Wearable generator with rotating oscillating mass

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Abstract. This paper reports the design, fabrication, and testing of a rotating, oscillating mass electromagnetic generator for wearable applications. This work presents a custom design architecture to evaluate the differences in generation output for swinging motion when driven at different frequencies, and load conditions. Body movement is characterized by large amplitude motion, such as the limbs when walking, whereas machine vibration displacement is relatively small and well catered with linear energy harvesters. The proposed study evaluates a rotational generator mounted on a swinging arm driven by a sinusoidal input motion to determine the parameters that lead to higher power output. Power measurement up to 0.25 μW was generated under sinusoidal input motion.

1. Introduction

Modern electronics are more ubiquitous and larger batteries are required to power them for longer periods of time. Energy harvesting from the surrounding in an inconspicuous way may help to alleviate this need. Employing a pendulum-driven architecture for portable energy generators has the advantage of reducing the traditional bulky electromagnetic generator footprint into a planar device. In addition, the generator presented here, a pendulum-based generator, can be implemented with low cost of manufacturing and simple assembly processes.

This work reports the design, fabrication, and testing of a rotating, oscillating mass electromagnetic generator for wearable applications. A custom design architecture is presented to evaluate the differences in generation output for swinging motion when driven at different frequencies, arm lengths, and load conditions. Body movement is characterized by large amplitude motion, such as the limbs when walking, whereas machine vibration displacement is relatively small and well catered with linear energy harvesters [1]. Rotational devices have the benefit of unlimited rotations when the conditions are optimal for this operation [2, 3]. This topology of kinetic generators follows the steps of the self-winding wristwatches. The proposed study evaluates a rotational generator mounted on a swing arm driven by a sinusoidal input motion to determine the parameters that lead to constant rotations. Self-excited rotations, or multiple rotations on the generator produce higher power output than a swinging generator as documented initially by [4]. The latest research evaluates architectures for wrist-worn energy harvesting [5], it shows a rotational structure that outperforms a linear architecture.
2. Pendulum Model

The energy \( E \) of a pendulum with a mass \( m \) at a distance \( l \) from the pivot that moves horizontally with a known function \( x(t) \overrightarrow{i} + y(t) \overrightarrow{j} \) can be represented in terms of the kinetic and potential energy by Eq. (1)

\[
E = \frac{1}{2} m l^2 \dot{\theta}^2 - mgl \cos \theta + \frac{1}{2} m(\dot{x}^2 + \dot{y}^2) + m l \dot{\theta} (\dot{x} \cos \theta - \dot{y} \sin \theta) - mgy
\]  

(1)

Where measuring the relative angular displacement for an accurate representation of the induced voltage on the generator is more practical than using the fixed coordinate values. The damping terms for the energy extraction processes are not included in Eq. (1). Thus, the average power \( P_{\text{avg}} \) that goes into an electrical damping system (generator) with damping constant \( b \) over a time \( T \) can be better determined as

\[
P_{\text{avg}} = \frac{1}{T} \int_0^T b \dot{\theta}^2 \, dt
\]

where the electrical power \( P_L \) can also be found measuring the voltage, the internal resistance \( R_i \) and electrical load \( R_L \) as presented by Eq. (2).

\[
P_L = \left( \frac{V}{R_i + R_L} \right)^2 R_L
\]  

(2)

3. Manufacturing

The pendulum-based generator design is comprised of a stator composed of photolithography fabricated coils on a flexible substrate. The rotor consisted of a multiple pole permanent magnet (PM) arrangement with small commercial magnets (1.1 mm x 1.1 mm x 5.1 mm).

The stator consists of multiple flexible copper-clad polyimide layers (18 \( \mu \)m thick copper on top of 20 \( \mu \)m thick polyimide) for a multi-stacked design (one layer stacked on top of the other). The coil consisted of multiple copper-track windings (100 \( \mu \)m linewidth) with a 10-pole arrangement. The 2-layers coil evaluated in this work had 15 \( \Omega \) of internal resistance. The copper-clad polyimide coil was manufactured using photolithography techniques and chemically attached using with ferric chloride etching, as described in Fig. 1. Fig. 2 shows the uniform and smooth vertical walls obtained using this chemical etching. Whereas Fig. 3 presents the photo of the tested generator used in this project.

The rotor is composed of a PMMA machined disk with encased miniature NdFeB permanent magnets material. The PMs are placed in alternating positions for a multi-pole magnetic arrangement (a total of 10 poles were tested) with an eccentric annular bronze mass. Only two sets of coils and one 2.5 cm in diameter PM rotor were used with the eccentric mass. The setup was finalized with a small shaft and assembled with low friction jewel bearings.

\[\text{Figure 1. Photolithography steps}\]
Once assembled, the generator was placed at the end of a pendulum arm driven with horizontal periodic motion. The linear sliding mechanism testbed is shown in Fig. 4. Driving frequencies of 1 Hz and 2 Hz, different placements for the arm lengths (38 mm, 165 mm, and 330 mm) and varied resistance loads (15 Ω, 75 Ω, 165 Ω, and 330 Ω) were evaluated.

Commercial data acquisition equipment (National Instruments Corp.) and software (LabVIEW) were used for the data recording. A custom driving platform was created with Fused Deposition Modeling (FDM) components, and off the shelf electronics.

**4. Results**

Fig. 5 shows a typical voltage output under these conditions. The 38 mm pendulum arm length placement has a natural frequency close to that of the generator, while the 165 mm and the 330 mm are fractions of the natural frequency.

Fig. 6 shows the output voltages under the different testing configurations. Fig. 7 presents the power output under the varied settings, where the matching load shows a higher power output as expected. Although not surprisingly, higher driving frequencies produce a higher voltage output, however, there are instances where the right configuration can produce a significant output (1 Hz at 38 mm arm length vs. 2 Hz at 165 mm arm length). The presence of harmonics in this preliminary investigation may explain this behavior. Based on the recorded oscillations periods, self-excited rotations were not observed.
Figure 4. Experimental setup with custom driving mechanism.

Figure 5. Voltage induced for 75Ω load at the shortest arm length and 2Hz of driving frequency

Figure 6. RMS voltages output under the different testing configurations.
5. Conclusions
An experimental evaluation under sinusoidal driving motion was developed for a custom-designed generator. The preliminary results show that under some combinations of parameters (frequency and placement in the evaluated cases) power can be highly increased.

Further work is needed to establish the parameters that help to promote self-excited rotations since they were not observed in this preliminary study. More winding (more stacked stators) induces more voltage and created more electrical damping which needs to be evaluated further as well.

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