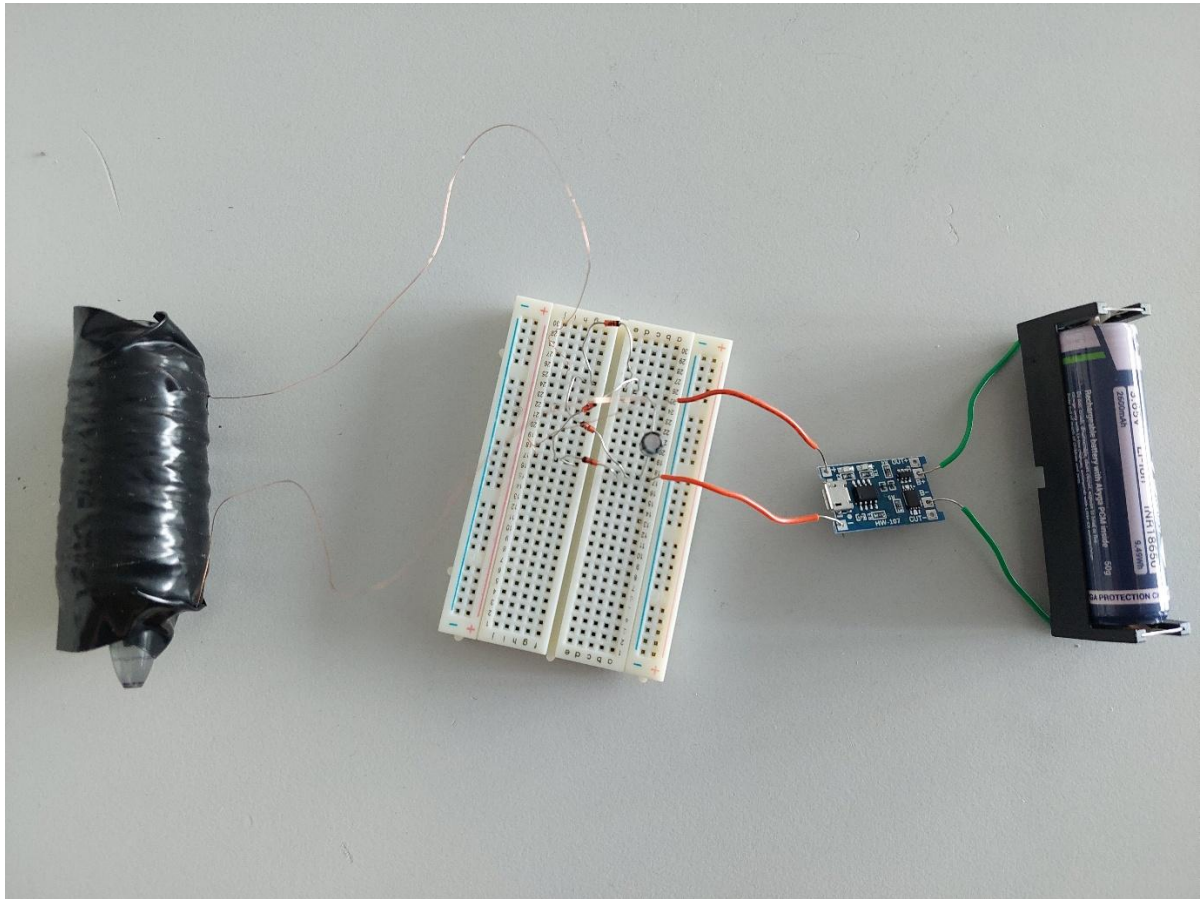




CHALMERS
UNIVERSITY OF TECHNOLOGY



Developing and testing a palm-sized shaking energy harvesting device

Simulation and bench prototype testing process

Bachelor's thesis in electrical engineering
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DEGREE PROJECT IN ELECTRICAL ENGINEERING 2026

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Front page: Prototype coil, bridge/capacitor breadboard, TP4056 module, and battery used in the final test.

[Own image]

Gothenburg, Sweden 2026

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Developing and testing a palm-sized shaking energy harvesting device

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Abstract

In the development of technology today, the energy problem remains one of the most challenging issues that electrical engineers must carefully consider. Although people use electricity daily, generating it is a relatively unfamiliar concept to those outside the engineering field. To raise awareness of this issue, the idea of creating a simple, compact power generator has emerged. One objective was to make the principle sufficiently accessible to be demonstrated and understood by younger students, while also investigating its potential for small-scale energy generation and storage. Improving understanding of energy generators for the next generation could open another potential for energy technology.

The project investigated the feasibility of converting human-generated mechanical motion into electrical energy using a compact vibration-based electromagnetic energy harvester. The system was based on Faraday's law of electromagnetic induction, in which a permanent magnet moved axially inside a copper coil during manual shaking. A numerical model was developed in MATLAB to calculate the magnetic field, magnetic flux linkage, induced voltage, and generated current. Electromagnetic behavior was also simulated using COMSOL Multiphysics and ANSYS Electronics Desktop, while LTspice was used to investigate the Schottky bridge rectifier and capacitor-smoothing circuit. A physical bench prototype consisting of the magnet-coil generator, rectification and filtering circuit, TP4056 charging module, and 18650 lithium-ion battery were constructed and experimentally tested. The constructed system remained a bench prototype and was not developed into a complete enclosed palm-sized product suitable for use by children.

Experimental measurements showed that the electrical output was intermittent and strongly dependent on the speed and consistency of manual shaking. The TP4056 charging indication and the measured positive battery-side current showed that current was transferred toward the battery during operation. However, a complete battery charge or a controlled long-term increase in battery state of charge was not quantitatively demonstrated. At the measured mean battery-side current of 0.2625 mA, the ideal constant-current equivalent charging time for a nominal 2600 mAh battery is approximately 9905 hours. This is not an experimentally demonstrated charging time

and excludes the intermittency of manual shaking, conversion losses, and the battery-charging profile. The developed prototype demonstrated the feasibility and educational value of shaking-based energy harvesting, while the limited output power remained an important area for future improvement.

Keywords: energy harvesting, energy storage system, palm-size device, shaking energy harvesting, digital model, MATLAB, COMSOL physics, bench prototype.

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Terminology and abbreviations

DC – Direct Current

AC - Alternating Current

FEM - Finite Element Method

AEDT - Ansys Electronics Desktop software. AEDT is an integrated simulation environment for the design and analysis of electronic and electromagnetic systems. In this project, Ansys Maxwell was used as the electromagnetic field solver. Maxwell provides two- and three-dimensional finite-element analysis for electromagnetic field problems and supports analyses involving permanent magnets, coils, induced currents, forces, and other electromagnetic quantities.

EMF - The induced electromotive force

RMS - Root Mean Square

B-field - The magnetic flux density. It measures the total strength and density of a magnetic field passing through a specific area, quantified in units of Tesla (T) or Gauss (G).

Br - Residual magnetism or remanent flux density. It measures the amount of magnetic field left inside a ferromagnetic material after the external magnetizing force is removed. A higher Br value means a stronger permanent magnet.

NdFeB - Neodymium Iron Boron ($Nd_2Fe_{14}B$) The industry abbreviation for the strongest type of permanent magnet currently available.

N42 - the material grade designation for neodymium (NdFeB) permanent magnets. N stands for neodymium and 42 denotes the maximum energy product of 42 MGOe (Mega Gauss Oersted), used to measure magnetic field strength.

MOSFET - Metal-Oxide Semiconductor Field-Effect Transistor is a small electronic component that acts as a switch or amplifier. By applying voltage, it controls the current in a circuit without requiring any moving parts.

IC - Integrated circuit is a semiconductor device that integrates components such as transistors, resistors, and capacitors

PMIC - Power Management Integrated Circuit. It is a specialized microchip that controls and distributes electrical power inside electronic devices. PMIC provides precise voltage and current to all subsystems.

CC/CV - Constant Current / Constant Voltage

AI - Artificial Intelligence

1 Introduction

1.1 Background

The growing demand for mobile and sustainable energy sources has led to increasing interest in energy harvesting technologies. These systems aim to capture small amounts of energy from the environment, including light, temperature differences, mechanical energy, radio waves, and biochemical energy. These energy sources are then converted into usable electrical energy.

One promising approach is the use of electromagnetic induction, where relative mechanical motion between a magnet and coil changes the magnetic flux linkage and induces an electromotive force. The principle of generating electrical energy through the relative linear motion of permanent magnets and copper coils has been previously applied in small-scale magnetic field generators and vibration energy harvesting systems [1][2]. A well-known example is the handshake flashlight or Faraday flashlight, in which a permanent magnet moves through a tubular casing and through a fixed coil, generating an electric current that can be stored and used to power the light source [1]. Similar principles have also been studied in linear electromagnetic vibration energy harvesting devices, in which the relative motion between a permanent magnet and an electromagnetic coil is used to convert mechanical vibrations of the environment into electrical energy [2].

The basic magnet and coil configuration studied in this project is not intended to represent a new principle of electromagnetic generation. Instead, this project's contribution is to study the entire energy conversion process in a compact and educational implementation, from the mechanical motion of the magnets and the electromagnetic induction generated to rectification, voltage smoothing, and energy storage in a rechargeable battery. MATLAB mathematical models were compared with finite element simulations in COMSOL Multiphysics and Ansys Electronics Desktop, while LTspice was used to study the rectification and filtering stages. The simulations were then compared with measurements from a physical prototype. The combined approach was used to evaluate both the feasibility and practical limitations of the manually shaken energy harvesting device.

Based on these core problems, the project focuses on creating a compact, simple device that is easily accessible to everyone, especially elementary and middle school children under supervision.

1.2 Purpose

The purpose of this project is to design, model, construct, and evaluate a compact, palm-sized energy-harvesting device with approximate dimensions of 100x70x35 mm. The device is intended to convert mechanical vibration from manual shaking into electrical energy, provide sufficient electrical output for the charging circuit, and

transfer the harvested energy to a rechargeable protected 3.7 V 18650 lithium-ion battery. The energy stored inside the battery can then be used to power low-power external loads.

1.3 Delimitations

The MATLAB model is limited to electromagnetic calculations based on the defined magnet, coil geometry, and prescribed magnet motion. COMSOL Multiphysics and Ansys Electronics Desktop are used for numerical comparison of selected electromagnetic cases, while LTspice is used to investigate the rectification and smoothing circuit. A complete multiphysics model simultaneously coupling the user's shaking force, magnet dynamics, electromagnetic response, rectifier, charging circuit, battery electrochemistry and thermal behavior is not included.

The speed of hand shaking is relative and measured based on human timing ability, so the speed may vary slightly when included in detailed calculations. The speed specifications have been referenced in [3][4]. [4] reports that the average maximum velocity of the hand during movement toward the target is approximately 1.01–1.13 m/s, while the average maximum velocity during return movement is approximately 0.93–1.05 m/s. Since the magnet in the proposed transmitter moves inside a closed tube and is affected by mechanical constraints and impacts, its velocity is expected to be lower than the maximum velocity of the hand. Therefore, a lower limit of 0.3 m/s is the safe value used for the system. Movement is limited to the axial direction of the tube, with the displacement studied being approximately ± 30 mm from the center position and the hand-shake frequency in the range of 3–8 Hz.

To avoid deviating from the project's original goal of creating a compact, palm-sized device, magnet dimensions were held fixed at 8 mm diameter and 30 mm length. Changing the size of the magnet directly affects the overall weight and dimensions of both the copper coil and the magnet, making the comparison more complex.

LTspice could not emulate the charging module due to limitations in component data as the TP4056 within the application library. However, after stabilizing the output power from the Schottky bridge, the input of the charging module would be stable enough for direct testing, so further emulation from the charging module was not necessary. Additionally, the charging module possesses a protection circuit, so low input voltage is under system control.

1.4 Clarification of the question

Is it possible to develop a compact, palm-sized product similar to a power bank to convert vibrational energy into electrical energy?

What is the average charging current and ideal/full charging time when using the specified shaking parameters?

Are there any risks involved in energy conversion? Does the device pose any risk of explosion?

What are the new features of this project compared to existing shake flashlights and electromagnetic vibration energy collectors?

2 Theory and background material

2.1 Biot-Savart law

In the early days of magnetism, people only knew that magnets attracted and repelled each other, as well as attracted metal materials, but they were completely unaware of the concept of a magnetic field and magnetic strength. Following experiments by Biot and Savart in the 19th century [6], it was determined that magnetic flux density is created by a constant electric current in the space surrounding a conductor.

Magnetic fields can be generated by current distributions and by magnetizing materials. In permanent magnets, the magnetic field originates from the magnetization of the material, representing the sum of the magnetic moments within the material. In the macroscopic electromagnetic model, this magnetization can be represented by equivalent volumetric and surface current densities. Thus, permanent magnets can be modeled using equivalent current distributions that produce corresponding magnetic fields. Biot and Savart conducted experiments on the force exerted by an electric current on a magnet placed near it. In 1820, Biot and Savart experimentally investigated the magnetic effects produced by electric currents. Based on their observations, the Biot–Savart law was formulated to describe the contribution $d\vec{B}$ to the magnetic flux density at an observation point P from a current element $I d\vec{l}$. For a steady current I , this contribution can be expressed as:

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \vec{r}}{r^3} \quad (1)$$

where B is magnetic field, $\hat{r}$ is a unit vector directed from $d\vec{l}$ toward point P. The product $I d\vec{l}$ ($I d\vec{l}$) is differential vector element along the direction of the current, r is the displacement vector from the current element to the observation point $r=|\vec{r}|$ and μ_0 is the permeability of free space [5][6]. The total magnetic flux density produced by the complete current distribution is obtained by integrating the differential contributions over the entire current path:

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{d\vec{l} \times \vec{r}}{r^2} \quad (2)$$

The Biot–Savart law provides the magnetic flux density generated by a prescribed steady current under magnetostatic conditions. In magnetostatic approximation, the charge and current distributions, as well as the associated electromagnetic fields, are assumed to be time independent. Under these assumptions, the magnetic field must satisfy the magnetostatic form of Maxwell's equations [6]. The general Ampère-Maxwell equations describe how both the current and the time change of the electric field produce a magnetic field:

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \leftrightarrow \oint_C \vec{B} d\vec{l} = \iint_S (\mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}) dS \quad (3)$$

where $\vec{J}$ is the current density, ε_0 is the permittivity of the vacuum. For steady-state conditions where magnetostatics assumes time-independent sources and fields ($\frac{\partial \vec{E}}{\partial t} = 0$), the Ampère–Maxwell equation reduces to $\nabla \times \vec{B} = \mu_0 \vec{J}$. This equation is consistent with the Biot–Savart law used in Equation (2) for calculating the magnetic field produced by steady currents. Thus, the equivalent bound-current representation of the permanent magnet can be treated using the magnetostatic form of Maxwell's equations.

In the Ampère-Maxwell equations describing the local characteristics of the field at a point, the Biot-Savart law provides an integral approach to determining the total field from a given current distribution. The knowledge is fundamental to calculating the B-field distribution generated by magnets. A uniformly magnetized permanent magnet can be represented by equivalent bound currents. The bound surface current density is defined as:

$$\vec{K}_b = \vec{M} \times \hat{n} \quad (4)$$

where $\vec{M}$ is the magnetization vector and $\hat{n}$ is the outward unit normal vector of the magnet surface. For a cylindrical magnet that is uniformly magnetized along its axial direction, the equivalent bound current circulates around the curved surface of the magnet, similar to the current flowing through the windings of a solenoid. The equivalent-current representation can be used to calculate the magnetic field of the permanent magnet using the Biot–Savart law.

2.2 Faraday's law

In 1831, Michael Faraday published the first research on electromagnetic induction in "Experimental Researches in electricity" [5]. A change in the magnetic flux through a conducting loop, caused for example by relative motion between a magnet and the loop or by a time-varying magnetic field, induces an EMF. If the conducting loop forms a closed circuit with finite impedance, the induced EMF produces an electric current. The relationship is described by Faraday's law of electromagnetic induction.

The magnitude of the induced EMF in an electrical circuit is directly proportional to the rate of change of the magnetic flux (ϕ_B) in the circuit.

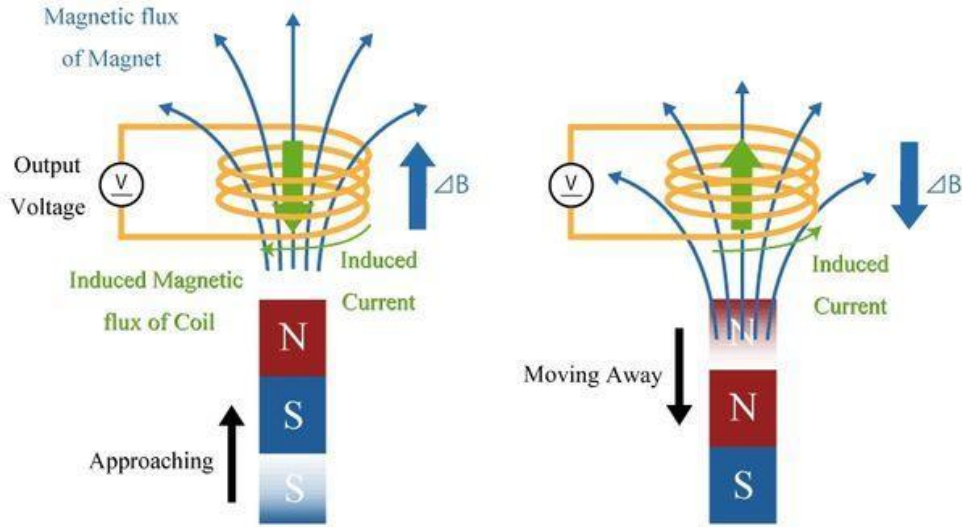


Figure 2.1: The image illustrates the relative magnet-coil motion, induced current, magnetic flux and the polarity of the induced voltage.

And the theorem is described by the formula below:

$$\varepsilon = -N \frac{\Delta \Phi_B}{\Delta t} \quad \text{or} \quad \varepsilon = -N \frac{\iint_{\Sigma(t)} \vec{B}(t) \cdot d\vec{A}}{dt} \quad (5)$$

where ε is EMF, N is the number of turns in the coil, and $\frac{\Delta \Phi_B}{\Delta t}$ is the rate of change of magnetic flux. Magnetic flux

$$\phi_B = |\vec{B}| \cdot A \cdot \cos \theta \quad \text{or} \quad \phi_B = \int_S \vec{B} \cdot d\vec{A} \quad (6)$$

where $B = |\vec{B}|$ is the magnetic flux density, A is the area of the coil and θ is the angle between the magnetic field and the normal to the surface.

Additionally, the magnetic flux through the coil depends on time only through the axial position of the moving magnet, $x(t)$, the magnetic flux may be written as $\phi_B = \phi_B(x(t))$.

