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FACULTY OF MECHANICS
DEPARTMENT OF MECHATRONICS, ROBOTICS AND DIGITAL FABRICATION

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RESEARCH OF ENERGY HARVESTER EFFICIENCY

Master's degree Thesis

Mechatronics Systems study programme, state code **621H73002**
Production and Manufacturing Engineering study field

Vilnius, 2019

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
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For student **Jurgis Verikas**.....
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2. Methodology of research
3. Theoretical research
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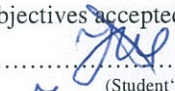
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Antrosios pakopos studijų **Mechatroninių sistemų** programos magistro baigiamasis darbas 4

Pavadinimas **Energijos keitiklio efektyvumo tyrimas**
Autorius **Jurgis Verikas**
Vadovas **Sigitas Petkevičius**

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Anotacija

Magistro baigiamajame darbe yra pateikiami horizontaliosios švytuoklės tipo energijos rinktuvo panaudojimo žemo energinio tankio sistemose tyrimo rezultatai. Atliekant magistro baigiamąjį darbą buvo tirtas energijos rinktuvas, skirtas konvertuoti mechaninių virpesių energiją į elektros energiją. Teoriniams tyrimams atlikti buvo sukurtas dinaminis sistemos modelis siekiant įvertinti ritės apvijų storio ir jų kiekio įtaką. Eksperimentiniai tyrimai buvo atliekami dviem etapais: ištirti ritės apvijų storio ir kiekio įtaką, bet įvertinti metalinės šerdies įtaką ritės įtampai. Tyrimo metu buvo nagrinėjamas įtampos pokytis keičiant elektromagnetines ritės savybes. Darbe pateikiami apibendrinti tyrimų rezultatai bei rekomendacijos sistemos įtampos rezultams pagerinti.

Darbą sudaro 5 dalys: įvadas, mokslinės literatūros, susijusios su tiriamuoju objektu, apžvalga, tiriamos problemos analizė ir formulavimas, teorinis tyrimas ir rezultatų įvertinimas, eksperimentinis tyrimas ir jo rezultatų įvertinimas, išvados ir literatūra.

Darbo apimtis – 48 puslapiai teksto be priedų, 27 iliustracijos, 5 lentelės, 18 bibliografinių šaltinių. Atskirai pridedami darbo priedai.

Prasminiai žodžiai: Prasminiai žodžiai: energijos rinktuvas, įtampa, energija, magnetinis laukas, virpesiai.

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Master Degree Studies **Mechatronics Systems** study programme Master Graduation Thesis 4

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Author **Jurgis Verikas**

Academic supervisor **Sigitas Petkevičius**

Thesis language: English

Annotation

The master's thesis presents the results of the study of the use of horizontal pendulum energy harvester in low energy density systems. In the Master's thesis, an energy harvester was investigated to generate electricity from low-density mechanical vibrations systems. To perform theoretical research, a dynamic system model was developed to evaluate the influence of the coil winding thickness and its winding amount. Experimental studies were carried out in two stages: to examine the influence of the thickness and quantity of coil windings, second to evaluate the influence of the metal core on the coil voltage. The study analyzed at the change in voltage by changing the electromagnetic coil properties. The thesis presents research results and recommendations for improving system voltage output.

Structure: introduction, scientific literature review, analysis and formulation of the problem, theoretical research and evaluation of results, experimental research and evaluation of its results, conclusions and literature.

Thesis consist of: 48 pages of text without appendixes, 27 pictures, 5 tables, 18 bibliographical references. Appendixes are included separately.

Keywords: Keywords: energy harvester, voltage, energy, magnetic field, vibrations.

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**DECLARATION OF AUTHORSHIP
IN THE FINAL DEGREE PAPER**

May 14, 2019

I declare that my Final Degree Paper entitled „Research of Energy HARvester Efficiency“ is entirely my own work. The title was confirmed on November 7, 2017 by Faculty Dean's order No. 317me. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers:
Doctor Sigitas Petkevičius.

The academic supervisor of my Final Degree Paper is Doctor Sigitas Petkevičius.

No contribution of any other person was obtained, nor did I buy my Final Degree Paper.



(Signature)

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LIST OF ABBREVIATIONS

MEMS – Micro-electromechanical Systems;

RF – radio frequency;

IC – integrated circuit;

etc. – ET Cetera;

CYTOP – a fluoropolymer that dissolves in exclusive fluorine-based solvents, so it can be used as a thin film coating with thicknesses less than $1\mu\text{m}$;

PZT – lead zirconate titanate;

Unimorph– a cantilever that consists of one active layer and one inactive layer;

LEM – Lumped Element Modeling;

FIG – Frequency Increased Generator;

e.m.f. – electromotive force;

EM – electro mechanics.

INTRODUCTION

Increasing global demand for energy, environmental and ecological problems leads to looking for alternative energy sources. One of them is kinetic energy from vibrations. Low frequency energy harvester can generate energy from ambient natural processes. As Faraday's law states the electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path. The total energy of pendulum energy harvester will be dependent to the electromagnetic properties of harvester coils and magnets.

This research will be presented the experimental results of generated energy dependence to the change of vibration and magnetic properties of coil. First part of experimental investigation will be performed with different wire thickness corresponding to number of windings. Second part is to investigate the influence of metal core inside the coil.

Research object – the energy harvester which is built in the Mechanical faculty of Vilnius Gediminas Technical University at the department of Mechatronics, Robotics and Digital Manufacturing.

Research goals and tasks (Aim) – to investigate the voltage and energy generated by harvester, these problems must be solved in this research:

- literature review of energy harvesters and selection of coil design;
- evaluate the dependence to the change of coil electromagnetic properties.

Research methods – experimental research will be done in the department of Mechatronics, Robotics and Digital Manufacturing. The results will be evaluated by software „Microsoft Office 2010“, Matlab and „National Instrument“.

Theme relevance – Global energy shortage, environmental pollution and climate change are the most urgent challenges mankind have ever faced. The hope of future energy security lies in the economical, efficient and clean use of existing energy, as well as development of new energy sources.

Equipment resource – all the equipment mentioned in this work used for experiments is the property of the Vilnius Gediminas Technical University. The harvester is being constructed in the laboratory of mechatronics and robotics.

Work approbation – in 2019, at the Lithuanian Young Scientists Conference "Science – the Future of Lithuania", the topic "Mechatronics" was reported. "Energy harvester research" (see Appendix).

1. LITERATURE REVIEW

1.1. Classification of energy harvesting devices

Before starting to discuss the different methods of energy harvesting, let's look at the definition of an energy harvesting device as understood in research. An energy harvesting device generates electric energy from its surroundings using some method of what is called Direct Energy Conversion techniques (converts charged particle's Kinetic energy into a voltage). Therefore, the energy harvesting devices here considered do not consume any fuel or substance, so that the maintenance problem does not apply. On the other hand, as the environment energy levels are very low (at least for today's electronic devices).

Energy for Direct Conversion may be classified in the in two groups: who or what provides the energy for conversion, and what type of energy is converted (de Silva, 2006). The classes are presented in Table 1.1.

Table 1.1. Classes of energy harvesting devices

Energy Source	Type of Energy
Human Kinetic	Kinetic, Thermal
Environment	Kinetic, Thermal, Radiation

In the first column can be distinguish between two kinds of devices. First, devices that use part of the energy of the user of the electronic appliance. In most cases it will be a human, but it could be also an animal. The second column may consider three types of energy: kinetic, electromagnetic radiation (including light and RF), and thermal.

The method of powering an embedded system by harvesting energy from environmental sources such as solar, wind, thermal and electromagnetic waves is known as energy harvesting. The purpose of energy harvesting is to increase lifetime of field nodes and devices. It helps in on-site charging of rechargeable batteries, traditional and super capacitors.

The most used vibration energy harvesting principles are electromagnetic, piezoelectric, electrostatic and magnetoelectric. The electromagnetic generators convert energy from environmental kinetic energy using the relative motion between permanent magnet and coil based on Faraday's law (Mateu, 2005).

Three main elements in energy harvesting device:

1) Energy Source: There are various energy sources. Anyone can be used for energy harvesting system. The sources such as vibrations, electromagnetic waves, thermal energy, wind energy, solar

energy etc. are used;

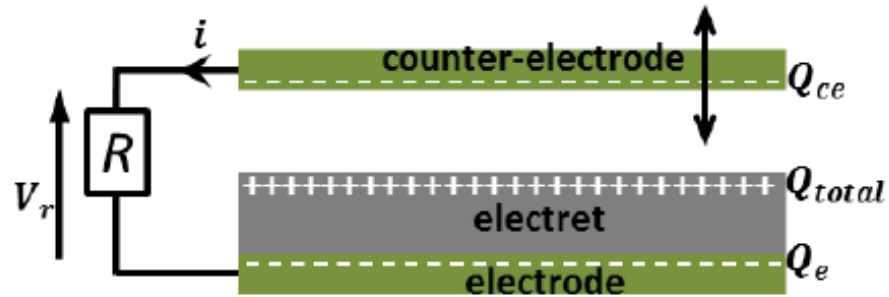
2) Energy Harvesting IC: This IC converts ambient energy into some of energy which can be stored in energy storage devices. For example mechanical stress into electrical signal, temperature difference into electric voltage etc;

3) Energy Storage: There are different ways energy can be stored which include rechargeable batteries, traditional capacitors, super capacitors etc. Super capacitors have characteristics viz. smaller size, higher efficiency, higher capacity etc.

1.2. Electrostatic energy harvesters

Electrostatic converters generate energy due to the presence of motion between two plates of a charged capacitor. This leads to a change of the electric potential through the capacitor. These converters are characterized by their limited output power and the most developed ones are designed for high working frequencies.

Electrostatic energy harvesters are based on a capacitive design (two charged electrodes spaced by an air gap). Vibrations induce changes in the geometry of the capacitor and a circulation of charges between the electrodes through the electrical load (Liu, 2006). Process is shown in Figure



1.1.

Fig. 1.1. Configuration of an operational electret

Variable out-of-plane gap configuration in which the counter electrode vibrates relative to the the total charge induced in the electret (q_{total}) is a sum of the charges in the electrode (q_e) and counter-electrode (q_{ce}).

$$q_{total} = q_e + q_{ce} \quad (1.1)$$

The most common method for electret manufacturing is via the ‘corona discharge’. This involves subjecting a point-grid-plane structure to a strong electric field leading to the implantation of charges at the electret surface. The most commonly used electret material is CYTOP polymer because of its capacity for significantly large surface charge density (Tsutsumino, 2006).

1.3. Piezoelectric energy harvesters

Most piezoelectric harvesters are designed in the form of a simple cantilever (with more than one material layer) having a tip mass to tune the operating. (Apo, 2014) Piezoelectric harvesters can consist of anamorph or bimorph design. Harvesters are composed of one layer of piezoelectric material (e.g. PZT) laminated on a flexible support layer (e.g. brass) while bimorph harvesters in Figure 1.2. are composed of two layers of piezoelectric material laminated on either side of a flexible support layer.

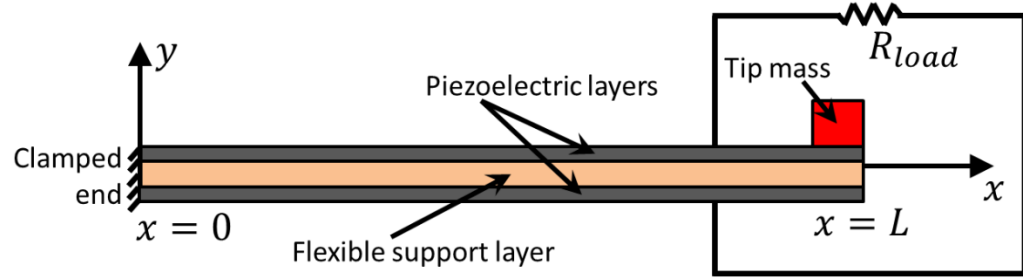


Fig. 1.2. Bimorph piezoelectric energy harvester

The most commonly used piezoelectric material is lead zirconate titanate (PZT) because of its significantly high piezoelectric properties (e.g. piezoelectric strain constant) when compared to the other piezoelectric materials. Piezoelectric harvesting systems tend to exhibit linear behavior in their dynamic and voltage responses, and as such are heavily reliant on cantilever resonance frequencies for appreciable power output. In some cases, electromagnetic harvesters can be used as the tip mass (placed at the end of a cantilever beam) where a magnet moves through the stationary coil. In such instances, the positions of the magnetic mass and coil within the electromagnetic harvester may also be switched. These electromagnetic systems can be modeled for their vibration characteristics similar to the piezoelectric cantilevers. Similar vibration modeling approach can be applied to cantilever-based electrostatic (Apo, 2014).

Piezoelectric materials have been also used to convert vibration to electric energy by the piezoelectric effect. Different piezoelectric converters have been investigated based on different architectures. In most cases, the converter employs a cantilever beam structure with different geometries for the piezoelectric layer such as rectangular and triangular. In general, the cantilever beam form can be used as unimorph structure with one piezoelectric layer or bimorph with two piezoelectric layers in both sides of the cantilever.

1.4. Magnetoelectric energy harvesters

Scientists also have tried to harvest kinetic energy based on the magnetoelectric effect. When a variable magnetic field is applied, the magnetostrictive material is strained which induces a stress on the piezoelectric material which generates electric energy.

Vibration converters performance is highly depending on the characteristics of the excitation source and the used physical principle to harvest energy (Huang, 2003). Some of the converters are working for one resonant frequency, others are developed to generate energy for wideband frequencies. Comparison of different developed devices is established depending in the energy outcome for different used harvesting principles relative to the working frequency. As it is shown in Figure. 1.3. piezoelectric and electrostatic principles have better energy outcome for higher frequencies and good performance especially in term of miniaturized converters which make these principles more suitable for MEMS applications. They reach maximally only some micro watts at low frequencies.

