Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 3498–3503

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

A novel hybrid energy harvester with increased power density

M. Moshrefi-Torbati[a]*, T. V. Lang[a], M. Hendijanizadeh[a], T. B. Le[b] and S. M. Sharkh[a]

[a] Electro-Mechanical Engineering Research Group, Engineering Science, University of Southampton, Southampton SO17 1BJ, United Kingdom
[b] Ho Chi Minh City University of Technology and Education,01 Vo Van Ngan, Thu Duc, Ho Chi Minh City, Vietnam

Abstract

In this paper, a novel hybrid energy harvester is investigated by using a rotational generator and a surface permanent magnet linear generator (SPMLG). The rotational generator that was developed by Hendijanizzaded [1] can harvest maximum power under the optimum design process with constrain on the relative displacement of the mass. The aim of adding the SPMLG is to increase electrical damping that will affect the displacement of the moving mass. This idea is different than the existing hybrid systems in which energy is harvested from two different sources, such as sunlight and sound or heat and light to increase power extracted. The interactions between different electromechanical parameters can be taken advantages of to improve the power harvesting of the device. By adding SPMLGs to a rotational generator, electrical damping of the system will be increased while the mechanical parameters of the system, for example, the resonant frequency, the spring stiffness and the seismic mass are unchanged. The system model of the rotational and the hybrid harvesters will be established and numerically simulated. Also, the power extraction between the original rotational generator and the hybrid harvester under the same conditions will be compared to confirm the viability of the method. Obviously, the trade-off for this power increase is the additional weight of the SPMLGs that must be considered in the calculations of the power density which is outside the scope of this paper.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: surface permanent magnet generator; hybrid; energy harvester; electrical damping.

1. Introduction

Maximizing extracted power has become the main concern in the ambient energy harvesting devices. Optimal design process can be applied to improve energy harvested [1 - 3] and integrating mechanisms into a hybrid system is also used in many researches.

Electromagnetic generators have been developed in high power large scale applications. Alternative linear electromagnetic generators are described in [4 - 10] that are used to convert kinetic energy to electrical energy.

* Corresponding author. Tel.: +44-023-8059-8583
E-mail address: M.M.Torbati@soton.ac.uk

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.464

However, rotational generators have been more dominant due to their higher efficiency of conversion [4]. To maximize the harvested energy, the parameters of a harvester need to be selected and tuned carefully. For example, in a rotational generator, its sprung mass and spring are selected that it resonates at the frequency of the external excitation. Also, adjusting the load of the generator's resistance to be equal to its internal impedance [11] improved energy capture. Hendijanizadeh *et al*. [1] determined the parameters of a constrained system by suggesting a set of alternative optimization design rules for selecting the mass, spring stiffness, gear transmission ratio, and load impedance for the constrained displacement of the seismic mass as guidance for obtaining maximum power harvesting.

Hybrid energy harvesters, which convert one or several energy sources into electric energy, have been exploited in many applications. Gambier *et al*. [12] introduced piezoelectric generator system that harvested from solar and thermal energy. Wu *et al*. [13] suggested a hybrid energy cell that can simultaneously harvest solar, wind and chemical energies from the environment to power some electric devices. This system can produce an open-circuit voltage of about 90 V and a short-circuit current density of about 0.5mA/m^2, which can be used to directly light up tens of blue LEDs.

Hybrid systems combining piezoelectric and electromagnetic devices to recover energy from mechanical vibrations have been investigated by many researchers [14 – 15]. Piezoelectric harvesters are suitable for micro-systems due to their high power density, while electromagnetic harvesters are dominant at relatively large size application [16]. A vibration harvester extracts maximum energy when its resonant frequency matches the excitation frequency. Thus, combining piezoelectric and electromagnetic components can increase the operating band width and the overall efficiency as well [17]. Chen *et al*. [18] introduced a special designed piezoelectric cantilever array and using coil and magnets as a proof mass to power wireless sensors nodes in smart grid with the total output power of 341.9 μW.

This paper will introduce a hybrid harvester to improve harvested power based on embedded SPMLGs into rotational generator that was developed by Hendijanizadeh [1]. This solution will keep the displacement of the moving mass within the constrained space of the device and simultaneously getting more extracted power. By adding SPMLGs to the rotational generator, electrical damping of the system will be increased while the mechanical parameters of the system, for example, the resonant frequency, the spring stiffness and the seismic mass are unchanged. The system model of the rotational and the hybrid harvesters will be established and numerically simulated. Also, the power extraction between the original rotational generator and the hybrid harvester under the same conditions will be compared to validate the possibility of the method.

