Investigation of a Multi-Rotor Triboelectric Nanogenerator using a Modular Flexible Circuit Board Stack

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Photo from iStock-627281636

Contents

Introduction

POWERING the BLUE ECONOMY

- Govt. commissioned study “Powering the Blue Economy” (Water Power Technologies Office 2019).
- Emerging “blue economy” applications requiring power at sea to:
  - Extend mission time and sensor payload (Green et al. 2019)
  - Reduce deployment and retrieval costs
  - Operate in remote and extreme environments (Branch et al. 2022).
- Target: Low-power ocean observation applications.

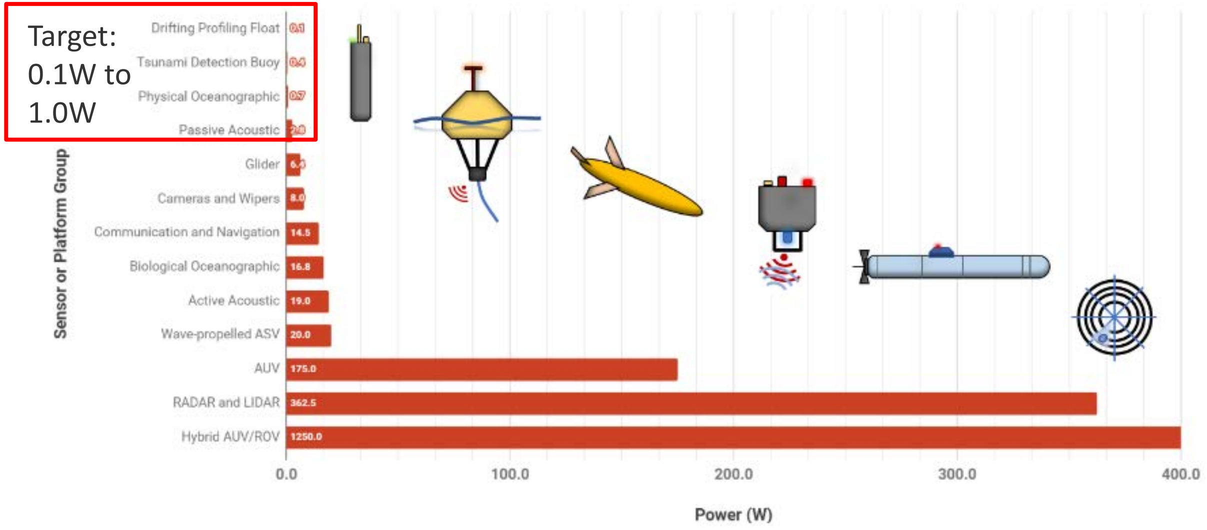
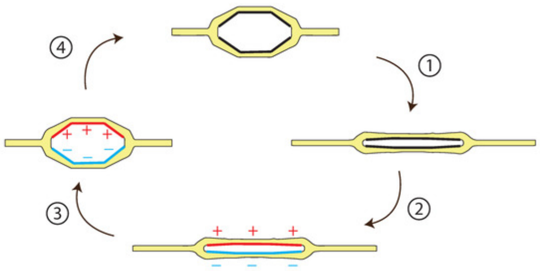


Figure from Green et al. (2019)

Introduction

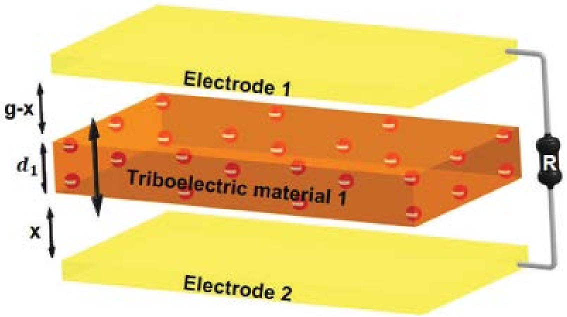
- Appetite for non-conventional energy harvesting technologies.
- Several research streams at the National Renewable Energy Laboratory.
  - Thermomagnetic generators (Kishore et al. 2019)
  - Piezoelectric materials (Mendoza et al. 2023)
  - Variable capacitance hyperelastic transducers (Niffenegger and Boren 2023).
- Triboelectric Nanogenerators show promise in wave energy harvesting field.