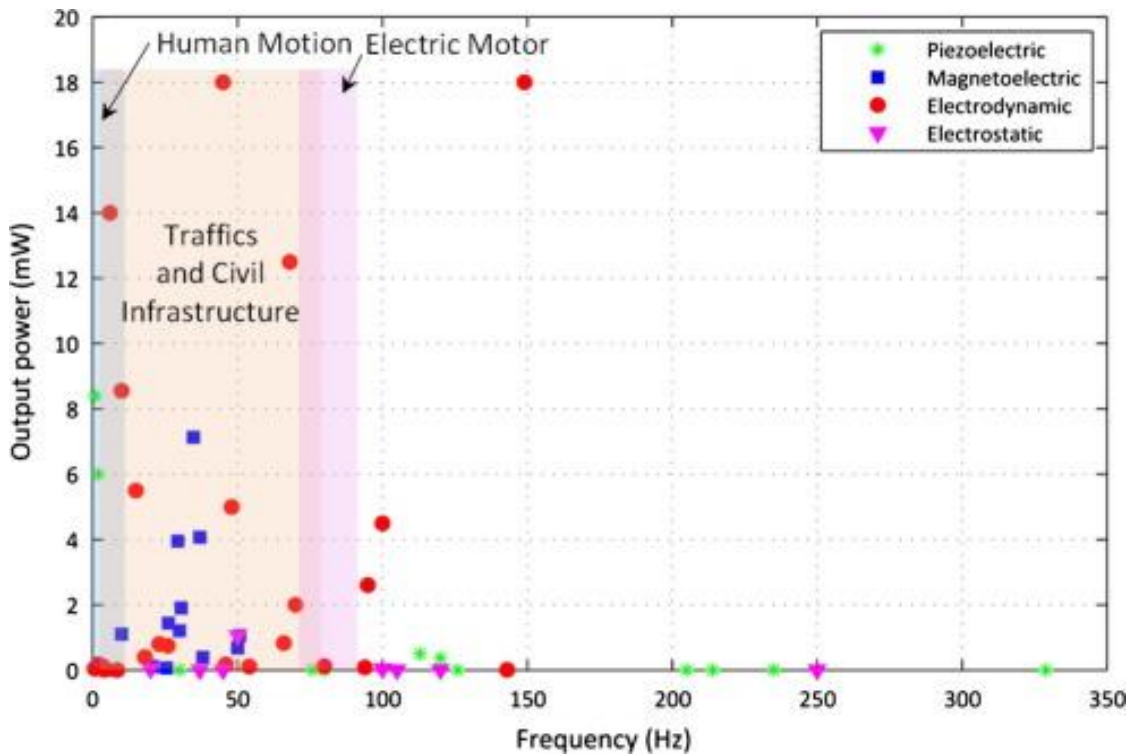


Fig. 1.3. Output power versus the working frequency

For main developed electromagnetic, electrostatic (Sasaki, 2005), piezoelectric (Shenck, 1999) and magnetoelectric (Tsutsumino, 2006) vibration transducers prototypes. Energy density is not mentioned in different research or only operating part is taken into account.

1.5. Electromagnetic converters

An electromagnetic linear vibration energy harvester with an array of rectangular permanent magnets as a springless proof mass. Instead of supporting the magnet assembly with spring element, ferrofluid has been used as a lubricating material. When external vibration is applied laterally to the harvester, magnet assembly slides back and forth on the channel with reduced friction and wear due to ferrofluid, which significantly improves the long-term reliability of the device. Electric power is generated across an array of copper windings formed at the bottom of the aluminum housing. A proof-of-concept harvester has been fabricated and tested with a vibration exciter at various input frequencies and accelerations (Song, 2017)

Although rotational motion is favorable for conventional power generation devices and systems, linear motion can be advantageous for some of the energy harvesting applications due to the inherent nature of the external vibration used as an energy source. In over-all, the rotor of an axial flux generator is connected to the shaft supported by the ball bearing, which maintains the narrow gap between the magnets and copper windings to maximize the output power Figure 1.4.

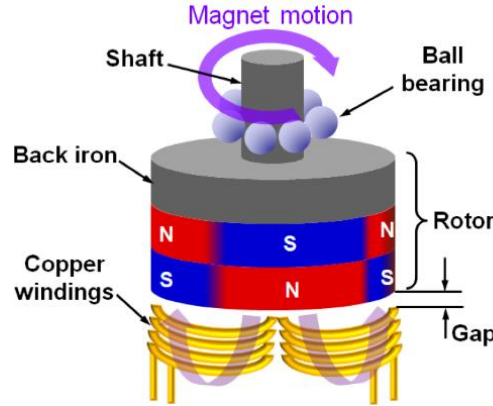


Fig. 1.4. Electromagnetic linear vibration energy harvester

Design employs a linear motion instead of the rotational counterpart to make use of the linear external vibration and to provide simple structure. The minimum gap between the winding and magnet array is defined by the thickness of the bottom side of the channel (Boisseau, 2012).

The conversion of mechanical to electrical energy for electromagnetic converters is based on the Faraday's law which is defined by:

$$V = N_d \cdot \phi \cdot dt \quad (1.2)$$

where V – the electromotive force, N – number of coil windings; ϕ –magnetic flux through a loop.

In general, electromagnetic converters consist of a combination of magnets and coils. Under excitation, a relative movement between coils and magnets leads to a variation of the magnetic flux density and the generation of energy through the coil. Different converters are realized for this purpose and can be classified depending on different criterion. In this section, we take into account only converters with one direction of excitation which are then classified depending on their mechanical design: use of cantilever, mechanical spring, magnetic spring or spiral spring.

1.6. Cantilever based vibrations converters

(Glynne-Jones, 2014) developed an electromagnetic converter based on cantilever beam. In this design, two alternative solutions were developed and compared focusing on improving the magnetic circuit of this converter. The first one was with a moving coil surrounding the moving magnetic assembly. The second was based on fixing the coil in between the moving magnetic assembly presented in Figure 1.4.

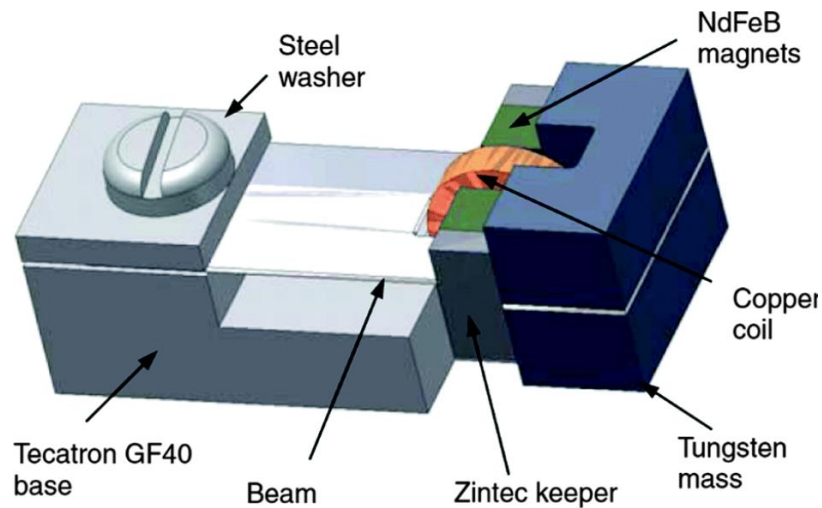


Fig. 1.5. Electromagnetic energy harvester based on cantilever beam

The converter was enhanced to work for low vibration level devoted to real applications. In this device, bulk magnetic materials and large coil winding density were used in order to realize useful level of output power from a compact system (Cepnik, 2011). The harvester is able to deliver $46 \mu\text{W}$ for a resistive load of $4 \text{ k}\Omega$ at a resonant frequency of 52 Hz and an acceleration of 0.06 g ($1 \text{ g} = 9.81 \text{ m s}^{-2}$).

1.7. Linear spring

(Amirtharajah 1998) Amirtharajah et al. apprehended a linear electromagnetic energy harvester in 1998. The proposed system has of a mass attached to a mechanical spring, a coil attached to the mass and a magnet fixed in the bottom of the housing.

(Seong, 2017) proposed a linear spring harvester shown in Figure 1.5. Schematic diagram of structure of the proposed generator, which consists of an armature, stator, and case. The armature consists of a permanent magnet, core, and shaft, while the stator consists of electromagnetic coils. A neodymium–ferrite (Nd-Fe) magnet is used for the permanent magnet. Non-magnetic stainless steel is used for the shaft, and steel 1010 is used for the core. Tension and compression springs were used to apply the resonance phenomenon to the armature.

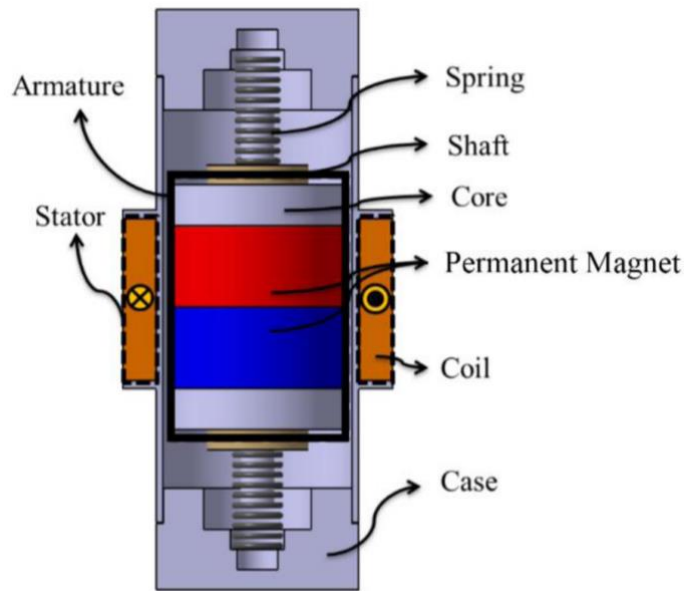


Fig. 1.6. Linear electromagnetic energy harvester using mechanical spring

(Cheng, 2007) used lumped element modeling (LEM) method to analyze the system behavior of magnetic energy harvesters. This method was used to develop an equivalent circuit model of the magnetic energy harvester. To validate the model, a developed setup was realized. The designed converter is based on the use of a moving magnet with 13 mm of diameter and 19 mm of length placed between two mechanical springs and surrounded with a 400 turns coil Figure 1.6. (b). An output power of 12.5 mW was achieved at 68 Hz and at 1 g.

As conclusion, it is reported that the increase of coupling strength is essential for maximizing the device performance which can be achieved by taking into account three design parameters the transduction coefficient K which is directly related to the strength of magnetic flux density in the coil, the mechanical damping coefficient b and the coil resistance R_{coil} .

1.8. Use of moving coil

A design study made by Arroyo et al. in 2013 uses fixed magnets and moving coil stacked between two planar springs placed on a closed ferromagnetic back iron (Arroyo, 2013). Figure 1.6. presents the developed design for this work.

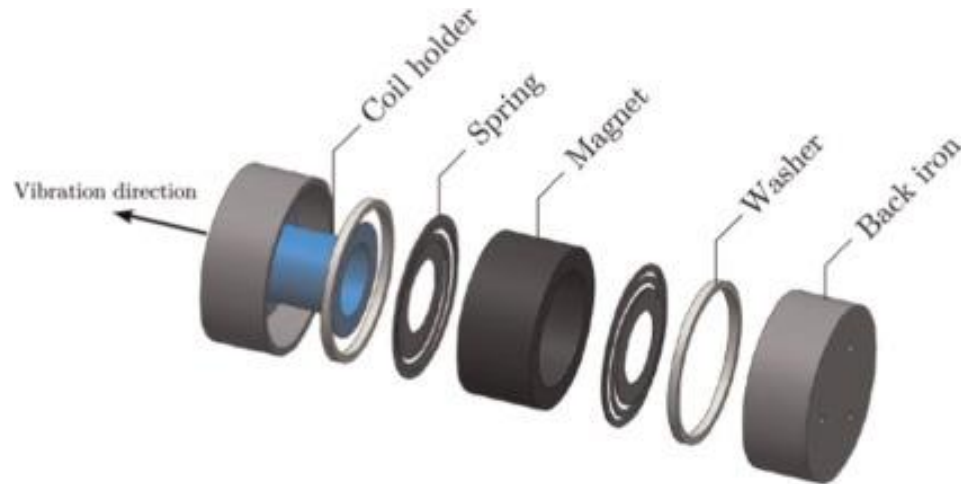


Fig. 1.7. Exploded view drawing of the converter using moving coil

The aim was that the current into the coil produces a self-induced magnetic field, which is also contained into the ferromagnetic core, ensuring much higher inductance than generators without back iron. The fabricated system has a volume of 10 cm^3 and is able to generate 2.75 mW at 1 g , 95 Hz and a resistance value of 16Ω . The converter was tested for different excitation with an acceleration from 0.2 to 1 g . The increase of acceleration leads to nonlinearity on the displacement and the increase of the bandwidth which reaches 10 Hz for 1 g .

