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Piezoelectric energy harvester impedance matching using a piezoelectric transformer

Hamid Jabbar[a], Hyun Jun Jung[b], Nan Chen[c], Dae Heung Cho[a], Tae Hyun Sung[a,*]

[a] Department of Electrical Engineering, Hanyang University, Seoul 04763, Republic of Korea
[b] Department of Mechanical Engineering, University of Maryland Baltimore County, Baltimore, MD 21250, USA
[c] School of Computer Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

A R T I C L E I N F O

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A B S T R A C T

To harvest maximum power from a piezoelectric energy harvester requires conjugate impedance matching, consisting of both resistive and inductive load. In practical circuits, dc-dc converters working in discontinuous conduction mode are used for emulated resistive impedance matching. These converters contain a large and expensive electromagnetic component to reduce the wire conduction losses. A new approach toward piezoelectric energy harvester resistive impedance matching is presented by using a step-down piezoelectric transformer with a bi-directional inductor-less half-bridge circuit working under zero voltage switching conditions. The large and expensive magnetic transformer and inductor in previous works are replaced with a ceramic component with no electromagnetic interference. The presented technique can reduce the circuit size and the ceramic transformer can be manufactured on the harvester cantilever.

1. Introduction

Piezoelectric energy harvesting technology is derived from structural damping where piezoelectric material is used to suppress the mechanical vibrations in the structure by dissipating the energy in the electrical load circuit [1,2]. In a piezoelectric energy harvesting system, instead of dissipating the energy in the load circuit, it is utilized for useful work in different electrical and electronics applications.

Piezoelectric energy harvesters in the form of cantilevers beams are used for generating energy from the low frequency vibrating structures. At low vibration frequencies, the reactance part of the loosely coupled piezoelectric energy harvester (PEH) impedance is capacitive because its impedance phase is well below zero degrees. To harvest the maximum energy from the piezoelectric material, conjugate impedance matching comprising of both resistive and inductive load components is required where the purpose of the inductor is to match the piezoelectric material inherent capacitance [3].

To estimate the energy available from the PEH, researchers utilize the passive electrical components such as resistor and inductor to find the relationship between the vibration frequencies, power generated and optimum load. The high value of the inductor is required to match the inherent piezoelectric capacitance; therefore, usually, the PEH is tested with the resistive load only. Also, as the real part of the PEH impedance increases between the fundamental resonance and anti-resonance frequencies of the harvesting system, the resistive impedance matching technique becomes feasible [4]. Using the resistive impedance matching allows for maximum power transfer when the resistive load impedance matches the modulus of the PEH equivalent output impedance [4].

In practical circuits, to transfer the optimum power from the piezoelectric energy harvester to the application load requires voltage rectification, resistive impedance matching, and voltage level converter circuits as shown in Fig. 1. For resistive impedance matching converter, the discontinuous conduction mode (DCM) dc-dc converters whose input emulates a resistor (R_e), such as a buck, boost, flyback, or buck-boost, can be used [4,5].

In the DCM dc-dc converters, considering the ideal components, neglecting the small ripple, the relationship between the emulated resistance, inductance, switching frequency, and duty-cycle can be easily obtained [6]. As the V_{rect} is the rectified dc input voltage of the DCM dc-dc converter in Fig. 1, the power is drawn by the dc-dc converter from the source is obtained by multiplying V_{rect}

* Correspondence to: 402, HIT, 222 Wangsimni-ro, Seongdong-Gu, Seoul, 04763, Republic of Korea.
E-mail addresses: jabbar81@hanyang.ac.kr (H. Jabbar), jung87@umbc.edu (H.J. Jung), nanchen0929@gmail.com (N. Chen), wheogmd7@naver.com (D.H. Cho), sungth@hanyang.ac.kr (T.H. Sung).

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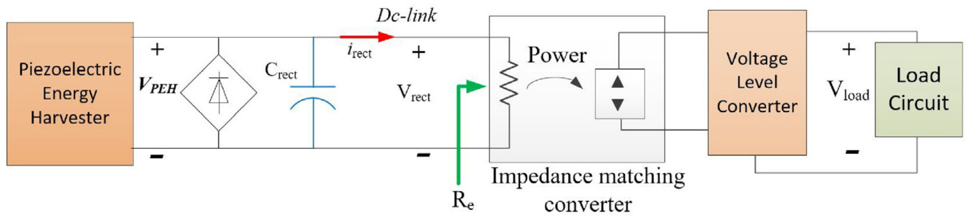

Fig. 1. A typical system for impedance matching and power conversion from a piezoelectric energy harvester.

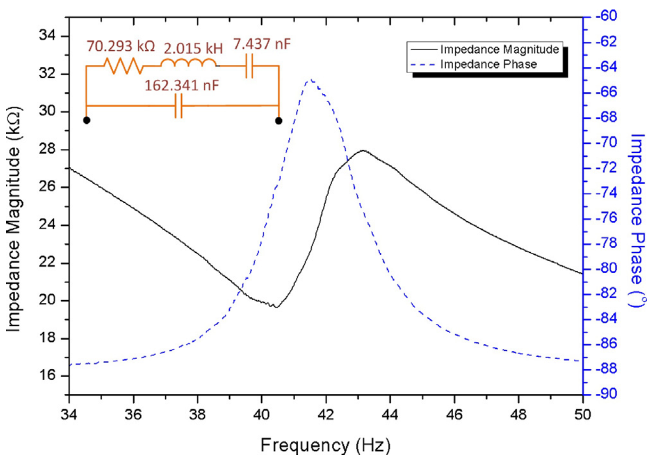

Fig. 2. Piezoelectric energy harvester impedance magnitude and phase along with its equivalent circuit.