2. System model

In this section, configuration of the generators are introduced and mathematically modeled. The conditions of the external excitation are identical throughout the modelling of the systems. The peak output power of the systems is derived based on considering the effects of the internal parameters of the systems and the external conditions.

2.1. Rotational generator

A free body diagram of a rotational energy harvesting system coupled to an electromagnetic generator is in Ref. [1]. In this diagram, m is the inertial mass; c_m represents the combined mechanical and electrical damping coefficient of the system. The size of the screw lead, l, defines the amount of linear movement of the mass that is converted to the rotational motion of the lead-screw.

The peak value of the output power, $P_{rot\text{-}peak}$, is [1]

$$P_{rot-peak} = R_{l,rot} i^2 = \frac{R_{l,rot}}{\left(R_{l,rot} + R_{i,rot}\right)^2} K_{t,rot}^2 \left(\frac{2\pi}{l}\right)^2 \omega_n^2 Z_r^2 \qquad (1)$$

where $R_{i,rot}$, $R_{l,rot}$ and $K_{t,rot}$ are the internal, the load resistance and the electromagnetic force constant of the rotational generator, respectively.

Maximum power occurs when the undamped natural frequency of the system is equal to the frequency of the excitation at which the corresponding relative displacement Z_r can be derived from Eq. (2) at resonant frequency as [1]

$$Z_r = \frac{m\omega_n Y}{\left(c_m + \frac{K_{t,rot}^2}{\left(R_{l,rot} + R_{i,rot}\right)}\right)\left(\frac{2\pi}{l}\right)^2} \tag{2}$$

This assumes that the excitation is known and the maximum value of Eq. (1) occurs when $\left(d / dR_r\right)\left(P_{rot-peak}\right) = 0$ which leads to the following expression [1]

$$R_r^2 = R_{i,rot}^2 + R_{i,rot}\frac{K_{t,rot}^2}{c_m} \tag{3}$$

2.2. Linear generator

Ideally, multiple-sided or a cylindrical linear generator would reduce the amount of flux losses and could potentially eliminate the cogging forces since they will cancel each other about the symmetrical axes. An example of an octagonal linear permanent magnet generator with axial flux configuration is depicted in Fig. 1. However, both multiple-sided and cylindrical designs are complex to manufacture, given the tight volume where the linear generator is to be fitted and hence the required machining accuracy.

In the present work, two flat SPMLGs, which are place in the symmetry, have been simulated. The armatures are called the primary elements corresponding to the stator windings. The secondary element, which is a seismic mass, consists of 0.5 mm sheets laminated together to reduce the eddy current losses.

Considering a pure resistive load, then the EMF induced in a length of wire is given by

$$E_{emf} = K_{t,lin}\dot{z} \tag{4}$$

where $K_{t,lin}$ is electromagnetic force constant of the SPMLG.

The peak output power, $P_{peak\text{-}lin}$, delivered to the resistive load is

$$P_{peak-lin} = R_{l,lin}i^2 = \frac{R_{l,lin}}{(R_{l,lin} + R_{i,lin})^2}K_{t,lin}^2\dot{z}^2 \tag{5}$$

where $R_{l,lin}$ and $R_{i,lin}$ are the load and armature resistances, respectively.

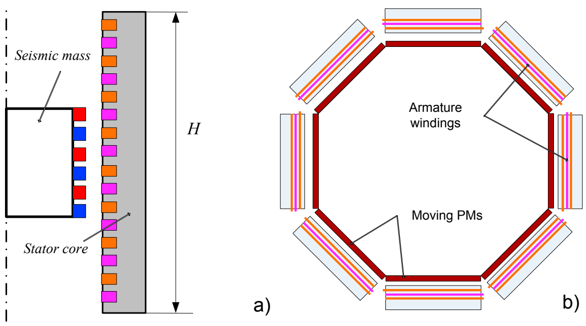


Fig. 1. a) A schematic diagram octagonal SPMLG; b) above view

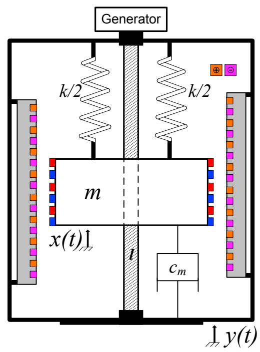


Fig. 2. A schematic diagram of proposed hybrid harvester

2.3. Hybrid system model

Fig. 2 shows the configuration of the proposed hybrid device. It combines a rotational generator in which a seismic mass is coupled to an electromagnetic generator through a lead screw and a SPMLG which includes two flat windings around the seismic mass. The governing equation of motion for the hybrid energy harvesting system shown in Fig. 2, with respect to relative displacement $z = x - y$, is