1.9. Use of moving magnet

In 2009, Galchev et al. designed a non-resonant Parametric Frequency Increased Generator (PFIG) devoted to generate energy subjected to low-frequency non-periodic vibrations. This type of converter is characterized by its non-resonant operation since it decouples the harvester operating frequency from that of the ambient environment. This allows the generator to work over a broad frequency range

The Parametric Frequency Increased Generator (PFIG) is designed to accommodate the large amplitudes associated with low-frequency vibrations, and because it works in a non-resonant fashion, the PFIG is able to operate over a wide band of frequencies. The PFIG utilizes a large inertial mass to couple kinetic energy, from the ambient, inside the generator structure, and pass a portion of it to one of two Frequency Increased Generators (FIGs), which then convert this mechanical energy to electrical

via electromagnetic induction. The converter is based on the use of inertial mass placed in the middle suspended through a spring. Two Frequency Increased Generator (FIG) are placed from both sides of the inertial mass. Each FIG is composed by magnet, coil which is ended by a spiral spring and an actuation magnet. Receiving an external vibration, the inertial mass is oscillating between the two FIG. This leads to the movement of one of top or bottom magnets and conversion of the mechanical energy to electrical (Galchev, 2009). FIG desing shown in Figure 1.8.

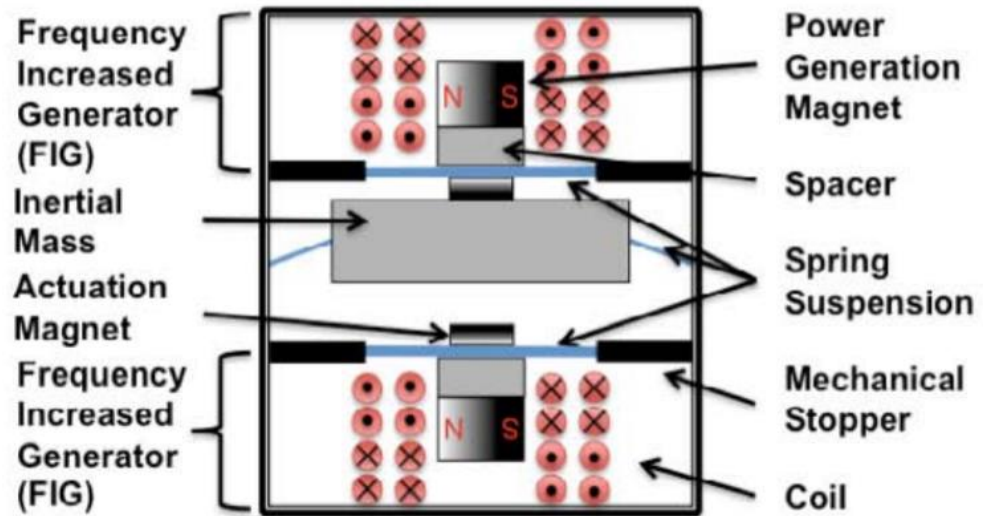


Fig. 1.8. Parametric Frequency Increased Generator (PFIG) design

For the realization, the authors used hybrid assembly that the three main parts (inertial mass, two FIG) can be moved in the z-direction using a micro positioner. This assembly was used to characterize the influence of different parameters and their optimization.

1.10. Magnetic spring based vibration converters

For the magnetic spring architecture, the main advantage is to have a system working for larger frequency bandwidth due to the nonlinearity of the system. However, this architecture has a functional limitation that such solution cannot be implemented in a metallic environment because of the use a moving magnet. Instead of that, the mechanical spring architecture can be used for such environment by attaching the coil to the mechanical spring using a non-magnetic mechanical spring. Behind electromagnetic converters based on cantilever beam and mechanical spring, researchers developed harvesters based on magnetic spring for more reliability and long lifetime. It is formed with a mechanical spring where a coil is attached. Magnets are placed inside the coil. The main advantages of this proposed architecture are the possibility to be placed

in magnetic environment, its compactness and the possibility to tune the resonant frequency by changing the stiffness spring or by using an added mass. At the end, the design overcomes one of the main limitation of the moving coil by avoiding the contact between the coil wires with the mechanical spring which leads to a better robustness for the converter (Bradai, 2004). Figure 1.9. present the design of Proposed mechanical design for the electromagnetic converter.

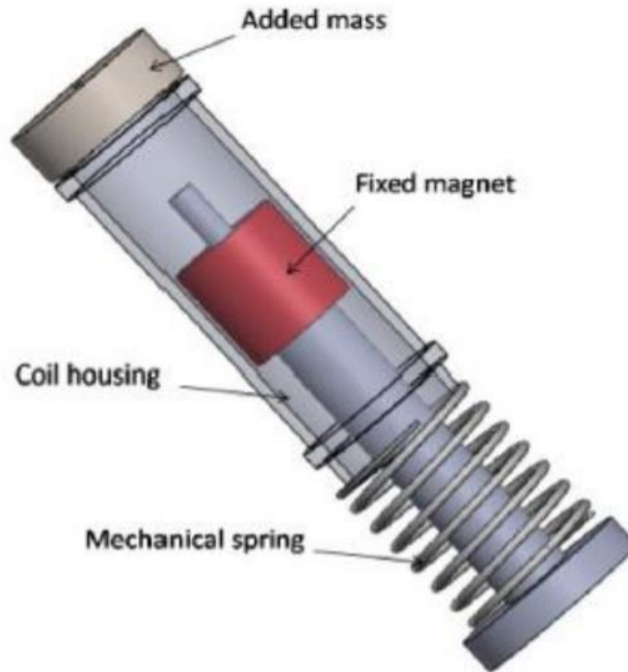


Fig. 1.9. Vibration converters based magnetic spring principle

The results show that the linear harvester provides more power for frequency range from 8 to 9 Hz which presents the resonant frequency for the harvester. For an excitation with higher frequency than the resonant frequency, the nonlinear converter presents higher energy outcome. For a frequency range 9.5–11.5 Hz and 0.2 g²/Hz, the nonlinear converter is able to generate 2.27 mW and only 0.68 mW is reached for the linear device with same input excitation.

1.11. Section conclusions

This section presented a review of recent publications as well as main theoretical concepts and principles used in the field of energy harvesting. The reader was introduced to energy harvesting models their possible applications and typical powering requirements. These were followed by a brief review of low frequency vibration converts. Most common configurations of harvester with their capabilities, limitations as well as areas of design improvement were elaborated. The results of literature review are presented it Table 1.2.

Table 1.2. Examples and suitability of presented energy harvesting techniques.

Methods	Suitability	Advantages	Disadvantages
Piezoelectric cantilever	Can be used with a simple cantilever having a tip mass to tune the operating frequency	Simple design which can be used with more than one material layer having a tip mass to tune the operating frequency	Heavily reliant on cantilever resonance frequencies for appreciable power output
Magnetoelectric cantilever	For converters consist of a combination of magnets and coils	Has better energy outcome for higher frequencies and good performance term converters which make these principles more suitable for MEMS applications	Performance is highly depending on the characteristics of the excitation source
Moving magnet	Inertial mass placed in the middle suspended through a spring	Can generate energy over a broad frequency range	Hybrid assembly that can be moved in the z-direction using a micro positioner
Magnetic spring	Vertical energy harvesting application	High reliability and long lifetime	More power for frequency range from 8 to 9 Hz which presents the resonant frequency for the harvester.

In general, this section introduced the reader to the field of energy harvesting, outlaying its basic principles, recent research achievements and commonly met issues or, in other words.

After the overview of energy harvesting devices and techniques, the aims of this research has been revised and clarified:

- compose mathematical model of harvester;
- evaluate the dependence to the coil number of windings and wire thickness;
- evaluate the dependence to the metal core inserted into coils. Core diameter dependence to the generated voltage;
- evaluate the dependence to the metal pot cover installed into coils. Pot wall thickness dependence to generated voltage.

2. METHODOLOGY OF RESEARCH

Research process is a sequence of steps, that's needs to be performed to reach the goal. Some steps cannot be done while others are not finished. Whole research process can be described as flow chart which will present the connection between these steps. Flow chart steps with sub-steps are presented bellow in Figure 2.1. Further all these steps will be explained in this work.

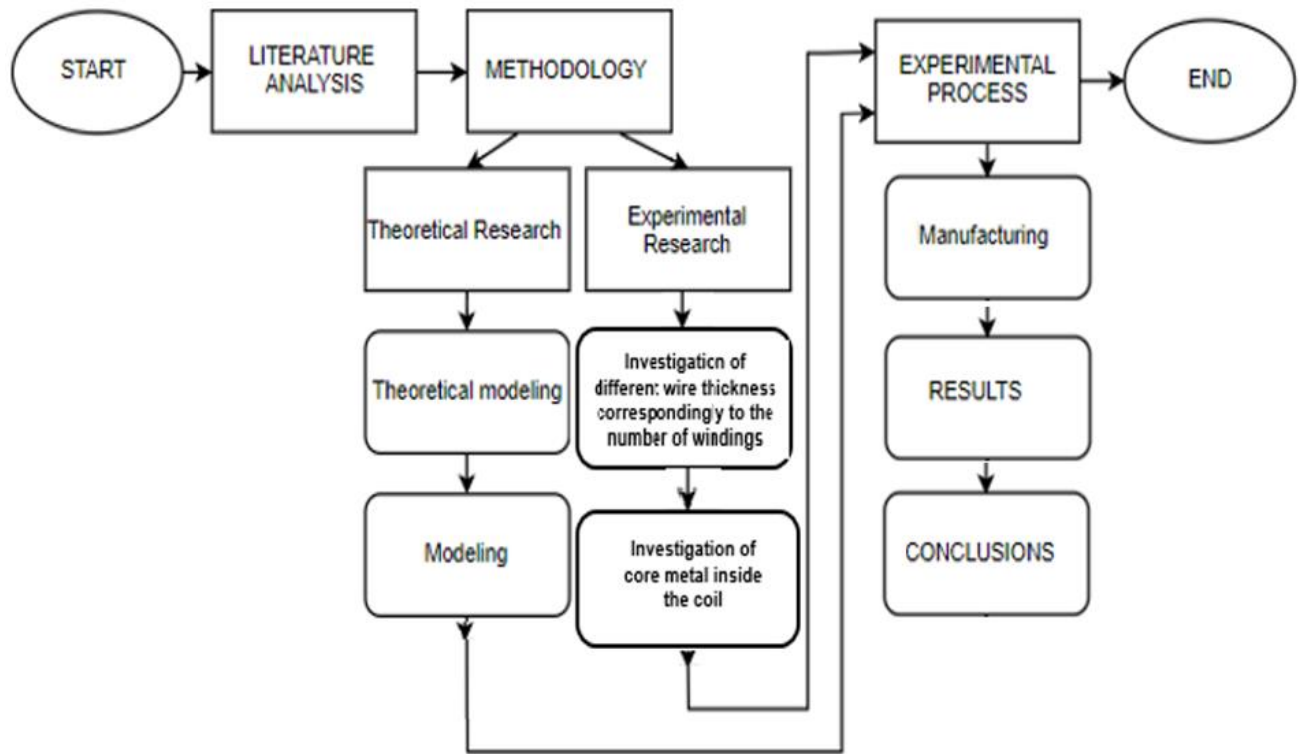


Fig. 2.1. Process sequence

Work begins with the literature review with the brief overview of similar devices and techniques already presented. After the literature review the aim of research will be clarified. In the methodology section the following task for theoretical and experimental research will be planned. In the theoretical research will be selected the design and created the mathematical model of harvester. When the theoretical experiments will be accomplished the experimental model will be built and tested. Data from experiments will be proceed and presented in the results sections. After the results final conclusion can be stated.

Each step takes time to complete it, so time planning is required. This research work will take approximately two months, including one reserved week for the emerging issues.

2.1. Theoretical research methodology

For the theoretical research the design of harvester will be selected. Energy harvesters cannot be cost effectively built and tested without prior modelling of its component. Preliminary design stage gives one the advantage to predict how developed configuration will perform. After the design selection the mathematical model of harvester will be created. The calculations will be performed by numerical compounding software Matlab version R2016b developed by Mathworks.

2.1.1. Design of harvester

The schematic structure of the proposed magnetic-spring based, low-frequency-vibration energy harvester is shown in Figure 2.2. The energy harvester is composed of a rotor structure suspended between magnetic plates and a series copper coils. A significant air gap is maintained between the magnet arrays so that the magnetic interaction between them is negligible.

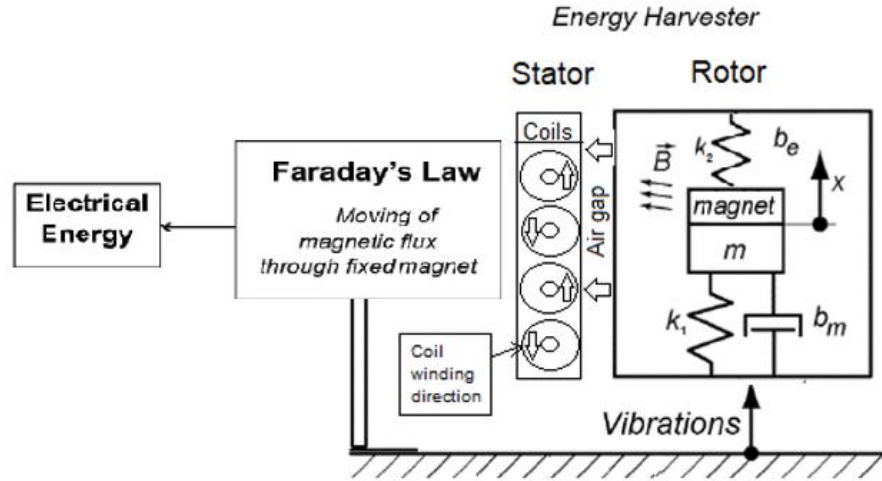


Fig. 2.2. Scheme of harvester design

When an external mechanical vibration is applied to the structure in the axial direction of the harvester, the suspended mass starts to oscillate within the magnetic springs, causing a relative displacement between the magnet arrays and the connected coils. The coils cut the concentrated magnetic-flux lines of the magnet arrays that in turn induce an electromotive force (e.m.f.), leading to a generation of voltage across the coil terminals according to Faraday's Law of EM induction.