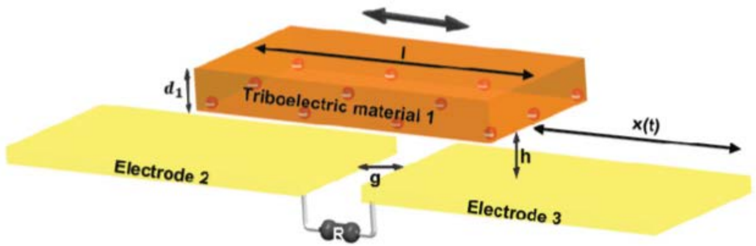
Hexagonal Distributed Embedded Energy Converter "hexDEEC" (Niffenegger and Boren 2023)

Triboelectric Nanogenerators

- Triboelectric nanogenerators (TENGs) are a nascent class of energy harvesters that produce electricity by the contact-separation of a triboelectric material and an electrode layer.



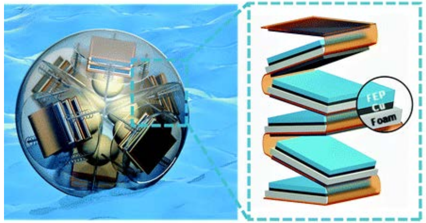
Contact separation mode of TENGs (Rodrigues 2019)



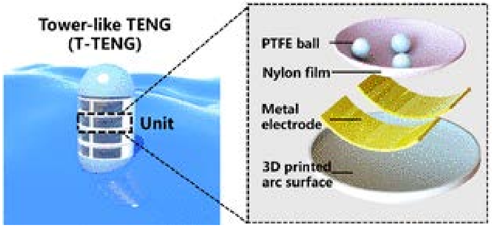
Sliding mode of TENGs (Rodrigues 2019)

Literature Review

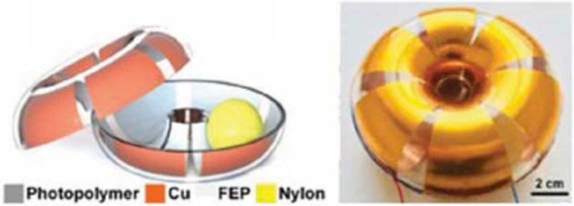
- Survey of wave energy conversion methods using TENG.
  - Major issue identified: many devices rely on single wave–single excitation, despite wave frequency being very low.



Spherical TENG (Liang et al. 2020)



Tower TENG (Xu et al. 2019)



Torus TENG (Liu et al. 2019)

- Solution: Using a **frequency multiplier device** to increase the number of excitations per wave.

Corn Popper (source: Fisher-Price)

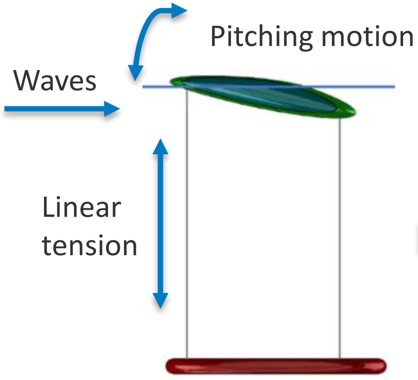
Salad Spinner (source: Bon-Appetit)

- Selected rotational TENG to increase frequency of excitation.

