**RESEARCH REPORT**

VTT-R-00084-22

# ENOMA, Energy autonomous systems, final content report

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beyond the obvious

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**Summary**

ENOMA, energy autonomous systems (Energiaomavaraiset järjestelmät). The project goal was to develop techniques for energy autonomous devices and systems, including energy generator techniques, their electronic load control and voltage conversion and energy management techniques.
The main developed techniques in VTT project were triboelectric energy harvesters and low velocity rotating energy harvesters.

ENOMA project was a Business Finland funded co-innovation type research project. The consortium included following research organisations: Tampere university (coordinator), VTT and university of Oulu. Tamlink Oy acted as the administrative coordinator. The consortium and the steering committee consisted of following companies: Abloy Oy, Cargotech Finland Oy, Forciot Oy, JC Inertial Oy, Micro Analog Systems Oy, Meluta Oy, Nokian Tyres Oy, Radientum Oy, Reka Rubber Oy, RCP Software Oy, Teknikum Group Oy, Wizense Oy, YL-verkot Oy.

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## Approval

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# Contents

# 1. Introduction

This report shows results on the main focus areas, triboelectric energy harvesting and low velocity rotational energy harvesting. In addition to these themes, studies were done on non-linear vibration energy harvesting and measurements of TEG characteristics. Additional reports show the results in more details, see chapter 4.

# 2. Triboelectric energy harvesting

## 2.1 Introduction

Triboelectric energy harvester is a type of kinetic energy harvester. It is based on surface charge creation when two different types, typically dielectric, of material surfaces touch each other. When the surfaces are drawn apart, electric energy is generated mainly due to the change in generator capacitance.

Triboelectric (nano) generators (TENG) may be utilized as large area, thin generators. In this project some generators were built for tests and especially for development of electronic converters for TENGs and other capacitive generator types. As there are no commercial effective electronic converters for TENGs, the focus was in developing such converter.

One of the challenges in electronic converters for triboelectric generators is that efficient energy conversion requires utilizing the high voltage output that is generated at the TENG output. When utilizing synchronously switched converter topologies, open load condition is often utilized as one operation phase during energy extraction. The open circuit voltage may be hundreds or thousands of volts. Efficient energy generation leads to these voltage levels to be generated at the TENG output electrodes at open load condition.

Voltage Threshold and Peak Triggered (VTPT) converter was developed for these high voltage energy harvesters. Patent applications on that technique were filed: FI 20205748 [1] and PCT/FI2021/050518 [2].

The techniques are presented in more details in the reports [3], [4] and [5]. Reports [9], [10] and [11] handle techniques in the same area of energy converters.

## 2.2 Harvester test bench

A testbench was built for testing and developing plate type generators. At this test bench the generator plates are connected to moving carriages that are moved by an electromagnetic actuator. A laser sensor is used for measuring the displacement.