2.1.2. Mathematical model

A model for the vibration energy conversion consist of mass-spring system which is shown in Figure 2.2. The mass displacement is caused by the input displacement. The damping includes the mechanical damping and the electrically induced damping. Here, the power from the mechanical system generated by electrical induced damping can be converted to electrical power, while the mechanical damping always causes the energy loss of the system.

$$y(t) = Y \sin(\omega t) \quad (2.1)$$

where: $y(t)$ – displacement; Y – is the amplitude; t – time; ω – angular frequency.

The system can be described as:

$$m\ddot{z}(t) + (b_e + b_m)\dot{z}(t) + kz(t) = m\omega^2 Y \sin(\omega t) \quad (2.2)$$

where: k – is the spring constant; b_e and b_m are the electrical induced damping coefficient and mechanical damping coefficient respectively; $z(t)$ – spring deflection; and $y(t)$ –displacement .

The generated power of the system is:

$$p = \frac{mY^2\zeta_e\left(\frac{\omega}{\omega_n}\right)^3\omega^3}{\left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2 + \left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2} \quad (2.3)$$

where: ω_n –natural frequency of the system; ζ – damping ratio from electrical and mechanical parts $\zeta = \zeta_e + \zeta_m = \frac{b_e + b_m}{2m\omega_n}$;

When the system is working at resonant frequency, the generated electrical power reaches maximum. Obviously, when the resonant frequency of the system matches the input frequency, the power is proportional to the mass. Therefore, larger magnet should be utilized as the mass in the energy harvesting device. Meanwhile, more power will be obtained at resonance if mechanical damping ratio is small enough and equals to the electrical damping ratio ($\zeta_e = \zeta_m$).

Mechanical damping ratio can be designed by structures as low as possible while electrical damping ratio can be optimized by circuit parameters. When the load resistance equals to the system resistance, the maximum power will be generated across the load.

$$E(t) = -N \frac{d\phi}{dz} = -NA \frac{dB}{dz} \frac{dz}{dt} \quad (2.4)$$

where: N – turns of the coil; A –area of the coil.

From (3.2), the magnetic damping force ($F = b_e \dot{z}(t)$) can be expressed as:

$$F_M = b_e \dot{z}(t) = NA \frac{dB}{dz} \frac{E(t)}{R_{coil} R_{Load}} \quad (2.5)$$

where: R_{Coil} and R_{Load} – the impedance of the coil and external load, respectively.

Based on (3.2), (3.4) and (3.5) Matlab Simulink model Figure 2.3. can be built to investigate the frequency response of the induced voltage if we acquire the relationship between and. For electromagnetic energy harvester, the induced voltage is determined according to Faraday's law.

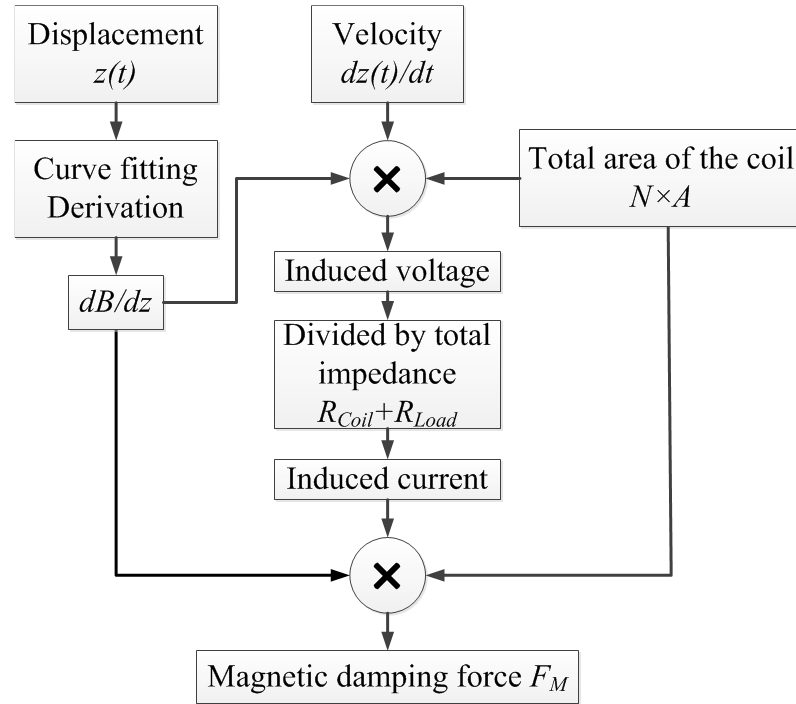


Fig. 2.3. Detailed process of calculating magnetic force damping F_M

Magnetostatic simulation can be carried out to obtain the relationship between Here, a five order polynomial function is chosen to fit the – curve using least square method.

$$B(z) = Az^5 + Bz^4 + Cz^3 + Dz^2 + Ez + F \quad (2.6)$$

where: $B(z)$ – average magnetic flux density over the coil area; z – distance from the magnet surface.

The relationship between $\frac{dB}{dz}$ and z is acquired through differential of (3.6).

Magnetostatic simulation can be carried out to obtain the relationship between (average magnetic flux density over the coil area) and (distance from the magnet surface). Here, a five order polynomial function is chosen to fit the – curve using least square method.

The detailed process of calculating F_M is explained in Figure 2.4. Given an input excitation, the product of $z(t)$ and k , the product of dB/dz and b_m , as well as the magnetic damping force F_M , are sent back to the system as a feedback. In addition, external circuit module can be added to investigate the relationship between the output and external load. A general system-level Simulink model of this energy harvester is described in Figure 2.4.

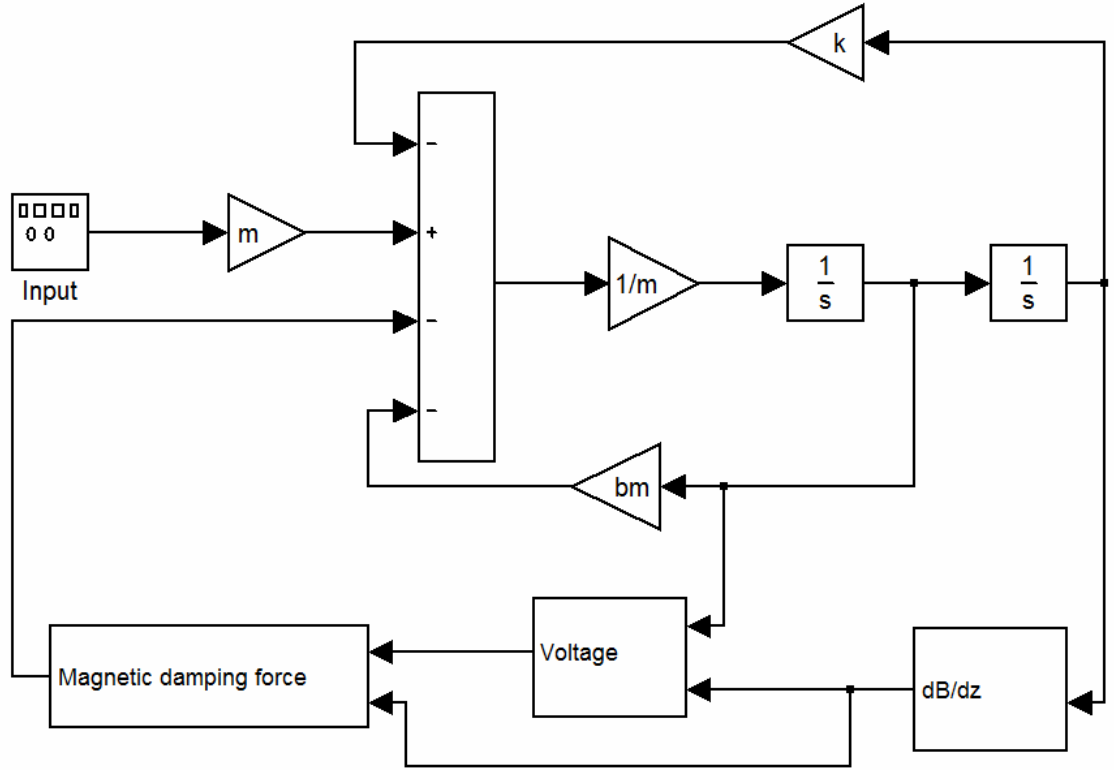


Fig. 2.4. Simulink model of the energy harvester

Here the *input* is a step sine wave, m – the mass of harvester; k – spring constant; bm – mechanical damping coefficient. The electromagnetic energy harvester is designed to work with low frequency

horizontal vibration input, which consists of a fixed copper coil on the stator planar plate and magnet arrays located on the rotor planar plate.

Energy harvesters with moving magnets have several benefits. First of all, using the magnets as the moving parts can increase the total mass of the device, which will increase the output power according to (Glynne-Jones). Besides, the magnets are fabricated on the top layer after the fabrication of the coils and beams, making the fabrication easier and more stable.

2.2. Experimental research methodology

To perform experimental research there are need for methodology how to perform the experiments. Since in this research state there is only a harvester built there are need for external energy source to excite vibrations. For this reason the stepper motor is used. The energy from power source is supplied into stepper motor, micro stepper and Arduino to correspond the vibrations from the vibrating table. By the micro step drive one rotation divided into 64 steps in order to achieve smooth run of motor. The starting rotational frequency for measurements is 0.5Hz and will be increased by 0.5Hz to the final 3.0Hz frequency which is the maximum rotational frequency what was able to achieve in that particular setup. All measurements were performed three times. From collected data averages will calculated for each measurement setup. All experimental data are presented in the following chapters bellow.

The electricity generated while magnet passes the coil is AC. The voltage occurs in the coil while the magnet entries the coil and while leaves it. In order to measure the total energy of harvester, the output should be DC. The construction diagram of a bridge rectifier is shown in the below Figure 2.5.. The bridge rectifier is made up of four diodes namely D1, D2, D3, D4 and load resistor R_L . The four diodes are connected in a closed loop (Bridge) configuration to efficiently convert the Alternating Current (AC) into Direct Current (DC). All measurements will be repeated with added bridge rectifier to the circuit.

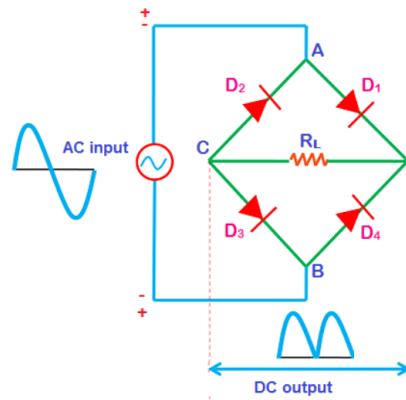


Fig. 2.5. Full wave rectifier

The four diodes D1, D2, D3, D4 are arranged in series with only two diodes allowing electric current during each half cycle. Diodes D1 and D3 are considered as one pair which allows electric current during the positive half cycle whereas diodes D2 and D4 are considered as another pair which allows electric current during the negative half cycle of the input AC signal.

2.2.1. Metal core influence

In general a magnetic core is a piece of magnetic material with a high magnetic permeability used to confine and guide magnetic assemblies. An electric current through a wire wound into a coil creates a magnetic field through the center of the coil, due to Ampere's circuital law.

Electromagnets all consists of a current carrying conductor, however the strength of the magnetic field produced also depends on the surrounding substance. Air is not particularly good at 'carrying' a magnetic field and so the field around a wire is quite weak. By adding a piece of ferromagnetic or ferromagnetic material in the center of the coil can increase the magnetic field by hundreds times.

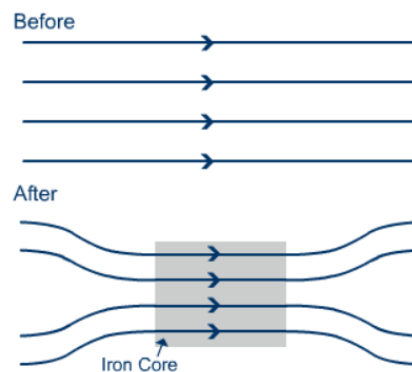


Fig. 2.6. Metal core effect to the magnetic field

By adding a piece of ferromagnetic or ferromagnetic material in the center of the coil can increase the magnetic field by hundreds times. The field of the wire penetrates the core material, magnetizing it, so that the strong magnetic field of the core adds to the field created by the wire. The amount that the magnetic field is increased by the core depends on the magnetic permeability of the core material. In this case the structural steel S235 (EN10025) will be used.

2.2.2. Metal pot core influence

Pot cores are used for inductors with low stray fields. The pot core coil generally consists of a coil former with one or two sections, the pot core halves made of soft magnetic, low-loss and usually high perm materials, the mounting plate and the retaining clamps Figure 2.7.

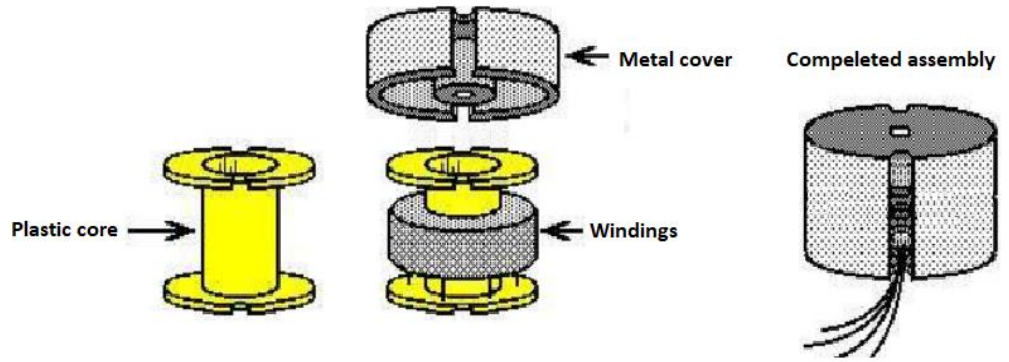


Fig. 2.7. Pot core structure used in the experiments

The coil is wound on plastic core which is inserted into the metal cover. Pot core coils can be supplied with defined shearing, the predetermined AL values for the individual materials and pot core geometries being achieved by grinding a defined air gap into the center leg of the pot core halves. The magnetic flux is also concentrated within the core and the path of the magnetic flux have a gap at the fit of the cups to each other. This gap has a high magnetic resistance and, eventually, the effective magnetic permeability of the core is always lower than the initial one.