Applying the chain rule gives: $\frac{\Delta \phi_B}{\Delta x} \cdot \frac{\Delta x}{\Delta t} = \frac{\Delta \phi_B}{\Delta t} \cdot v$ (7)

where $v = \frac{\Delta x}{\Delta t}$

From equations (5), (6) and (7), the induced voltage depends on the number of turns (N), the magnetic flux density(B), and the speed of the magnet's movement and the cross-sectional area of the coil through which the magnetic flux passes.

$$\varepsilon = V_{ind} = \left| -N * A_{coil} * \frac{\Delta \phi_B}{\Delta x} * v \right| \quad (8)$$

However, the expression is only an approximation and is not generally applicable to the multilayer coil considered in this project. The magnetic field generated by the

permanent magnet is spatially nonuniform, and the individual coil turns have different radial and axial positions. Consequently, the magnetic flux through each turn may differ. A more general representation is obtained by calculating the magnetic flux through each individual turn $\phi_k(t) = \int_{S_k} B(r, t) \cdot dA$ where S_k is the surface bounded by the k turns. The total flux linkage of the coil is $\lambda(t) = \sum_{k=1}^N \phi_k(t)$ and the induced EMF is $\varepsilon(t) = -\frac{\Delta\lambda(t)}{\Delta t}$ or $\varepsilon(t) = -\frac{\Delta\lambda(t)}{\Delta x}v(t)$ (9)

The formula considers the different positions and sizes of each individual wire loop, making it more suitable for the multilayer winding studied in this project.

2.3 Resistance of conductor

According to Faraday's law, the more turns of wire, the greater the voltage produced. However, in practice, winding more turns of wire increases the resistance of the generating unit.

Within the same area, to increase the number of turns, the system can only reduce the thickness of the wire. Free electrons have more difficulty moving and the number of collisions with metal atoms increases. This consequence is the main reason for the increase in resistance in copper coils.

$$R = \rho \frac{L}{A} \quad (10)$$

where R is resistance, ρ is resistivity of material ($\rho_{copper} = 1.72 \times 10^{-8} \Omega m$ at $20^\circ C$), L is length of conductor and A is cross-sectional area of conductor [7].

2.4 Schottky bridge

A full-wave bridge rectifier converts the alternating voltage generated by the copper coil into a pulsating unidirectional voltage. A bridge rectifier consists of four diodes connected in a special configuration. When alternating current enters, the bridge rectifier will always allow the current to flow in a specific direction, producing direct current at the output. During each half-cycle of the input AC current, two diodes in the bridge rectifier circuit conduct simultaneously, while the other two diodes remain reverse-biased. Therefore, the rectified output voltage is reduced by approximately two diode forward voltage drops ($V_{out}(t) \approx |V_{in}(t)| - 2V_F$). A Schottky bridge rectifier is used in the system. A Schottky bridge rectifier is based on the principle of a conventional bridge rectifier, but it uses Schottky diodes instead of conventional semiconductor diodes. Because Schottky diodes have a significantly lower forward voltage drop V_f than traditional PN diodes (approximately 0.15-0.45 V compared to 0.6-0.7 V for silicon diodes).

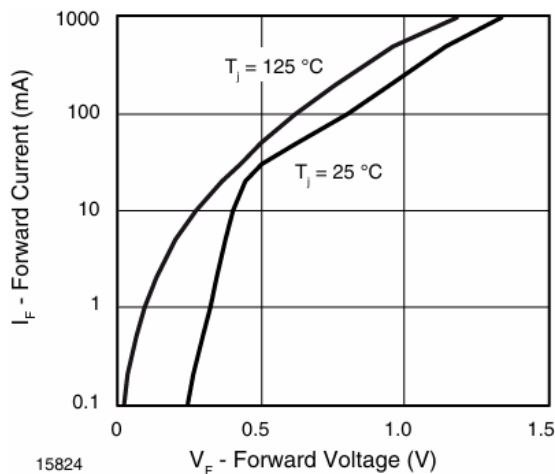


Figure 2.2: Forward-voltage characteristic of the BAT85 Schottky diode as a function of forward current. Diagram from datasheet of BAT85.

Furthermore, the characteristics of Schottky diodes offer the following benefits:

- Reduced energy loss: Less energy is dissipated as heat, increasing the overall efficiency of the rectifier.
- Reduced operating temperature: The device operates cooler, potentially reducing the need for heat dissipation. This does not significantly affect the current system.

By reducing energy losses, Schottky diodes improve the efficiency of the entire system, especially in low-voltage systems where the supply voltage is already low.

2.5 Ripple Voltage

The output of the bridge rectifier is not a smooth DC voltage, because its magnitude continues to vary with the input waveform and load current. To be able to use the electricity generated after passing through the Schottky bridge, the circuit needs a smoother current and more stable DC. Electrolytic capacitors are used to filter noise and smooth the voltage immediately after conversion from AC to DC [8].

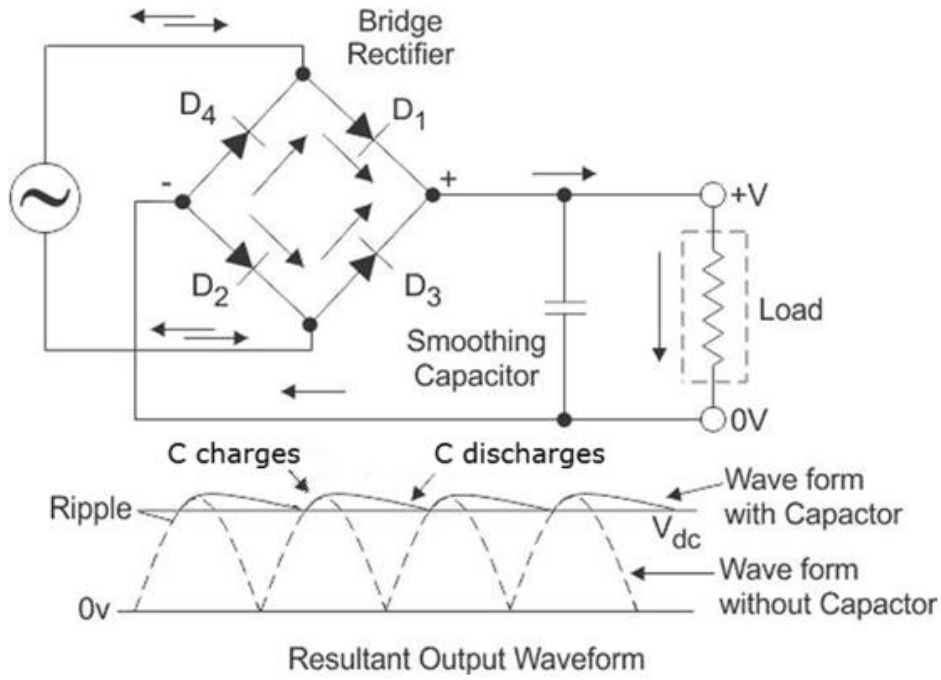


Figure 2.3: Illustration of the movement of electric current on the bridge and the operating principle of an electrolytic capacitor during charging and discharging.

The capacitor connected behind the full-bridge rectifier acts as a low-pass filter, storing energy when the voltage rises and releasing energy when the voltage drops to smooth out ripple. When the output voltage of the bridge circuit rises to its peak, the capacitor absorbs and stores electrical energy (C charges point). When the output voltage of the bridge circuit decreases (after passing the peak), the capacitor begins to discharge the stored energy into the load (C discharges point). This process helps maintain the voltage at a high level, preventing it from dropping too low to zero, thereby creating a smoother and more stable DC voltage waveform.

$$R_{load} = \frac{V_{DC}}{I_{load}}$$

And the capacitor current-voltage relation $I = C * \frac{\Delta V}{\Delta t}$

For a full-wave rectifier, the frequency of peak occurrences will double:

$$\Delta t = \frac{1}{f_r} \rightarrow I = C * \Delta V * f_r \rightarrow C = \frac{I}{f_r * \Delta V_{ripple}} = \frac{I}{2f_{AC} * \Delta V_{ripple}} \quad (11)$$

where I is the approximately constant load current, f_r is the frequency of repetition of the charging peaks for the capacitor, f_{AC} is the frequency of the induced AC voltage at the coil terminals before rectification and ΔV_{ripple} is the allowable peak-to-peak ripple voltage. The expression assumes a periodic full-wave rectified source, a relatively small

voltage ripple, and an approximately constant load current between successive charging peaks. For an ideal sinusoidal AC power source with frequency f_{AC} , a conventional full-wave rectifier bridge produces two rectification peaks per input cycle with $f_r = 2f_{AC}$. However, the relationship should not be directly applied to the mechanical oscillation frequency of the magnet. In a shaker generator, the magnetic flux linkage is a nonlinear function of the magnet position, and therefore a single mechanical oscillation can produce more than one induced voltage peak. Furthermore, manual shaking produces variations in magnet velocity, peak amplitude, and the time interval between successive voltage pulses.

The energy stored in a capacitor:

$$U_{charging} = U_{stored} = E_c = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} QV = \frac{1}{2} CV^2$$

The higher the peak voltage (V) and the larger the capacitance (C), the more energy is stored in the capacitor. The capacitor releases the stored energy to power the load, filling the voltage gap caused by the voltage drop. Increasing the capacitance can reduce voltage ripples, but it also increases the charge required to raise the capacitor voltage. In the proposed shaker generator, these assumptions are not fully met. Manual shaking produces an irregular voltage waveform with varying amplitude and frequency, while the TP4056 does not act as a constant resistive load. Therefore, Equation (11) is used only as an initial estimate for selecting the smoothing capacitance. The actual behavior of the capacitor and rectifier is evaluated using circuit simulations and experimental measurements.

2.6 TP4056 module

The component is an integrated module that works with a rechargeable battery, comprising the main component, the TP4056 chip, with a protection circuit (IC DW01A and MOSFET FS8205A). The TP4056 is a linear charging IC designed for single-cell lithium-ion batteries. TP4056 controls the battery charging process using constant current and constant voltage charging stages and terminates the charging process when the charging current drops to a specified stop level. The charging module contains the DW01A battery protection IC along with a dual MOSFET FS8205A. The TP4056 performs charging control, while the DW01A and FS8205A provide battery protection functions.

TP4056 1A Battery Charger Module with Protection Circuit

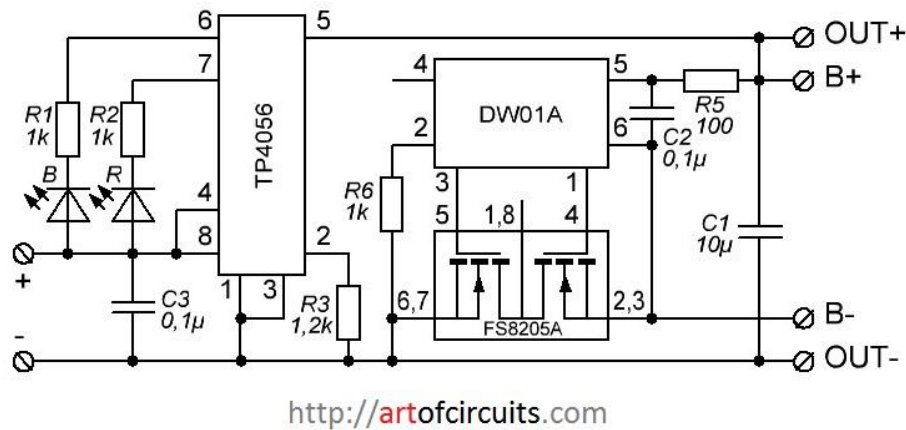


Figure 2.4: Circuit schematic of the TP4056-1A Micro USB Li-ion battery charger module with protection. Source: Art of Circuits [9]

The FS8205A IC contains two N-channel MOSFETs connected in series in opposite polarity. These MOSFETs are controlled by the DW01A protection IC and allow independent disconnection of the battery charge and discharge paths under various fault conditions. Under normal operation, both MOSFETs are switched on, allowing current to flow between the battery and the external circuit. If overcharging is detected, the DW01A will control the MOSFET in the charge path to prevent further charging. If over-discharging or excessive discharge current is detected, the MOSFET in the discharge path will be controlled to interrupt the discharge current. The series connection in opposite polarity is necessary because otherwise, the body diode of a single MOSFET would allow current to flow in one direction even when the MOSFET is switched off.

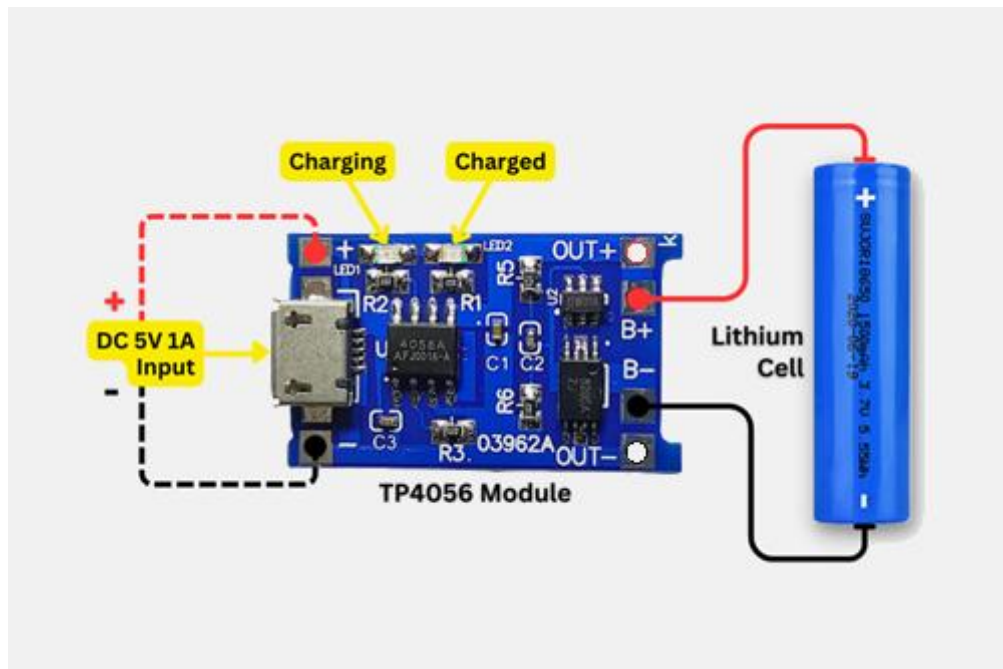


Figure 2.5: Example wiring configuration of a TP4056 charging module and lithium-ion battery. Adapted from Blikai [10]

The module was chosen due to its characteristics suitable for low-voltage systems. The module supports battery charging and external load connection. The TP4056 IC only regulates the charging process, not the battery discharge process. During discharge, current from the battery can be supplied to the load connected to the OUT+ and OUT- terminals via the module's protection circuit. The maximum charging current for the TP4056 is 1000 mA, but the current can be reduced by replacing resistor R3.

The default value for R3 is 1.2 k Ω , equivalent to 1000 mA. Numbers below are the custom values provided by the distributor Electrokit [11]:

10 k Ω $\rightarrow$ 130 mA

5 k Ω $\rightarrow$ 250 mA

3 k Ω $\rightarrow$ 400 mA

2 k Ω $\rightarrow$ 580 mA

1.66 k Ω $\rightarrow$ 690 mA

1.5 k Ω $\rightarrow$ 780 mA

1.33 k Ω $\rightarrow$ 900 mA

The adjustment is only effective when the generated current is greater than 130 mA and reduces the current demand placed on the rectified energy collector. The actual charging current of the battery is still limited by the power of the hand-shake generator. The TP4056 provides a simple and cost-effective method for demonstrating the transfer

of harvested energy to single-cell lithium-ion batteries. However, the TP4056 is not specifically designed for weak and high-impedance energy sources. The shaker generator produces limited and intermittent current and connecting it to a conventional battery charger can overload the generator enough to reduce its input voltage. Therefore, the use of the TP4056 represents a more practical prototype solution than an optimized harvested energy management system. The TP4056 is retained in this prototype because the goal is to demonstrate the feasibility of converting energy generated through rectification and regulation to the rechargeable 18650 battery. A dedicated energy-harvesting PMIC could be studied in future development to improve source matching, startup behavior, and overall energy transfer efficiency.

2.7 Safety considerations for lithium-ion batteries and permanent magnets

The power output generated by the hand-shaken electromagnetic generator is relatively low, and the device still contains components requiring appropriate safety precautions. The main risks relate to the rechargeable lithium-ion battery and the NdFeB N42 permanent magnet rather than the induced voltage generated directly by the copper coil.

The prototype uses a rechargeable 18650 lithium-ion battery. Lithium-ion batteries have a high energy density and can cause fire or overheating if overcharged, short-circuited, mechanically damaged, overheated, or charged outside the manufacturer's specified conditions. Mechanical damage and improper charging can cause internal short circuits, leading to rapid overheating and over-temperature phenomena. For this reason, the battery should only be charged within the voltage, current, and temperature limits specified by the manufacturer.

The prototype TP4056 module includes the DW01A and FS8205A protection circuits, which provide additional protection against conditions such as overcharging, over-discharging, overcurrent, and short circuits. However, these electronic protections should not be considered a substitute for proper battery handling.

Attention should be paid to this project because the device is intentionally subjected to repeated mechanical vibration. Therefore, the 18650 batteries must be securely fixed with a sturdy battery holder to prevent free movement, impact against the device housing, or repeated impacts. Do not use or charge batteries showing signs of deformation, swelling, overheating, leakage, unusual odors, or other physical damage. The battery terminals must also be protected against accidental short circuits.

A transparent potting compound may be applied to selected parts of the circuit after the system has been completed. The material can improve electrical insulation, reduce the risk of accidental contact with exposed conductors, and provide additional mechanical support for components and connections subjected to repeated shaking.

N42 NdFeB permanent magnets also require mechanical safety precautions. Despite their relatively small size, they exert a strong magnetic pull-on ferromagnetic material and can deform under excessive impact. The magnets should not be allowed to escape from the copper coil tube during use. Both ends of the vibrating tube must be sufficiently secure to prevent the magnets from escaping during strong vibrations. The magnets should also be kept away from magnetically sensitive equipment and medical devices where the manufacturer specifies a safe distance from magnetic fields when removed from the copper tube.

Because the project is partly intended as an educational demonstration, access to the internal magnets and lithium-ion battery should be restricted. Children are not permitted to disassemble any parts without tools.

3 Method

Using Biot-Savart's law, the magnetic field generated by the equivalent current distribution of a permanent magnet is shown to be position-dependent. The magnetic flux density varies with position and distance from the magnet, decreasing rapidly as distance increases. A three-dimensional MATLAB model was developed to visualize this behavior, showing the magnetic field is strongest near the magnet and weakens with distance. This spatial variation is important, as the induced electromotive force depends on the rate of change of the magnetic field that the coil experiences.