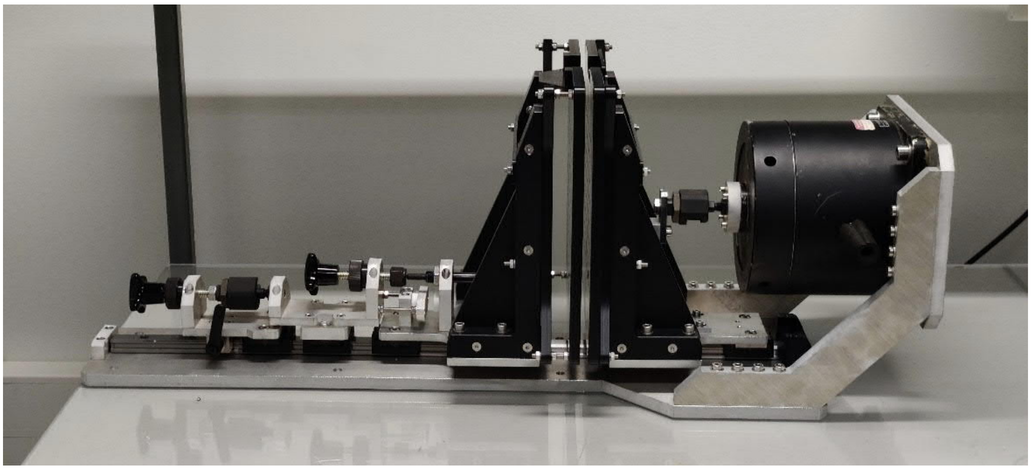

*Figure 1. A testbench for kinetic energy harvesters.*

## 2.3 TENG tests

Some TENGs were built for development work. No advanced materials or surface structures were utilized here, but some basic dielectric materials to select these materials for test generators. Material development was not in this project's scope.

Reports [4] and [5] present measurements of the properties on the TENG utilized with the converter development work.

## 2.4 Electronic converter for capacitive generators

An energy conversion method and an electronic solution for such method was developed. The solution can be utilized in energy conversion from high voltage generators with capacitive output impedance (piezo, triboelectric, electrostatic generators). Here "high voltage" refers to generators with several hundreds of volts or kilovolts output in open load condition. When used with the implemented converter, the maximum voltage is 500V.

Report [3] presents a theoretical analysis of the VTPT converter operation in more details. Report [5] presents an electronics solution of a VTPT converter in more details.

Figure 2 show the block diagram of the VTPT converter. After several development versions, an electronic converter board utilizing VTPT method was implemented (Figure 3). The trigger properties may be adjusted for operation according to generator type and the properties of the application.

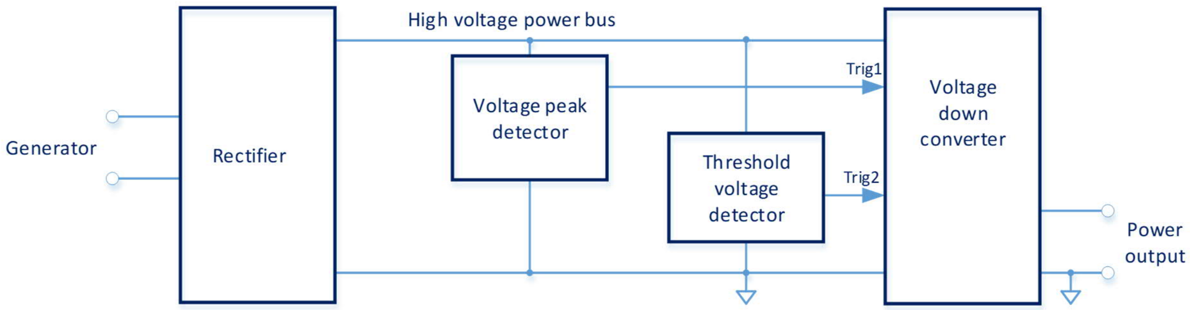


*Figure 2.Block diagram of the VTPT converter*

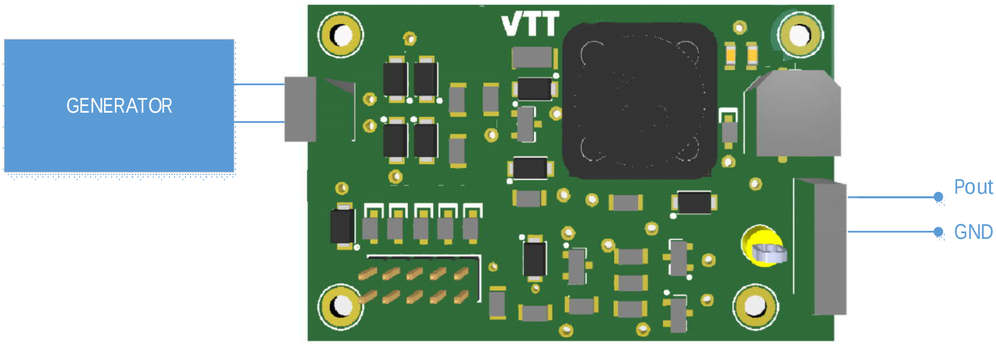


Figure 3. An electronic VTPT converter board.