For this experiment U – shaped cores were built with different wall thickness: 2mm, 3mm, 4mm from structural steel S235 (EN10025). Measurements were performed in the same way and the results are presented in the results sections.

2.3. Experimental equipment and devices

The result of harvester energy is directly dependent from the equipment used in the research. The following section describes equipment and its properties which were used in this experimental research of the energy harvester. The properties of the harvester components are listed below.

The copper coils were wound in six segments with each segment being wound in a direction different from the other and each having the same turns of wire per coil. Three variants of stators were prepared for the experiments with six coils inside. The coil design specifications and parameters are prescribed in the Table 2.1.

Table 2.1. Stator configuration variants with coil specifications.

Parameter	Characteristics		
	I	II	III
Variant of coil setup	I	II	III
Number of coils in stator	6	6	6
Wire thickness, mm	0.1	0.25	0.5
Wire material	Copper	Copper	Copper
Wire surface	lacquered	lacquered	lacquered
Number of windings	2000	650	150

In the stator of harvester coils are placed in different winding direction in order as it is shown in Figure 2.8.

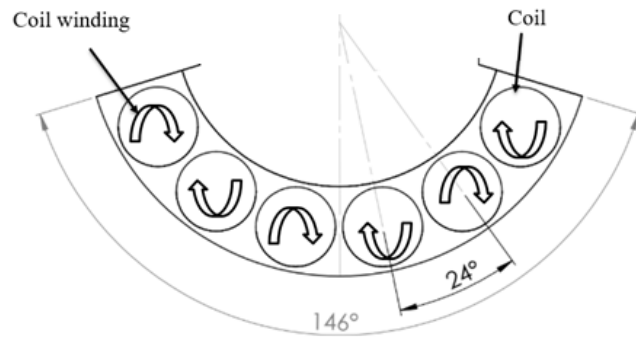


Fig. 2.8. Coils configuration on the stator

The purpose of such coils alignment is to increase the electromagnetic properties of coils and achieve higher voltage results. When the magnet cover the first coil magnetic flux starts in the coil and continuously passes to the end of first coil to the second coil the beginning. This magnetic flux flow is repeated in all coils. The design of the cylindrical coils and the stator respectively is simpler and more technological, but this results in a lower effective area of the coils, resulting in a lower energy transformation factor.

The magnets were designed from NdFeB N52 type material and were obtained commercially. Magnet properties are shown in the Table 2.1.

Table 2.1. Permanent magnet specification.

Parameter	Characteristics
Shape	Block
Dimensions, mm	15x10x3
Material (Material): NdFeB	Material (Material): NdFeB
Tolerance	+ / - 0.1 mm
Coating	Nickel-plated (Ni-Cu-Ni
Magnetisation	N52 through the thickness of 5 mm
Strength	approx. 5 Kg
Weight	5 g.
Magnetic properties of magnetic materials N52	1.42 to 1.47 Br [T] 14200-14700
Coercivity HCJ minutes, kA/m	955
Energy product (BH), kJ/m ³	380 to 422

The fabricated moving magnet composite was composed with three magnets each with dimensions 15mm×10×3mm. This magnet and coil configuration ensures effective use of the coils and the absence of constant zero voltage regions (magnet outside the coil area, or cancellation effects). Layout of magnets are presented in Figure 2.9.

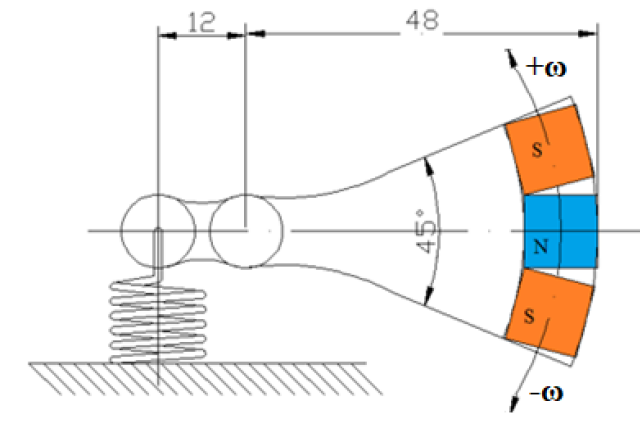


Fig. 2.9. Magnets configuration on the rotor

The moving magnet composite was assembled using Loctite® epoxy (Henkel Corp, USA) and clamped together for two days to allow the epoxy set properly.

The design of fabricated of the low frequency energy harvester and characterized is shown in Figure 2.10. As shown in the stator e) is fixed to the non-movable frame, rotor with magnets composite d) was mounted from other end. In order to simulate low frequency vibrating table, the simple construction frame was built for measurements. The main parts of this model is: frame, stepper motor, stator and rotor.

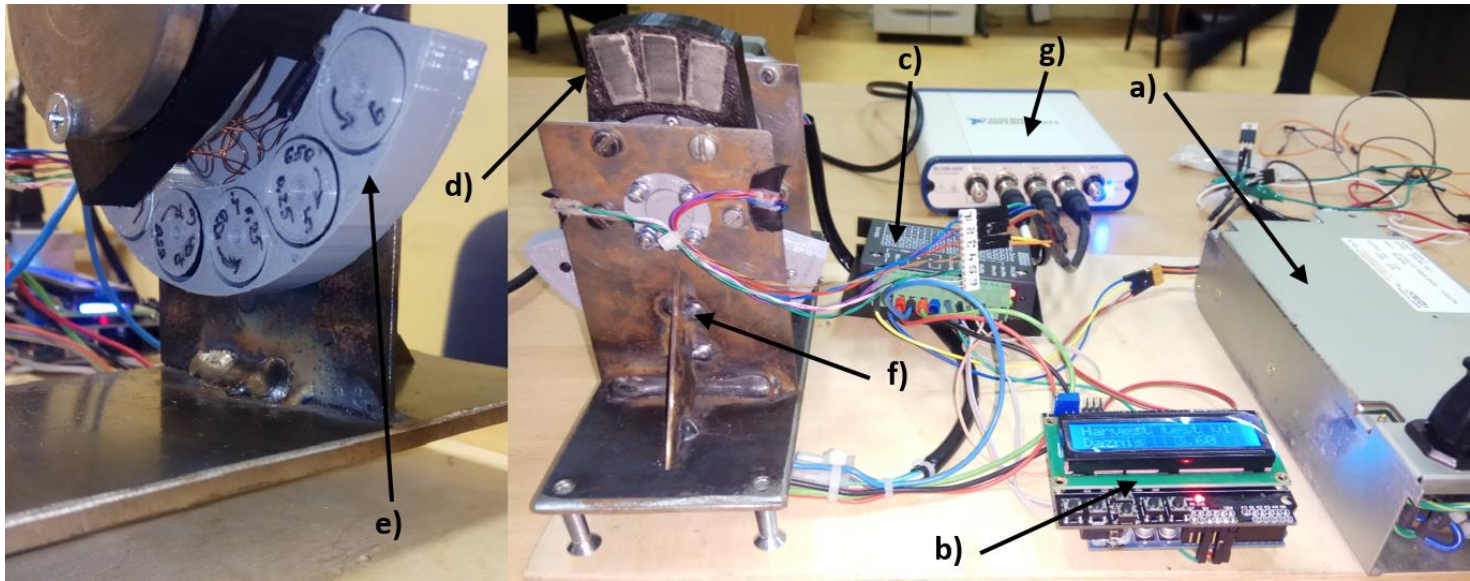


Fig. 2.10. Scheme of experimental setup:

a) power source; b) Arduino controller; c) Microstep drive controller; d) Harvester rotor with permanent magnets; e) harvester stator with coils; f) harvester frame; g) National Instruments data acquisition module.

A significant air gap is left between coil and magnet. To excite low frequency vibrations stepper motor was used. By the micro step drive one rotation was divided into 64 steps. Voltage was measured with a National Instrument data acquisition module (g), which was connected to a computer. By software voltage response recordings from the harvester in respect to the time.

3. RESULTS OF THEORETICAL RESEARCH

A general model for the vibration energy conversion is the standard mass-spring system. In this system, the mass displacement is caused by the input displacement. The damping includes the mechanical damping and the electrically induced damping. Here, the power from the mechanical system generated by electrical induced damping can be converted to electrical power, while the mechanical damping always causes the energy loss of the system. Theoretical calculation values are presented in the Table 3.1.

Table 3.1. Theoretical calculations values.

Parameter	Denotation	Value
Number of windings	N	2000, 3000, 4000
Wire diameter	d	0.1 mm
Mass of rotor	m	0.15 kg
spring constant	k	25 N/m
Angular frequency	ω	2 Hz
Electrical induced damping coefficient	b_e	0.000005 Nms/rad
Mechanical damping coefficient	b_m	5Ns/m
Impedance of the coil	R_{Coil}	0.0005 μ H
Impedance of the external load	R_{Load}	0.00005 μ H

In theory the voltage directly depends to the product of winding number and area of coil wire. The number of windings were selected according Arroyo design study in 2013 where he uses fixed magnets and moving coil. For the simulation it is selected three different numbers of windings: 2000, 3000 and 4000. The magnetic flux through the wire loop is proportional to the number of magnetic flux lines that pass through the loop. When the flux through the surface changes, Faraday's law of induction says that the wire loop acquires an electromotive force (EMF). This law states that the induced electromotive force in any closed circuit is equal to the rate of change of the magnetic flux enclosed by the circuit.

Modeling the horizontal movement of the magnets with a maximum amplitude of ± 30 mm, corresponding to an angle of 106° for the pendulum. The harvester pendulum acts as a standard mass-spring system with damping. The gradual or exponential reduction of vibration through resistance of the vibrational

forces or by damping. In Figure 3.1. it is presented the steady state response graph.

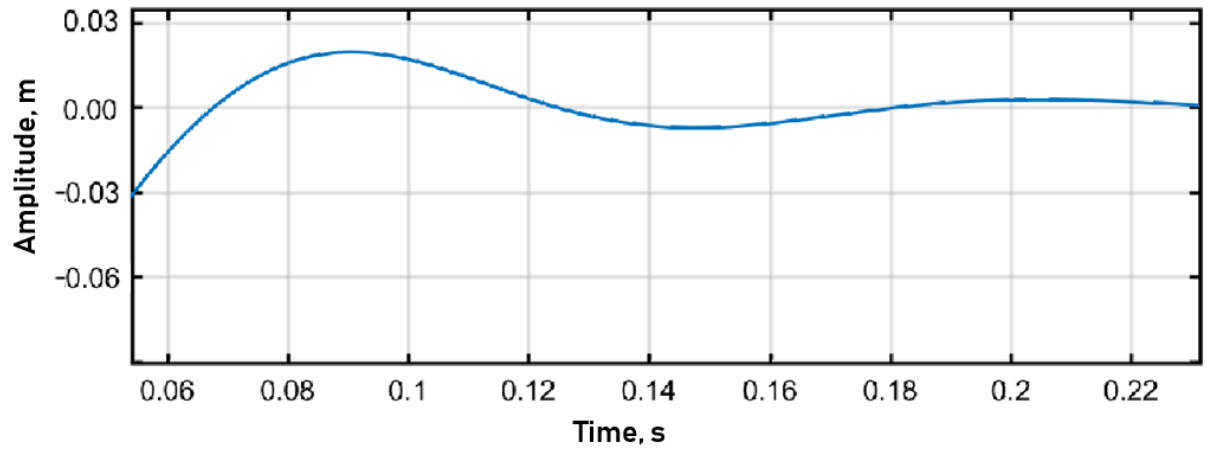


Fig. 3.1. Step response of pendulum

Magnet arrays with two side magnets are utilized to provide the constant magnet field. According to Faraday's law, the voltage will be generated when the magnetic flux through the copper coils changes during the vertical movement. When the magnet approaches the coil, induced current will flow through the coils. When the magnet passes the middle of coil, current with the opposite direction will be generated. Since there are three magnets in the stator, in one swing four points where sine wave and current change its direction. Theoretical calculation results are presented in the Figure 3.2.

