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Comparative methods to assess harmonic response of nonlinear piezoelectric energy harvesters interfaced with AC and DC circuits

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ABSTRACT

Nonlinear piezoelectric energy harvester (PEH) has been widely investigated during the past few years. Among the majority of these researches, a pure resistive load is used to evaluate power output. To power conventional electronics in practical application, the alternating current (AC) generated by nonlinear PEH needs to be transformed into a direct current (DC) and rectifying circuits are required to interface the device and electronic load. This paper aims at exploring the critical influences of AC and DC interface circuits on nonlinear PEH. As a representative nonlinear PEH, we fabricate and evaluate a monostable PEH in terms of generated power and useful operating bandwidth when it is connected to AC and DC interface circuits. Firstly, the harmonic balance analysis and equivalent circuit representation method are utilized to tackle the modeling of nonlinear energy harvesters connected to AC and DC interface circuits. The performances of the monostable PEH connected to these interface circuits are then analyzed and compared, focusing on the influences of the varying load, excitation and electromechanical coupling strength on the nonlinear dynamics, bandwidth and harvested power. Subsequently, the behaviors of the monostable PEH with AC and DC interface circuits are verified by experiment. Results indicate that both AC and DC interface circuits have a peculiar influence on the power peak shifting and operational bandwidth of the monostable PEH, which is quite different from that on the linear PEH.

1. Introduction

Recently, researchers have been searching alternatives to harvest vibration energy in environment to provide a green power supply for small devices. To enlarge the operational bandwidth and improve the output power, nonlinear dynamics [1–4] have been widely introduced in the piezoelectric energy harvesters (PEH). Nonlinear systems such as Duffing-type PEH have been widely investigated and shown significant improvements in bandwidth and harvested power [5–8]. The main superiority of these nonlinear PEHs as compared to the linear PEH is the existence of high-energy oscillations in a wide frequency bandwidth [9]. When the nonlinear PEH surfs on the high-energy orbits, a huge output power enhancement can be

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achieved. Similar to these single degree of freedom (SDOF) nonlinear PEHs, the multi-DOF systems were added with the magnetic interaction induced nonlinearity to pursue a wide operational bandwidth recently. Two kinds of 2-DOF nonlinear PEHs have obtained preliminary results [10–15]. One is using the magnetic force to integrate two independent SDOF systems (such as cantilever piezoelectric beams), while the other is adding the magnets forces into a linear 2DOF PEH. Both configurations can be further designed into monostable [10], bistable [11,12] and even multistable. Results of the first configuration show that high-energy oscillations around the first and second resonances maintain a much wider operational bandwidth than that in SDOF nonlinear PEHs. Meanwhile, internal resonance and modal interactions [13,14,16,17] clearly observed in the second configurations have attracted great interests due to an energetic saturation vibration and enhanced energy transfer between modes that promote an exceptional wide-bandwidth harvesting performance.

Along with the abundant designs of nonlinear PEHs, the electric circuits for energy conversion and storage also received great attentions. In application, the alternating current generated by piezoelectric patches needs to be transformed into direct currents. Indeed, standard rectifying circuits (DC interface) are required to interface the PEH and electronic load in practice. Researchers have designed advanced nonlinear circuits, such as resistive impedance matching circuit [18] and parallel/series-SSHI (synchronized switch harvesting on inductor) [19,20], to improve the efficiency of energy harvesting. Hence, it is of great importance to understand the inherent relations between circuits and the dynamics of linear/nonlinear piezoelectric energy harvesters. Shu and Lien [21] investigated the optimal AC-DC power generation for a linear piezoelectric PEH. The trends in vibration, rectified voltage and average power observed in Ref. [25] are indeed very similar to those of AC circuit in Ref. [22]. As the resistance increases, there are two power peaks, one is close to the open circuit while the other is close to the short circuit when the electromechanical coupling coefficient is strong enough. Rupp et al. [23] developed a computational methodology based on harmonic balance method for accurate analysis of the interaction between linear piezoelectric PEHs and a nonlinear circuit with diodes. As the inherent relations between linear PEHs and standard rectifying circuits becoming clear, a few researches begin to explore the role of non-rectifying and rectifying circuits on the nonlinear PEHs. Liu et al. [24] evaluated a bistable PEH connected to DC and SSHI circuits and observed unique impacts from such advanced circuits upon the power generation outputs as compared to that by connecting an AC interface circuit. Yet, the comprehensive understanding of the influences of these rectifying circuits on the behaviours of nonlinear piezoelectric energy harvesters are still inadequate. Given the sensitivities of nonlinear PEH observed in the studies surveyed above, such as ability or inability to induce the high-energy oscillations, it is critical to identify the roles of the realistic rectifying circuits upon the dynamics of nonlinear PEHs.

Given these unknowns, a preliminary research focusing on the effect of load resistance on the dynamics of monostable PEH has been conducted by authors in Ref. [25]. It is observed in the simulations that the increase of resistance will result in an exceptional shift of power peak. In this work, we are motivated to further explore the effect of AC and DC interfaces circuits on the nonlinear dynamics of monostable PEH in a more generic scenario (various load resistances, excitations, electromechanical coupling strengths) and more importantly, ascertain the inherent mechanisms behind these interesting phenomena. First, we conduct harmonic balance analysis and equivalent circuit modeling (ECM) to predict performances of nonlinear PEH with AC and DC interface circuits. By using these methods, we are interested to figure out how the two circuits affect the nonlinear dynamics and how it in turn affects the performance of monostable PEH. The theoretical and simulation results are experimentally validated and reveal the similarities and differences in the trend of the resonant power peak shift against various load resistances in AC and DC interfaces and the sensitivity to excitation. Further analysis and simulation also unlock the influence of electromechanical coupling strength on the power output for both interface circuits.

2. Modeling

The schematic of the nonlinear piezoelectric energy harvester investigated in this paper is shown in Fig. 1. It is made of a piezoelectric bimorph cantilever with a tip mass. The tip mass carries a permanent magnet that interacts with another magnet held in the acrylic holder attached to the rig. The threaded acrylic holder is movable, thus the repulsive magnetic force between these two magnets can be adjusted by tuning the distance between the magnets. When the magnetic force is large enough to make the cantilever beam buckle, the system turns to be a bistable PEH. Otherwise, it is a monostable or quasi-linear PEH. The governing equations of this kind of nonlinear PEH can be written according to the fundamental, lowest-order mode of dynamic response using

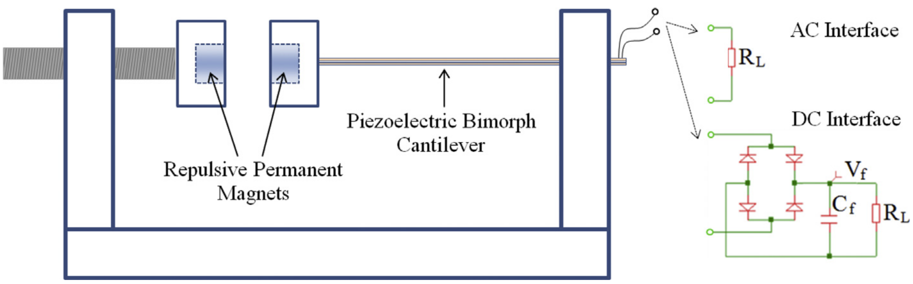

Fig. 1. Schematic of monostable PEH connected to AC or DC interface circuit.