A real magnet is not a current-carrying wire, so project model it as an equivalent surface current using magnetization. From [6] the magnetization vector $\vec{M}$ of the magnetic material is

$$\vec{B}_M = \mu_0 \vec{M} \rightarrow M = \frac{B_M}{\mu_0} = \frac{1.315}{4\pi \times 10^{-7}} \approx 1046444 \text{ A/m}$$

where $B_M = |\vec{B}_M| = B_r$ and $B_r = 1.315 \text{ T}$ from datasheet N42

Assume the magnet is a cylindrical shape with length $L = 30 \text{ mm}$ and radius $R = 4 \text{ mm}$. The z -axis is defined along the longitudinal axis of the magnet ($z=0$ at the magnet center). The two pole faces are therefore located at $z = \pm L/2 = \pm 15 \text{ mm}$. The magnetic field is evaluated at observation points located a distance $d = 30 \text{ mm}$ from either pole face, corresponding to axial positions $z = \pm 30 \text{ mm}$. Magnetic Field on the Axis of a Circular Wire Loop has an equation from appendices 8.4:

The axial magnetic flux density $B_z(z) = \frac{B_r}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right)$ where $z = d + \frac{L}{2}$

At 0 mm from magnet: $z = 0 \text{ mm} + 15 \text{ mm} = 15 \text{ mm} = 0.015 \text{ m}$

$$\begin{aligned} B_z(z) &= \frac{B_r}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right) \\ &= \frac{1.315}{2} \left(\frac{0.015 + \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.015 + \frac{0.03}{2}\right)^2}} - \frac{0.015 - \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.015 - \frac{0.03}{2}\right)^2}} \right) \\ &= 0.6575 \cdot (0.991 - 0) \approx 0.6516 \text{ T} \end{aligned}$$

At 1 mm from magnet: $z = 1 \text{ mm} + 15 \text{ mm} = 16 \text{ mm} = 0.016 \text{ m}$

$$\begin{aligned}
B_z(z) &= \frac{B_r}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right) \\
&= \frac{1.315}{2} \left(\frac{0.016 + \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.016 + \frac{0.03}{2}\right)^2}} - \frac{0.016 - \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.016 - \frac{0.03}{2}\right)^2}} \right) \\
&= 0.6575 \cdot (0.992 - 0.243) \approx 0.4925 \text{ T}
\end{aligned}$$

At 10 mm from magnet: $z = 10 \text{ mm} + 15 \text{ mm} = 25 \text{ mm} = 0.025 \text{ m}$

$$\begin{aligned}
B_z(z) &= \frac{B_r}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right) \\
&= \frac{1.315}{2} \left(\frac{0.025 + \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.025 + \frac{0.03}{2}\right)^2}} - \frac{0.025 - \frac{0.03}{2}}{\sqrt{0.004^2 + \left(0.025 - \frac{0.03}{2}\right)^2}} \right) \\
&= 0.6575 \cdot (0.995 - 0.928) \approx 0.044 \text{ T}
\end{aligned}$$

Above equations are calculated axial flux density on the magnet axis at specified distances from the pole face. These parameters show that the magnetism around the magnet decreases significantly with distance.

Faraday's law is applicable to both single-turn and multi-turn coils. The limitation arises from the simple assumption that the magnetic flux density is uniform across the coil area and the same for all turns. By this approximation, the magnetic flux can be expressed as $\Phi \approx BA$, and the induced voltage can be estimated using a single effective coil area. However, this approximation becomes less accurate for the multi-turn coil used in this project because the individual turns are located in different axial and radial positions and experience different magnetic flux densities. In other words, as the copper wire reaches a certain length, successive turns overlap, causing the coil to form multiple layers. These multiple layers lead to the problem of non-uniform magnetic force acting on the coil. The further away from the magnet, the weaker the effect of the magnetic field B .

$$\varepsilon = V_{Ind} = -N \frac{\Delta \Phi_B}{\Delta t} \text{ where } \phi = \int_A B dA \text{ or } \phi(r, z) = \int_0^{2\pi} \int_0^{R_{now}} B_z(r, z) * r dr d\theta$$

If the field is axisymmetric and does not depend on θ , this simplifies to

$$\phi(r, z) = \int_0^{R_{now}} B_z(r, z) * 2\pi r \, dr$$

where the factor r is the Jacobian of cylindrical coordinates $dA = r \, dr \, d\theta$ ($0 \leq r \leq R_{now}$), R_i is the inner radius of the coil, R_o is the outer radius of the coil, R_{now} is the radius of the considered circular coil turn ($R_i \leq R_{now} \leq R_o$) and $B_z(r, z)$ is the axial component of the magnetic flux density on the surface surrounded by that wire loop.

The magnetic field effect of the magnet on the copper wire will change and shift as the magnet moves from top to bottom and vice versa. The magnet's magnetic force is strongest at the two poles, which significantly affects the current generated when these poles pass through. Assuming the magnet is in the center, when the magnet moves to the top, the induced voltage will reach a negative peak, and when it moves down, it will reach a positive peak. The negative induced voltage value indicates the polarity of the induced electromotive force according to Lenz's law. When the magnet reverses its movement, the rate of change of the magnetic flux also reverses, causing the induced voltage to change polarity. Therefore, the generator produces an alternating voltage. The Schottky bridge rectifier then converts this bipolar waveform into a DC output suitable for the charging circuit.

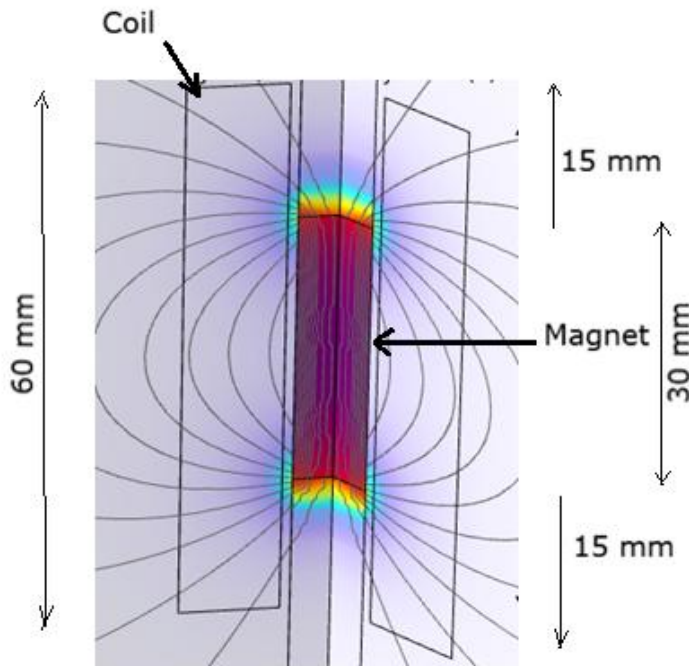


Figure 3.1: Illustration of the axial motion of the permanent magnet inside the copper coil.

The coordinates can be easily calculated using $x(t) = A \sin(2\pi * f_m * t)$ mm where A would be 30 mm and f_m is the number of complete reciprocating movements of the magnet

per second, but amplitude can change if the magnet's range of movement extends beyond the copper coil. From this sinusoidal oscillation, the position of the magnet is entirely dependent on time. In other words, the energy generated depends on the speed of the shaking (distance/position and time).

The project uses a cylindrical tube with an inner radius of 5 mm and a length of 60 mm, inside which a permanent magnet moves along its axis. According to equation (10), the resistance of the copper coil increases as the cross-sectional area of the conductor decreases. Therefore, the wire diameter must be chosen to balance the resistance and the number of turns that can be contained in the available coil volume. A very thin wire with a diameter under 0.1 mm will allow for a larger number of turns but results in significantly higher coil resistance. Conversely, a very thick wire with a diameter over 0.5 mm will reduce the coil resistance but significantly reduce the number of turns that can be wound in the same area. For these reasons, an intermediate wire diameter is preferred to balance the number of turns that can be achieved and the coil resistance.

Assuming the wire has a thickness diameter of 0.2 mm and is wound 6000 turns, the thickness created in the copper coil is calculated as

$$N_{axial} = \frac{L_{coil}}{d_{wire}} = \frac{60mm}{0,2mm} = 300 \text{ turns per radial layer}$$

If 6000 turns are wound around the tube for 300 turns per radial layer, then the winding requires 20 radial layers. The outer winding radius for ideal packing will be equal to the radius of the tube with the thickness of 20 layers. $R_o = R_i + N_{turns}d_{wire} = 5 \text{ mm} + 20 * 0,2 \text{ mm} = 9 \text{ mm}$

Each turn length is $L_{turn} = 2\pi r_{current}$. Since the coil consists of 20 radial layers, and each layer has approximately 300 axial turns, the total length of the wire is calculated by adding the circumferences of the turns.

$$L_{wire} = \sum_{k=1}^{20} 300 * 2\pi r_k \approx 263,9 \text{ m}$$

where r_k represents the centerline radius of the k-th radial layer.

$$\text{From (10)} \Rightarrow R = \rho \frac{L}{A} = 1.72 \times 10^{-8} \Omega m \frac{263,9 \text{ m}}{\pi(0.1 \text{ mm})^2} = 144 \Omega$$

The system will use Schottky bridge to convert the generated AC current into DC current. During each conduction cycle, the two BAT85 diodes conduct in series. The voltage drop across the bridge can be approximated as $V_{loss,bridge} \approx 2V_F$. Based on Figure 2.2, the voltage drops across the Schottky bridge changes depending on the current generated. The voltage drops across the full bridge is twice the voltage drop

across a single BAT85 diode. V_F is the forward voltage of a BAT85 diode at the corresponding forward current. As shown in Figure 2.2, the forward voltage is dependent on the current, so it should not be considered a fixed value. At a forward current of approximately 100 mA, the forward voltage drop reaches approximately 400 mV per diode, corresponding to a total bridge loss of approximately 800 mV. The voltage generated by the coil must be significantly higher than the required input voltage of the TP4056 (3.9 V) to compensate for the bridge rectifier losses and the resulting voltage variation. Therefore, a target generator voltage of approximately 5 V was chosen to provide additional voltage amplitude instead of being considered the theoretically required minimum voltage.

After passing through the Schottky bridge, the current will still have ripples between peaks. To solve this problem, a filter will be added to process the voltage before connecting to the charging module. A parallel RC circuit acts as a frequency filter, increasing voltage stability, discharging excess charge, and preventing sudden voltage drops. Additionally, the remaining excess AC current component in the DC source after rectification creates a ripple. Filtering capacitors store energy near the peaks of the rectified waveform and releases that energy between the peaks, reducing voltage ripple. A parallel resistor is not necessarily required for filtering when connecting the TP4056, as the charging module itself is a load. Adding a low-value parallel resistor would continuously dissipate some of the limited power captured and could therefore reduce the energy available for charging the battery. The TP4056 draws current from the rectified power source during charging, so it also acts as a non-linear variable load. In low-power hand-shaken electromagnetic generators, even 0.5 mA represents a significant portion of the available current. Therefore, a low-value parallel resistor will reduce the power supplied to the TP4056 and the battery.

Before conducting actual project testing, the magnets and coils will be calculated and modeled in MATLAB and verified using FEM to check the reliability of the MATLAB model.

Finite Element Method software is a digital tool that simulates how objects react to real-world physical conditions. It breaks down structures into thousands of "elements" to calculate stress, temperature, or vibration, helping engineers test designs before manufacturing. These software programs are categorized and applied based on their core purposes:

- **Structural & Mechanical Analysis:** Calculating strength, deformation, and stress under load. The most popular include Ansys, Abaqus, or SolidWorks Simulation.

- **Multiphysics Simulation:** Integrating the analysis of multiple physical phenomena simultaneously (heat, electricity, magnetism, fluid dynamics). Notable examples include COMSOL Multiphysics and Siemens' Simcenter.
- **Civil Engineering & Construction:** Specialized for evaluating building structures, beams, slabs, bridges, and roads. Typical examples include SAP2000 or ETABS.
- **Open-Source Applications:** Free or specialized solutions for research such as CalculiX.

COMSOL Multiphysics and Ansys Electronics Desktop were chosen for the project due to the two advantages mentioned above. The purpose of using two FEM solvers is not simply to replicate the same calculation. Instead, COMSOL and AEDT are used as independent numerical references to evaluate implementations in MATLAB. Magnet size, coil shape, material properties, and motion conditions are kept consistent across models. Comparisons focus on magnetic field distribution, induced voltage waveforms, polarity, peak values, and the dependence of magnet position and velocity on the magnetic field. This consistency between independently implemented models increases confidence that observed behavior is not solely due to assumptions or implementation errors in a single simulation environment.

The single objective of COMSOL is to determine the induced voltage across the coil terminals. The application achieves this by taking the integral of the electromagnetic fields over the entire multi-turn coil domain.

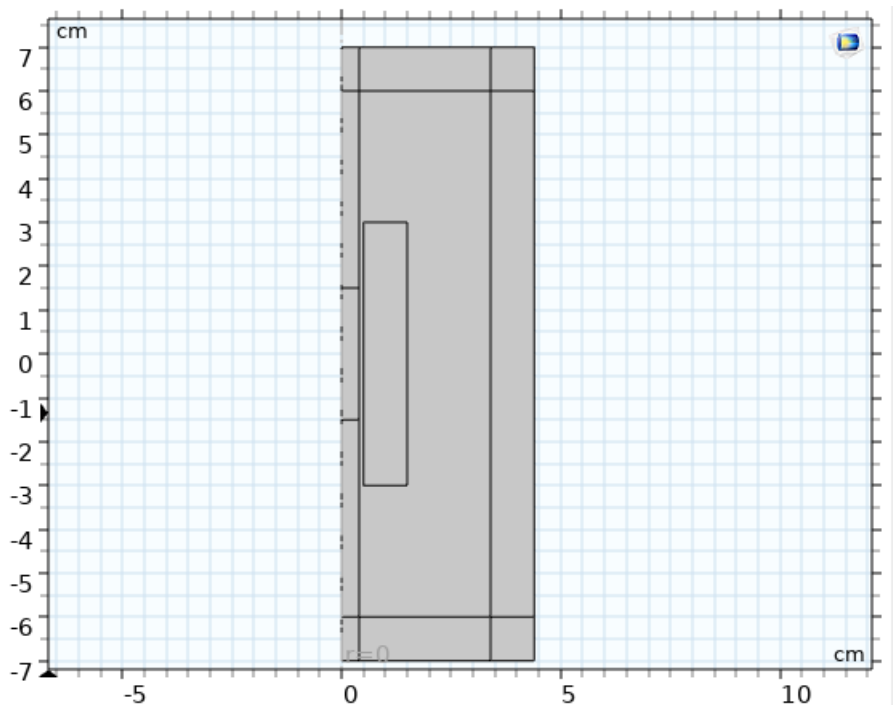


Figure 3.2: Geometry of the hand-shaken electromagnetic generator model implemented in COMSOL.

The magnet domain is small rectangle and located at the origin (0;0). The copper coil domain is a large rectangle and located slightly to the left of the center. Because the model uses a 2D Axisymmetric setup (a 2D cross-section tracking radius R and height Z), the coil domain represents a solid ring wrapping around the central axis. Under the Coil 1 feature settings, the conductor model is set to Homogenized multiturn. This treats the entire rectangular domain as an evenly distributed block of wires bundled together. In the COMSOL model, the coil contains 6000 turns, and the imposed coil current is set to $I_{coil}=0$ A. Therefore, no external load current is imposed on the coil, and the calculated quantity mf.VCoil_1 represents the induced coil voltage under open-circuit conditions. The voltage is generated by the time-varying magnetic flux linkage caused by the motion of the permanent magnet relative to the coil.

Unlike COMSOL, which is primarily used to test the electrical output (induced voltage) of entire multi-turn coils, ANSYS is used to test the distribution of the electromagnetic field and the physical interaction between the moving magnet and the coil. The AEDT solves Maxwell's equations over the entire three-dimensional geometry to determine the spatial distribution of magnetic flux density (magnetic field B) and magnetic field strength (magnetic field H). The permanent magnets were modeled with realistic dimensions and magnetic properties, while the copper coils were represented physically with 20 turns of wire. The copper coils were wound in circles of equal radius, each turn spaced at a uniform distance and stretched across a 60 mm cylinder to simulate a copper coil of similar height but with fewer turns. An axial translation motion setup is applied so that the magnet moves through the fixed coil at a predetermined velocity. The coil is connected to an external circuit (a resistance $R = 100 \Omega$) instead of a hypothetical one.

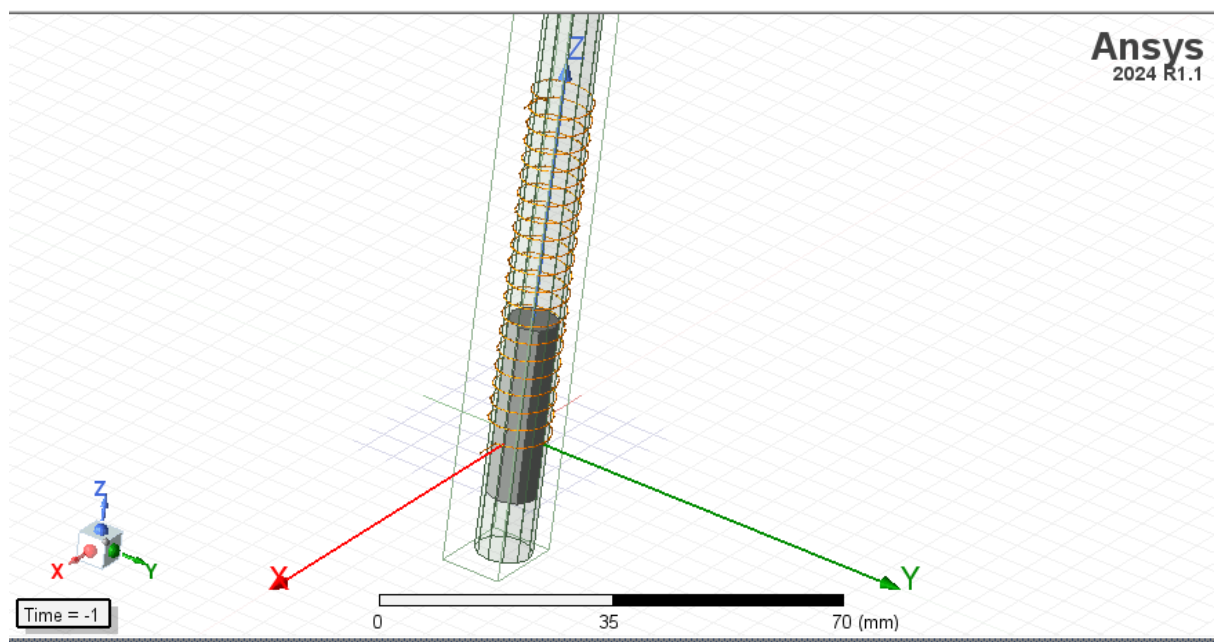


Figure 3.3: Geometry of the permanent magnet and copper coil model implemented in AEDT.

Although COMSOL Multiphysics and ANSYS Electronics Desktop provide finite-element methods for detailed electromagnetic of the generator, these applications have limitations when modeling complete power-conditioning circuits containing practical electronic components such as Schottky diodes and electrolytic capacitors. These components exhibit nonlinear electrical characteristics that are more effectively analyzed using circuit simulation software. LTspice is employed in the next stage of the project to simulate the rectification circuit, enabling evaluation of the Schottky bridge rectifier and smoothing capacitor under realistic operating conditions. The “.tran 0 10” command is used to perform a transient analysis over a simulation period of 10 s in LTspice. The analysis allows the time-dependent voltage and current waveforms to be observed before and after the rectifier and filter. It is particularly useful for evaluating the charging and discharging behavior of the smoothing capacitor, the resulting voltage ripple, and the current supplied to the load.