Envisioned WEC Integration

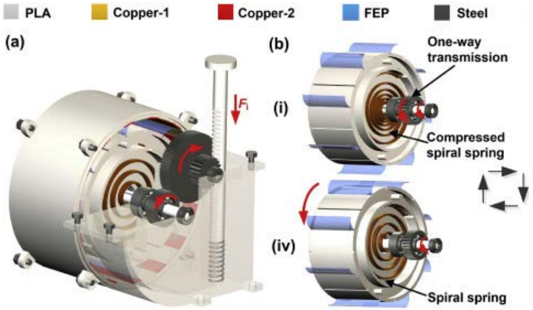
- Wave energy converter (WEC): Two-body device consisting of heave plate connected to pitching body.

- Power Take-Off (PTO): Linear to rotational gearbox to flywheel and rotary generator.



Two-body pitching WEC by Tom et al. (2023)

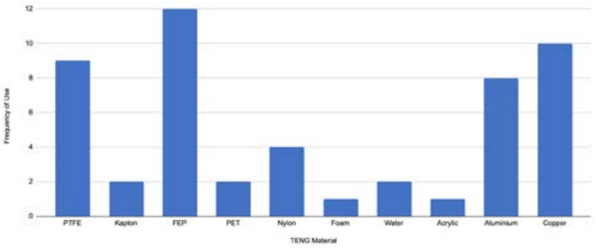
Salad Spinner (source: Bon-Appetit)



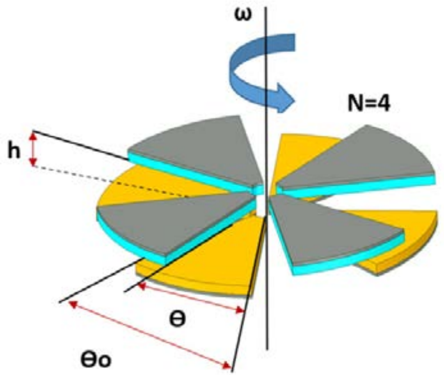
Flywheel and spiral spring TENG (Yang 2019)

Methodology – Design Study

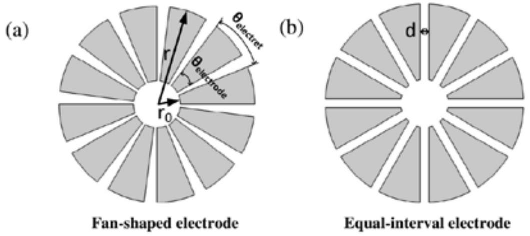
- Investigated the factors driving power output of TENGs.
  - Surveyed literature for material use. Selected FEP, Copper.
  - Investigated axial generator design. Looked at geometry, electrode layout.



*Materials surveyed – Polytetrafluoroethylene (PTFE), Kapton, **Fluorinated Ethylene Propylene (FEP)**, Polyethylene Terephthalate (PET), Nylon, Foam, Water, Acrylic, Aluminium, **Copper.** Source: C. Kenny NREL*



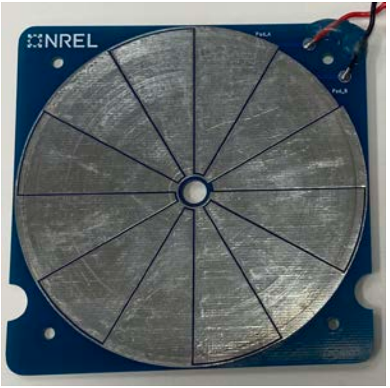
Rotational generator where ω = angular speed, N = number of wedges, h = separation distance, Θ_o = Angle of Wedge



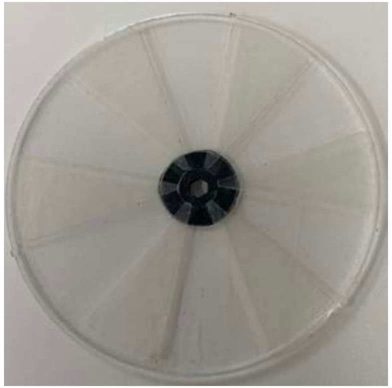
Electrode design where r = radius and $\Theta_{electrode}$ and $\Theta_{electret}$ are the angles of the electrode and electret respectively