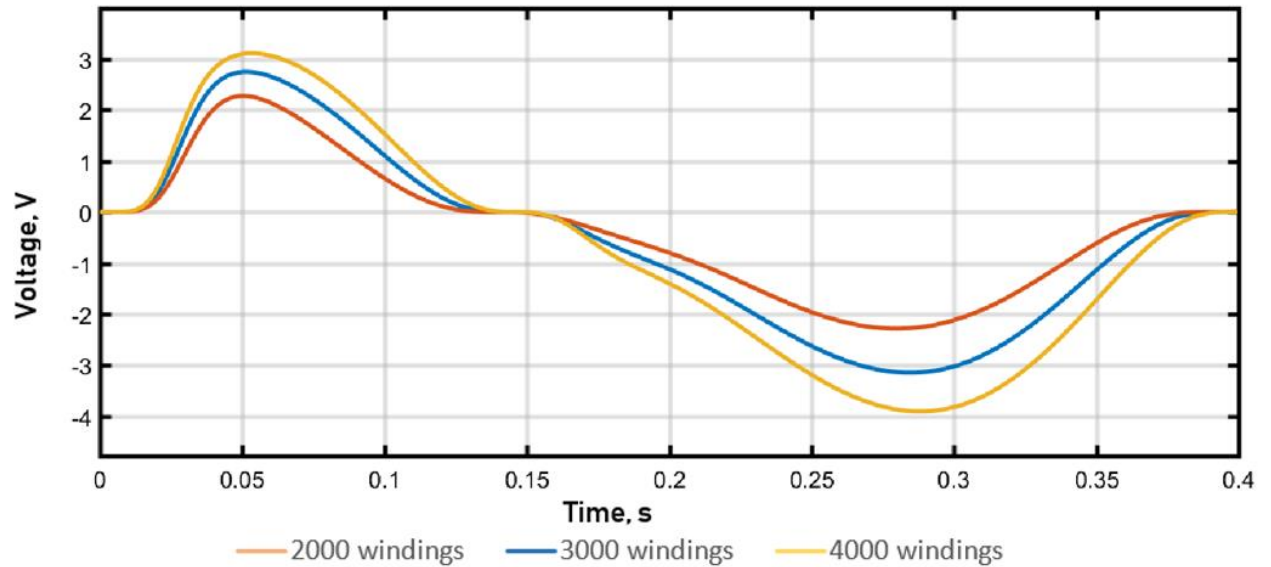


Fig. 3.2. Theoretical results.

With the 2Hz sine wave input maximum voltage is 3.97 V obtained with 4000 windings. As the number of windings decreased, the output voltage decreased. With 3000 and 2000 windings voltage is 3.11 V and 2.24 V correspondingly.

Section conclusions:

- The design and the theoretical calculations of low-frequency-vibration energy harvester were presented;
- Harvester reaches steady state in 0.25 seconds;
- At the 2 Hz rotational frequency is presented the maximum value of voltage is 3.97 V with 4000 windings in the coil;
- Lowest voltage is 2000 windings 2.24V. It can be stated that the voltage is dependent to the number of windings.

4. RESULTS OF EXPERIMENTAL RESEARCH

The following section describes elaboration of different setups prototypes; customized equipment and experimental measurements as well as experimental studies with different configuration throughout the research period. The aim of experimental studies was to evaluate dynamic and electric characteristics of harvester prototypes and verify adequacy of the developed coil model.

Experiments performed during the course of research may be grouped to the following groups: 1) investigations of separate coil, its dependence to the number of windings corresponding to wire thickness; 2) investigation of metal core and pot core influence on coil performance. The last chapter of this section is devoted to summarize experimental research and rehash main conclusions.

4.1. Different coil windings

For each set of different coils and stator configuration experiments were performed in frequency ranges from 0.5 Hz to 3.0 Hz in two different circuit configurations. At first all coils were measured one by one in all frequency ranges. Measurements were performed without any load connected into the circuit. The voltage was measured directly from the coil to reduce the length of wire and losses due to resistance of wire. After all measurements were done the capacitor with diode bridge was added and all experimental measurements were repeated with added load in the circuit.

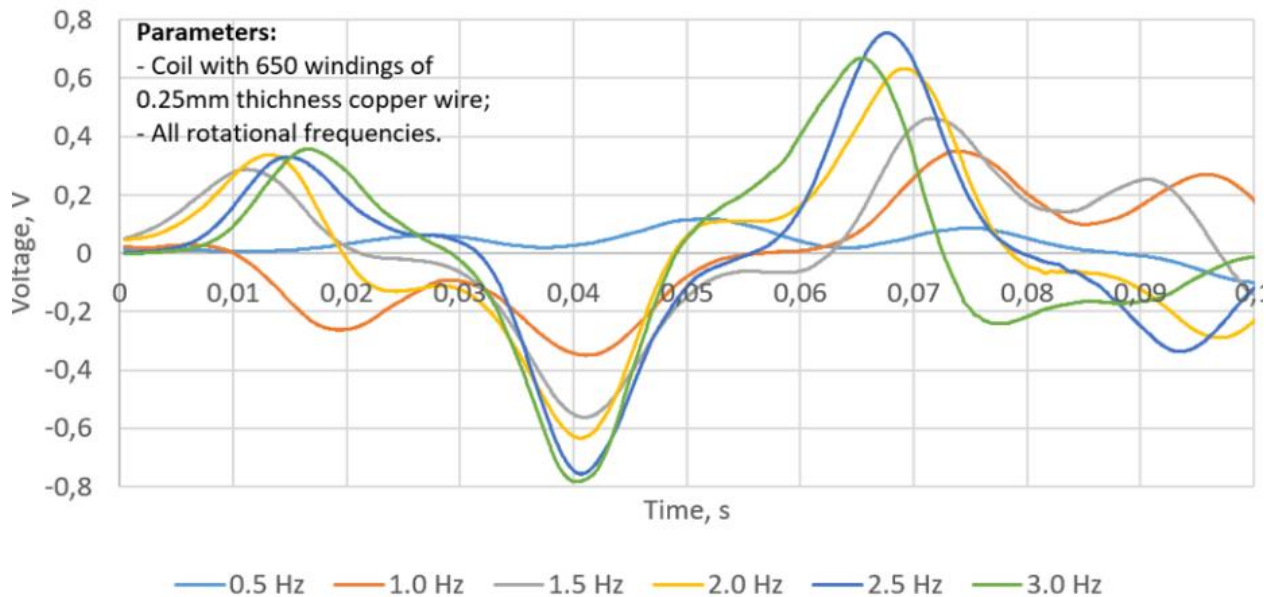


Fig. 4.1. II stator with coils design setup

In the graph there is presented the measured voltage from the second coil in the assembly in the respect of rotating rotor frequency. The maximum generated voltage is at the frequency of 2 Hz. In the theory voltage should be proportional to the frequency, it can be seen that from 0.5 Hz till 2.0 Hz it

was increasing. The voltage drop at 3.0Hz can be explained in the fault of stepper motor. The motor reach 3.0Hz rotational frequency on its limits. During the experiments the motor became hot and before the final measure of 3.0 Hz it had be left for a few minutes to cool down. For that reason the 2.0Hz of rotational frequency was choose as an optimal frequency to have a refine between different stator variants. In the graph Figure 4.2. it is presented all six coils voltage from the II stator setup rotating at 2.0 Hz.

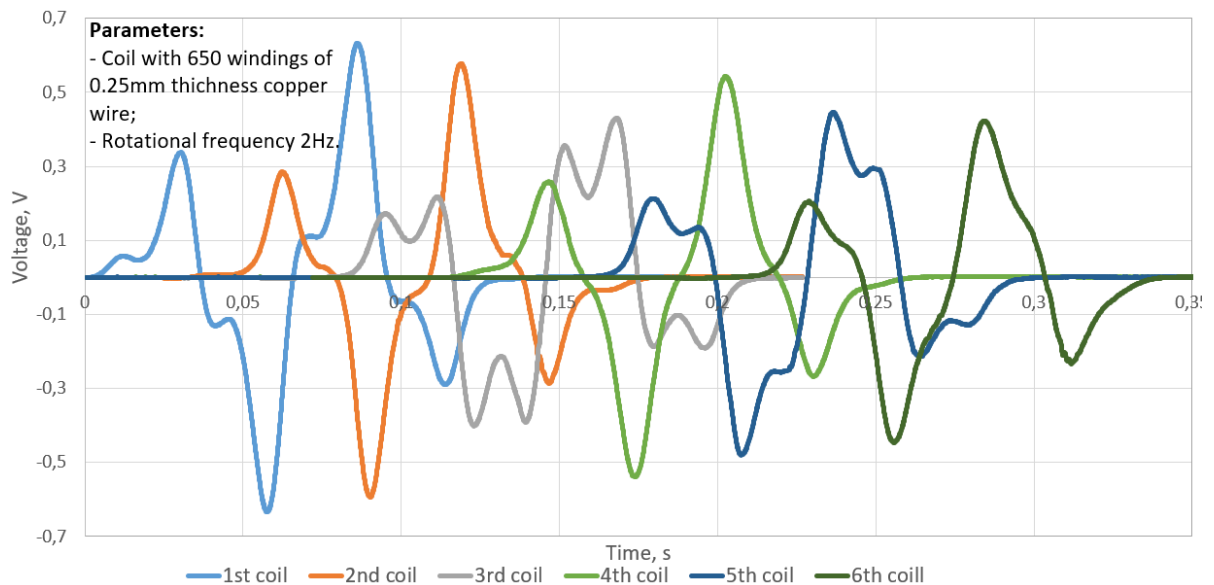


Fig. 4.2. Measured voltage from the II stator and coils set in the respect of rotating rotor frequency

It can be stated that the highest generated voltage occurs in the coil number 1 (0.6V) and the lowest voltage generates by the number 6 coil (0.27V). It can be explained that magnets in the rotor reach the coil number 1 without any effect on the magnetic field when the coil number 6 is reached last with reduced magnetic field from first five coils during the rotation.

To measure the total energy the capacitor added to the circuit and measured the total energy. Again can be seen the same problem of motor that on 2.5Hz total energy is higher than the 3.0Hz. The maximum energy is approximately 0.07V at the 2.5Hz. The higher frequency faster charges the capacitor while on the low frequency charging time is longer, but generated energy has longer discharge time compared to the energy generated at higher frequency. The results of first coil voltage

in the II stator coil variant is presented in the Figure 4.3.

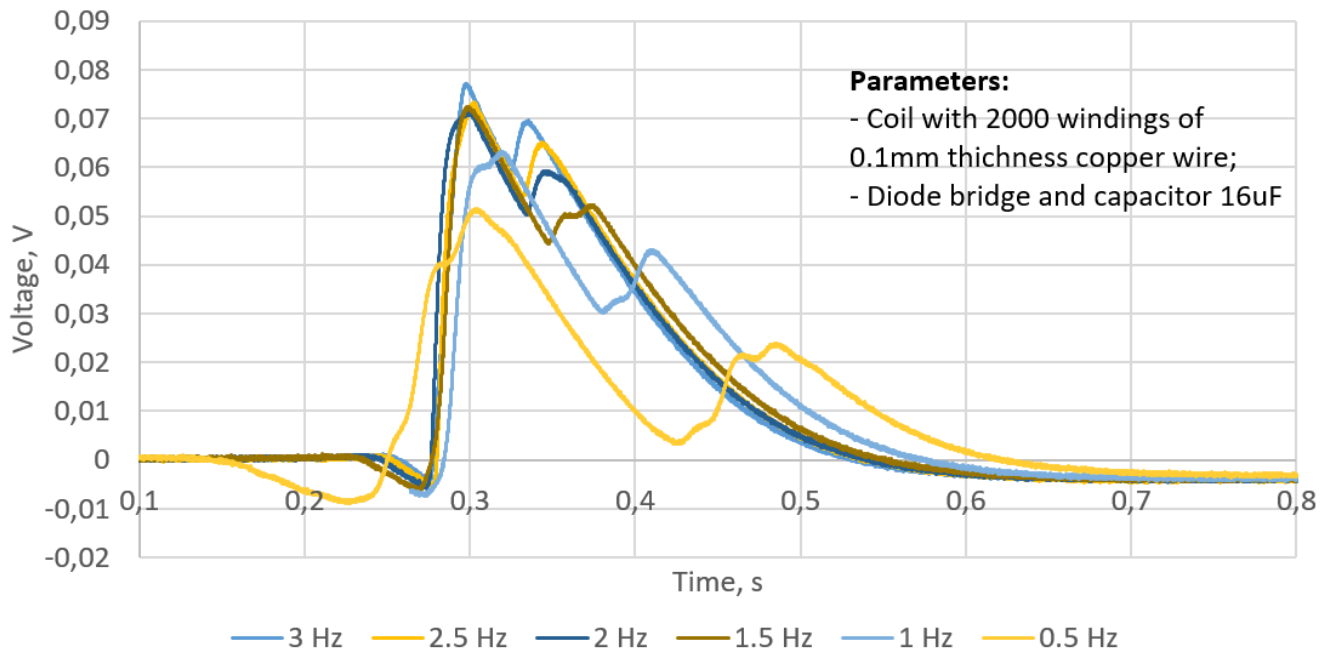


Fig. 4.3. First coil voltage in the II stator setup in the respect of rotating rotor frequency

Another interesting phenomena can be seen from the graph that before charging the capacitor is discharged to approximately to the same negative -0.01 independent to the rotational frequency.

4.2. Coils connected in series

The maximum voltage is from the I variant of stator: 1.38V, while the III variant coil reached only 0.17V. It can be stated that the increase of wire area do not compensate the decrease of total number of windings. It is important to mention that thicker wire is more difficult to roll into coil with gaps. Additional gaps increase distance between the windings. It cause the total volume of copper reduction which better can be seen the graph Figure 4.4.