## 2.5 Triboelectric converter powered wireless sensor

A proof of concept system of a triboelectric generator powered IoT sensor was developed. It consists of a triboelectric generator and a VTPT converter powering a low power wireless sensor. An IoT system was realized for receiving the sensor data and to forward the data for further actions, in this case data was forwarded to an IoT system UI on a PC.

Figure 4shows the implementation of the TENG powered sensor. Figure 5 shows the system blocks. The wireless sensor (RSL10) sends data as an BLE beacon, Ingics module receives it and forwards data through Wifi access point to CloudMQTT broker. The data is presented in Things Board UI (Figure 6).

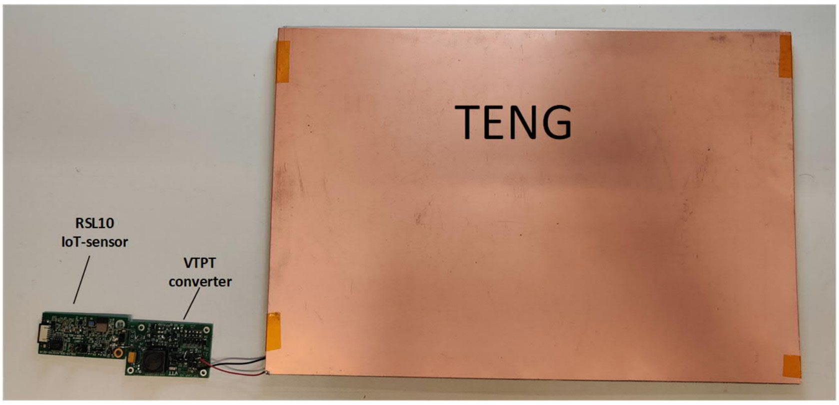


Figure 4. TENG powered wireless IoT sensor implementation.

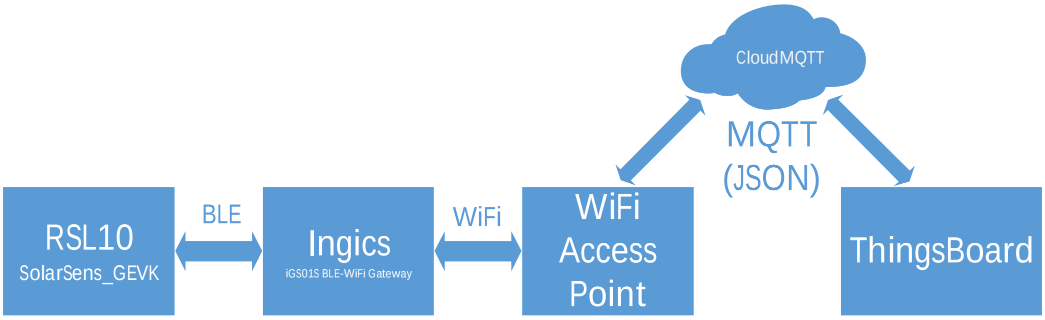


Figure 5. IoT Proof of concept system block diagram.