Generation 1 Prototype

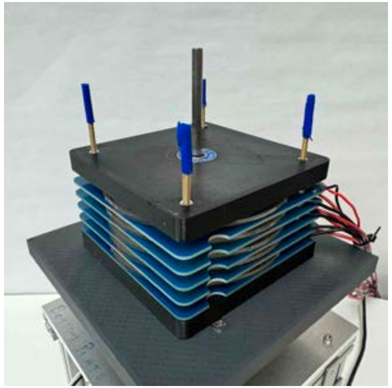
- Rigid printed circuit board stator, rigid acrylic disk.
- Mounted to motorized test stand.



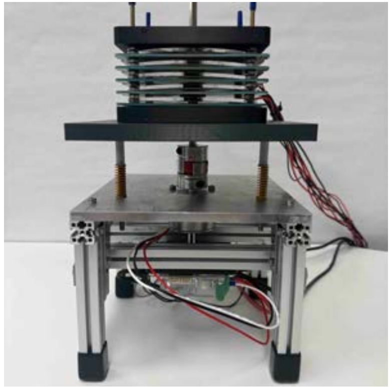
A) Stator – Printed Circuit Board



B) Rotor – Acrylic disk with FEP



C) Stack of 5 Stator-Rotor pairs

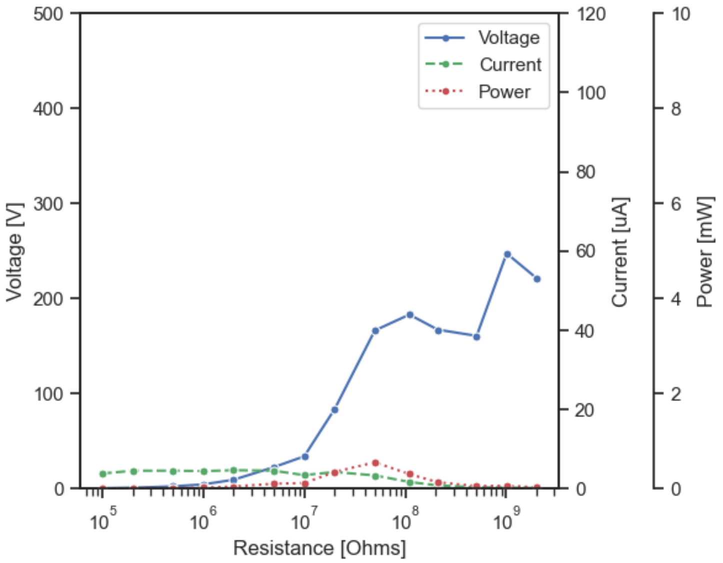


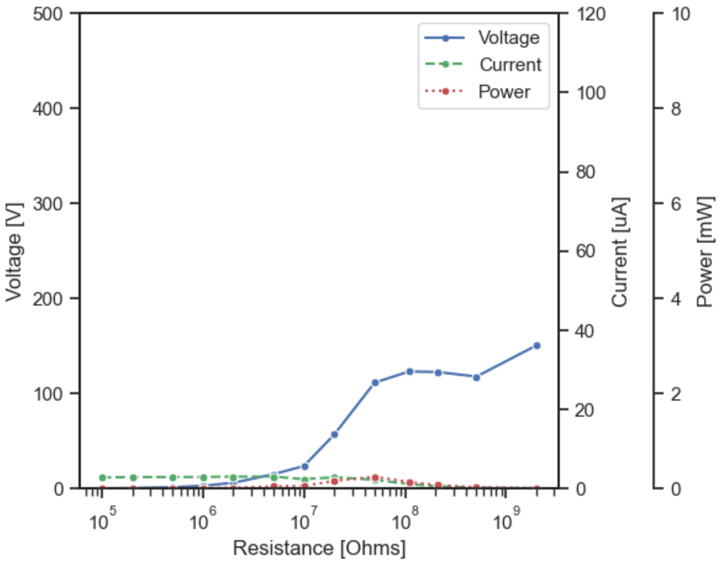
D) 5-stack mounted to Test Rig

Photos source: C. Kenny NREL

Results: Generation 1. Stack of 1.

