

## CONTINUOUSLY ROTATING ENERGY HARVESTER WITH IMPROVED POWER DENSITY

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**Abstract:** In this paper, we present and demonstrate a rotational energy harvesting generator and a method to improve its power density at low operational speeds. The electro-mechanical behavior of the generator is described using direct current (DC) motor theory. Reported results from a previously designed and tested maximum power point tracking (MPPT) circuit are discussed. The effects of imposing a current limit to continuously obtain maximum power transfer from the generator to a load will also be shown. Lastly, off-axis experimental results are presented to illustrate the variation of power generation at different offset distances.

**Key words:** energy harvesting, rotational generator, maximum power point tracking, double pendulum

### 1. INTRODUCTION

Motion-driven energy harvesters are widely researched [1], and are beginning to be exploited commercially. Most of the devices reported are inertial, relying on the relative displacement of a proof mass and the frame from which it is suspended to drive the transduction mechanism [2]. The source motion is typically linear, but rotational motion can also be exploited [3], as in self-powered wrist-watches [4]. In either case, however, the source motion is oscillatory in nature, in order to have the acceleration required to produce forces against the inertial mass. It would be useful in a number of applications, such as machine monitoring, to power an energy harvester directly from continuous rotating motion. This concept was previously introduced by us in [5], using direct current (DC) motors to assemble a prototype.

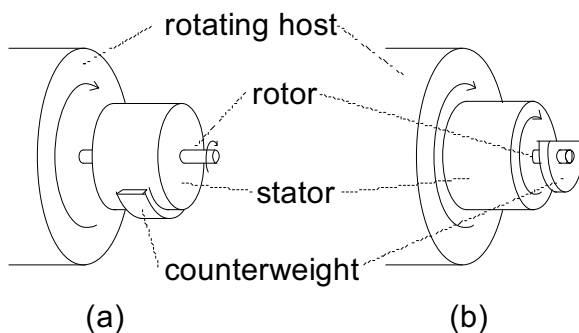


Fig. 1: Possible implementations of the gravitational torque rotating energy harvester – (a) rotation of the rotor, with an offset mass on the stator; and (b) rotation of the stator with an offset mass on the rotor.

This method retains the single-point-of-attachment advantage of inertial harvesters, but obtains the counterforce from gravity, rather than inertia, using an eccentric mass attached to the stator (or rotor) of a

conventional rotating generator (Fig. 1), with the rotor (or stator) being fixed to the rotating source.

Fig. 2 shows a schematic of the gravitational torque generator [5]. Here, the rotor is driven directly from the rotation of the host, and an offset mass is attached to the stator at a distance  $L$  from the axis of rotation.

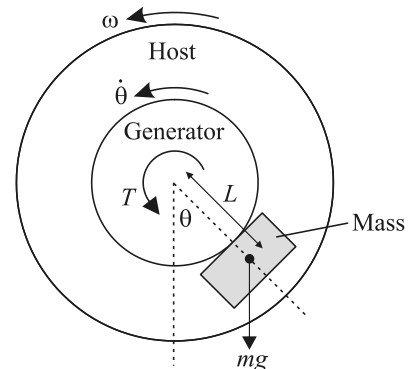


Fig. 2: Schematic of the gravitational torque generator.

As the rotor rotates, the mass will be deflected by an angle  $\theta$  in the direction of rotation, resulting in a gravitational torque,  $T_g = mgL \sin(\theta)$  pulling the mass downwards. For a fixed rate of rotation, the mass will be stable at an angle  $\theta$  such that  $T_g$  equals the motor torque  $T_m$ . With the mass stable, the internal generator velocity will equal the host velocity  $\omega$ . If, however,  $T_m$  exceeds the maximum gravitational torque  $mgL$ , the mass will flip over, and continue to rotate along with the rotor, and consequently the power output will drop.

The motor torque is given by

$$T_m = K_E I_A \quad (1)$$

where  $K_E$  is the motor constant and  $I_A$  is the armature current in the rotor.

