Mechanical Systems and Signal Processing 101 (2018) 55–66

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Effects of electrical loads containing non-resistive components on electromagnetic vibration energy harvester performance

Hui Zhang, Lawrence R. Corr, Tianwei Ma *

Department of Civil and Environmental Engineering, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 5 August 2017
Accepted 16 August 2017

Keywords:
Vibration energy harvesting
Electromagnetic harvester
Non-resistive components
Electrical loads

ABSTRACT

To further advance the existing knowledge base on rectified vibration energy harvester design, this study investigates the fundamental effects of electrical loads containing non-resistive components (e.g., rectifiers and capacitors) on electromagnetic energy harvester performance. Three types of electrical loads, namely (I) a resistor with a rectifier, (II) a resistor with a rectifier and a capacitor, and (III) a simple charging circuit consisting of a rectifier and a capacitor, were considered. A linear electromagnetic energy harvester was used as an illustrative example. Results have verified that device performance obtained from pure-resistive loads cannot be generalized to applications involving rectifier and/or capacitor loads. Such generalization caused not only an overestimation in the maximum power delivered to the load resistance for cases (I) and (II), but also an underestimation of the optimal load resistance and an overestimation of device natural frequency for case (II). Results obtained from case (II) also showed that it is possible to tune the mechanical natural frequency of device using an adjustable regulating capacitor. For case (III), it was found that a larger storing capacitor, with a low rectifier voltage drop, improves the performance of the electromagnetic harvester.

1. Introduction

Harvesting energy from ambient vibrations has received increasing attention since the late 90s. One of the research motivations in this field is the desire of supplying sustainable power to miniature electronic devices, such as wireless sensors, medical implantable electronic devices, and wireless transmitters, to achieve their autonomous and self-sustained long-term operation. Generally, vibration energy can be converted to electricity through three basic conversion mechanisms, i.e., electromagnetic, piezoelectric, and electrostatic. Based on the three conversion mechanisms, numerous schemes and devices have been developed for a variety of applications as summarized in recent review articles [1–4]. As reported in the literature, device performance has been conventionally evaluated using the power delivered to pure-resistive electrical loads (resistors). It is noticed that although issues exist in piezoelectric energy harvesting [5], the effect of a pure-resistive electrical load on device dynamics can be approximately equivalent to adding additional damping to the device [6–9]. Based on the change in device damping, device performance can be theoretically derived. However, such device performance cannot be generalized for applications based on electrical loads containing non-resistive components, e.g., rectifiers and capacitors (which are essential components of charging circuits). For an electromagnetic vibration energy harvester (EVEH), the voltage drop of a rectifier is the same order of magnitude as the generated voltage of the harvester. Thus, introducing a

* Corresponding author.
E-mail address: tianwei@hawaii.edu (T. Ma).

http://dx.doi.org/10.1016/j.ymssp.2017.08.031
0888-3270/

rectifier to the electrical load reduces the output power of harvester, and such reduction cannot be ignored. On the other hand, research efforts on the method of synchronized switch harvesting on inductor (SSHI) [10–12] have shown that for a piezoelectric vibration energy harvester, it could be possible to enhance device performance due to the presence of a rectifier in the electrical load. Considering the need of applications based on charging circuits, electrical loads containing non-resistive components have been considered in vibration energy harvesting [13–16] and their overall performance has been investigated [10,14,16–23]. However, in past and existing research efforts, typically limiting simplifying assumptions were made (e.g., constant rectifier voltage, no impact on harvester dynamics); therefore, providing an opportunity to continue and expand the investigation into the performance impact of introducing non-resistive components to electrical loads, specifically for electromagnetic energy harvesters. Note that the conversion mechanism of an electromagnetic harvester, which is inductive, is fundamentally different to that of a piezoelectric harvester and an electrostatic harvester, which are capacitive. Therefore, the results obtained from this study may not be directly generalized for capacitive devices.

2. Theoretical analysis

The governing equations of a linear electromagnetic vibration energy harvester connected to an electrical load (Fig. 1) under harmonic base excitation (i.e., the displacement of the base is $x_0(t) = A\cos\omega t$) can be generally written as [24]

$$m\ddot{x}(t) + c_m\dot{x}(t) + kx(t) + \kappa I(t) = f(t), \tag{1}$$

$$L_w\dot{I}(t) + R_wI(t) + V(t) = \kappa\dot{x}(t), \tag{2}$$

where $x(t)$ denotes the displacement of the seismic mass m, c_m the mechanical damping coefficient, k the mechanical stiffness of the harvester, κ the electromechanical coupling coefficient, and $f(t) = mA_e\cos\omega t$ in which $A_e = A\omega^2$; while L_w, R_w, $I(t)$, and $V(t)$ represent the inductance and internal resistance of the winding, the induced current, and the voltage across the electrical load, respectively.

In this paper, the device performance is comprehensively evaluated by multiple metrics, i.e., the response velocity amplitude $\dot{x}_{amp}$, the normalized average power delivered to the load P_L, the normalized average input power of the excitation P_f, and the coupling efficiency of the excitation η [24], defined as

$$P_L = \frac{1}{mT}\int_0^T V(t)I(t)dt, \tag{3}$$

$$P_f = \frac{1}{mT}\int_0^T f(t)\dot{x}(t)\mathrm{d}t, \tag{4}$$

$$\eta = \frac{\int_0^T f(t)\dot{x}(t)\mathrm{d}t}{\int_0^T |f(t)\dot{x}(t)|\mathrm{d}t}, \tag{5}$$

where T is a reasonable period of time of a periodic vibration, e.g., $T = \frac{2\pi}{\omega}$ for steady-state vibration. It is noticed that there are many metrics used for evaluating device performance, such power delivered to the load, power density, and load voltage. However, these criteria can only describe device performance in the process of energy transfer from the device to the electrical load. The coupling efficiency, η, and the normalized average input power of the excitation, P_f, provide additional significant information about the work done by the excitation in the process of energy transfer between the excitation and the harvester.

2.1. Pure-resistive electrical loads

When a resistor is used as the electrical load, $V(t) = R_LI(t)$ where R_L is the load resistance, and the normalized average power delivered to the load is $P_L = \frac{R_L}{mT}\int_0^T I(t)^2\mathrm{d}t$. For low-frequency excitations (e.g., bridge vibrations and machine vibrations), typically $\omega L_w \ll R_w + R_L$; therefore, the electromechanical coupling, shown in Eq. (2), can be approximated as an algebraic relationship, i.e., $(R_w + R_L)I(t) = \kappa\dot{x}(t)$. The effect of the electromechanical coupling on the device dynamics can be calculated as $\kappa I(t) = \frac{\kappa^2}{R_w+R_L}\dot{x}$, which is equivalent to adding additional damping to the device. The governing equation of device dynamics is thus rewritten as

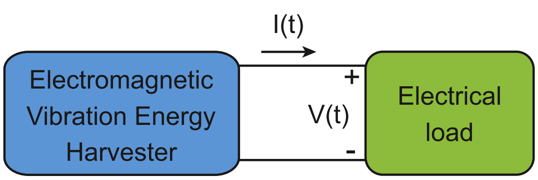

Fig. 1. Schematic diagram of an electromagnetic vibratory energy harvester with electrical load.