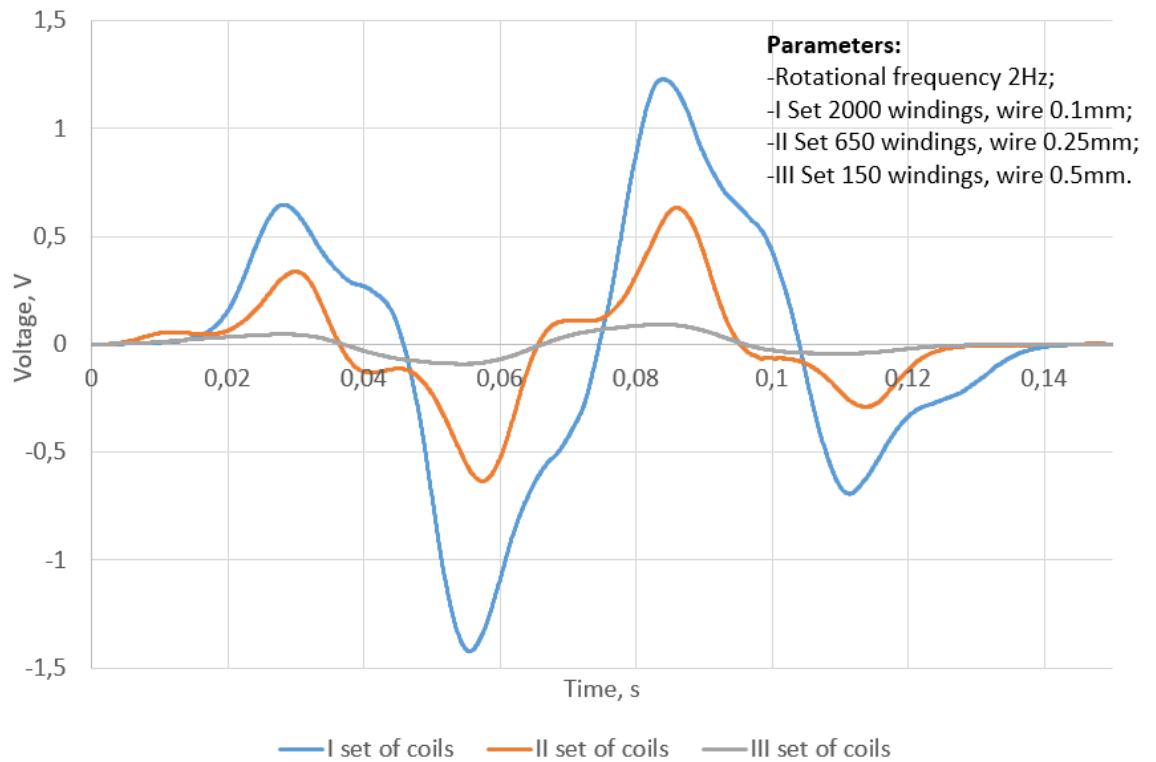


Fig. 4.4. Voltage from coil number 1 the three stator design variants

I with 2000 winds of 0.1mm thickness wire; II with 650winds of 0.25mm thickness wire; I with 150 winds of 0.5mm thickness wire without load at the rotational frequency of 2.0Hz. II with 650winds of 0.25mm thickness wire; I with 150 winds of 0.5mm thickness wire at the rotational frequency of 2.0Hz. Where the total energy is measured at the same frequency (2.0Hz). Results from experiment are shown in Figure 4.5.

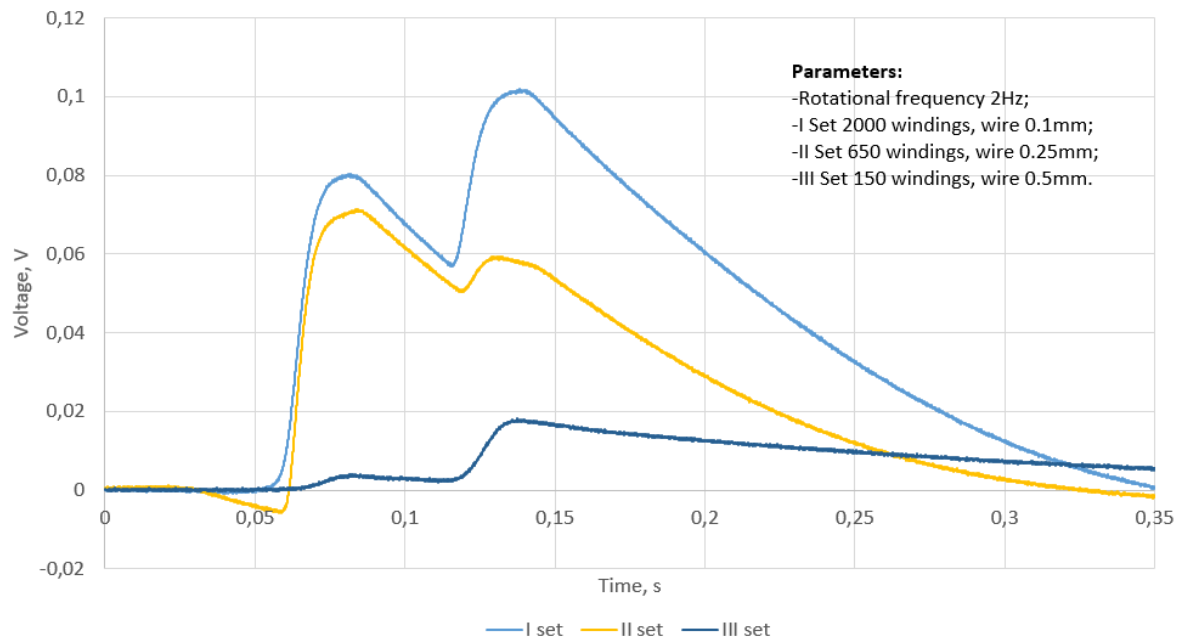


Fig. 4.5. Graphical representation of total energy from the three stator design variants

The maximum energy under the load to the charging the compensator is 0.105V by the I variant of stator design. The charging time for different coils is approximately but it can be stated that the discharge time is depended to the thickness of the wire.

4.3. Coils with core inside

As already investigated, the highest voltage was generated by the first coil set, which had the highest number of windings and the lowest thickness of copper wire. To test the influence of metal core three simple cores were made from the same ferrous metal. The only difference between cores are diameter. Three types of cores were made with the following diameters: 2, 3, 4mm.

From the graphical representation of the experiment in Figure 4.6 can be stated that the increase of core diameter is directly to the increase of voltage generated by the coil. With the 2mm core total voltage generated at the 2 Hz is 2.62V, 3mm core – 3.64V, 4mm core – 3,83V. In the Figure 4.9 can be seen that the coil without any core generated the 1.38V. This simple improvement lead the the increase of 1.24 or 89.8% increase in voltage. Furthermore the thicker core leads to better results in voltage. The 4mm core increased the total voltage from 1.38V to 3.83V. It is 2.45V increase or 177.5%.

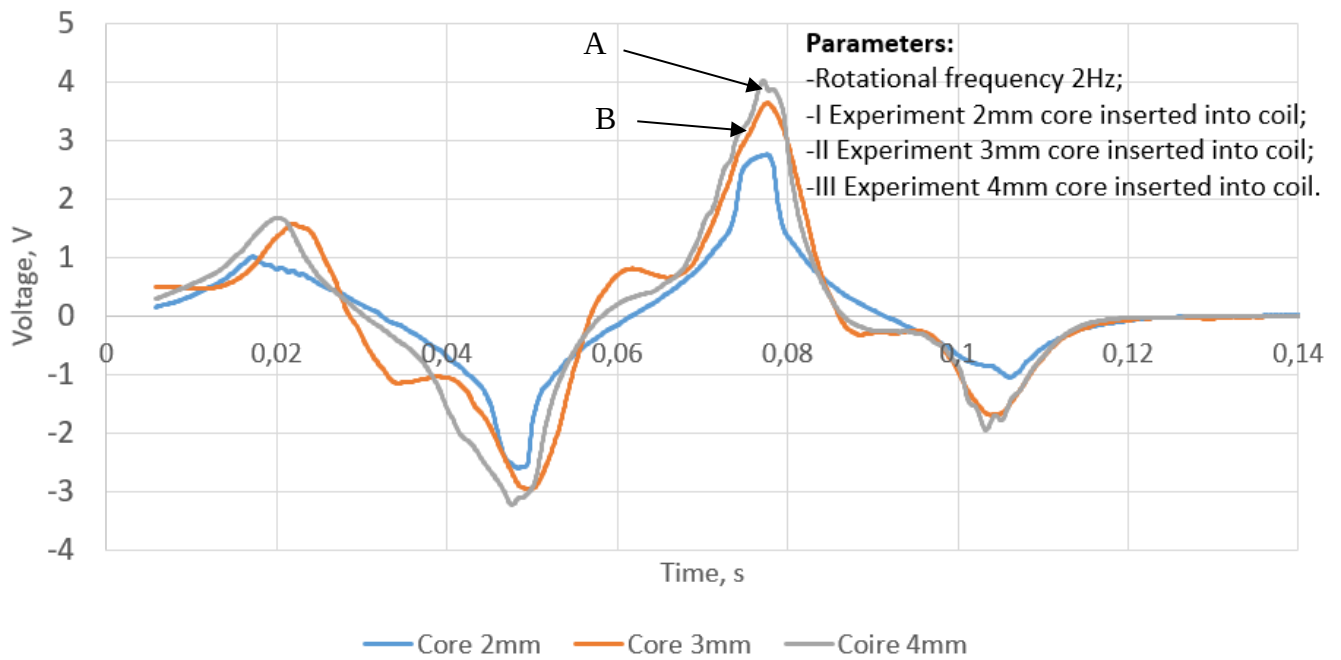


Fig. 4.6. Metal core voltage results

From the other hand from the graph can be stated that additional metal in the core creates additional friction for stepper motor. For comparisment of 2mm core (A) and 4mm core (B) the thicker metal at the peak point creates a voltage swing, while the thinner metal core has much smoother voltage response.

4.4. Coils with metal pot covers

To test the influence of metal pot core, three pot coverts were made from the same ferrous metal. The only difference between covers are the diameter of wall thickness and core inside.. In total three were made with the following wall thickness: 2, 3, 4mm. Cover wall 2mm represent the voltage generated in the coil with 2mm pot, Cover wall 3mm represent the voltage generated in the coil with 3mm pot, Cover wall 4mm represent the voltage generated in the coil with 4mm pot. The maximum voltage is from the III variant of pot: 2.65V, while the I variant pot reached o 2.31V. It can be stated that the increase of voltage is related to the increase of pot thickens. On the other hand it is important to mention that thicker pot generates higher magnetic forces which creates the resistance for rotations. It means that although the stepper motor was set to rotational frequency of 2Hz it do not reach it by the magnetic traction to the metal pot.

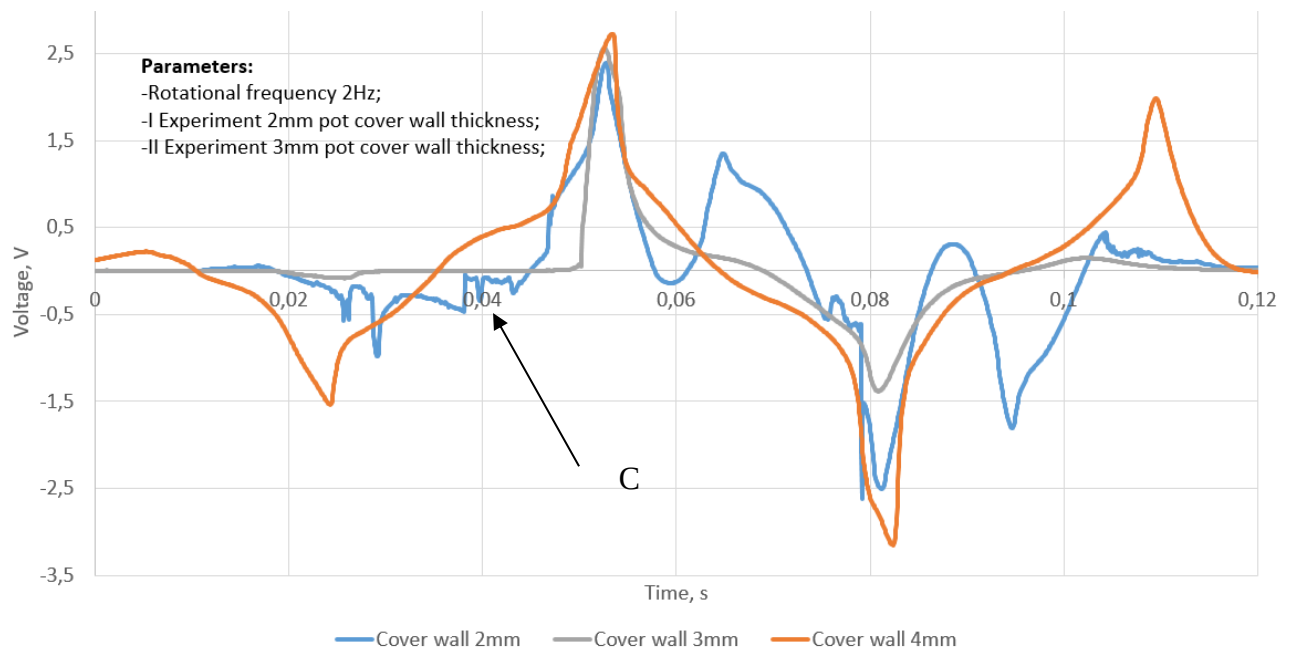


Fig. 4.7. Pot core voltage results

During the experiments it was possible to see by eye how stators slows down when magnets cover the metal pots. Those drawbacks can be seen in the graph. The voltage curve is not uniformly increasing or decreasing. The voltage response is not smooth, it is clearly visible peak and steep curves in the graph (C).

4.5. Section conclusions and suggestions

This section presented the reader with equipment, customized experimental stands and fabrication of different stators variants with coils variants as well as experimental studies performed during the course of research. Experimental studies were performed exploring the different frequencies and circuit configuration: with load or without load. Experiments performed during the course of the research were grouped into four case analysis studies: 1) investigations of effects in different coil winding properties; 2) investigations of all coils connection in series; 3) investigations of total coil performance in circuit without or load; 4) investigations of coil performance with metal core inside; 5) investigations coil performance inside metal cover.