- Prototype run at 500rpm until charge saturation, then discharged for 3 minutes.

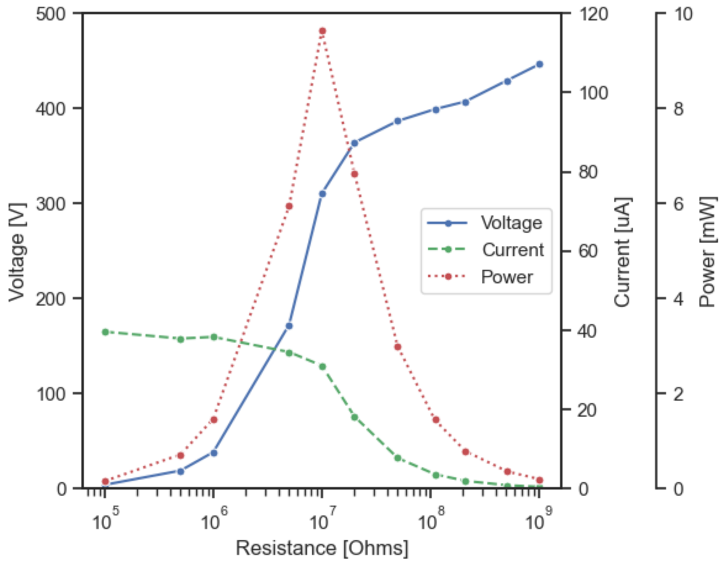


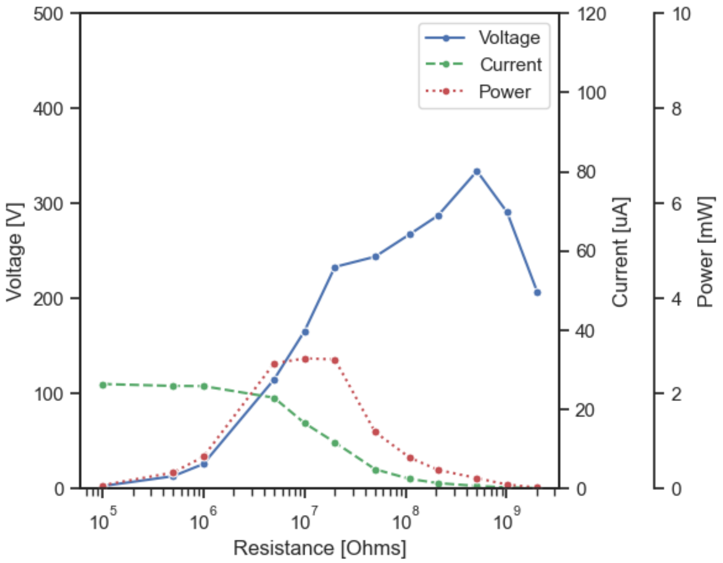


- Gen 1. Stack of 1. Charged.
  - Max power output: 0.55mW
  - Max RMS voltage: 247V
  - Max current: 4.6uA.
- Gen 1. Stack of 1. Discharged.
  - Max power output 0.24mW
  - Max RMS Voltage: 151V
  - Max current: 3.0uA.

Results: Generation 1. Stack of 5.

- Prototype run at 500rpm until charge saturation, then discharged for 3 minutes.

