Mechanical Systems and Signal Processing 111 (2018) 210–221

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 piezoelectric energy harvesting

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ARTICLE INFO

Article history:
Received 17 November 2017
Received in revised form 28 February 2018
Accepted 6 April 2018

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

ABSTRACT

This study investigates the fundamental effects of electrical loads containing non-resistive components (e.g., rectifiers and capacitors) on piezoelectric energy harvesting performance. Theoretical, numerical and experimental studies have been carried out to investigate three types of electrical loads, namely (I) a rectifier followed by a resistor, (II) a rectifier followed by a regulating capacitor and a resistor, and (III) a simple charging circuit consisting of a rectifier and a capacitor. It is shown that device performance based on pure-resistive loads cannot be generalized to applications involving non-resistive components, i.e., rectifiers and capacitors. Results from cases (I) and (II) show that the rectifier voltage drop leads to a decrease in the power delivered to the load resistance and to an increase in the natural frequency of the device but does not change the optimal resistance corresponding to a driving frequency. The regulating capacitor, however, results in increases in both the optimal load resistance and the natural frequency of the device. Therefore, tuning the natural frequency of a piezoelectric device is possible through an adjustable regulating capacitor with an appropriate rectifier. From case (III), it has been found that a larger storing capacitor, with a low rectifier voltage drop, improves the piezoelectric energy harvesting performance.

1. Introduction

In vibration energy harvesting, mechanical energy from ambient vibrations can be converted to electricity generally based on three basic conversion mechanisms, i.e., electromagnetic [1–5], piezoelectric [6–10], and electrostatic [11,12]. Compared to electromagnetic and electrostatic mechanisms, piezoelectric energy harvesting has received more attention in the existing research efforts based on a comprehensive literature review. There are numerous energy harvester schemes and devices, each developed for a variety of applications, as summarized in the review articles [10,13,14]. The device performance is conventionally evaluated by the power delivered to pure-resistive electrical loads, i.e., resistors. The effect of a pure-resistive electrical load on device dynamics is usually modeled as additional damping. Based on changes in device damping, device performance can be theoretically evaluated. It is noted that for piezoelectric devices such simplification of the effect of a pure-resistive electrical load is not unconditional [15]. It is valid for low-frequency excitations, i.e. the fundamental period of the excitation is much longer than the characteristic time constant determined by the capacitance of the piezoelectric device and the resistance. Furthermore, because of the qualitative difference between non-resistive and resistive components, results obtained from pure-resistive electrical loads cannot be generalized for applications

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https://doi.org/10.1016/j.ymssp.2018.04.015

involving non-resistive ones, e.g., those containing rectifiers and capacitors, which are essential for the desired functions of many circuits.

Electrical loads containing non-resistive components have been considered in piezoelectric vibration energy harvesting [16–19]. Strategies of power conditioning and impedance matching have been proposed to optimize the overall performance of rectified piezoelectric devices [17,19–24]. In many studies, particularly those involving experimental investigations, relatively weak electromechanical coupling has been the case and thus the influences of the switching of the rectifier on the device dynamics are insignificant or can be ignored in some cases. Numerical examples of strong electromechanical coupling have been considered under the assumption of ideal diodes and a large regulating capacitance such that voltage output of the rectifier can be treated as a constant [25,26]. As diodes play a critical role in an AC-DC interface, variations in diode properties, e.g. the forward voltage drop, can alter the dynamics of the harvester, thereby affecting the energy harvesting performance. To the best knowledge of the authors, however, there has been no report in the literature focusing on the impact of the properties of such non-resistive components on the energy harvesting performance. Therefore, the goal of this study was to continue and expand the investigation into the performance impact of non-resistive components of the electrical load for piezoelectric energy harvesters. Focus was placed upon the regulating capacitance and forward voltage drops of the diodes in the rectifier. Three types of electrical loads were considered in this study, i.e., (I) a rectifier followed by a resistor, (II) a rectifier followed by a regulating capacitor and a resistor, and (III) a simple charging circuit consisting of a rectifier and a capacitor. A qualitative theoretical analysis was first carried out for each case, followed by a detailed numerical and experimental study, in which piezoelectric devices based on the PMN-PT material operating in the 31-mode were considered. The results show that such non-resistive components can dramatically affect the performance of a piezoelectric harvester with an effect qualitatively different than that on an electromagnetic harvester [27].

2. Theoretical analysis

While a piezoelectric material can be poled to provide different modes of electromechanical coupling, existing efforts in energy harvesting have been focused on the 31-mode, which is normally realized through transverse vibrations of a beam. Not as intensively studied, the 33-mode operation, realized through longitudinal vibrations, has also been considered for energy harvesting. It is noted that with proper mathematical modeling, the governing equations for the two modes are of the same format, therefore, the same model applies to both modes as long as proper parameters are used and the boundary conditions are correctly identified [15] Without loss of generality, consider a simple linear piezoelectric vibratory energy harvester, which is connected to an electrical load as shown in Fig. 1. The device can be a "stack type" operating in the 33-mode, or a commonly used bimorph cantilever beam operating in the 31-mode. If only the fundamental vibration mode is considered, the system equations for a harmonic base excitation can be written as [6,15]

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

$$C_p\dot{V}(t) + I(t) = -\kappa\dot{x}(t), \tag{1b}$$

where x denotes the displacement of the seismic mass m, c_m the linear mechanical damping coefficient, k the mechanical stiffness of the harvester or the short-circuit stiffness of the piezoelectric device, κ the electromechanical coupling coefficient, and $f(t) = -\alpha m A_e \cos\omega t$ in which $A_e = A\omega^2$ representing the amplitude of the base acceleration, and α is the correction factor [15]; $V(t), I(t)$, and C_p, represent the induced voltage, the current through the electrical load, and the capacitance of the piezoelectric element defined in the terms of the constrained permittivity [6], respectively. It is noted that some key parameters, such as the coupling coefficient κ and the capacitance C_p, are dependent on the geometry of the device. In this study, the cantilevered, prismatic beam structure with a rectangular cross section was considered. In-depth investigations of the geometrical dependence of the device parameters have been omitted in order to focus on the impact of non-resistive components of the electrical load.

In this study, the device performance is evaluated by multiple metrics, i.e., the response velocity amplitude $\dot{x}_{\text{amp}}$, the average power delivered to the load P_L, the average input power of the excitation P_f, and the coupling efficiency of the excitation η [28], defined as

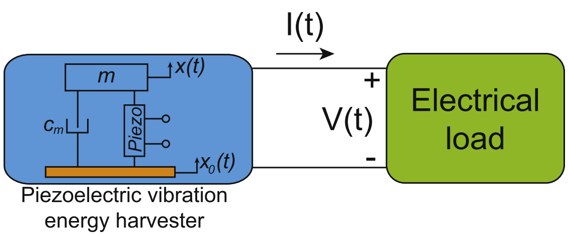

Fig. 1. Schematic diagram of a piezoelectric vibratory energy harvester with electrical load.