$$M\ddot{z} + C_{hybrid}\dot{z} + kz = -m\ddot{y} \tag{6}$$

where C_{hybrid}, the combined mechanical and electrical damping coefficient of the hybrid system, is defined as

$$C_{hybrid} = \left(c_m + \frac{K_{t,rot}^2}{R_{l,rot} + R_{i,rot}} \right) \left(\frac{2\pi}{l} \right)^2 + \frac{K_{t,lin}^2}{R_{l,lin} + R_{i,lin}} \tag{7}$$

If it is assumed that the base is subject to a sinusoidal excitation, the displacement of the mass can be represented by $x(t) = X \sin(\omega t + \phi_X)$, the magnitude Z of the relative displacement of the mass, $z(t) = Z \sin(\omega t + \phi_Z)$, is

$$\frac{Z}{Y} = \frac{m\omega^2}{\sqrt{(k - M\omega^2)^2 + [(c_m + c_{eR} + c_{eL})\omega]^2}} \tag{8}$$

Again, maximum power occurs when undamped natural frequency of the system is equal to the frequency of the excitation at which the corresponding relative displacement $Z_{r\text{-}h}$ can be derived from Eq. (8) after substituting for the electrical damping coefficient from Eq. (7)

$$Z_{r-h} = \frac{m\omega Y}{\left(c_m + \frac{K_{t,rot}^2}{R_{l,rot} + R_{i,rot}} \right) \left(\frac{2\pi}{l} \right)^2 + \frac{K_{t,lin}^2}{R_{l,lin} + R_{i,lin}}} \tag{9}$$

The maximum output power of the linear and the rotational generators are

$$P_{lin-peak} = \frac{R_{l,lin}}{(R_{l,lin} + R_{i,lin})^2} K_{t,lin}^2 \omega^2 Z_{r-h}^2 \tag{10}$$

$$P_{rot-peak} = \frac{R_{l,rot}}{(R_{l,rot} + R_{i,rot})^2} K_{t,rot}^2 \left(\frac{2\pi}{l}\right)^2 \omega^2 Z_{r-h}^2 \tag{11}$$

3. Numerical studies

In the original rotational generator, based on Eq. (2) and the parameters given in Table 1, the relative displacement at resonant frequency is 0.3 m and by applying Eq. (3), the optimum load resistance for the system is 6.5 Ω. Hence, the average harvested power at resonance frequency obtained from Eq. (1) is 12 W [1].

Table 1. System parameters for the rotational energy harvesting device [3]

Parameters	Z_0	C_m	$K_{t,rot}$	$R_{i,rot}$	Y	f	m	l
Value	0.3	0.003	0.0634	3.4	1	0.5	8	2
Units	m	NmsRad^{-1}	VsRad^{-1}	Ω	m	Hz	kg	mm

In a hybrid system, the combined linear and rotational generators will improve the multiple damping effects on the coupled system. More specifically, higher induced damping will result in higher potential of energy conversion; however, higher induced damping effect will subsequently reduce the relative displacement and velocity. The total harvested power of a hybrid system is the sum of the powers harvested from the individual systems, i.e.,

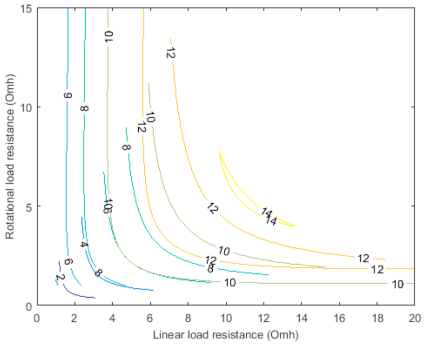
$$P_{H-peak} = P_{lin-peak} + P_{rot-peak} \tag{12}$$

Table 2. System parameters for linear energy harvesting devices [3]