4 Simulation and cross-comparison

To verify the accuracy of the theory, a MATLAB numerical model was created to test the impact of the parameters on the generated power. Each stage of the simulation was independently compared between models along with the corresponding electromagnetic theory.

First, the magnetic field was calculated using a direct numerical method applying Biot-Savart's law. The resulting magnetic field distribution exhibited the expected axial symmetry of a uniformly magnetized cylindrical permanent magnet. It's important to distinguish here between equivalent magnetization current and real measurable current. Therefore, the equivalent magnetization current value is the current assigned to one mathematical loop representing a 1 mm magnet slice. The thickness depends on how many imaginary layers of the magnet are used (here $N_{mag_loops} = 30$). The equivalent magnetization current only exists in the Biot-Savart mathematical model, while the actual current generated by the shaking generator is calculated later from Faraday's law and Ohm's law.

Second, the magnetic flux through each coil increased with the coil radius, consistent with the increasing surrounding area predicted by Faraday's law.

Third, the total magnetic flux linkage changed continuously with the magnet's position, confirming that the interaction between the moving magnet and the entire coil was accurately represented.

Finally, the differential magnetic flux linkage produced an induced voltage waveform consistent with the sinusoidal oscillation of the magnet. The generated current was then estimated using the calculated coil resistance and external load resistance.

Overall, the simulation combines electromagnetic field theory [6], numerical integration, interpolation, and circuit analysis into a single model capable of predicting the electrical output of a vibrating magnet generator. MATLAB simulation will be tested with four parameters from the magnet and coil. Each time the test results are tested on different parameters, MATLAB will readjust the default parameters for the same major categories: Magnet and Copper coil. The default parameters below were selected because the data aligns with the system's original design objective: a palm-sized device that converts energy through manual shaking. Setting default values that are excessively high or low would result in less favorable comparative performance. The default values were calculated and determined based on sources [1], [3], and [4]. Frequency and Motion Amplitude will not change simultaneously, nor will Diameter of wire and Coil Height. This provides a consistent reference condition for comparing the effect of each parameter on the calculated output. The repeated values shown in the gray boxes of the results table represent the same reference configuration, not

independent test conditions. The results provide better data for future optimization of the energy production process.

Table 4.1: Results of peak induced voltage for different parameters

Magnet (4x30) Copper wire		Frequency (Hz)			Motion Amplitude (m)		
		3	8 (default)	10	0.03	0.015 (default)	0.01
Diameter of wire (m)	0.0001	0.263140	0.701707	0.877134	6.246137	0.701707	0.159051
	0.0002 (default)	0.294980	0.786614	0.983267	5.823263	0.786614	0.216637
	0.00035	0.335736	0.895297	1.119121	5.094019	0.895297	0.351512
Coil Height (m)	0.01(invalid)	34947.268118	93192.714982	116490.893728	896879.612596	93192.714982	6.231944
	0.06 (default)	0.294980	0.786614	0.983267	5.823263	0.786614	0.216637
	0.1	0.007435	0.019826	0.024783	0.231549	0.019826	0.007720

To avoid altering the original purpose of the project, the magnet dimensions are fixed because increasing the magnet size would increase the weight and overall size of the copper coil. Therefore, the magnet will remain fixed at the size of 8 mm diameter and 30 mm length. The obtained peak induced voltage value demonstrates how the amplitude of the magnet's oscillation greatly affects energy transfer. At a doubling of the amplitude from 15 mm to 30 mm, the induced voltage obtained increased 7.4 times ($\frac{5.823263}{0.786614}$). At a tripling of the frequency from 3 Hz to 10 Hz, the induced voltage obtained increased 3 times ($\frac{0.983267}{0.294980}$). This result shows that the amplitude of oscillation has a greater influence on the induced voltage generated than the frequency of oscillation. Although both of these values are related to the speed of the magnet, the amplitude also affects the position of the magnetic field that the magnet exerts on the copper coil. In other words, changing the amplitude changes both velocity and the portion of the spatial flux-linkage curve traversed by mag.

The test of the effect of the copper coil height also yielded physically impractical results for the smallest coil size (10 mm). By reducing the coil height while maintaining a total winding of 6000 turns and a wire diameter thickness of 0.2 mm, the model compressed the same number of turns into a significantly smaller winding area. This resulted in an unrealistic coil shape and generated induced voltage values of tens or hundreds of thousands of volts. These values are inconsistent with the physical scale of the

generator and should therefore be considered numerical spurious phenomena rather than accurate predictions. Thus, results using non-physical parameters are excluded from the optimization analysis.

Due to the processing capabilities and speed limitations of the AEDT, the model can only operate for a certain number of turns of wire; otherwise, the program will crash or the analysis process will take hours. Starting the coil model with 1000 turns and gradually reducing the number of turns if the AEDT fails, the results showed that the model operated stably with a relatively low number of turns, 20 turns.

Below are images obtained from MATLAB, COMSOL, and AEDT illustrating the direction of magnetic field lines and the B-field value in Tesla:

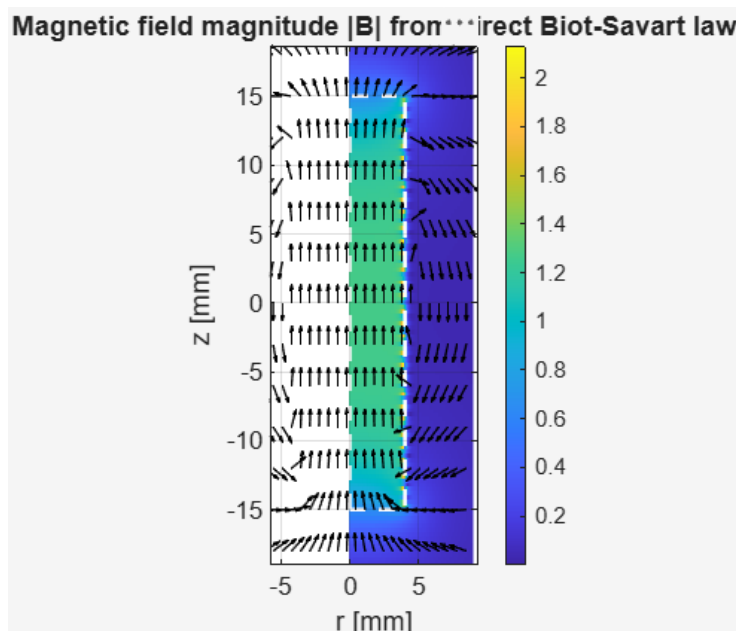


Figure 4.1: Magnetic flux-density (B-field) distribution around the permanent magnet calculated using the MATLAB model.

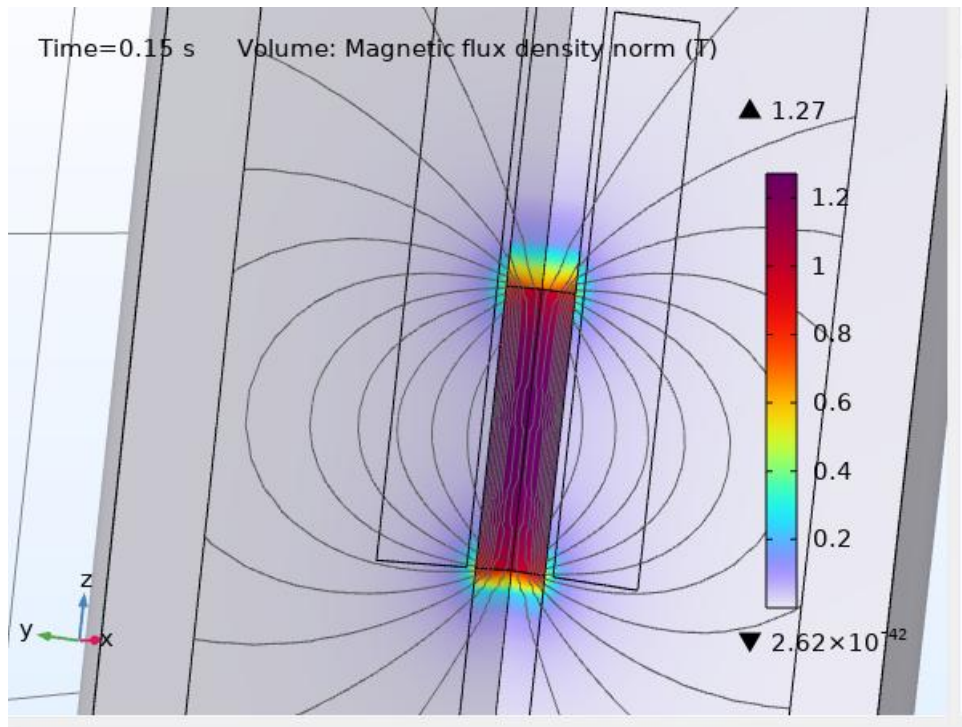


Figure 4.2: Magnetic flux-density (B-field) distribution around the permanent magnet calculated using the COMSOL model.

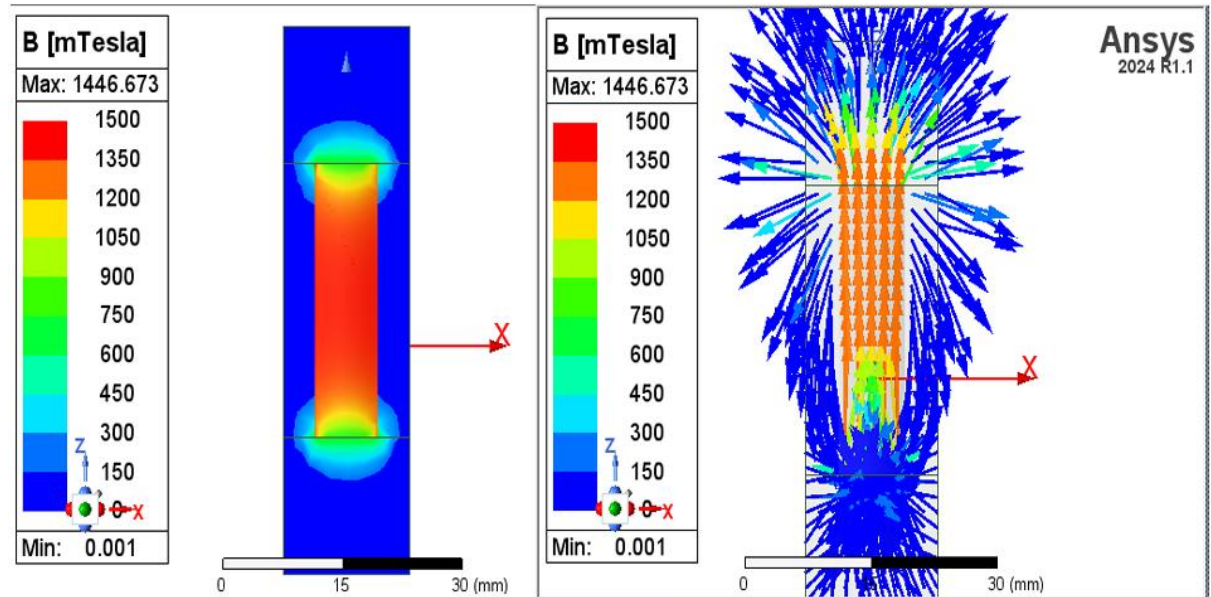


Figure 4.3: Magnetic flux-density (B-field) distribution around the permanent magnet calculated using the AEDT model.

The initial magnetic field analysis was used as a consistency check for the implementation in MATLAB. The result supports the consistency of MATLAB model for the analysis and calculation of the B-field from the magnet datasheet. For a permanent

magnet with a residual magnetic flux density of approximately 1.2 T, the calculated magnetic flux density is concentrated near the poles of the magnet and decreases as the distance from the magnet increases. The initial analysis only considered the magnetic field distribution of a stationary permanent magnet, excluding copper coils or magnet movement. MATLAB, COMSOL, and AEDT produced qualitatively similar spatial magnetic field distributions. However, differences were observed in their calculated peak values. These values are small dots located along the sides of the magnet but are not continuous in the graph. This is an error in the model created by MATLAB. The MATLAB model demonstrated similarity in magnetic flux density at identical spatial locations, along with convergence at both poles. The core of the magnet has values ranging from 1 to over 1.2 Tesla. The poles have values ranging from 0.75 to 0.9 Tesla, and the area of the sides along the length of the magnet is almost zero Tesla, which can be observed visually based on the graph's color.

The table below shows the difference between the results of AEDT, COMSOL, and MATLAB for the same parameter. AEDT has a speed setting instead of frequency like the MATLAB and COMSOL models, so this conversion value needs to be calculated beforehand ($f_m = \frac{velocity}{2\pi \cdot Amplitude}$) to ensure data consistency in the comparison.

Table 4.2: Comparison of induced-voltage results from MATLAB, COMSOL, and AEDT

	MATLAB	AEDT	COMSOL
Magnet: N42 cylindrical magnet Diameter = 8 mm Length = 30 mm $B_r = 1.315$ T Amplitude motion = 30 mm Frequency = 0.18568 Hz (35 mm/s) Coil: Inner radius = 5 mm Length = 60 mm Wire diameter = 0.2 mm Total turn = 20 turns	0.465 mV	0.287 mV	0.488 mV
Magnet: N42 cylindrical magnet Diameter = 8 mm Length = 30 mm $B_r = 1.315$ T Amplitude motion = 30 mm Frequency = 2.122 Hz (400mm/s) Coil: Inner radius = 5 mm Length = 60 mm Wire diameter = 0.2 mm Total turn = 20 turns	0.005318 V	0.0009 V	0.0056 V

MATLAB results are close to the numerical FEM results obtained from COMSOL. Errors are unavoidable. Comparing MATLAB and COMSOL results show a difference of approximately 4.7% at 0.18568 Hz and 5% at 2.122 Hz when normalized to COMSOL. In contrast, the AEDT simulation results are completely different, with a deviation of up to 83%. The AEDT results differ significantly from those of MATLAB and COMSOL. However, a direct comparison of percentage errors is not entirely appropriate because the AEDT model uses different electrical boundary conditions and a simpler motion configuration. The AEDT model uses a 100 Ω external load, while COMSOL is described as calculating the open-circuit winding voltage. Therefore, the AEDT results should be considered a qualitative comparison rather than a direct confirmation of the magnitude of the induced voltage.

If we consider the MATLAB output to be usable, then the necessary parameters for the project would be:

- Magnet:

- N42 cylindrical magnet
- Diameter = 8 mm
- Length = 30 mm
- $B_r = 1.315 \text{ T}$
- Amplitude motion = 30 mm
- Frequency = 8 Hz
- Coil:
 - Inner radius = 5 mm
 - Length = 60 mm
 - Wire diameter = 0.2 mm
 - Total turn = 6000 turns

which are the parameters required for the energy generator to produce a minimum voltage 5 V. The induced voltage can be greater if the magnet moves at a higher frequency and faster speed. The induced voltage waveforms obtained from MATLAB and COMSOL may appear as mirror images of each other because the voltage polarity depends on the reference orientation chosen for the coil terminals and the direction of the magnet's movement. Reversing any convention changes the sign of the calculated induced voltage without altering the physical magnitude or overall characteristics of the waveform. Therefore, when comparing the two models, the magnitude and shape of the waveform, along with the polarity convention used in each simulation, should be considered.

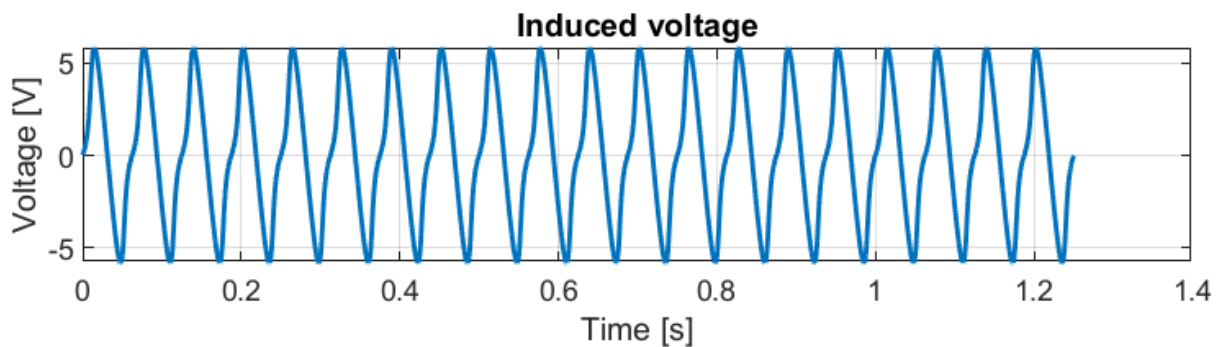


Figure 4.4: Induced-voltage waveform calculated using the MATLAB model.

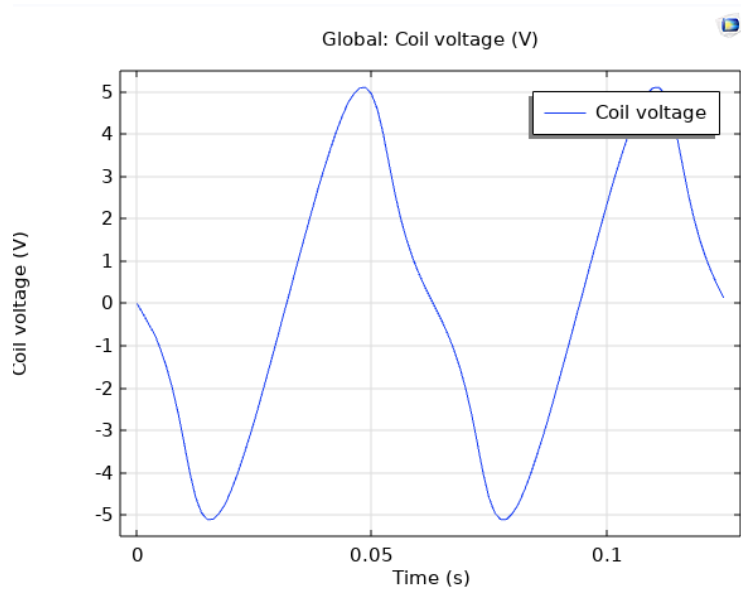


Figure 4.5: Induced-voltage waveform calculated using the COMSOL model.

Under the above conditions, the maximum induced voltage in MATLAB is 5.823263 V and in COMSOL is 5.1081 V. Regardless of the calculated data, the voltage is sufficient to activate the TP4056 charging module after accounting for the voltage drop across the Schottky bridge.