Maximum load power is obtained when an impedance match is achieved between the armature

resistance,  $R_A$  and the load resistance,  $R_L$ . With the assumption that  $T_m < mgL$ , the output electrical power is then given by

$$P_{elec} = \frac{(K_E \omega)^2}{4R_L} \quad (2)$$

Experimental results reported in [5] confirmed that maximum power was obtained when the load was matched to the armature resistance. Also, the mass had a higher tendency to flip over at lower load resistances, because of higher armature currents leading to an increase in motor torque.

## 2. USE OF GEARBOXES

There are limitations to the amount of power that is harvested when the generator is operating at low speeds because the output power is proportional to  $\omega$ . This suggests that attaching a gearbox to up-convert the source rotation speed would be beneficial. However, installing a conventional gearbox between the host structure and the generator will not necessarily provide any benefit, as the maintenance of a gearing ratio between the input and output axle speeds normally depends on the gearbox housing being prevented from rotation. In energy harvesting applications, the gearbox cannot be mounted to a fixed object.

Instead, we have adopted the gravitational torque approach also to limit the gearbox motion. One possibility is shown schematically in Fig. 3. Here an additional offset mass, or counter-weight, is attached to the gearbox housing to impede its rotation.

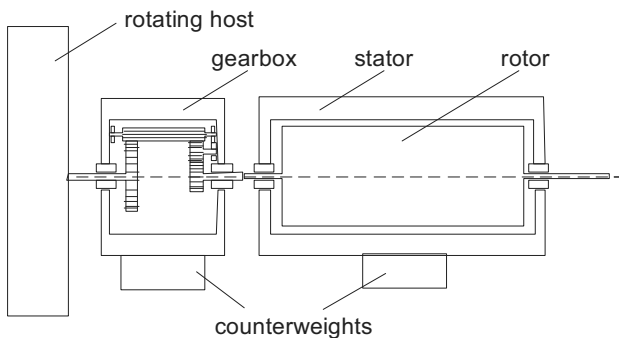


Fig. 3: Schematic description of a gearbox attachment between the rotation source and rotational generator.

## 3. EXPERIMENTAL RESULTS

Fig. 4 shows the experimental setup including a gearbox to up-convert the rotation speed. In this prototype, the gearbox is fixed to the chassis of the generator. Consequently, a single counterweight can

be used to prevent the rotation of both the stator and the gearbox housing. The total volume of generator plus gearbox was  $29 \text{ cm}^3$ .

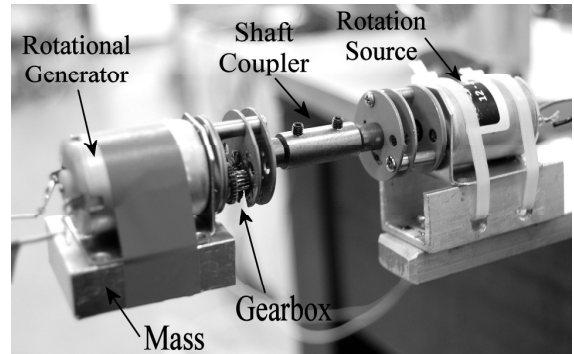


Fig. 4: Setup with gearbox attached to the rotational generator.

Fig. 5 shows the greatly increased output power when using a 15:1 gear ratio to up-convert the rotation speed. Output power above 50 mW was achieved with a host rotation rate of only 118 RPM.

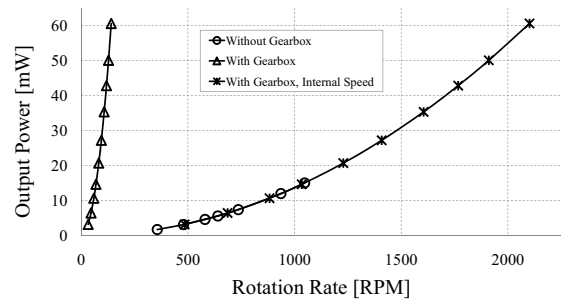


Fig. 5: Comparison of output power vs. rotation rate for harvester with and without a gearbox to up-convert low speeds.