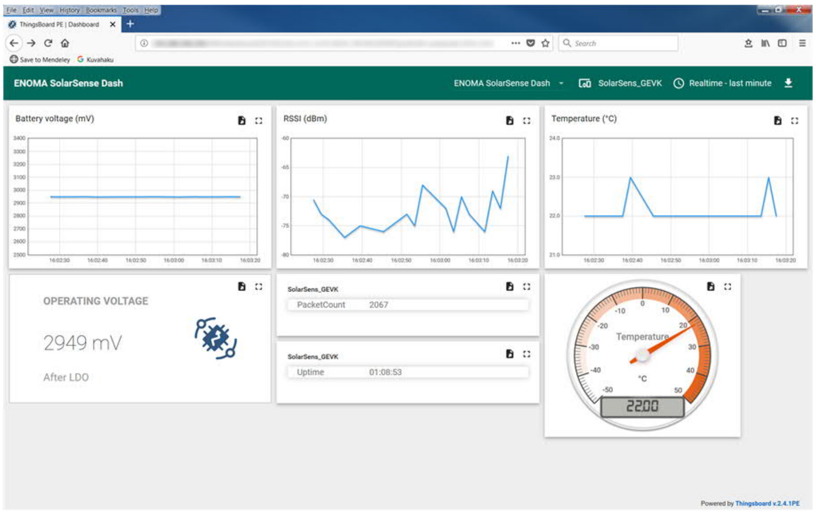


Figure 6. IoT system UI with information on the sensor board voltage and temperature.

Figure 7. shows the converter output capacitor voltage when operation starts, and sensor transmissions start. Here we see the charging events (square) and the sensor measurement and data transmission events (circle). In this case one measurement requires more than one generator impact in average.

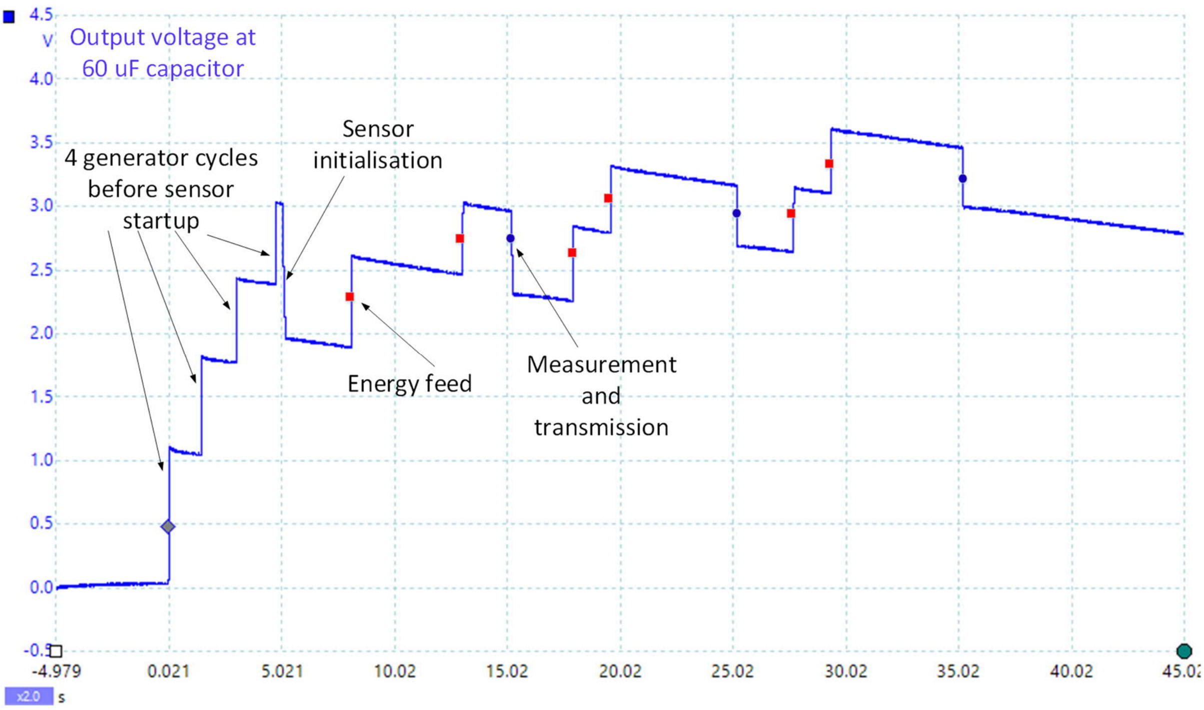


*Figure 7. Output capacitor voltage during sensor cold start and measurements*

## 2.6 Conclusions

The presented converter solution with Voltage Threshold and Peak Triggering can o be used with various kinetic generators for energy harvesting. This solution is targeted especially for applications with random low frequency (<1Hz) and impact type mechanical excitation without constant frequency impacts or vibration. In the target applications the load electronics can be powered even from single impacts.