Under simulated conditions, the generator produces a maximum open-circuit induced voltage exceeding 5 V. The value demonstrates that the generator can achieve the voltage range necessary for the subsequent rectification and charging stages. However, the maximum induced voltage should not be interpreted as a continuous 5 V DC voltage, as the generated voltage changes continuously with the position and velocity of the magnet. The data provides information assuming the generator's output. The vibrating generator can produce a nearly sinusoidal induced voltage with a peak amplitude of approximately 5 V and an oscillation frequency of 8 Hz. Although the induced voltage waveforms obtained from MATLAB and FEM are not completely sinusoidal, due to the flux linkage being a nonlinear function of the magnet position. The magnetic field is not spatially uniform, and the rate of change of the coil flux varies depending on whether the magnet is near the center of the coil, near the coil ends, or farther away. Consequently, even when the magnet motion is sinusoidal, the resulting induced-voltage waveform is not perfectly sinusoidal. An ideal sinusoidal voltage source is used in the LTspice model as a simplified and controlled input. The purpose of

the LTspice simulation is not to accurately reproduce the waveform generated by the moving magnet, but rather to study the operation of the rectifier and filter circuits under different component values and input conditions. Specifically, the effect of changing the smoothing capacitance and load on the rectified output voltage and voltage ripple are compared.

$$\text{From (11), } C = \frac{I}{2f_{AC} \Delta V_{ripple}} = \frac{0.002A}{2 * 8 \text{ Hz} * (7-2)V} = 25 \mu F$$

These values are taken from MATLAB, where 8 Hz is the mechanical shaking frequency ($f_{AC} \approx f_m$) and assume the ripple voltage obtained after rectification ranges from 2 to 7 volts. $f_{AC} \approx f_m = 8 \text{ Hz}$ is a first order simplifying assumption. The actual simulated waveform can have multiple voltage peaks within a single cycle of mechanical oscillation.

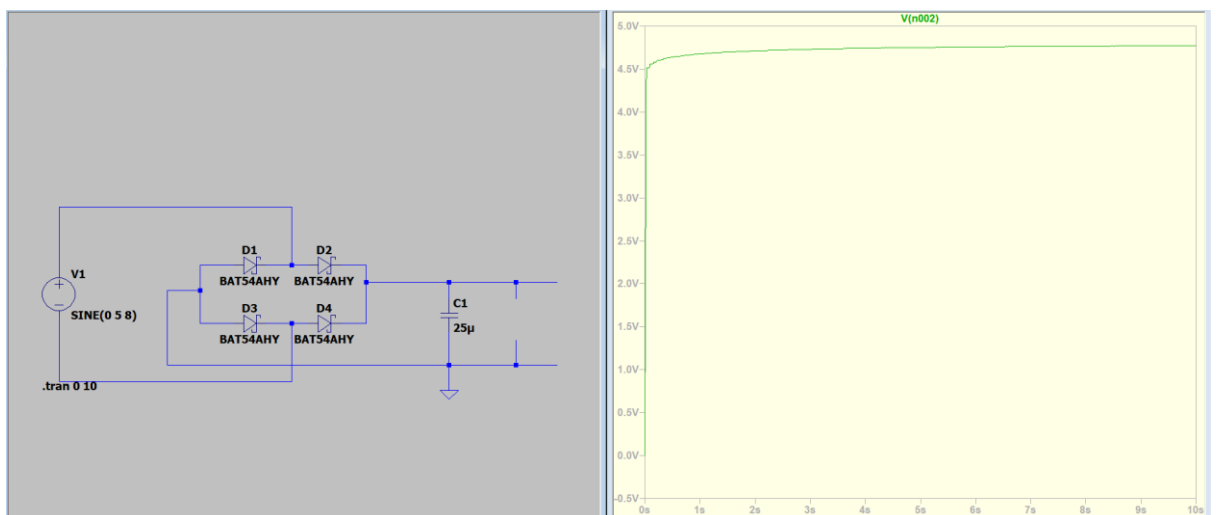


Figure 4.6: LTspice simulation of the rectifier and smoothing-capacitor circuit without a parallel resistive load.

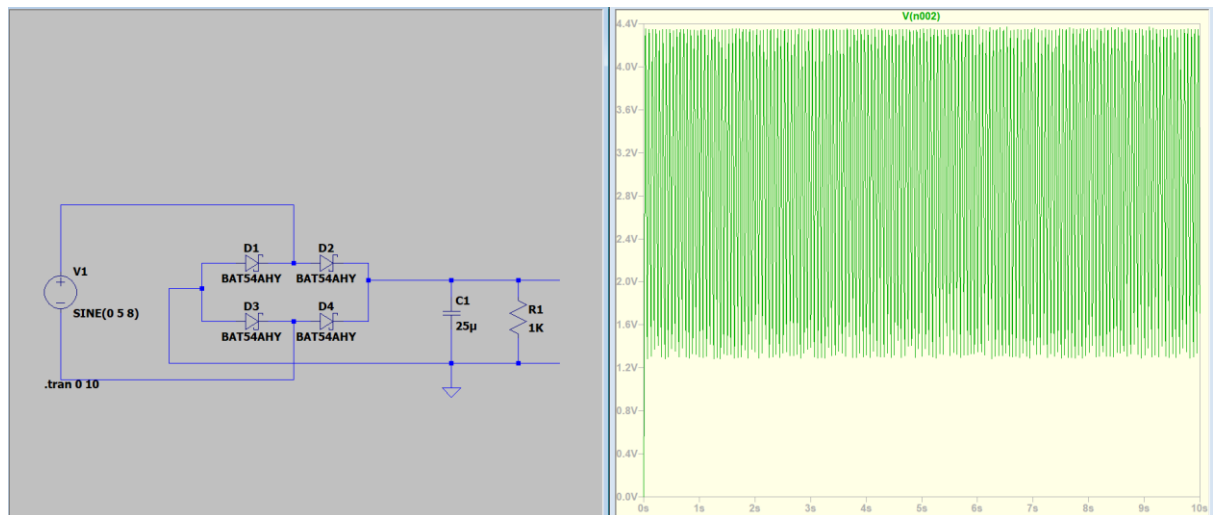


Figure 4.7: LTspice simulation of the rectifier and smoothing-capacitor circuit with parallel resistor $R = 1\text{ k}\Omega$.

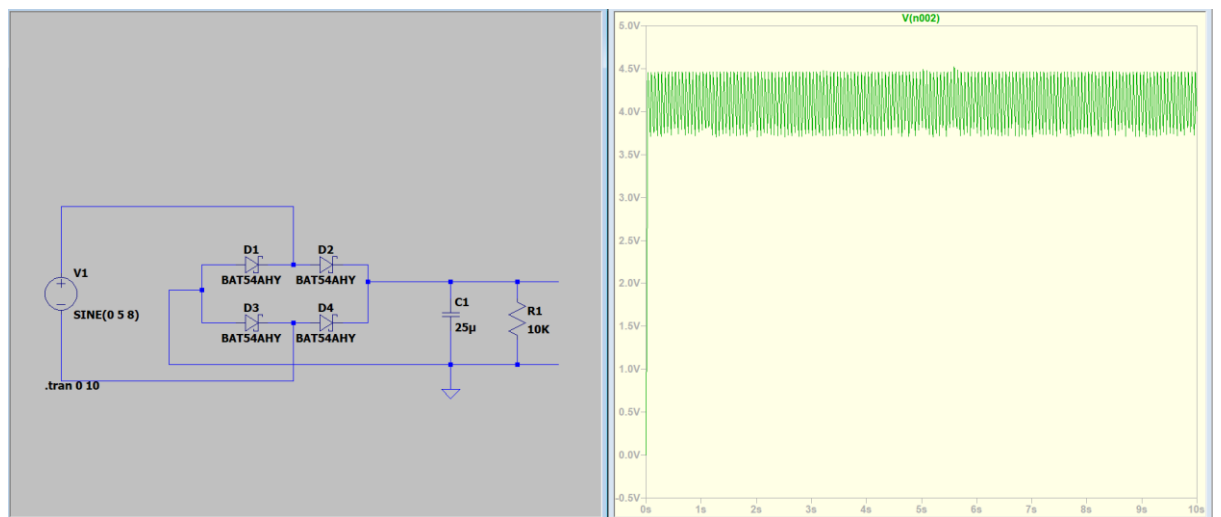


Figure 4.8: LTspice simulation of the rectifier and smoothing-capacitor circuit with parallel resistor $R = 10\text{ k}\Omega$.

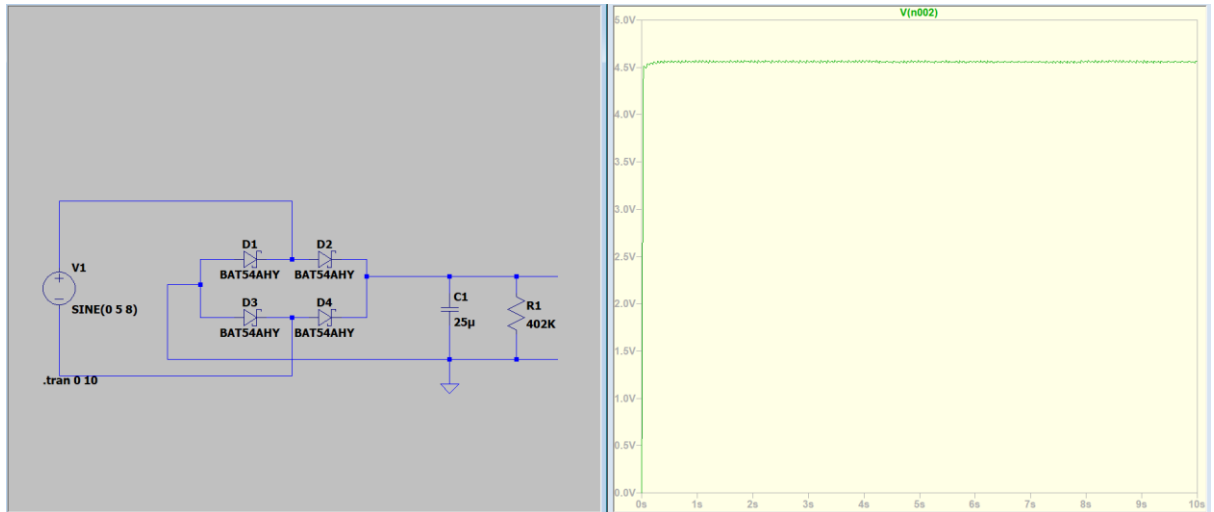


Figure 4.9: LTspice simulation of the rectifier and smoothing-capacitor circuit with a high resistive load with $R = 402 \text{ k}\Omega$. A resistance of approximately $0.4 \text{ M}\Omega$ was measured with a multimeter between the selected TP4056 module terminals under a non-operating measurement condition.

Figures from 4.6 to 4.9 provide the most comprehensive view of the impact of parallel RC circuits on the output after rectification. The electrolytic capacitor helped stabilize the voltage very well, maintaining an operating voltage above 4 V (the charging condition for the TP4056 module is above 3.9 V). The higher the resistance, the smoother the output voltage. Increasing the parallel load resistance reduces the discharge current drawn from the filter capacitor. Therefore, the capacitor loses less charge between successive rectification peaks, resulting in a smaller voltage ripple. Although the same thing happens without load resistance, the voltage without resistance will have a certain curvature. In practice, the circuit will not end at the point where an electrolytic capacitor is connected in parallel. Therefore, that case will not occur.

Furthermore, the TP4056 is an active and nonlinear battery-charging circuit whose input behaviour depends on several factors, including the input voltage, battery voltage, programmed charging current, and operating state of the charger. In addition, the energy-harvesting generator used in this project provides a weak and intermittent input that varies with the manual shaking motion. Consequently, the actual interaction between the generator, rectifier, smoothing capacitor, TP4056 module, and battery

cannot be represented accurately by a single fixed resistance. The nonlinear and intermittent behaviour of the TP4056 was not simulated in LTspice. The 402 k Ω resistor was used only as a simplified high-resistance/off-state load to investigate the behaviour of the rectifier and filtering circuit under a very light load.

5 Results

The project utilized a hollow cylindrical tube with a diameter of 10 mm and a height of 90 mm. A copper wire with a diameter of 0.2 mm was wound around this tube. The copper coil was wound 6000 turns with a height of 60mm around the center of the tube. The copper coil was wound manually around the tube, one turn at a time. The number of turns here is counted and recorded 100 turns at a time, for a total of 60 times. The wire was wound continuously along the axial direction until the first layer was completed. The same procedure was then repeated for each subsequent layer until a total of approximately 6000 turns had been achieved. During the winding process, the turns were kept as compact and uniform as practically possible. Insulating tape was applied where necessary to secure the windings and prevent the coil from becoming loose. Before beginning the winding process, a sufficient length of copper wire was left unwound at the starting end to provide an electrical connection to the subsequent circuit. After 6000 turns had been completed, a sufficient length of copper wire was also left at the finishing end. These two wire ends therefore form the electrical terminals of the coil. The hollow part inside has a radius of 5 mm, which is the radius of the plastic tube. The actual thickness of the copper coil after 6000 turns is 8 mm. Therefore, the total radius from the center of the copper coil is approximately 13 mm. The copper wire is wound around the outer surface of the hollow cylindrical tube. The cross-sectional area of the copper wire block $A_{winding} = \pi(R_o^2 - R_i^2)$ where R_i is the inner radius and R_o is the outer radius of the winding. This represents the total winding region rather than the actual cross-sectional area occupied by copper, since the physical winding also contains wire insulation and voids between adjacent turns. The difference in copper coil thickness between the hypothetical numerical model and the prototype stems from the manual winding, as mentioned in the description. The measured DC coil resistance of the copper coil is 145 Ω . The value was measured at the two ends of the copper coil after winding 6000 turns. The simulated and experimental voltage values cannot be considered geometrically identical, but the obtained copper coil resistance values from the hypothesis are still very accurate and serve as a reference and foundation before delving into prototype implementation.

The permanent magnet used in the prototype had a diameter of 8 mm and an axial length of 30 mm. The tube provided approximately 90 mm of available axial space for the magnet. Since the magnet itself occupied 30 mm of this space, the maximum travel distance of the magnet center was approximately 60 mm. If the center of the tube is the starting position, the magnet moved within an amplitude of ± 30 mm.

Below are the results obtained using an oscilloscope to observe the induced voltage generated by the copper coil and magnet before passing through the Schottky bridge.

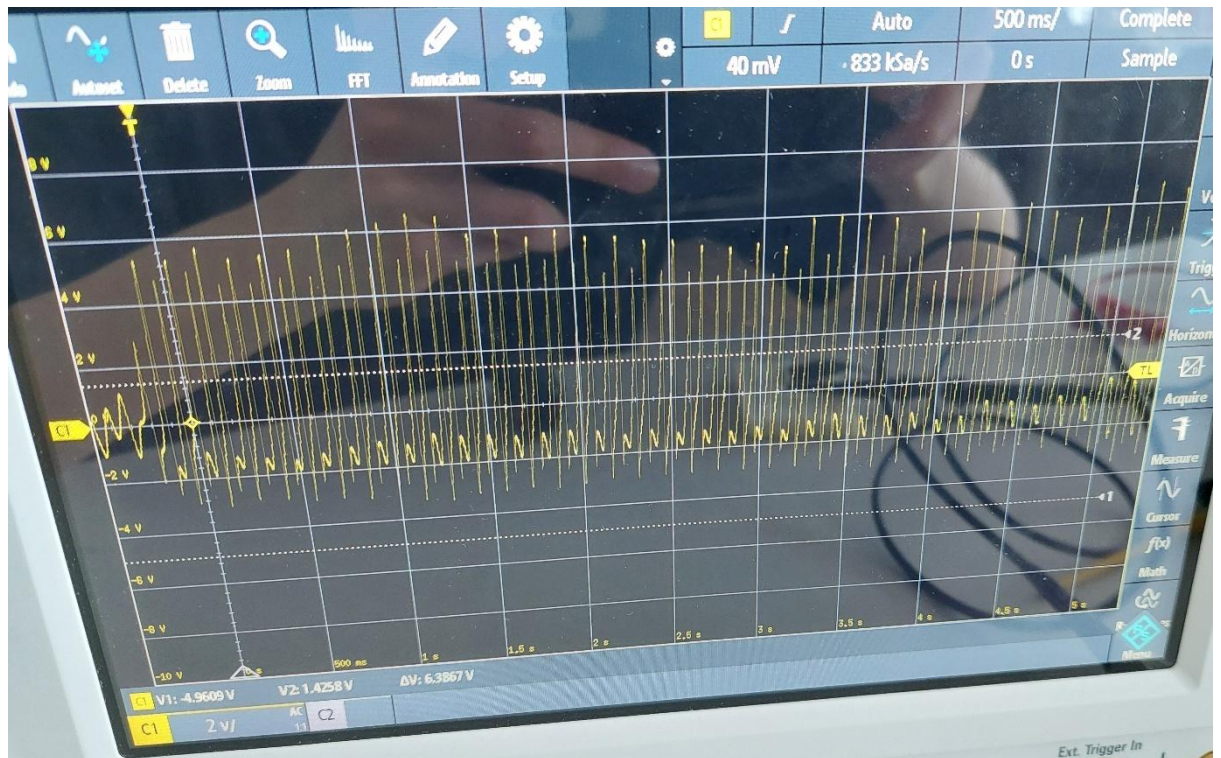


Figure 5.1: Measured AC voltage waveform generated by the prototype before the Schottky bridge rectifier.

Because the excitation is done manually, the movement of the magnet is not perfectly uniform, leading to significant variation in the measured peak voltage. With the magnet and coil shapes fixed, the induced voltage is primarily determined by the movement of the magnet relative to the coil, especially its instantaneous velocity and position, as these factors determine the rate of change of the magnetic flux linkage. Changes in the manual shaking force produce different positive and negative voltage peaks. During experimental measurements, the observed peak voltage remained below approximately 8 V, even when the device was shaken as vigorously and quickly as possible by hand. Figure 5.1 shows the result obtained from a closed circuit between a generator and a resistor 39 kΩ. The measured current is approximately 0.2 mA, which satisfies Ohm's law when $I = \frac{V}{(R_{load} + R_{coil})} = \frac{8\text{ V}}{(39\text{ k}\Omega + 145\text{ }\Omega)} \approx 0.21\text{ mA}$. The induced voltage generated by the device is alternating current because the magnet moves continuously in both directions relative to the coil. According to Faraday's law, reversing the direction of movement changes the rate of change of the magnetic flux link and thus reverses the polarity of the induced electromotive force. Therefore, the generator produces alternating current before the rectification stage. The negative voltage values observed during the measurement represent a reversal of the voltage polarity relative to the selected reference voltage and are an expected part of the alternating current waveform. To utilize this generated energy, a rectifier with four Schottky diodes BAT85 is used to convert AC to DC.