In principle, this suggests that the power density can be arbitrarily increased by increasing the gear ratio. In practice, however, limits exist, since both gearbox size and internal friction increase with increasing gear ratios.

## 4. MAXIMUM POWER POINT TRACKING

If the maximum motor torque limit is not reached, power is maximised for a load impedance equal to the armature resistance. A maximum power point tracking converter was previously developed [6] which achieves such an input impedance for a wide range of generator speeds, while when combined with other power processing circuitry, provides constant output voltage and stores excess energy in a capacitor. A Boost converter was chosen to implement the impedance match, by changing its duty cycle,  $\delta$ , according to the equation below:

$$R_{IN} = R_{OUT} (1 - \delta)^2 \quad (3)$$

Here,  $R_{IN}$  is the load presented to the generator and will be matched to  $R_A$ . Fig. 6 shows the circuit schematic which was built and tested. A PIC microcontroller was chosen to implement the control loops necessary to perform impedance matching. A more detailed description of this circuit and its experimental results were reported in [6]. The experimental results obtained showed successful matching of the Boost converter's input impedance to the armature resistance during constant and varying generator speeds. Additionally, the output voltage was regulated at 3.3 V throughout the experiment.

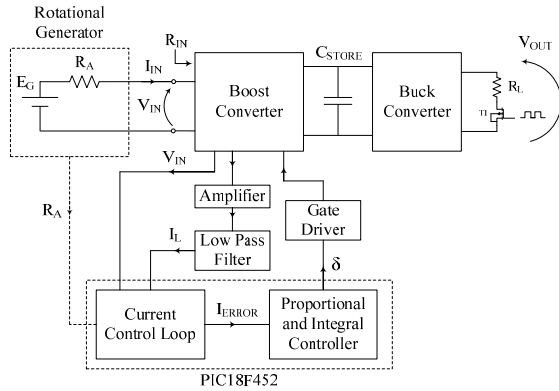


Fig. 6: Schematic of the power processing circuitry.

Currently, the prototype makes use of a DC motor as a generator. Whilst the use of a DC generator provides an easy interface for impedance matching, this does raise one notable reliability issue – brush life on the DC motor. A brush life of approximately 7500 hours can be expected from the average DC motor when used within its rated capacity [7]. This is unlikely to be suitable for many monitoring situations where energy harvesters would be deployed.

One probable solution is to use a brushless DC motor or a small synchronous machine. However, this results in the generator producing trapezoidal or sinusoidal 3-phase outputs which will require rectification from a 3-phase diode bridge as part of the maximum power point tracking circuit.

## 5. CURRENT LIMIT EFFECTS

Above some  $\omega_m$  (Fig. 7) a matched load will cause the maximum motor torque to be exceeded, at which point the optimal regulation strategy is to limit the armature current to maintain  $T_m < mgL$ .

The generator and power converter will no longer be impedance matched once the current limit is enforced. However, the mass will still be held at a position where  $\theta \approx 90^\circ$ .

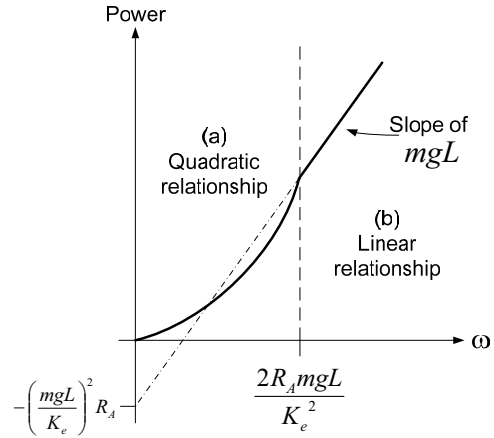


Fig. 7: Two regions of operation defined by (a) impedance match and (b) current limit.