As triboelectric generators have often relatively high (>1 kV) open load output voltage, this solution enables utilizing the output charge with converter electronics that cannot withstand that high voltages also after the maximum voltage has been reached once or several times. The basic solution can be modified to be used with other types of generators with capacitive output impedance such as piezo generators and electrostatic kinetic generators, too. When utilizing separate peak detector and threshold voltage detector circuits and parameters for both output terminals, this technique can be utilized in even wider range of generator and application types.

The implemented sensor PoC system shows that TENG can be utilized as practical energy source for low power sensors etc. operating with typical supply voltages by utilizing an appropriate electronic converter.

# 3. Self-contained low velocity rotational energy harvester

## 3.1 Introduction

Powering electronics in rotating objects is a challenge in IoT systems. In rotating objects both charging or replacing batteries is often not possible or require expensive actions. Wired power feed requires often expensive slip rings. In some cases, wireless energy transfer through inductive or capacitive energy transmitters is possible. However, they require additional devices outside of the rotating object which add the system cost.

Here the focus is in generating electricity with

- no additional devices outside of the rotating object
- a self-contained harvester that offers electric power for load electronics
- low velocity applications with rotational velocity <5 RPS.

The solution is presented in more details in report [6].

## 3.2 Operation principle

The axle and the generator frame have a velocity difference that generates a voltage at the generator output. By loading this voltage, electric energy is generated, and mechanical torque is created (Figure 8). A brush DC generator with planetary gear (1:67 ratio) is used as the generator.

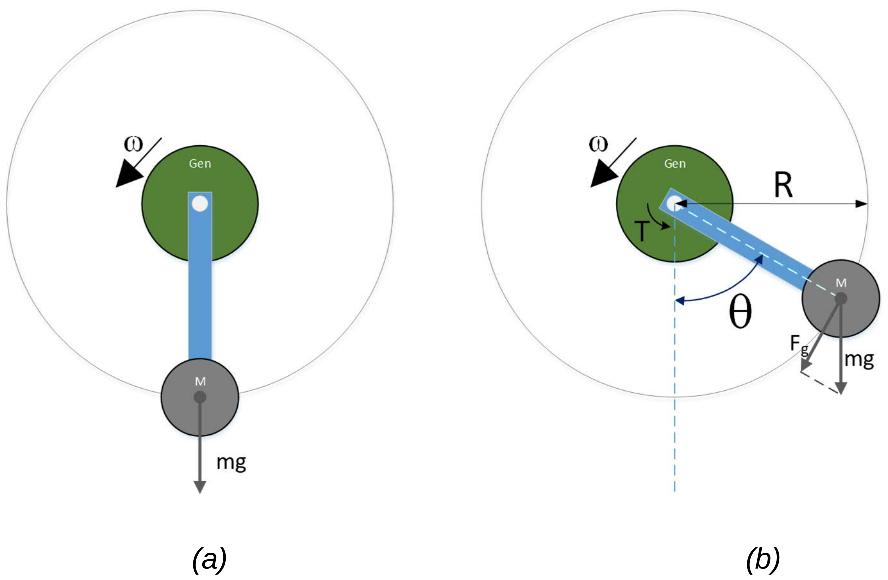


*Figure 8. Principle of rotating generator with eccentric mass induced gravitational torque. (a) Mass position in no-load condition. (b) When electrically loaded, the generator generates energy and creates a torque at the axle that leads mass to move to balanced position where gravitational torque is same as generator torque.*

## 3.3 Electronic converter

The generated energy is converter electronically to eventually charge a rechargeable battery. First the voltage is rectified, the boosted to higher voltage, regulated for battery charger which charges the battery. Here the battery is used as power source (Figure 9).