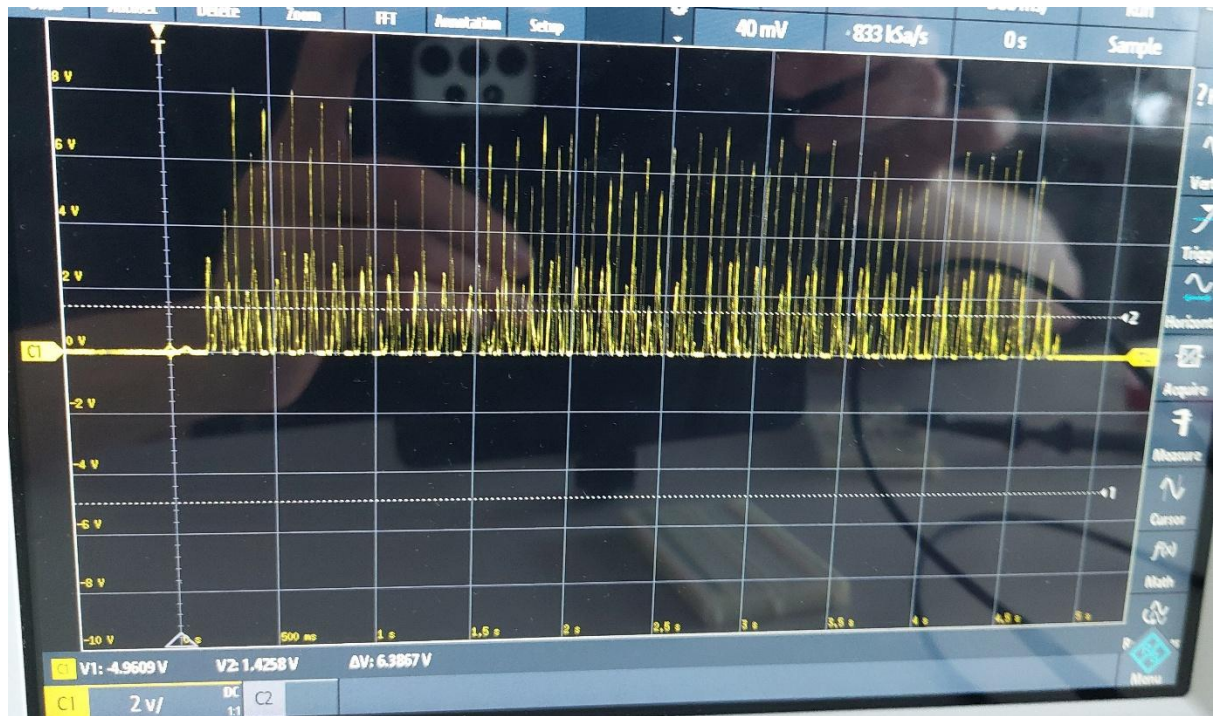


Figure 5.2: Measured DC voltage waveform generated by the prototype after the Schottky bridge rectifier.

In contrast to the bipolar AC waveform measured before rectification, the output signal after the bridge rectifier is DC, demonstrating successful full-wave rectification. However, the waveform fluctuates significantly, with the voltage dropping to near zero between successive peaks. The variation in peak amplitude is mainly due to the uneven movement of the magnets created by the handshaking. During each conduction interval, there are two Schottky diodes in the current path, resulting in a corresponding voltage drop approximately twice the forward voltage drop in the instantaneous current. Therefore, the measured waveform shows that the bridge rectifier converts AC voltage to DC, but this DC source is unstable. Consequently, a smoothing capacitor is needed to reduce voltage ripples before connecting to the charging circuit.

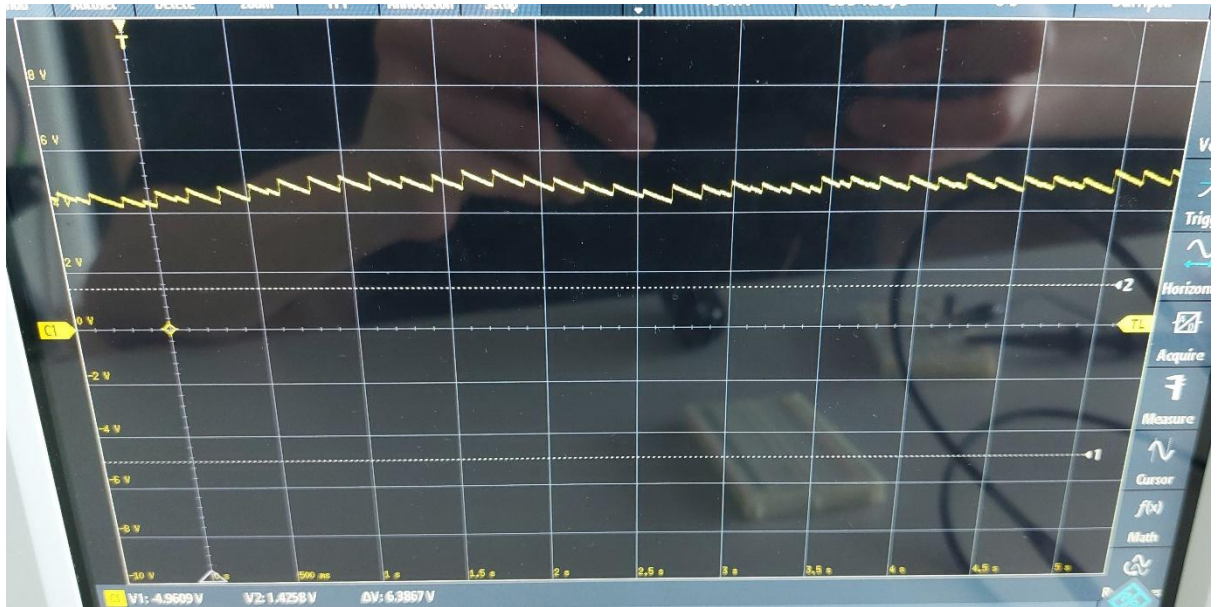


Figure 5.3: Measured rectified output-voltage waveform after smoothing with a 47 μF electrolytic capacitor.

Figure 5.3 shows the output voltage of the rectified generator after connecting a electrolytic capacitor 47 μF in parallel with a resistive load 39 $\text{k}\Omega$. Compared to the bridge rectified waveform without the capacitor, the voltage no longer experiences large dips between successive voltage peaks. Instead, the capacitor is charged when the rectified generator voltage exceeds the capacitor voltage and then discharged through the load between charging intervals. This connection produces smooth DC voltage that still exhibits a sawtooth ripple. The electrolytic capacitor 47 μF was used in the physical prototype because a 25 μF capacitor was not available. For comparison, two 56 μF electrolytic capacitors were connected in series, resulting in an equivalent capacitance of approximately 28 μF . The experimentally observed output waveform did not show a substantial difference between the approximately 28 μF and 47 μF configurations under the tested conditions. The capacitor 47 μF was retained for the prototype due to component availability and its good signal smoothing performance.

The RC time constant [6] of the test circuit is approximately $\tau = 39 \text{ k}\Omega \times 47 \mu\text{F} = 1.83 \text{ s}$. This time interval is relatively long compared to the time interval between successive charging pulses. Therefore, the capacitor retains a significant portion of its charge between generator excitations. Under measurement conditions, the smoothed voltage remains within the 4–5 V range despite the uneven input signal.

On the other hand, the resistor 39 $\text{k}\Omega$ represents a relatively light load, consuming only about 0.1 mA at this voltage. Therefore, it should not be assumed that the measured smoothing performance remains unchanged when the TP4056 charging module is connected. The TP4056 creates a non-linear and potentially heavier load, which can increase the capacitor's discharge rate and thus increase voltage ripple. Therefore, this

experiment demonstrates the effectiveness of the capacitor $47\ \mu\text{F}$ in smoothing under the defined test load $39\ \text{k}\Omega$ conditions, not the continuous operation of the TP4056. Before testing the system with the TP4056 charging module, the resistive load $39\ \text{k}\Omega$ was replaced with three LEDs connected as a simple visual test load. The purpose of the testing was to verify that the rectified and smoothed generator output could produce sufficient rectified voltage under some shaking conditions to activate the charging module and generate a small battery-side current. The light emitted from the LEDs provided a qualitative indicator that electrical energy was being transferred through the rectification and smoothing stage. This test was used as a preliminary check before connecting the TP4056 charging module, thus reducing the risk of incorrect wiring or insufficient input conditions during the charging stage evaluation.

To check if the generated voltage and current meet the required value before connecting to the charging module, the system connects three $2.1\ \text{V}\ 20\ \text{mA}$ LEDs in series and parallel with electrolytic capacitors to create a load that requires a minimum voltage of $6.3\ \text{V}$ to power all three LEDs.

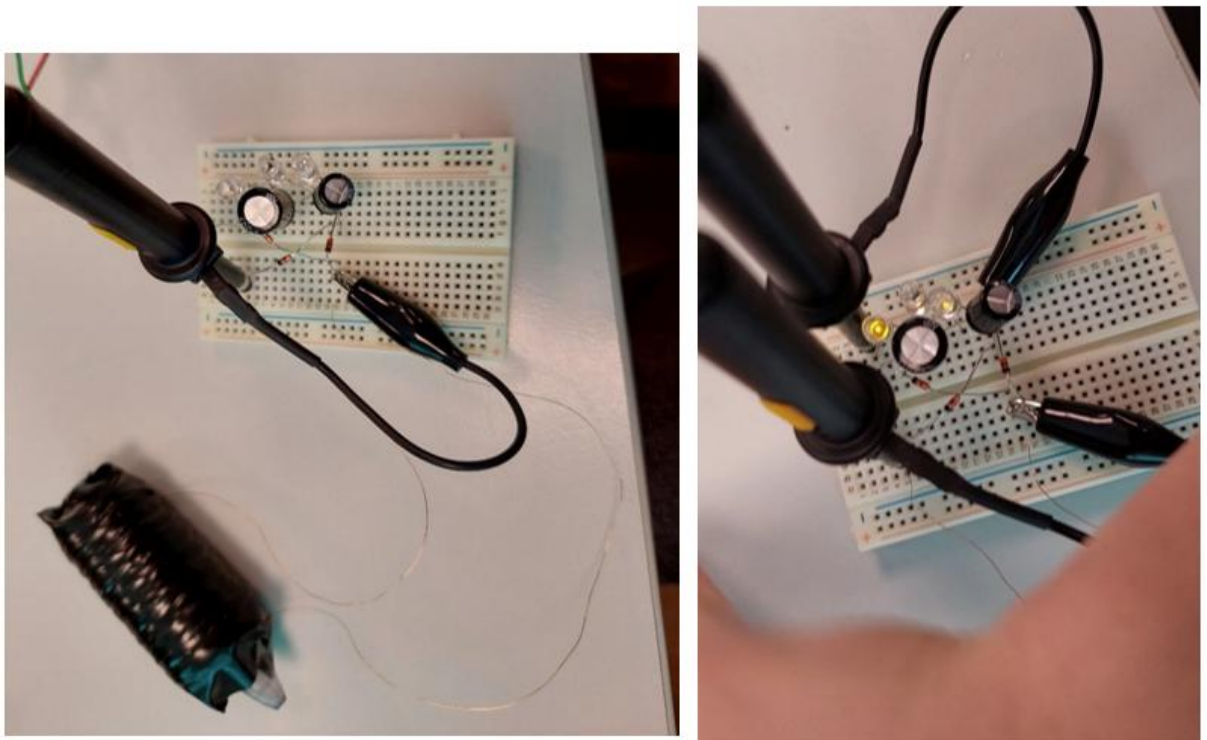


Figure 5.4: Experimental test setup with three LEDs connected in series and the LEDs illuminated during generator operation.

Under the influence of a certain shaking force, the lights illuminate with gradually increasing intensity until a certain level is reached. After reaching maximum brightness, the three LEDs slowly dim after the shaking stops or slows down and turn off completely within approximately 0.3 seconds. The time value is determined by human reflexes, so the value is for reference only. These developments demonstrate that the

power generation system is functioning as expected. The amount of electricity generated is sufficient to power the charging module. The capacitors are working correctly as the three light bulbs do not flicker when the current fluctuates. A capacitor value that is too high as 100 μF will keep the capacitor constantly charging, while a value that is too low as 10 μF will cause it to discharge too quickly. After verifying that the output value of the power generation and AC-to-DC conversion is stable, the system performs a final test with the charging section.

To generally check the voltage across the entire system, the following three points will be observed specifically for each part of the system at the same time:

- Voltage generated from the copper coil and magnet (electrical energy generated)
- Input voltage of the TP4056 module (electrical energy converted from AC to DC)
- Output voltage of the TP4056 module (energy stored)



Figure 5.5: Measured induced voltage, TP4056 input voltage, and battery-side output voltage during manual operation of the generator (TP4056 output voltage).



Figure 5.6: Measured induced voltage, TP4056 input voltage, and battery-side output voltage during manual operation of the generator (TP4056 output voltage).



Figure 5.7: Measured induced voltage, TP4056 input voltage, and battery-side output voltage during manual operation of the generator (TP4056 output voltage).

Figures from 5.5 to 5.6 show the results obtained with induced voltage displayed via oscilloscope, input voltage module displayed via the central measuring instrument, and output voltage module displayed via the measuring instrument on the right. The measurements demonstrate the effectiveness of the Schottky bridge rectifier and smoothing capacitor in converting the generator's unstable AC output into a more stable DC voltage. Under the tested manual shaking conditions, the TP4056's input voltage remained within approximately 3.8–5.6 V and did not exceed 6 V.

The battery terminal voltage was 3.830 V before the test. A dynamic voltage of approximately 4.0–4.2 V was observed during operation, but the measurement point and transient nature of this reading did not allow it to be interpreted reliably as a change in the battery cell voltage. It is therefore not used as evidence of increased battery state of charge. Evidence is limited to the TP4056 charging indication and the positive battery-side current measured during four 10-second shaking trials. No measurable change in battery state of charge or battery terminal voltage was established.

These are the specific parameters obtained for the system to operate (TP module enters charging state). Figure below is an oscilloscope image at the input point of the TP4056 module. In other words, this is the ripple voltage point of the Schottky bridge after being smoothed by the electrolytic capacitor.

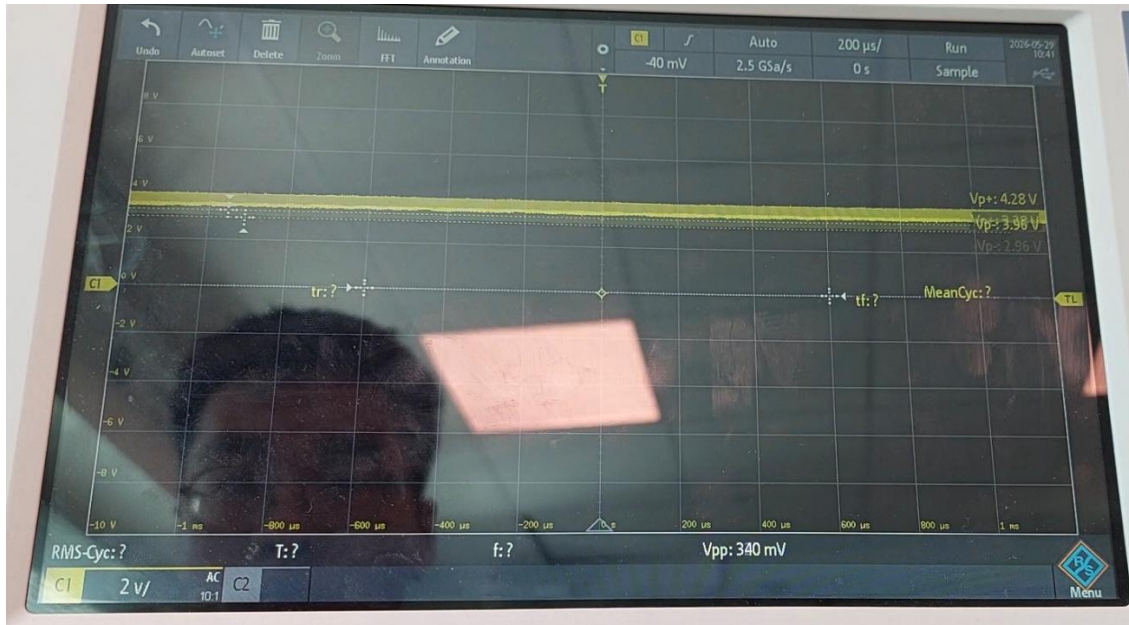


Figure 5.8: Oscilloscope measurement of the voltage at the input of the TP4056 charging module during manual shaking.

The above results allow for a more visual observation of the value obtained at this point when the charging module is operating. To further verify that current is actually being supplied to the battery, a baseline measurement should first be taken when the generator is idle and no charging input is applied. The voltage measured under these conditions is then compared to the voltage measured at the same location when the generator is supplying sufficient input voltage to activate the charging module. The transient voltage observed during operation is not used as evidence of a change in battery state of charge because the measurement point could not be reconstructed unambiguously. Evidence of current transfer is instead based on the TP4056 charging indication and the positive battery-side current measured in series between the charging module and the battery.

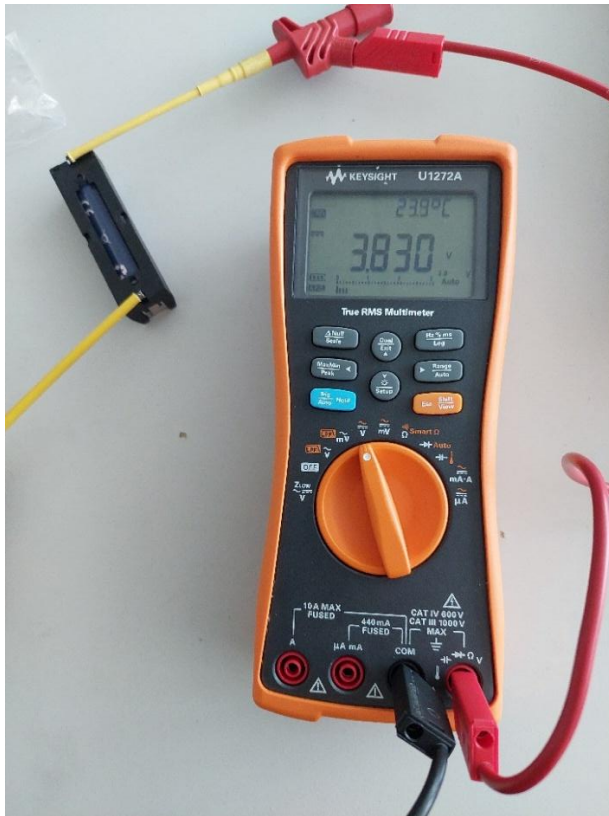


Figure 5.9: Voltage measured across the terminals of the 18650 battery before the charging test.

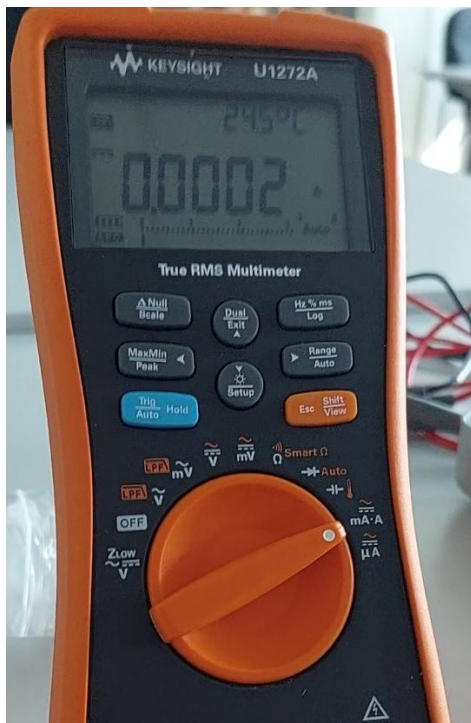


Figure 5.10: Battery-side charging current measured between the TP4056 module and the 18650 battery during manual shaking.