Essentially, before the current limit,

$$P_{out}(\omega) = R_L \left( \frac{K_E \omega}{R_A + R_L} \right)^2 \quad (4)$$

After the current limit,

$$P_{out}(\omega) = mgL\omega - R_A \left( \frac{mgL}{K_E} \right)^2 \quad (5)$$

In Eq. 5, the output power is taken to be the power generated from the rotation ( $mgL\omega$ ), net of the power dissipated in the armature resistance. This indicates a linear relationship between  $P_{out}$  and  $\omega$ . Power is further maximised if a high gear ratio is used to reach  $\omega_m$  at the generator at the lowest possible host frequency.

## 6. OFF-AXIS POWER GENERATION

There might be situations where it is preferable to mount the rotational generator off the axis of rotation, causing the generator to behave like a double pendulum [5]. The test bench in Fig. 8 confirmed the Simulink predictions of [6] – bigger offset distances result in a reduction of generated power.

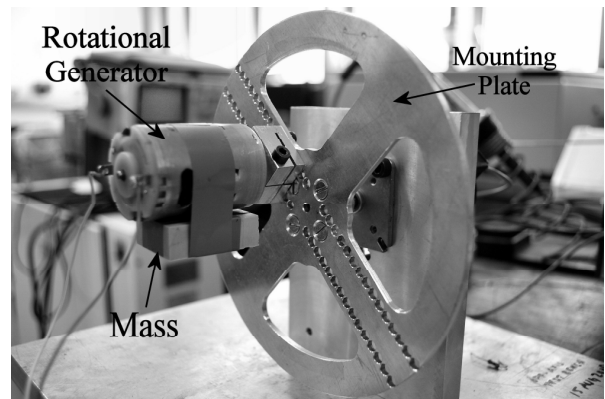


Fig. 8: Off-axis test bench.

Although the output power is unchanged at low host speeds, the maximum speed for effective generation (limited by the flip over condition) is greatly reduced in the off-axis case. For an armature resistance of  $\approx 1.5 \Omega$ , the generator provided the most output power when impedance matched and at zero offset distance (Fig. 9). In addition, the generator has a higher tendency to flip over when mounted off-axis or when too much armature current flows. The generated power also shows a square law dependency on rotation speed.

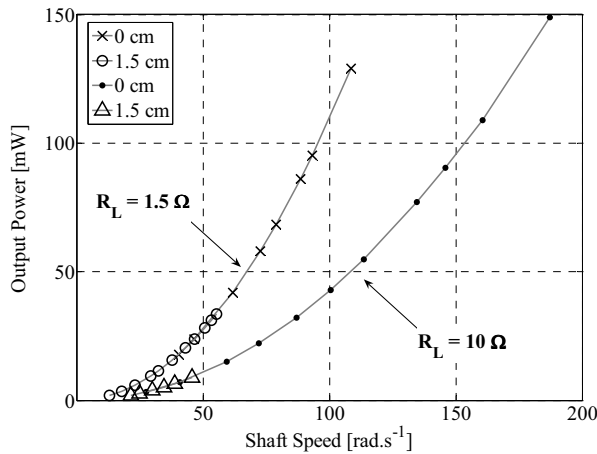


Fig. 9: Off-axis results when  $R_L = 1.5 \Omega$  and  $10 \Omega$ . Legend indicates the offset distances from the axis of rotation.

## 7. CONCLUSION

Attaching a gearbox between the generator and source increases the power output of the energy harvester proportionally to the gear ratio squared, if the maximum motor torque is not exceeded. This overcomes the limitations of low speed operation. The power processing circuitry successfully implemented an impedance match between generator and load, and also provided output voltage regulation, as is necessary for device interfacing. Imposing a limit on the armature current changes the dependency of power on rotation speed. This condition is necessary to continuously transfer power optimally from the generator to a load. Off-axis performance depends largely on the offset distance and due to its chaotic behavior, it will be necessary to design a control mechanism for optimum power generation.

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