves present the simulation results of standard DC approach, OSECE and series-SSHI from MATLAB+PSIM. The black curve with circle dots, blue curve with square dots and red curve with star dots present the experimental results. With the wind speed increasing, the power output of three interfacing circuits will also increase. Comparing the experimental results to simulation results, the experimental results of standard DC approach and series-SSHI are close to the simulation results and the OSECE technique are more losses. The main reason for the losses between the experimental and simulation results is because in the simulation the ideal transformer is used and in the experiments there are losses when the transformer stored and transfer the electrical energy. The maxima power of Series-SSHI is higher than others but the optimal load range is very narrow. Although the power output of OSECE is between standard DC approach and series-SSHI, the optimal load range is the largest one and it can be used in more applications without considering the load effect.



(a). (b). (c)

Fig. 5. Experimental and simulation results in different wind speed (a) U=3m/s (b) U=4m/s (c) U=5m/s.

4. Conclusion

In this study, the equivalent circuit model of galloping-based piezoelectric energy harvester (GPEH) with different interfacing circuits is proposed and simulated in circuit simulator MATLAB and PSIM to compare the power output. The experimental results show good agreement with the simulation results and when the wind speed exceed the critical value the GPHE will begin to flutter. With the wind speed increasing, the power output will also increase. As the comparison in VPEH, the standard DC approach is the basic rectifier circuit and the worst power output. In this three circuits, the power output of series-SSHI is the best one and around 4 times than the standard DC approach and 2 times than OSECE. The disadvantage of the series-SSHI is high load-depending. The optimal load range of the OSECE is the largest one and it's the most advantage of this interfacing circuit. According to the different applications, the interfacing circuits will be the one of the most important part to increase the power output and the impedance matching.

Acknowledgements

The funding of this project, from Agence Nationale de la Recherche, France under ANR FLUTTENER project, is gratefully acknowledged.

References

[1] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," Power Electronics, IEEE Transactions on, vol. 17, pp. 669-676, 2002.

[2] S. Roundy and P. K. Wright, "A piezoelectric vibration based generator for wireless electronics," Smart Materials & Structures, vol. 13, pp. 1131-1142, Oct 2004.

[3] H. A. Sodano, et al., "A review of power harvesting from vibration using piezoelectric materials" vol. 36. Thousands Oaks, CA, USA: Sage, 2004.

[4] S. Roundy, "On the effectiveness of vibration-based energy harvesting," Journal of Intelligent Material Systems and Structures, vol. 16, pp. 809-823, Oct 2005.

[6] E. Lefeuvre, et al., "A comparison between several approaches of piezoelectric energy harvesting," Journal De Physique Iv, vol. 128, pp. 177-186, 2005.

[7] Y. Y. Chen, et al., "A self-powered switching circuit for piezoelectric energy harvesting with velocity control," European Physical Journal-Applied Physics, vol. 57, 3090, Feb 2012.

[8] S. Michelin, and O. Doaré, "Energy harvesting efficiency of piezoelectric flags in axial flows." Journal of Fluid Mechanics 714 (2013): 489-504.

[9] Lihua Tang, Liya Zhao, Yaowen Yang, Lefeuvre, E., "Equivalent Circuit Representation and Analysis of Galloping-Based Wind Energy Harvesting," Mechatronics, IEEE/ASME Transactions on, vol.20, no.2, pp.834,844, April 2015.

[10] Zhao, Liya, Lihua Tang, and Yaowen Yang. "Synchronized charge extraction in galloping piezoelectric energy harvesting." Journal of Intelligent Material Systems and Structures (2015): 1045389X15571384.

[11] E. Lefeuvre, A. Badel, A. Benayad, L. Lebrun, C. Richard, and D. Guyomar, "A comparison between several approaches of piezoelectric energy harvesting," Journal De Physique Iv, vol. 128, pp. 177-186, 2005.

[12] D. Guyomar, A. Badel, E. Lefeuvre, and C. Richard, "Toward energy harvesting using active materials and conversion improvement by nonlinear processing," Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control, vol. 52, pp. 584-595, 2005.

[13] E. Lefeuvre, A. Badel, C. Richard, and D. Guyomar, "Piezoelectric energy harvesting device optimization by synchronous electric charge extraction," Journal of Intelligent Material Systems and Structures, vol. 16, pp. 865-876, 2005.

[14] A. Badel, D. Guyomar, E. Lefeuvre, and C. Richard, "Piezoelectric energy harvesting using a synchronized switch technique," Journal of Intelligent Material Systems and Structures, vol. 17, pp. 831-839, 2006.

[15] Y. Wu, A. Badel, F. Formosa, et al., Piezoelectric vibration energy harvesting by optimized synchronous electric charge extraction. Journal of Intelligent Material Systems and Structures 24(12): 1445–1458, 2012.