The initial battery voltage before the charging test was measured at 3.830 V. During the operation of the vibration generator, the TP4056 changed operating state as the rectified and smoothed input voltage increased above approximately 4 V, and the red CHRG indicator illuminated. A transient voltage of approximately 4.0–4.2 V was observed during operation. However, the measurement point and transient nature of this reading did not allow it to be interpreted reliably as a change in the battery cell voltage. Therefore, this reading is not used as evidence of an increase in battery state of charge. The charging current was measured in series between the TP4056 module and the positive terminal of the battery holder. The measurement was recorded on video, and observation of the recorded values showed an average current of approximately 0.2 mA throughout the test period. A more accurate determination of the average charging current required recording $i(t)$ over a fixed shaking interval (10 s) and perform four experiments under nearly identical conditions. Current readings were extracted from the recording at one-second intervals. Because the current varied with the manual shaking motion, the time-average current was estimated from $I_{avg} \approx \frac{1}{N} \sum_{k=1}^N I_k$. The charge transferred during the measurement interval was estimated numerically from $Q \approx \sum_{k=1}^N I_k \cdot \Delta t = N \cdot I_{avg} \cdot \Delta t = I_{avg} \cdot T$ where $T = N \cdot \Delta t$.

Table 5.1: Charging current measured between the TP4056 B+ terminal and the positive terminal of the battery.

	1st time (mA)	2nd time (mA)	3rd time (mA)	4th time (mA)	
1s	0,1	0,2	0,1	0,3	
2s	0,2	0,2	0,2	0,4	
3s	0,3	0,2	0,1	0,3	
4s	0,5	0,3	0,2	0,3	
5s	0,4	0,2	0,3	0,4	
6s	0,4	0,2	0,2	0,3	
7s	0,4	0,2	0,2	0,5	
8s	0,3	0,3	0,2	0,2	
9s	0,3	0,2	0,3	0,2	
10s	0,2	0,1	0,4	0,2	
I_avg	0,31	0,21	0,22	0,31	= 0,2625 mA

The battery charging current measurements were repeated four times under manual shaking conditions, each lasting 10 seconds. Current values were recorded from the multimeter display at 1-second intervals. The average current obtained in the four experiments were 0.31, 0.21, 0.22, and 0.31 mA, respectively, resulting in an overall average current of 0.2625 mA. The standard deviation between the four trial averages was approximately 0.055 mA, demonstrating the variation caused by manual shaking. The individual measured current values ranged from 0.1 to 0.5 mA. Based on a nominal

battery capacity of approximately 2600 mAh and an average measured charging current range of approximately 0.2625 mA, a rough estimate of the theoretical charging time can be made from $Time = \frac{\text{Capacity of battery}}{\text{charging current}}$. Reference [7] allows for an average estimated charging time of approximately 9905 hours at 0.2625 mA current. The total amount of charge transferred was estimated at approximately 0.0105 C over four separate 10-second trials. Because the four tests were not conducted consecutively, the average amount of charge transferred during the 10-second test was $Q \approx I_{avg} \cdot \Delta t = 0.2625 \text{ mA} \cdot 10 \text{ s} = 2.625 \text{ mC}$. These measurements quantitatively demonstrated the current transfer towards the battery during the charger's operation. The current generated by manual shaking is discontinuous and changes with the movement of the magnet, while TP4056 follows a CC/CV charging process rather than maintaining the assumed constant current throughout the entire charging cycle. During the constant-current (CC) stage, the charging circuit attempts to regulate the charging current while the battery voltage gradually increases. When the battery approaches the charging voltage limit, the charger enters the constant-voltage (CV) stage. During this stage, the battery voltage is maintained near its charging limit while the charging current gradually decreases until the charging process is terminated. Therefore, the actual charging time will be longer. 9905 hours value should consequently be interpreted as an idealized reference rather than as a demonstrated battery charging time.

The physical TP4056 module retained original $R_{PROG}(R3)$ value of 1.2 k Ω , corresponding to a nominal programmed charging current of approximately 1 A. The value represents the charging-current setting of the TP4056 and should not be interpreted as the current supplied by the electromagnetic generator. The generator was unable to provide a current approach to the programmed value. Four repeated 10 s battery-side measurements resulted in an overall average current of approximately 0.2625 mA. The actual charging current was limited primarily by the available power from the manually shaken generator rather than by the nominal 1 A current setting of the TP4056.

The full circuit system works well but depends heavily on hand-shaking speed to achieve consistent charging power. The charging process is easily observed through the two LEDs of the TP4056 module. To keep the red LEDs continuously lit, the shaking force must not only be stable but also neither too small nor too large. In the reported manual shake tests, the measured voltage supplied to the TP4056 input remained within the observable range of approximately 3.8–5.6 V. No sustained higher input voltages were observed under these test conditions. Therefore, the system did not need a 5V voltage regulator for TP4056 IC. However, if the system is fine-tuned to obtain a higher voltage, a voltage regulator is necessary. The blue LED on the TP4056 module functions as expected, indicating whether the battery is fully charged or if there is no battery inside the circuit. These two indicator lights are the clearest signals for the user to know the charging status of the system when LEDs are on, off, and blinking.

6 Conclusions/ Discussion

6.1 The impact of the device on the environment and people

The research project involves a vibration-based energy harvesting device that converts mechanical motion into electrical energy and stores the generated energy in a rechargeable battery. A potential societal benefit is that this device can provide a simple and accessible illustration of electromagnetic induction, energy conversion, energy loss, and energy storage.

From a sustainability perspective, the system utilizes unused mechanical vibrations as an energy source and requires no fuel in the energy conversion process. However, this does not make the entire device environmentally sustainable. The prototype requires copper wire, NdFeB permanent magnets, electronic components, lithium-ion batteries, and casing materials. The production and recycling or disposal of these components consumes resources and energy. Furthermore, the prototype's relatively low power output means that the amount of energy harvested during operation needs to be considered in relation to the amount of material required to manufacture the device.

Ethical and safety aspects must be considered simultaneously because the device is ultimately designed for use by young students. The prototype contains a rechargeable lithium-ion battery and a strong permanent magnet. Improper charging, short circuits, mechanical damage, or improper handling of the battery could create safety risks for both the user and the environment. The permanent magnet could also pose a mechanical risk if it detaches from the generator tube or is handled near magnetic objects or equipment sensitive to magnetic fields.

6.2 Conclusions

First, MATLAB simulations successfully fulfilled their intended role in the project by providing a numerical model of the electromagnetic energy harvesting system. The developed model incorporated the key physical parameters of the permanent magnet and copper coil, allowing for the estimation of the magnetic field, induced voltage, and generated current. The simulation results were then compared with experimental measurements and the COMSOL model, providing further cross-check for the numerical method.

The results show that the development of a vibration-based energy harvesting device is technically feasible. The relative motion between the permanent magnet and the copper coil generates a changing magnetic flux, producing an induced voltage according to Faraday's law. However, the compact size of the proposed device poses significant limitations on the amount of energy that can be harvested. With a palm-sized generator, the available electrical power is relatively low. At the measured mean

current of 0.2625 mA, the ideal constant-current equivalent is approximately 9905 hours. The actual manual-shaking charging time was not determined and would be longer because of intermittency, conversion losses, and CC/CV charging. The experiment demonstrated that the current measurement was on the battery side, not a complete battery charging cycle.

Despite these limitations, the project has demonstrated the potential for generating, converting, and storing electrical energy using relatively simple electromagnetic materials and principles. The prototypes and simulations developed provide a practical demonstration of the relationship between mechanical motion, magnetic flux, electromagnetic induction, rectification, and electrical energy storage. This is another objective of the project: to make the principles of energy harvesting and energy conversion more accessible to those without expertise in electrical engineering. Vibration-based electromagnetic energy harvesting provides a concrete example of converting mechanical motion into electrical energy and can complement more familiar examples of renewable and harvested energy, such as solar and wind power. The simplicity and ease of understanding of the operating principle make this concept particularly suitable for special education demonstrations at the primary or secondary school level.

Furthermore, safety limitations remain before the system can be considered suitable for use as a self-contained consumer or educational product. The mechanical movement of the permanent magnets requires safe end stops and a housing capable of withstanding repeated impacts. The 18650 lithium-ion battery also requires appropriate charging and protection circuitry, secure installation, insulation, and protection against short circuits and mechanical damage. These requirements are particularly important before the device can be considered suitable for use in children's education.

Finally, the main contribution of this project was not the introduction of a new electromagnetic-generation principle. Moving-magnet generators, shake flashlights, and vibration-based electromagnetic energy harvesters operated according to Faraday's law of electromagnetic induction. Instead, the project investigated the complete energy-conversion chain within one compact experimental system: electromagnetic field and induced-voltage modelling, numerical comparison using MATLAB and FEM software, AC-to-DC rectification, capacitor smoothing, interfacing with a lithium-ion charging module, and direct measurement of the battery-side current. The system-level investigation distinguishes the work from a study concerned only with electromagnetic generation or the operation of a conventional shake flashlight.

Overall, the prototype demonstrates the feasibility of converting human-generated mechanical motion into electrical energy using a compact electromagnetic system. At the same time, the prototype identifies output power and energy transfer efficiency as

key limitations requiring further development. The TP4056 module was selected because it provided a simple and accessible method for demonstrating energy transfer toward a lithium-ion battery while providing the required charging functionality. However, the experiments showed that the TP4056 is not well matched to this application because the generator provides a weak, high-impedance, and intermittent electrical source, whereas the charging module is better suited to a more stable input supply. Future development should therefore consider a power-management circuit specifically designed for energy-harvesting applications and very-low-power input sources.

7 References

- [1] P. L. Brach, P. Poulouse, and A. Zeytinci, "The Faraday flashlight: A unique freshman hands-on experiment for both engineering and technology," in Proc. 2006 Fall ASEE Middle Atlantic Section Conf., Oct. 2006.
- [2] M.-C. Chiu, Y.-C. Chang, L.-J. Yeh, and C.-H. Chung, "Numerical assessment of a one-mass spring-based electromagnetic energy harvester on a vibrating object," *Archives of Acoustics*, vol. 41, no. 1, pp. 119–131, 2016, doi: 10.1515/aoa-2016-0012.
- [3] H. Kinoshita, S. Kawai, K. Ikuta, and T. Teraoka, "Individual finger forces acting on a grasped object during shaking actions," *Ergonomics*, vol. 39, no. 2, pp. 243–256, 1996, doi: 10.1080/00140139608964455
- [4] Cieřlik, Karol & Lopatka, Marian. (2022). Research on Speed and Acceleration of Hand Movements as Command Signals for Anthropomorphic Manipulators as a Master-Slave System. *Applied Sciences*. 12. 3863. 10.3390/app12083863.
- [5] M. Faraday, "Experimental researches in electricity. Series I and II," *Philosophical Transactions of the Royal Society of London*, vol. 122, pp. 125–162, 1831.
- [6] H. A. Radi and J. O. Rasmussen, *Principles of Physics: For Scientists and Engineers*. Berlin, Germany: Springer, 2013, pp. 859–998. [Online]. Available: <https://doi-org.proxy.lib.chalmers.se/10.1007/978-3-642-23026-4> [Accessed: Aug. 7, 2026].
- [7] P.U. Ekholm, L. Fraenkel, and S. Hörbeck, *Formler & tabeller i fysik, matematik & kemi: för gymnasieskolan. 9:e uppl.* Malmö, Sweden: Konvergenta HB, 2019. ISBN: 978-91-973708-8-2.
- [8] R. Nave, "Rectifier circuits," *HyperPhysics*, Department of Physics and Astronomy, Georgia State University. [Online]. Available: [HyperPhysics – Rectifier Circuits](#). [Accessed: Aug. 7, 2026].
- [9] Art of Circuits, "TP4056-1A Micro USB Li-ION Battery Charger Module with Protection," Art of Circuits. [Online]. Available: Art of Circuits product page. [Accessed: Aug. 16, 2026].
- [10] Blikai, "What is TP4056 module? All you need to know," Jun. 7, 2024. [Online]. Available: Blikai TP4056 article. [Accessed: Aug. 17, 2026].
- [11] Electrokit Sweden AB, "USB-micro charger module TP4056 for Li-Ion/LiPo 0.1–1A," Electrokit. [Online]. Available: Electrokit TP4056 product page. [Accessed: Aug. 17, 2026].

8 Appendices

8.1 Circuit schematics

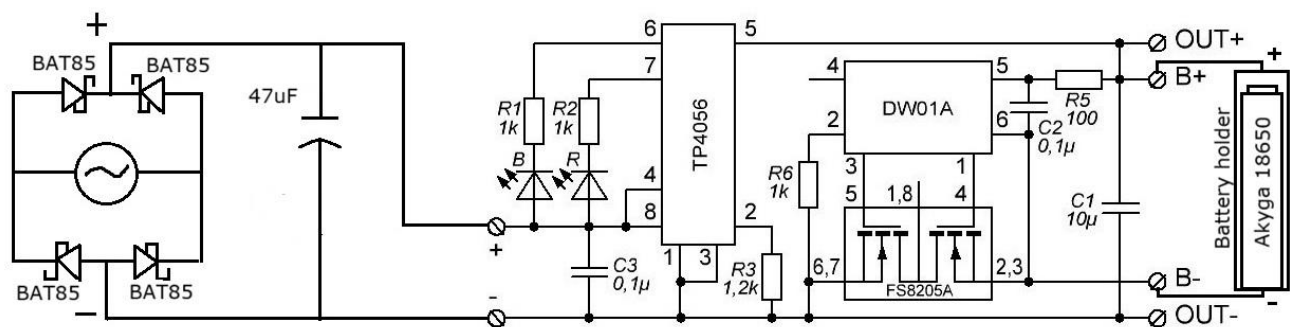


Figure 8.1: Complete circuit schematic of the energy-harvesting and battery-charging system, including the Schottky bridge rectifier, electrolytic smoothing capacitor, TP4056 charging circuit, DW01A and FS8205A battery-protection circuit, and an 18650-battery holder. Adapted from Art of Circuits [9].

8.2 Components list

	Manufacturer/distributor	Footprint	Description
Magnet	Magnordic	-	Diameter: Ø 0.8 cm Height: 3 cm Strength: approx. 2.7 kg Material: NdFeB Magnetism: N42 = 12900-13200 Gauss = 1,29-1,32 T Max temperature: 80°C Surface: nickel-plated (Ni-Cu-Ni) Size: 8 mm x 30 mm
Coil wire	Electrokit	-	Length: 360m Diameter: Ø0.20mm Temperature range: 200°C Insulation: PUR (polyuretane) Weight: 100g Dimensions: Ø54 x 22mm (hole: Ø22mm)

Schottky diod BAT85	Vishay	DO-35	Current: 200 mA Voltage: 30 V Voltage drop: 0.5 V
Electrolytic capacitor 47uF		-	Capacitance: 47 uF Diameter: 5 mm Height: 11 mm Pitch: 2 RoHS: RoHS compatible Temperature: 85 °C Tolerance: ±20% Voltage: 25 V
TP4056 Module	NanJing Top Power ASIC Corp	-	Overvoltage protection: 4.3V Undervoltage protection: 2.4V Overcurrent protection: 3A Input voltage Voltage via micro-USB: 5V Voltage via solder connection: 4.5-6V Battery (solder connection): B+ and B-
18650 Battery Holder	Comfortable electronic co. Ltd	-	Battery holder for 1x 18650 cell. Dimensions: 75x21x21 mm. PCB mounting.
18650 Battery	Akyga	-	Specifications: Nominal capacity: 2600 mAh (minimum 2500 mAh) Nominal voltage: 3.65 V Maximum charge voltage: 4.2 V End-of-discharge voltage: 2.75 V (cutoff voltage) Standard charge: 0.2C - 500 mA Fast charge: 0.5C - 1300 mA Maximum discharge current: 1.5 A Operating temperature, charging: 0 to 45 °C Operating temperature, discharging: -20 to 60 °C Terminals: Standard battery terminals Battery type: Li-Ion INR18650-26M Model: AKY2454 Weight: 50 g Dimensions: Height: 69.5 mm Diameter (ø): 18.5 mm

8.3 Program code

MATLAB code:

```
%=====
% MATLAB model for shaking magnet generator
% Author: Duc Thinh Dinh
%=====
% Magnet:
% N42 cylindrical magnet
% Diameter = 8 mm
% Length = 30 mm
% Br = 1.315 T
%
% Coil:
% Inner radius = 5 mm
% Length = 60 mm
% Wire diameter = 0.2 mm
% 300 axial turn positions
% 20 radial winding layers
% Total = 6000 turns
%
% The code:
% 1. Represents the permanent magnet by equivalent current loops
% 2. Applies Biot-Savart directly to current elements dL
% 3. Calculates Bz(r,z)
% 4. Integrates flux through turns of different radius
% 5. Sums the flux through all 6000 turns
% 6. Applies Faraday's law
% 7. Estimates the generated current
%
% Local function magnetField_BiotSavart is at the bottom.
% MATLAB R2016b or newer is required for local functions in scripts.
%=====
clear;
close all;
clc;
%% =====
% 1. CONSTANTS
% =====
mu0 = 4*pi*1e-7; % Permeability of free space [H/m]
rho_copper = 1.72e-8; % Copper resistivity [ohm*m] (1.68-1.72)
%% =====
% 2. MAGNET
% =====
Br = 1.315; % Residual magnetic flux density [T]
Rm = 4e-3; % Magnet radius [m]
Lm = 30e-3; % Magnet length [m]
```

```

% Sinusoidal magnet movement:
% zmag(t) = A*sin(2*pi*f*t)
A_m = 30e-3; % Motion amplitude [m]
f = 8; % Shaking frequency [Hz]
omega = 2*pi*f;
% Magnetization of the permanent magnet
M = Br/mu0; % Magnetization [A/m]
% Divide the magnet into equivalent circular current loops [customizable]
Nmag_loops = 30;
% Divide every equivalent loop into small current elements [customizable]
% numerical discretization of one equivalent magnet loop
nR = 100;
% Axial thickness represented by one equivalent loop
dz = Lm/Nmag_loops;
% Equivalent magnetization current
% only used inside the magnetic-field model.
% It is not a real generated current.
I_loop = M*dz;
% Center positions of the equivalent magnet loops
z_loop = linspace(-Lm/2 + dz/2, Lm/2 - dz/2, Nmag_loops);
fprintf('MAGNET\n');
fprintf('Radius = %.2f mm\n',Rm*1e3);
fprintf('Length = %.2f mm\n',Lm*1e3);
fprintf('Br = %.3f T\n',Br);
fprintf('Equivalent magnet loops = %d\n',Nmag_loops);
fprintf('Current elements per loop = %d\n\n',nR);
%% =====
% 3. COIL
% =====
Ri = 5e-3; % Coil inner radius [m]
Lcoil = 60e-3; % Coil length [m]
dwire = 0.2e-3; % Copper wire diameter [m]
% Coil parameters
Nturns = 6000;
Nz_positions = floor(Lcoil/dwire); % 300 axial turn positions = 60mm/0.2mm
Nr_layers = ceil(Nturns/Nz_positions); % 20 radial winding layers= 6000
turns/300layers
% Axial center of each turn position
z_turns = linspace(-Lcoil/2 + dwire/2, Lcoil/2 - dwire/2, Nz_positions);
% Radius at the center of each radial winding layer
% Layer 1:
% Ri + 0.5*dwire
%
% Layer 20:
% Ri + 19.5*dwire
r_turns = Ri + ((1:Nr_layers)-0.5)*dwire;
% Outside of the complete winding
Ro = Ri + Nr_layers*dwire;
fprintf('COIL\n');
fprintf('Inner radius = %.2f mm\n',Ri*1e3);
fprintf('Outer radius = %.2f mm\n',Ro*1e3);