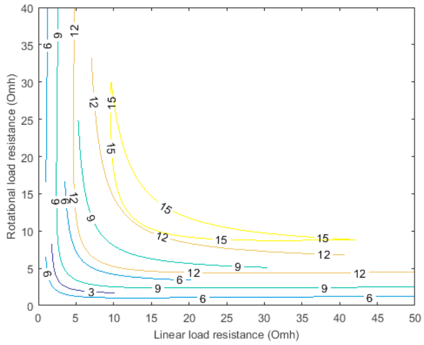
Parameters of linear Generators	1	2	3	4
EMF constant, $K_{t,lin}$ (Vsm^{-1})	10	20	21	42
Internal resistance, $R_{i,lin}$ (Ω)	1.6	4	1.6	0.8

The SPMLG will in effect add damping to the rotational system and as a result the maximum relative displacement of the seismic mass will be reduced. Therefore, load resistance of both linear and rotational generators will need to be tuned to get the maximum output power at the constrained maximum displacement of the device (Z<0.3m). Based on Eqs. (9), (10) and (11), the harvested power of a hybrid energy harvester which is given by Eq

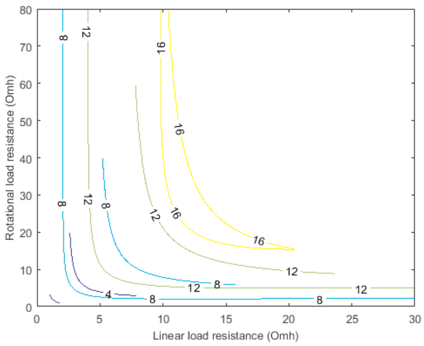
(12) can be calculated for various linear generators with different internal resistances $R_{i,lin}$ and emf constants $K_{t,lin}$. In Fig. 3 the total power of a hybrid system for four different cases is plotted wherein the load resistance of both the linear and rotational generators are optimised.



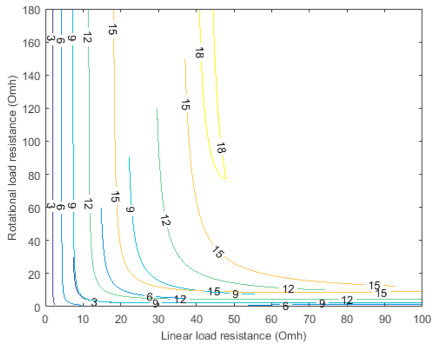
Linear generator 1 ($K_{t,lin}$=10 Vs/m, $R_{i,lin}$=1.6 Ω)



Linear generator 2 ($K_{t,lin}$=20 Vs/m, $R_{i,lin}$=4.0 Ω)



Linear generator 3 ($K_{t,lin}$=21 Vs/m, $R_{i,lin}$=1.6 Ω)



Linear generator 4 ($K_{t,lin}$=42 Vs/m, $R_{i,lin}$=0.8 Ω)

Fig. 3. Output power contour graph of the hybrid harvester versus load resistances of the linear and rotational generators.

Table 3. Output power of the hybrid harvester versus optimum value of the linear and rotational load resistance.

Cases	1	2	3	4
Output power of the hybrid harvester (W)	14	15	16.5	18
Optimum linear load resistance (Ω)	5.6	17.1	13.7	44.5
Optimum rotational load resistance (Ω)	11.3	14.6	29	180
Power increase (%)	18	25	38	50

By combining the four different linear generators shown in Table 2 with the original rotational system, the resulting increase in the output power of the hybrid harvester in comparison with the original rotational generator is 18%, 25%, 38% and 50%. Obviously, the trade-off for this power increase is the additional weight of the linear generator that must be considered in the calculations of the power density which is outside the scope of this paper.

4. Conclusion and future work

This paper presented a novel hybrid energy harvesting device that consisted of a lead screw based rotational generator and a surface permanent magnet linear generator (SPMLG). The electromechanical coupling model of the hybrid energy harvester was established and numerically simulated. The single rotational generator harvested an average output power of around $12W$ in response to a base excitation of 0.5 Hz with amplitude of 1 m. For the same conditions, the hybrid energy harvester, under the effects of mechanical and electrical damping from both linear and rotational generators responds with the reduced relative displacement of its seismic mass. As a result, the output power of the rotational generator is reduced. However, the total output power of the hybrid harvester is increased in comparison with the original rotational generator. Considering the relatively low additional mass and volume of the hybrid system, the resulting increase in the output power of the harvester is very encouraging.

