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A study of electromagnetic vibration energy harvesters with different interface circuits

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ABSTRACT

A dimensionless analysis of piezoelectric vibration energy harvester was conducted in the previous work where the harvested power and energy harvesting efficiency were normalised and determined from two non-dimensional variables of resistance and force factor. This paper has developed a dimensionless analysis of an electromagnetic vibration energy harvester where the harvested power and energy harvesting efficiency are normalised and determined from two similar non-dimensional variables of resistance and equivalent force factor. The harvested power and efficiency are compared for the electromagnetic harvester with different interface circuits. The aim is to disclose some similarity and limitations of the piezoelectric and electromagnetic harvesters in a dimensionless scale.

1. Introduction

Electromagnetic vibration energy harvester (EMVEH) with an interface circuit converts vibration energy of a structure into usable electrical energy, which is an attractive renewable energy source. In addition to the energy generation apparatuses, interface circuits are indispensable elements in these energy harvesting systems to control and regulate the flows of energy. Previously, piezoelectric vibration energy harvesters with different electric energy extraction and storage interface circuits were studied to enhance the power outputs of energy harvesters as listed in Table 1, including dimensionless and normalised harvested power studies [2–5,13,18,20,24,30,31,38–41,43–46,47], energy efficiency investigations [4,39,43,47], single load resistor interface circuit [4,5,8,11,13,21,22,26,31–33,37–39,41–44,47], standard interface circuit [6,7,16,18,24,38–40,43–45], synchronous electric charge extraction (SECE) interface circuit [2,18,43], series or parallel "synchronous switch harvesting on inductor" (SSHI) circuits [18,24,40,43,44]. Electromagnetic vibration energy harvesters were studied [1–3,6–15,19,20,23,25–35,36,48,49], including those connected with synchronized magnetic flux extraction (SMFE) circuit or other RLC circuits [42,17,22,46,2,34,35,3,15,19,49]. Most of these research papers have discussed optimizations of harvested power of piezoelectric vibration energy harvesters (PVEHs) while dimensionless optimisation of harvested power and energy harvesting efficiency of electromagnetic vibration energy harvesters have only been addressed in limited works.

In these aforementioned works, none has simultaneously normalised and optimised both "harvested resonant power" and "energy harvesting efficiency". Furthermore, none has used the normalised resistance and normalised force factor in their analyses for optimised harvested resonant power and energy harvesting efficiency. Previously, most reports focus on optimised power generation related only to electrical components. This work adds the mechanical components in the

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Nomenclature

B	magnetic field density value or magnetic field strength
l	the length of the coil in the electromagnetic generator
D	short circuit mechanical damping of the single degree of freedom system
e	2.718281828
F	excitation force
F_M	magnitude of the excitation force
$\|F\|$	magnitude of the excitation force
f_n	natural frequency
i	square root of -1
I	current in the circuit
K	short circuit stiffness of the single degree of freedom (SDOF) system
L_e	self inductance of the coil
M	oscillator mass of the single degree of freedom system
P_h	harvested power
P_{in}	input power
$\frac{P_h}{((M^2\|\ddot{y}\|^2)/D)}$	dimensionless resonant harvested power
$\frac{P_{h\ max}}{((M^2\|\ddot{y}\|^2)/D)}$	peak dimensionless resonant harvested power
s	Laplace variable
T	Period of the excitation force signal
V	output voltage of the SDOF system
V_M	output voltage amplitude of the SDOF system
$\|V\|$	modulus or amplitude of the output voltage
y	base excitation displacement
$\dot{y}$	base excitation velocity
$\ddot{y}$	base excitation acceleration
Y_M	base excitation displacement amplitude
z	relative displacement of the mass with respect to the base
$\dot{z}$	relative velocity of the mass with respect to the base
$\ddot{z}$	relative acceleration of the mass with respect to the base
$\|z\|$	amplitude of the relative displacement
z_M	relative displacement amplitude of the mass with respect to the base
α_N	normalised equivalent force factor
η	resonant energy harvesting efficiency
η_{max}	maximum resonant energy harvesting efficiency
ξ	mechanical damping ratio
ω	excitation frequency
π	3.1415928
φ	delay phase angle of the response displacement to the excitation force

Subscripts

C	damping dissipated
e	extracted vibration energy
eq	equivalent
h	harvested energy
in	input
M	magnitude
max	maximum value
m	after the inversion process
N	normalised

Superscripts

-1	inverse
S	clamped
*	complex conjugate
—	time average
.	the first differential
..	second differential

Special function

$\langle\ \rangle$	time averaged
$\|\ \|$	modulus or absolute value

Abbreviations

N/A	not available
SDOF	single degree of freedom
SL	single load

Figure legends

SL Freq	simulated results of the single degree of freedom harvester connected to a single load using frequency analysis

analyses by using the equivalent force factor as an optimisation element as both electrical and mechanical components are critically related to the harvested resonant power and efficiency. Since the normalised energy harvesting efficiency provides important design guidelines for vibration-based energy harvesting systems, dimensionless analyses and optimisations are the focuses of this work.

Researchers have been seeking optimisation design methods to maximise the harvested energy. For example, Cepnik et al. [8] optimised electromagnetic energy harvesters through direct computation of the electromagnetic coupling and indicated that the maximum possible efficiency of the vibration energy harvesters is 50%. Elvin and Elvin [13] pointed out that the maximum harvested power of an electromagnetic vibration harvester would not be larger than the one-eighth of the maximum input power. Elvin and Elvin [13] studied the effect of coupling coefficient and parasitic tuning ratio on the

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