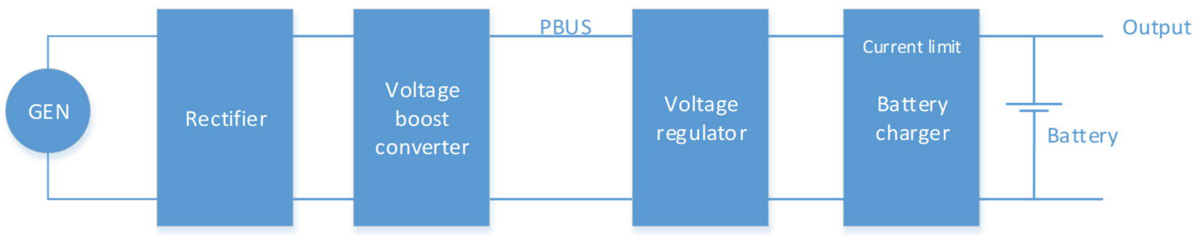


*Figure 9. The functional blocks of the converter electronics.*

Figure 10 shows the electronic boards of the converter. Here a modular system is used to enable modification of the converter through changing a board when required. The harvester electronics consists of three modules:

1. Load control and voltage boost converter
2. Voltage buck and regulating converter
3. Battery charger

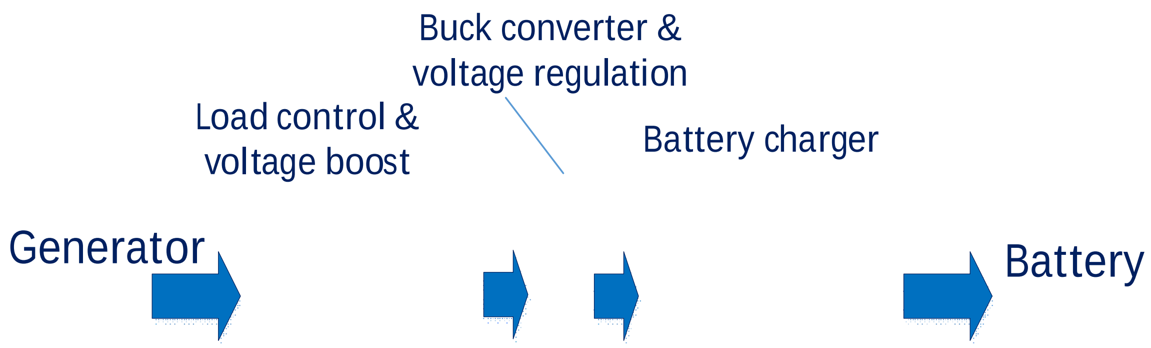


*Figure 10. Harvester electronic modules.*

## 3.4 Mechanical assembly

Figure 11 shows the mechanical assembly of the harvester including the gear generator, the electronics boards and the battery attached in the harvester frame. The frame is manufactured by 3D printing.

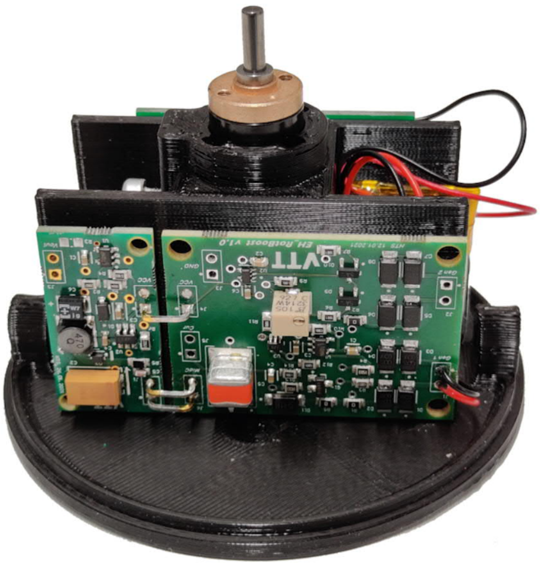

*Figure 11. Harvester setup containing the generator, the electronic boards, and the battery in the harvester frame.*