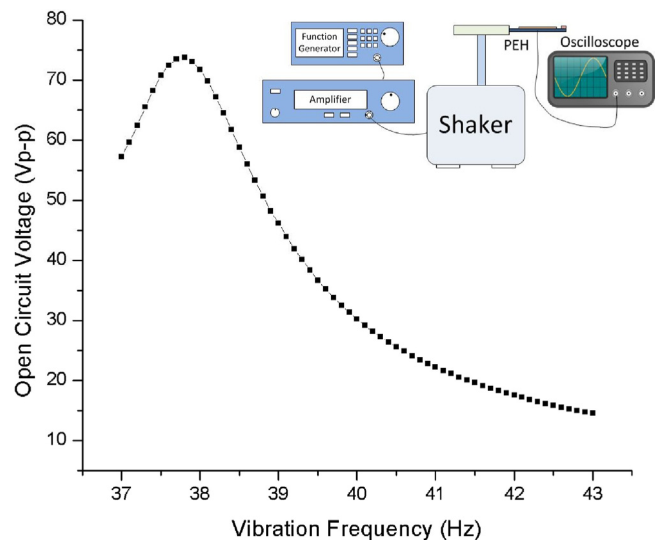

Fig. 3. Piezoelectric energy harvesting open circuit voltage with the experimental setup.

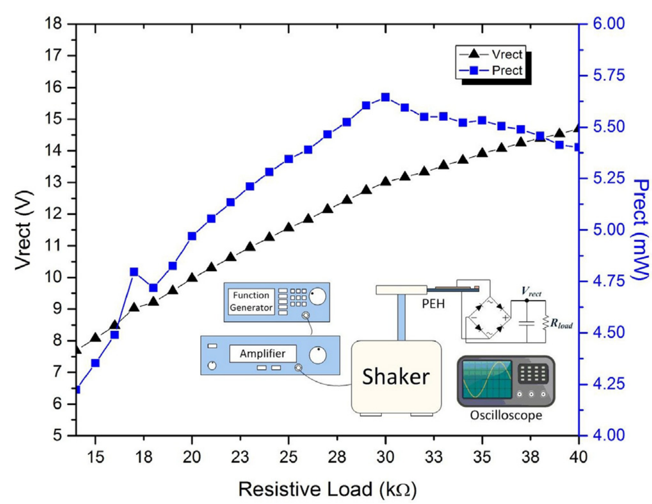

Fig. 4. Piezoelectric energy harvester rectified voltage and power harvested under different resistive loads.

with the average value of the pulsating dc-link current i_{rect}. Therefore, a dc-dc converter that can be controlled to change the dc-link voltage and current will be seen as an effective load resistance to the piezoelectric energy harvester. In real world applications, the vibration amplitude and frequency can change requiring an adaptive control circuit to operate the impedance matching converter at the optimum point with varying input conditions [5,7,8]. These control system needs to have simple control technique with low power consumption.

In [5], the DCM flyback converter and in [4], the DCM buck-boost converter is used for resistive impedance matching. The switching frequency in the DCM dc-dc converter is kept low to reduce the switching losses. To reduce the wire resistance losses in the magnetic components of these converters, thicker wires are used which results in large size inductor and transformer. When designing the harvesting circuit, a trade-off is reached between the switching frequency, switching losses and the magnetic component size [4,5,9,10].

The alternate of a large inductive component in DCM dc-dc converters can be a piezoelectric material working in its resonance frequency range. In this range, the piezoelectric material exhibits inductive behavior. This principle is utilized in the piezoelectric transformer (PT), whose input has a complex inductive impedance which allows power to be transferred to an isolated application load [11]. Also, the piezoelectric transformer can be manufactured on the same substrate as the piezoelectric energy harvester, thus reducing the size of the electrical circuit. In [12], the PT was used in a power converter for driving piezoelectric actuators. In [13] the PT output was used for impedance matching with a piezoelectric transducer. Usually, the piezoelectric transformer output impedance matching with its application-specific load is discussed. But in this paper, we try to match the piezoelectric energy harvester output impedance with the input impedance of the piezoelectric transformer and its driving circuit.

In this paper, a piezoelectric transformer (PT) based switching converter is used for performing the impedance matching and to step-down the voltage of piezoelectric energy harvester, simultaneously transferring the harvested power to the isolated load without any electromagnetic interference (EMI). To operate the PT at its resonance frequency, an inductor-less half bridge driving circuit operating at zero voltage switching (ZVS) condition is used without any inductive component. The switching frequency and duty-cyle of the converter can be controlled so that the dc-link voltage and current can be varied and the converter can act as a varying emulated resistive impedance load to the piezoelectric energy har-