```

```

fprintf('Coil length = %.2f mm\n',Lcoil*1e3);
fprintf('Wire diameter = %.3f mm\n',dwire*1e3);
fprintf('Total turns = %d\n\n',Nturns);
fprintf('Axial turn positions = %d\n',Nz_positions);
fprintf('Radial winding layers = %d\n',Nr_layers);
%% =====
% 4. COIL RESISTANCE
% =====
% Every radial layer has a different circumference.
% Each layer contains Nz_positions turns.
Lwire = 0;
% every radial layer contains 300 turns of the same circumference
for iz = 1:Nz_positions
for ir = 1:Nr_layers
r_now = Ri + (ir-0.5)*dwire;
Lwire = Lwire + 2*pi*r_now;
end
end
% Copper wire cross-sectional area
Awire = pi*(dwire/2)^2;
% Approximate DC resistance
Rcoil = rho_copper*Lwire/Awire;
fprintf('COIL RESISTANCE\n');
fprintf('Estimated wire length = %.2f m\n',Lwire);
fprintf('Wire cross-sectional area = %.3e m^2\n',Awire);
fprintf('Estimated coil resistance = %.2f ohm\n\n',Rcoil);
%% =====
% 5. BIOT-SAVART FIELD GRID
% =====
% The magnet and coil are axisymmetric.
% Therefore, the magnetic field only needs to be calculated in the
% r-z plane.
%
% r: radial distance from the magnet axis
% z: axial position relative to the magnet center
r_field_max = r_turns(end); % zero margin
Nr_field = 81; %the number of points used to sample the radial direction
% [customizable] maybe 45=9/0.2mm +1
Nz_field = 301; %the number of points used to sample the axial direction
% [customizable]
r_field = linspace(0,r_field_max,Nr_field);
% The coil extends from -30 mm to +30 mm.
% The magnet moves approximately +/-15 mm.
% Maximum relative distance is therefore approximately +/-45 mm.
z_field_max = Lcoil/2 + A_m; % 60/2 +15mm =45mm
z_field = linspace(-z_field_max,z_field_max,Nz_field);
fprintf('Calculating direct Biot-Savart field...\n');
[Bradial,Bz] = magnetField_BiotSavart( ...
r_field, z_field, ...
Rm, z_loop, I_loop, nR, mu0);
% Magnetic-field magnitude

```

```

Bmag_2D = sqrt(Bradial.^2 + Bz.^2);
fprintf('Biot-Savart calculation completed.\n\n');
%% =====
% 6. MAGNETIC FLUX THROUGH DIFFERENT TURN RADIUS
% =====
% Magnetic flux through one circular turn:
%  $\Phi(R,z) = \int B_z(r,z) \cdot 2\pi r \, dr$ 
%
% The integration starts at the magnet axis and ends at the radius of
% the specific copper turn.
%
% Because each radial winding layer has a different radius, each layer
% receives a different flux.
Phi_radius = cumtrapz( r_field, Bz.*(2*pi*r_field), 2);
% Phi_radius(iz,ir) represents the magnetic flux through a circle with:
% axial position z_field(iz) & radius r_field(ir) relative to the magnet center
%% =====
% 7. TOTAL FLUX LINKAGE VERSUS MAGNET POSITION
% =====
% Magnet-position lookup table
% Flux linkage is first calculated as a function of magnet position.
% It can then be interpolated for every time step.
zmag_lookup = linspace(-Lcoil/2,Lcoil/2,Nz_field);
% 60mm/300=0.2mm=wire diameter easy to debug for the time step
Phi_total_lookup = zeros(size(zmag_lookup));
% Matrices representing all 6000 real copper turns
% Rturn: radius of each turn
% Zturn: axial position of each turn
[Rturn,Zturn] = meshgrid(r_turns,z_turns);
fprintf('Calculating flux linkage through all %d turns...\n',Nturns);
for k = 1:length(zmag_lookup)
    zmag = zmag_lookup(k);
    % Position of each copper turn relative to the magnet center
    zrel = Zturn-zmag;
    % Flux through every individual copper turn
    % Phi_radius was already integrated radially.
    % We now interpolate it using: turn radius & relative axial position
    Phi_turns = interp2(r_field,z_field,Phi_radius, ...
        Rturn,zrel,'linear',0);
    % At every physical turn radius Rturn(iz,ir)
    % and every relative axial position zrel(iz,ir),
    % estimate the corresponding flux from Phi_radius
    % Sum the magnetic flux through all 6000 turns
    % flux linkage:
    %  $\lambda = \sum(\Phi_i)$ 
    Phi_total_lookup(k) = sum(Phi_turns,'all');
    % is the flux linkage when the magnet is at zmag_lookup(k)
end
fprintf('Flux-linkage calculation completed.\n\n');
%% =====
% 8. MAGNET MOTION

```

```

% =====
% Simulate ten complete oscillation cycles
Ncycles = 10; %[customizable]
t_end = Ncycles/f;
samples_per_cycle = 500; %[customizable]
dt = 1/(f*samples_per_cycle);
t = 0:dt:t_end;
Nt = length(t);
t = linspace(0,t_end,Nt);
% Magnet position
zmag = A_m*sin(omega*t);
% Magnet velocity
v = A_m*omega*cos(omega*t);
fprintf('MAGNET MOTION\n');
fprintf('Amplitude = %.2f mm\n',A_m*1e3);
fprintf('Frequency = %.2f Hz\n',f);
fprintf('Maximum velocity = %.3f m/s\n', ...
max(abs(v)));
%% =====
% 9. FLUX LINKAGE VERSUS TIME
% =====
% Interpolate the total flux linkage using the instantaneous magnet position
% the magnet position changes continuously with time (from position zmag)
Phi_total = interp1(zmag_lookup,Phi_total_lookup,zmag, 'pchip');
% lamda (z) -> lamda (t)
%% =====
% 10. FARADAY'S LAW
% =====
% Faraday's law:
%  $V_{ind} = -d(\Phi_{total})/dt$ 
% Phi_total already contains the sum of the magnetic flux through all
% 6000 copper turns.
Vind = -gradient(Phi_total,t);
%% =====
% 11. GENERATED CURRENT
% =====
% External resistive load
Rload = 100; % Load resistance [ohm] -[customizable]
% First-order current approximation
% This model currently treats the coil and load as purely resistive.
% It does not yet include:
% coil inductance
% Schottky bridge
% smoothing capacitor
% TP4056
% battery
% electromagnetic damping
Iload = Vind/(Rcoil + Rload);
% Simplified short-circuit current
Ishort = Vind/Rcoil;
%% =====

```

```

% 12. RESULTS
% =====
Vpeak = max(abs(Vind));
Vrms = sqrt(mean(Vind.^2));
Ipeak = max(abs(Iload));
Irms = sqrt(mean(Iload.^2));
Ishort_peak = max(abs(Ishort));
fprintf('=====\n');
fprintf('CALCULATED RESULTS\n');
fprintf('=====\n');
fprintf('Peak induced voltage = %.6f V\n',Vpeak);
fprintf('RMS induced voltage = %.6f V\n',Vrms);
fprintf('\nCoil resistance = %.2f ohm\n',Rcoil);
fprintf('Load resistance = %.2f ohm\n',Rload);
fprintf('Total resistance = %.2f ohm\n', ...
Rcoil + Rload);
fprintf('\nPeak load current = %.6f A\n',Ipeak);
fprintf('Peak load current = %.3f mA\n',Ipeak*1e3);
fprintf('RMS load current = %.6f A\n',Irms);
fprintf('RMS load current = %.3f mA\n',Irms*1e3);
fprintf('Simplified short-circuit peak = %.3f mA\n', ...
Ishort_peak*1e3);
fprintf('=====\n\n');
%% =====
% 13. FIGURE 1: 2D MAGNETIC-FIELD MAP
% =====
% Complete horizontal coordinate
x_field = [-fliplr(r_field(2:end)), r_field];
Bx_full = [-fliplr(Bradial(:,2:end)), Bradial];
Bz_full = [fliplr(Bz(:,2:end)), Bz];
% Complete magnetic-field magnitude
Bmag_full = sqrt(Bx_full.^2 + Bz_full.^2);
Bnorm = sqrt(Bx_full.^2 + Bz_full.^2);
% Avoid division by zero where the field is extremely small
Bnorm(Bnorm < 1e-12) = 1e-12;
Bx_normalized = Bx_full./Bnorm;
Bz_normalized = Bz_full./Bnorm;
%fewer arrows than field-grid points for clearer visual
arrow_step_x = 6; % [customizable]
arrow_step_z = 10; % [customizable]
x_index = 1:arrow_step_x:length(x_field);
z_index = 1:arrow_step_z:length(z_field);
[X_arrow,Z_arrow] = meshgrid(x_field(x_index), z_field(z_index));
Bx_arrow = Bx_normalized(z_index,x_index);
Bz_arrow = Bz_normalized(z_index,x_index);
figure(1);
imagesc( r_field*1e3,z_field*1e3,Bmag_2D);
set(gca,'YDir','normal');
xlabel('r [mm]');
ylabel('z [mm]');
title('Magnetic field magnitude |B| from direct Biot-Savart law');

```

```

colorbar;
axis equal;
axis tight;
grid on;
hold on;
% Magnet boundary in the positive-r_field half plane
rectangle( ...
'Position',[0,-Lm/2*1e3,Rm*1e3,Lm*1e3], ...
'EdgeColor','w', ...
'LineWidth',1.5, ...
'LineStyle','--');
quiver( X_arrow*1e3, Z_arrow*1e3, Bx_arrow, Bz_arrow, 0.45, 'k');
xlim([-10 10]);
ylim([-25 25]);
hold off;
%% =====
% 14. FIGURE 2: TOTAL FLUX LINKAGE
% =====
figure(2);
plot(zmag_lookup*1e3,Phi_total_lookup,'LineWidth',1.5);
xlabel('Magnet center position [mm]');
ylabel('Total flux linkage [Wb-turn]');
title('Flux linkage through all 6000 turns');
grid on;
%% =====
% 15. FIGURE 3: 3D MAGNETIC-FIELD SLICE
% =====
% Convert the axisymmetric two-dimensional field into a Cartesian
% three-dimensional field for visualization.
% [customizable]
x = linspace(-12e-3,12e-3,41);
y = linspace(-12e-3,12e-3,41);
z = linspace(-45e-3,45e-3,81);
[X,Y,Z] = meshgrid(x,y,z);
% Radial coordinate of every Cartesian point
R_field_3D = sqrt(X.^2 + Y.^2);
% Interpolate the cylindrical field components
Bradial_3D = interp2(r_field, z_field, Bradial, R_field_3D,Z, 'linear', 0);
Bz_3D = interp2( r_field, z_field, Bz, R_field_3D, Z,'linear', 0);
% Convert radial field into x and y components
Bx = zeros(size(R_field_3D));
By = zeros(size(R_field_3D));
index = R_field_3D > 1e-12;
Bx(index) = Bradial_3D(index).*X(index)./R_field_3D(index);
By(index) = Bradial_3D(index).*Y(index)./R_field_3D(index);
% Complete field magnitude
Bmag = sqrt(Bx.^2 + By.^2 + Bz_3D.^2);
figure(3);
slice(X,Y,Z,Bmag,0,0,0);
shading interp;
colorbar;

```

```

xlabel('x [m]');
ylabel('y [m]');
zlabel('z [m]');
title('Magnetic field magnitude |B| around N42 magnet');
axis equal;
axis tight;
grid on;
view(35,25); % [customizable]
hold on;
% Draw the physical magnet
[xm,ym,zm] = cylinder(Rm,60);
zm = zm*Lm-Lm/2;
surf( xm,ym,zm, ...
'FaceColor',[0.6 0.6 0.6], ...
'EdgeColor','none', ...
'FaceAlpha',0.75);
% Draw inner coil boundary
[xc1,yc1,zc1] = cylinder(Ri,80);
zc1 = zc1*Lcoil-Lcoil/2;
surf( ...
xc1,yc1,zc1, ...
'FaceColor','none', ...
'EdgeColor','w', ...
'LineStyle','--');
% Draw outer coil boundary
[xc2,yc2,zc2] = cylinder(Ro,80);
zc2 = zc2*Lcoil-Lcoil/2;
surf( xc2,yc2,zc2, ...
'FaceColor','none', ...
'EdgeColor','w', ...
'LineStyle','--');
hold off;
%% =====
% 16. FIGURE 4: MOTION, FLUX AND VOLTAGE
% =====
figure(4);
subplot(3,1,1);
plot(t,zmag*1e3,'LineWidth',1.4);
ylabel('Position [mm]');
title('Magnet position');
grid on;
subplot(3,1,2);
plot(t,Phi_total,'LineWidth',1.4);
ylabel('Flux linkage [Wb-turn]');
title('Total coil flux linkage');
grid on;
subplot(3,1,3);
plot(t,Vind,'LineWidth',1.4);
xlabel('Time [s]');
ylabel('Voltage [V]');
title('Induced voltage');

```

```

grid on;
%% =====
% 17. FIGURE 5: GENERATED CURRENT
% =====
figure(5);
plot(t,Iload*1e3,'LineWidth',1.4);
xlabel('Time [s]');
ylabel('Current [mA]');
title(['Generated current, Rload = ',num2str(Rload),' ohm']);
grid on;
%% =====
% LOCAL FUNCTION: DIRECT BIOT-SAVART CALCULATION
% =====
function [Bradial,Bz] = magnetField_BiotSavart( ...
r_field, z_field, ...
Rm, z_loop, I_loop, nR, mu0)
%=====
% This function calculates the field of the permanent magnet using
% direct numerical Biot-Savart integration.
% The magnet is represented by equivalent circular current loops.
% Every circular loop is divided into nR current elements.
%
% Biot-Savart law:
%  $dB = \mu_0 I / (4\pi) * \text{cross}(dL, R) / |R|^3$ 
% Observation points are placed in the XZ plane:
% x = r_field
% y = 0
% z = z_field
% Because of axial symmetry, Bx at y = 0 corresponds to Bradial.
% It is unnecessary to calculate every angular position around the magnet
%=====
% Create the field observation grid
[R_field_3D,Z] = meshgrid(r_field,z_field);
X = R_field_3D;
Y = zeros(size(R_field_3D));
% Initialize the total magnetic-field components
Bx = zeros(size(R_field_3D));
Bz = zeros(size(R_field_3D));
% Angular positions around one equivalent circular loop
theta = linspace(0,2*pi,nR+1);
% Small distance limit used to avoid division by zero
Rminimum = 0.02e-3; % [customizable]
% Biot-Savart coefficient
C = mu0*I_loop/(4*pi);
% Calculate the field from every equivalent magnet loop
for iz = 1:length(z_loop)
% Axial position of the current loop
z_source = z_loop(iz);
% Divide the circular current loop into small elements
for it = 1:nR
% Beginning of the current element

```

```

P1 = [Rm*cos(theta(it)), Rm*sin(theta(it)), z_source];
% End of the current element
P2 = [Rm*cos(theta(it+1)), Rm*sin(theta(it+1)), z_source];
% Current-element vector
dL = P2-P1; %dl= [dx dy dz]
% Midpoint of the current element
P = 0.5*(P1+P2);
% Vector from the current element to every observation point
Rx = X-P(1);
Ry = Y-P(2);
Rz = Z-P(3);
% Distance between source and observation points
R = sqrt(Rx.^2 + Ry.^2 + Rz.^2);
% Avoid numerical division by zero
R(R < Rminimum) = Rminimum;
R3 = R.^3;
% Cross product:
% cross(dL,R)
% dL is constant for one current element.
% R is different at every observation point.
% dL x R = [dLy*Rz - dLz*Ry]
% dLz*Rx - dLx*Rz
% dLx*Ry - dLy*Rx
cross_x = dL(2).*Rz - dL(3).*Ry;
cross_z = dL(1).*Ry - dL(2).*Rx;
%cross_y = dL(3).*Rx - dL(1).*Rz;
% Differential magnetic field
dBx = C*cross_x./R3;
dBz = C*cross_z./R3;
%dB_y = C*cross_y./R3;
% Sum the contribution from this current element
Bx = Bx+dBx;
Bz = Bz+dBz;
end
end
% At y = 0 and x >= 0:
% Bx = Bradial
Bradial = Bx;
end

```

8.4 Detailed calculations for the systems of equations

Magnetic Field on the Axis of a Circular Wire Loop has an equation:

$$B = \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + x^2)^{3/2}}$$

A permanent magnet of length L is modeled as a stack of these loops from $z' = -L/2$ to $z' = +L/2$. Then integrate the fields produced by every infinitesimal slice dz' along the full length of the magnet:

$$B(z) = \int_{-L/2}^{L/2} \frac{\mu_0 I R^2}{2(R^2 + (z - z')^2)^{3/2}}$$

The current in a tiny horizontal slice of the magnet with thickness $dI = Mdz'$

$$\begin{aligned} \rightarrow B(z) &= \int_{-L/2}^{L/2} \frac{\mu_0 (Mdz') R^2}{2(R^2 + (z - z')^2)^{3/2}} \leftrightarrow B(z) = \frac{\mu_0 M R^2}{2} \int_{-L/2}^{L/2} \frac{1}{2(R^2 + (z - z')^2)^{3/2}} dz' \\ &\leftrightarrow B(z) = \frac{\mu_0 M R^2}{2} \left[\frac{-(z - z')}{R^2 \sqrt{R^2 + (z - z')^2}} \right]_{-L/2}^{L/2} \rightarrow B(z) \\ &= \frac{\mu_0 M}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right) \\ \Rightarrow B(z) &= \frac{B_r}{2} \left(\frac{z + L/2}{\sqrt{R^2 + (z + L/2)^2}} - \frac{z - L/2}{\sqrt{R^2 + (z - L/2)^2}} \right) \text{ where } z = d + \frac{L}{2} \end{aligned}$$

8.5 The use of AI

The project used ChatGPT (OpenAI) in the preparation of this report to improve the language, support figures to a limited extent, and support improved and searchable syntax for MATLAB to use in the model. Figure 2.1 was created using ChatGPT and the arrows are added to illustrate the direction of current, magnet movement, B-field, and flux effects. The technical content of the figure is based on [6] and then re-checked against [5] and [7]. Figure 2.3 was modified from [8] with AI support used only for the quick setup of combined layouts of generator, basic full bridge, and smoothing capacitor. Sources are cited in the figure captions and corresponding reference lists.

Documents created or modified by AI should not be considered independent technical sources. The equations, component specifications, circuit diagrams, physical principles, and numerical values shown in relation to these images have been cross-referenced by the author with the cited original documents, manufacturer's datasheets, simulation software results, or experimental measurements. The author remains responsible for the technical content and conclusions presented in this report.



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