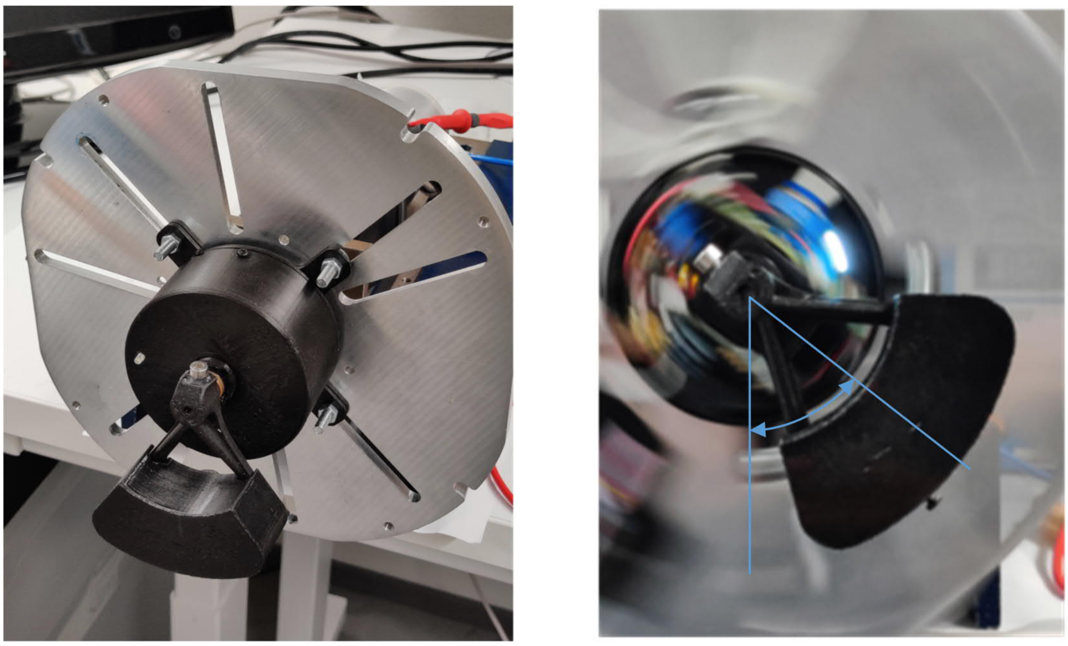

*Figure 12. Left: the harvester attached to a nonrotating plate. Generator at rotating plate. A torque is generated, and the eccentric mass has reached the equilibrium angle.*

## 3.5 Harvester performance

Figure 13 shows the PoC generator battery charging performance as a function of rotational velocity. The charging starts in this case near 1 RPS and reaches the maximum recharge power at 2.8 RPS. At higher velocities the power stays at maximum value.