Future work will include detailed analysis of the characteristics of the hybrid energy harvester, particularly the trade-offs in changing various parameters of the electromagnetic linear generator and its structure. Furthermore, a unified energy harvesting interface circuit will be designed for the hybrid energy harvester, which can simultaneously harvest energy from both the electromagnetic linear and rotational generators in an efficient manner.

References

[1] Hendijanizadeh, M., Moshrefi-torbati, M., & Sharkh, S. M, "Constrained Design Optimization of Vibration Energy Harvesting Devices," *J. Vib. Acoust* 136(2), 021001 (Nov 20, 2013), VIB-12-1177.

[2] Hendijanizadeh, M., "Design and Optimisation of Constrained Electromagnetic Energy Harvesting Devices," PhD thesis, University of Southampton, 2016.

[3] M Hendijanizadeh, S M Sharkh, S J Elliott and M Moshrefi-Torbati, "Performance analysis and validation of thermoelectric energy harvesters," *Smart Materials and Structures* (2013), *22*(9), 95014.

[4] H. Arof, A. M. Eid and K. M. Nor, "Permanent magnet linear generator design using finite element method,"*ICEEC '04. 2004 International Conference on*, Cairo, Egypt, pp. 893-896.

[5] E. Ilhan, B. L. J. Gysen, J. J. H. Paulides and E. A. Lomonova, "Analytical Hybrid Model for Flux Switching Permanent Magnet Machines," *IEEE Transactions on Magnetics*, vol. 46, no. 6, pp. 1762-1765, June 2010.

[6] Milano, P., & Energia, D., "Novel Modeling Design of Three Phase Tubular Permanent Magnet Linear Generator for Marine Applications," *2009 International Conference on Power Engineering, Energy and Electrical Drives*, Lisbon, 2009, pp. 78-83.

[7] F. Rinderknecht, "The linear generator as integral component of an energy converter for electric vehicles," *European all-wheel drive congress*, Graz (2011).

[8] F. Rinderknecht and H. G. Herzog, "Calculation of a linear generator for a hybrid vehicle concept," *The XIX International Conference on Electrical Machines - ICEM 2010*, Rome, 2010, pp. 1-5.

[9] S. Zhou, H. Yu, M. Hu, C. Jiang and L. Huang, "Nonlinear Equivalent Magnetic Circuit Analysis for Linear Flux-Switching Permanent Magnet Machines," *IEEE Transactions on Magnetics*, vol. 48, no. 2, pp. 883-886, Feb. 2012.

[10] Z. Q. Zhu, X. Chen, J. T. Chen, D. Howe and J. S. Dai, "Novel linear flux-switching permanent magnet machines," *International Conference on Electrical Machines and Systems*, Wuhan, 2008, pp. 2948-2953.

[11] Yeatman, E. M., "Energy harvesting from motion using rotating and gyroscopic proof masses," *Proc. of the Institution of Mech. Eng., Part C: J. Mech* (2007). *222*, 27–36.

[12] Gambier, P., Anton, S. R., Kong, N., Erturk, A., & Inman, D. J., "Piezoelectric, solar and thermal energy harvesting for hybrid low-power generator systems with thin-film batteries," *Meas. Sci. Technol.* **23** (2012) 015101.

[13] Wu, Y., Zhong, X., Wang, X., Yang, Y., & Wang, Z. L., "Hybrid energy cell for simultaneously harvesting wind, solar, and chemical energies," *Nano Res* (2014), *7*(11), 1631–1639. y

[14] A. Collado and A. Georgiadis, "Conformal hybrid solar and electromagnetic (EM) energy harvesting rectenna," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 8, pp. 2225-2234, Aug. 2013.

[15] Li, P., Gao, S., & Cai, H. (2015), "Modeling and analysis of hybrid piezoelectric and electromagnetic energy harvesting from random vibrations," 401–414.

[16] Zuo, L., & Tang, X., "Large-scale vibration energy harvesting, Intelligent Material Systems and Structures," *Intelligent Material Systems and Structures,* 2013, 24(11) 1405–1430.

[17] G. Poulin, E. Sarraute, F. Costa, "Generation of electrical energy for portable devices: Comparative study of an electromagnetic and a piezoelectric system," *Sensors and Actuators A: Physical*, Volume 116, Issue 3, 29 October 2004, Pages 461-471, ISSN 0924-4247.

[18] Chen, W., Cao, Y., & Xie, J., "Powering wireless sensor nodes in smart grid," *Mechanical Science and Technology 29,* (10) (2015) 4313~4318.