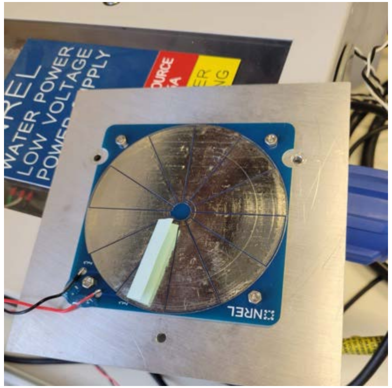




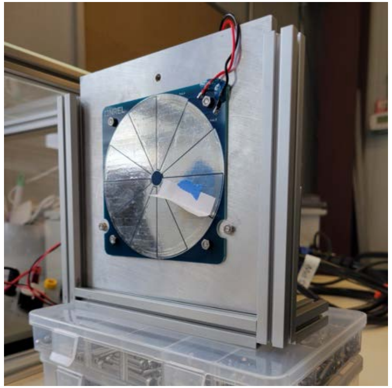
- Gen 1. Stack of 5. Charged.
  - Max power output: 9.6mW
  - Max RMS voltage: 446V
  - Max current: 40uA.
- Gen 1. Stack of 5. Discharged.
  - Max power output: 2.7mW
  - Max RMS Voltage: 334V
  - Max current: 26uA.

Lessons Learned from Gen 1

- A separate friction element was required on the stator, which was time consuming to add and remove.
- It was difficult to set a consistent gap between the rotor and stator.
- The use of a vinyl cutter made it difficult to align the cut FEP segments with the rotor disk.



Friction element using adhesive strip



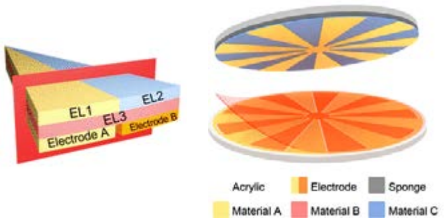
Stator mounted and ready for assembly

Photos source: G. Trayner NREL

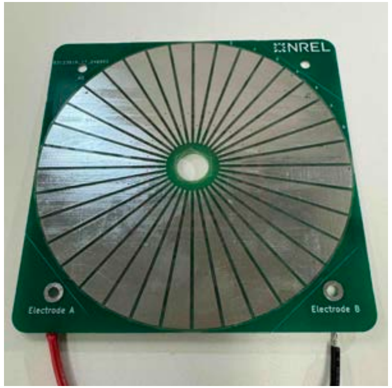
Cutting FEP sheet using the vinyl cutter

Generation 2 Prototype

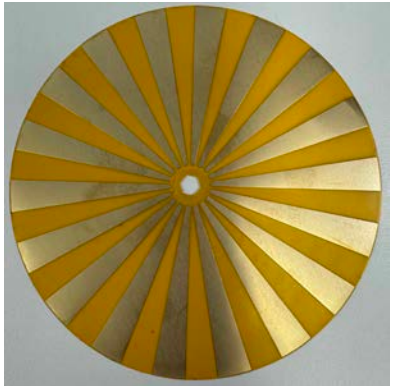
- Friction element added by using flexible circuit board, resulting in contact at low speeds and separation at high speeds.
- TENG converted to 3-layer configuration by applying FEP film to stator (Deng et al. 2020).
- Increased electrode count from 12 to 36.



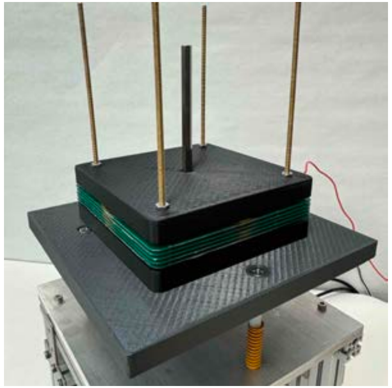
3-layer TENG configuration (Deng et al. 2020)