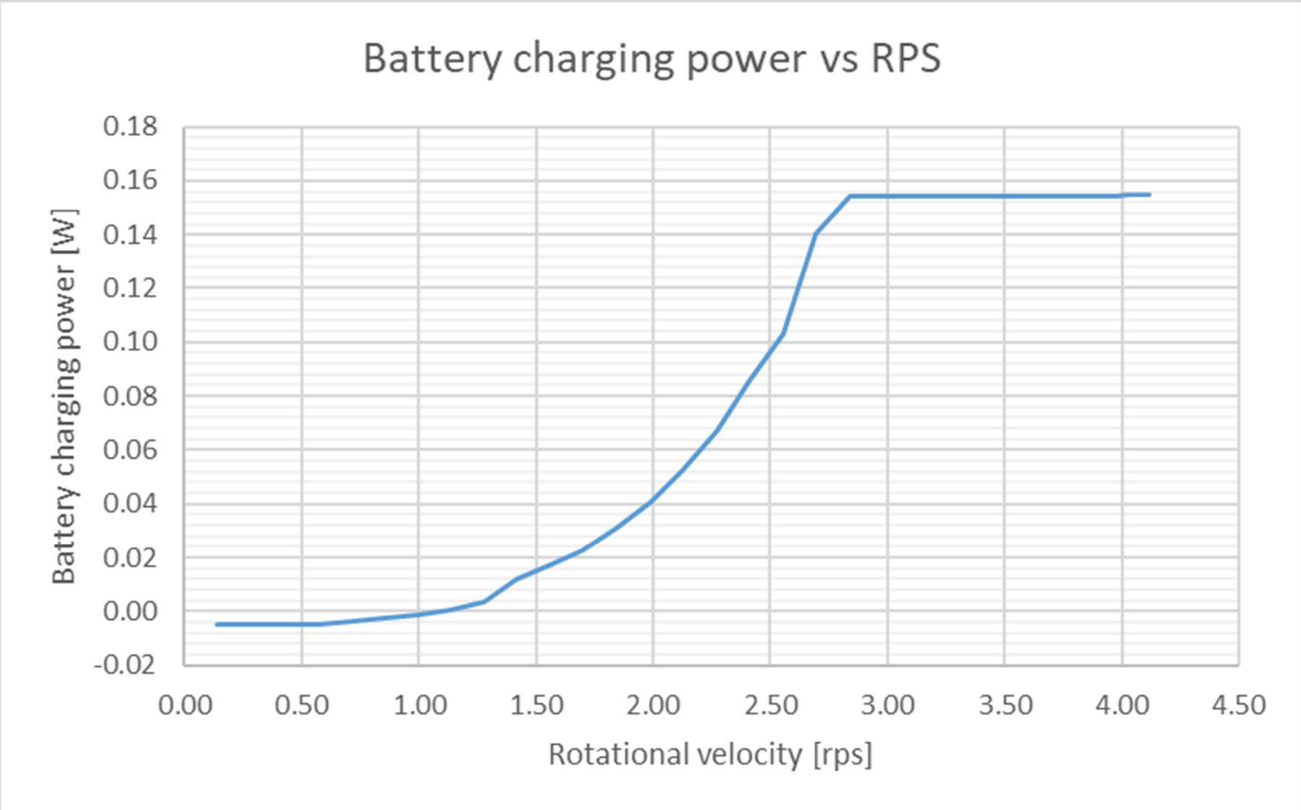


*Figure 13. Battery charging power vs rotational velocity.*

## 3.6 Conclusions

A harvester PoC device was developed for low velocity applications. The device is self-contained, meaning that the system does not require any additional devices or special structures outside of the harvester device. The harvester is suitable for applications, where the load electronics is attached at the same rotating base, or even in the same enclosure as the generator.

This harvester is targeted to applications with relatively constant velocities and small acceleration. For more dynamic applications, active control of load control must be used. The generated energy from the harvester is fed to a rechargeable battery. The battery is the used as power source for the load electronics for instance a wireless IoT sensor. The harvester was adjusted to operate at rotational velocities up to ca. 3.3 RPS (200 RPM). The charging starts at 1 RPS and the maximum charging power 155 mW is reached at 2.8 RPS and continues up to 3.3 RPS.

4.

## 4. Documents

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[2] H. Huovila and P. Härkönen, “Energy Harvesting,” Patent application, PCT/FI2021/050518, 2021.
[3] P. Härkönen, “A Theoretical Analysis of a Voltage Threshold and Peak Triggered TENG Converter,” VTT report, 2021.
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[8] P. Härkönen, “Modelling and Analysis of Non-Linear Vibrational Energy Harvesters - VTT report”, 2020.
[9] P. Härkönen, “Rectifiers and Voltage Doublers with Capacitive Generators - VTT report”, 2020.
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