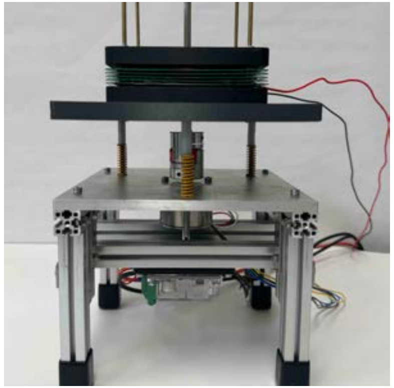
A) Stator – Printed Circuit Board with FEP film across



B) Rotor – Flexible Circuit Board



C) Stack of 5 Stator-Rotor pairs

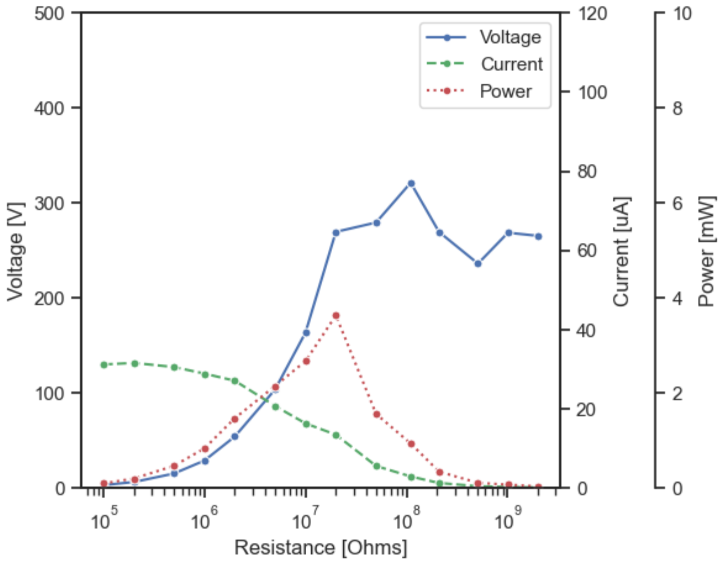


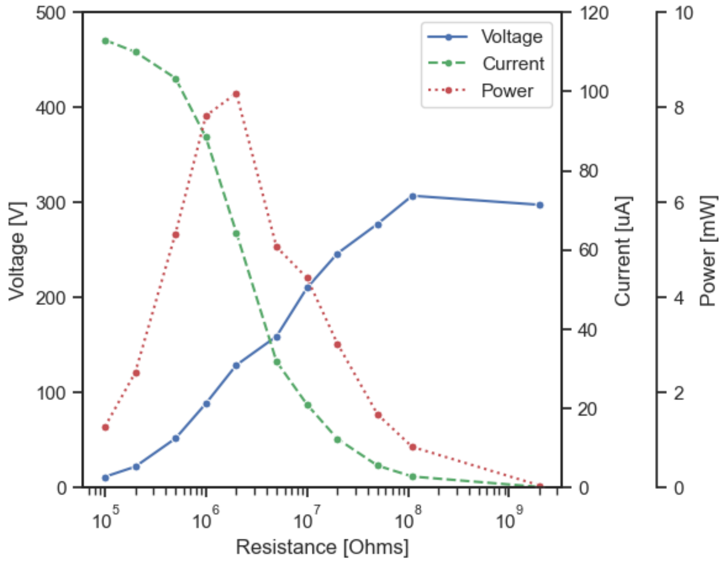
D) 5-stack mounted to Test Rig

Photos source: C. Kenny NREL

Results: Generation 2 – Stacks of 1 and 5

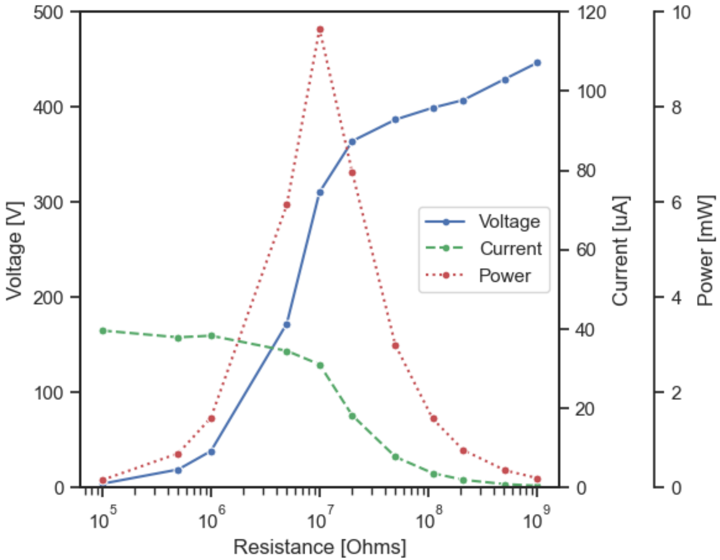
- Prototype run at 500rpm until charge saturation.

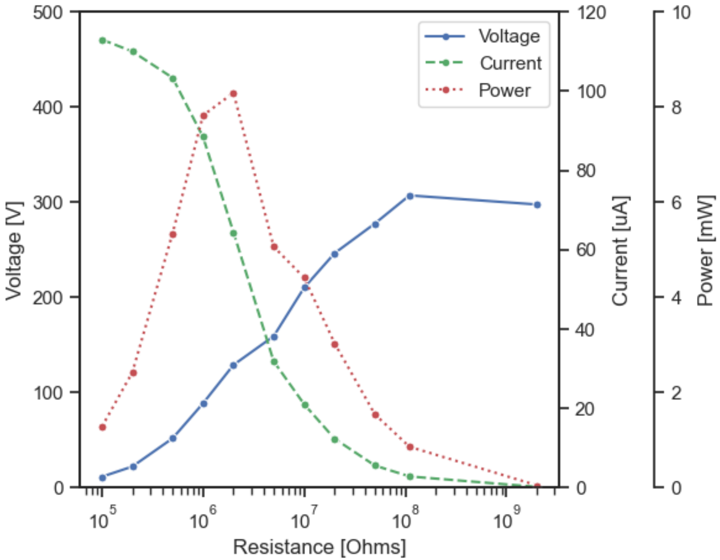


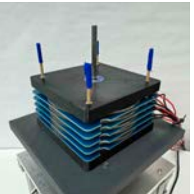


- Gen 2. Stack of 1. Charged.
  - Max power output: 3.6mW
  - Max RMS voltage: 321V
  - Max current: 32uA.
- Gen 2. Stack of 5. Charged.
  - Max power output: 8.3mW
  - Max RMS Voltage: 307V
  - Max current: 113uA.

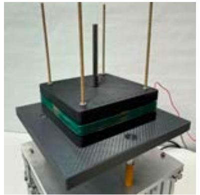
Results Comparison – 5 Stack







- Gen 1. Stack of 5. Charged.
  - Max power output: 9.6mW
  - Max RMS voltage: 446V
  - Max current: 40uA.



- Gen 2. Stack of 5. Charged.
  - Max power output: 8.3mW
  - Max RMS Voltage: 307V
  - Max current: 113uA.

Discussion

- General observations:
  - Stacking of stator-rotor pairs results in both increased current and voltage.
  - Internal impedance of gen 2 prototype far less than gen 1.
- Generation 2 advantages:
  - Can eliminate brushes with use of flexible circuit board
  - Space-efficient design.
- Generation 2 disadvantages:
  - Increased friction between rotor and stator.
- Ultimately need to compete with electromagnetic generator:
  - Cannot recommend this prototype at this time.

Conclusion

- Use of flexible circuit boards explored in hopes of improving power density.
- Further work:
  - Increase stack quantity
  - Improve power aggregation by use of rectifier bridge and series connection onto DC bus
  - Use of management module to smooth power profile.

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