From the conclusions of case analysis study devoted for analysis of effects of connected electric circuit to performance of three stator variants (I, II, III) may be summarized to:

Table 4.1. Summary of experimental results.

Criteria	Important factor
Dynamics (low frequency, visible peaks in voltage response)	1. Increase steps of motor. 2. Increase the frequency of rotation. 3. Increase torque of motor
Improvements for better results output response (voltage and power)	1. Reduce to the minimum the gap between stator and rotor. 2. Use of more powerful magnets with stronger magnetic field 3. Reduce the coil wire diameter 4. Insert a metal core into coils

CONCLUSIONS

1. Design of low frequency pendulum electromagnetic harvester selected. Stator consist of six cupper coils while stator has three Neodymium magnets;
2. After the experimental research have been found that the highest voltage is generated by separate coil which had 2000 windings of 0.12mm thickness wire. Coil generated the 1.38V at the frequency of 2Hz. The increase of wire thickness cause in reduction of windings as a result the voltage was decreasing;
3. The biggest increase in generated voltage compared to the coil with only cupper windings was from metal core. Inserting 4mm diameter core increased the total voltage from 1.38V to 3.83V or 177.5%
4. The metal pot cover also led in the increase of generated voltage compared to coil with only cupper wire windings. Voltage in the 4mm wall thickness pot cover was 2.65V, increased by 92.2%. During the experiments with pot covers it was possible to feel a strong braking between magnets and coils while moving the rotor by hand.
5. In the future, more detailed experimental research are required to investigate the dependence of magnetic forces between the magnets in rotor and coils in the stator.

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APPENDIX

RESEARCH OF ENERGY HARVESTER EFFICIENCY

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Abstract. The demands for electric energy has been only increasing in last decades. Current technological limitations of batteries push forward to search for alternative energy sources. Future prospective technology are vibration energy harvesters that converts kinetic vibration energy into electrical energy. In this article will be presented the experimental results of generated energy dependence to the change of magnetic properties of coil. First part of experimental investigation will be performed with three different wire thickness correspondingly to the number of windings. Second part is to investigate the influence of metal core inside the coil. The highest voltage was generated by coil with the highest number of windings and the biggest diameter core installed in it at the 2 Hz rotational frequency.

Keywords: harvester, kinetic energy, vibrations, Faraday's Law, electromotive force.

Introduction

Increasing global demand for energy, environmental and ecological problems leads to looking for alternative energy sources. One of them is kinetic energy from vibrations. Low frequency energy harvester can generate energy from ambient natural processes like a swing of an arm while walking or jogging. As Faraday's law states the electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path. The total energy of pendulum energy harvester will be dependent to the electromagnetic properties of harvester coils.

This article will be presented the experimental results of generated energy dependence to the change of vibration and magnetic properties of coil. First part of experimental investigation will be performed with different wire thickness and winding ratio coils setups. Second part is to investigate the influence of metal core inside the coil.

1. Literature review

(Galchev 2009 et. al.) Designed a non-resonant Parametric Frequency Increased Generator (PFIG) devoted to generate energy subjected to low-frequency non-periodic vibrations. This type of converter is characterized by its non-resonant operation since it decouples the harvester operating frequency from that of the ambient environment. This allows the generator to work over a broad frequency range.

The converter is based on the use of inertial mass placed in the middle suspended through a spring. Two Frequency Increased Generator (FIG) are placed from both sides of the inertial mass. Each FIG is composed by magnet, coil which is ended by a spiral spring and an actuation magnet. Receiving an external vibration, the inertial mass is oscillating between the two FIG. This leads to the movement of one of top or bottom magnets and conversion of the mechanical energy to electrical.

Scientists also have tried to harvest kinetic energy based on the magnetoelectric effect. When a variable magnetic

field is applied, the magnetostrictive material is strained which induces a stress on the piezoelectric material which generates electric energy (Huang 2003).

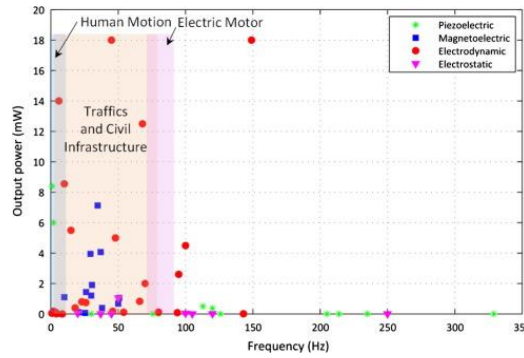


Fig. 1.. Output power versus the working frequency.

For main developed electromagnetic, electrostatic (Sasaki 2005), piezoelectric (Shenck 1999) and magnetoelectric (Tsumino 2006) vibration transducers prototypes.

Vibration converters performance is highly depending on the characteristics of the excitation source and the used physical principle to harvest energy. Some of the converters are working for one resonant frequency, others are developed to generate energy for wideband frequencies. Comparison of different developed devices is established depending in the energy outcome for different used harvesting principles relative to the working frequency

2. Modelling and fundamentals of vibration energy harvesting

Energy harvesters cannot be cost effectively built and tested without prior modelling of its component. Preliminary design stage gives one the advantage to predict how developed configuration will perform. A general model for the vibration energy conversion is the standard mass-spring system. In this system, the mass displacement is caused by the input displacement. The damping includes the mechanical damping and the electrically induced damping. Here, the power from the mechanical system generated by electrical induced damping can be converted to electrical power, while the mechanical damping always causes the energy loss of the system. The schematic structure of the proposed magnetic-spring based, low-frequency-vibration energy harvester is shown in (Fig. 2)

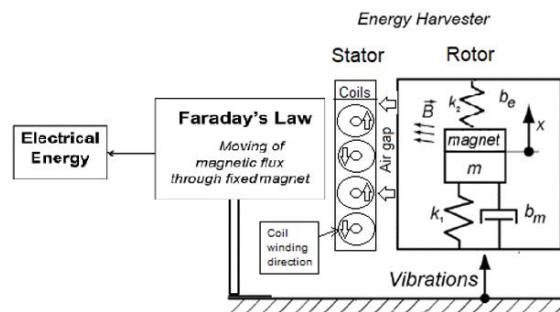


Fig. 2. Scheme of harvester design.

The energy harvester is composed of a rotor structure suspended between magnetic plates and a series copper coils. A significant air gap is maintained between the magnet arrays so that the magnetic interaction between them is negligible. When an external mechanical vibration is applied to the structure in the axial direction of the harvester, the suspended mass starts to oscillate within the magnetic springs, causing a relative displacement between the magnet arrays

and the connected coils. The coils cut the concentrated magnetic-flux lines of the magnet arrays that in turn induce an electromotive force (e.m.f.), leading to a generation of voltage across the coil terminals according to Faraday's Law of EM induction

A model for the vibration energy conversion consist of mass-spring system which is shown in (Fig. 2.) The mass displacement is caused by the input displacement. The damping includes the mechanical damping and the electrically induced damping. Here, the power from the mechanical system generated by electrical induced damping can be converted to electrical power, while the mechanical damping always causes the energy loss of the system.

3. Methodology and equipment

The harvester will be tested with a setup as shown in (Fig. 5.) The energy from power source is supplied into stepper motor, micro stepper and Arduino to correspond the vibrations from the vibrating table. By the micro step drive one rotation divided into 64 steps in order to achieve smooth run of motor. The starting rotational frequency for measurements is 0.5Hz and will be increased by 0.5Hz to the final 3.0Hz frequency. 3.0Hz is the maximum rotational frequency what was able to achieve in that particular setup. Voltage was measured with a National Instrument data acquisition module, which was connected to a computer. By software voltage response recordings from the harvester in respect to the time.

For each set of different coils and stator configuration experiments were perform in frequency ranges from 0.5Hz to 3.0 Hz in two different circuit configuration. At first all coils were measured one by one in all frequency ranges. Measurements were performed without any load connected into the circuit. The voltage was measured directly from the coil to reduce the length of wire and loses due to resistance of wire. All measurements were performed three times. From collected data averages where calculated for each measurement setup

Experiments will be carried out in two stages: First part of experimental investigation will be performed with different wire thickness and winding ratio coils setups. Second part is to investigate the influence of metal core inside the coal.

3.1. Equipment in the research

This section is divided into two main parts – the first one describes main equipment that were used to perform experiments, while the second part presents the sequence of experiments.

The magnets were designed from NdFeB N52 type material and were obtained commercially. Magnet properties are shown in the Table 1.

Table 1. Permanent magnet specification.

Parameter	Characteristics
Shape	Block
Dimensions, mm	15x10x3
Material (Material): NdFeB	Material (Material): NdFeB
Tolerance	+ / - 0.1 mm
Coating	Nickel-plated (Ni-Cu-Ni)
Magnetisation	N52 through the thickness of 5 mm
Strength	approx. 5 Kg
Weight	5 g.
Magnetic properties of magnetic materials N52	1.42 to 1.47 Br [T] 14200-14700
Coercivity HCJ minutes, kA/m	955
Energy product (BH), kJ/m ³	380 to 422

The fabricated moving magnet composite was composed with three magnets (each with dimensions 15mmx10x3mm height).

This magnet and coil configuration ensures effective use of the coils and the absence of constant zero voltage regions (magnet outside the coil area, or cancellation effects).

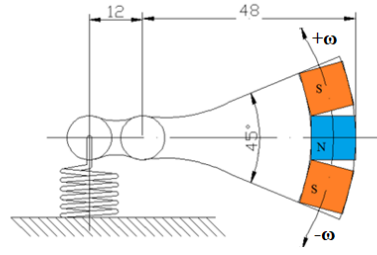


Fig.3. Magnets configuration on the rotor.

The moving magnet composite was assembled using Loctite® epoxy (Henkel Corp, USA) and clamped together for two days to allow the epoxy set properly.

The copper coils were wound in six segments with each segment being wound in a direction different from the other and each having the same turns of wire per coil. Three variants of stators were prepared for the experiments with six coils inside. The coil design specifications and parameters are prescribed in the Table 2.

Table 2. Permanent Stator setup variants with coil specification.

Parameter	Characteristics		
Variant of coil setup	I	II	III
Number of coils in stator	6	6	6
Wire thickness, mm	0.1	0.25	0.5
Wire material	Copper	Copper	Copper
Wire surface	lacquered	lacquered	lacquered
Number of windings	2000	650	150

In the stator of harvester coils are placed in different winding direction in order as it is shown in the (Fig. 5.) The purpose of such coils alignment is to increase the electromagnetic properties of coils and achieve better voltage results.

When the magnet cover the first coil magnetic flux starts in the coil and continuously passes to the end of first coil to the second coil the beginning. This magnetic flux flow is repeated in all coils.

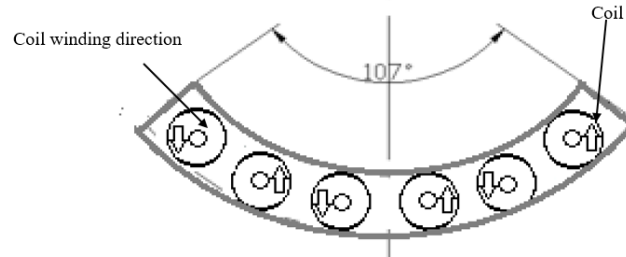


Fig. 4. Coils configuration on the stator.

3.2. Experimental model

The harvester configurations modeled in this study are shown in (Fig. 5.). In order to simulate low frequency vibrating table, the simple construction frame was built for measurements. The main parts of this model is: frame, stepper motor, stator and rotor.

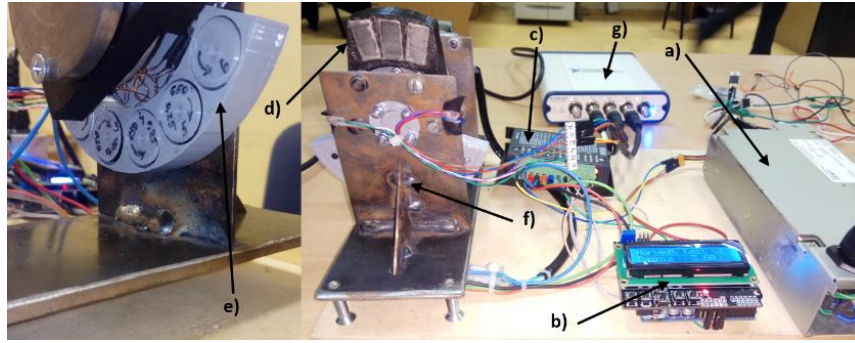


Fig. 5. Scheme of experimental setup. (a) power source; b) Arduino controller; c) Microstep drive; d) Harvester rotor with permanent magnets; e) Harvester stator with coils; f) Harvester frame; g) National Instruments data acquisition module.

The design of the harvester fabricated and characterized is shown in (Fig. 5. (d) and (e)). As shown in this figure, (Fig. 5. (a) stator e)) is fixed to the non-movable frame, rotor with magnets composite was mounted from other end. To excite low frequency vibrations stepper motor was used. By the microstep drive one rotation was divided into 64 steps.

4. Experimental results and analysis

Section below presents experimental study of dynamic and electric characteristics. The harvester was tested with a energy harvesting setup as shown in (Fig. 5.). Experiments were carried out in two stages: First part of experimental investigation will be performed with different wire thickness and winding ratio coils setups. Second part is to investigate the influence of metal core inside the coil. All experimental data are presented in the following chapters bellow.

4.1. Experimental results of coils with different coil windings

The maximum voltage is from the I variant of stator: 1.38V, while the III variant coil reached only 0.17V. It can be stated that the increase of wire area do not compensate the decrease of total number of windings. The thicker wire is more difficult to roll into coil with gaps. Additional gaps increase distance between the windings. It cause the total volume of copper reduction which better can be seen the graph (Fig. 7.)

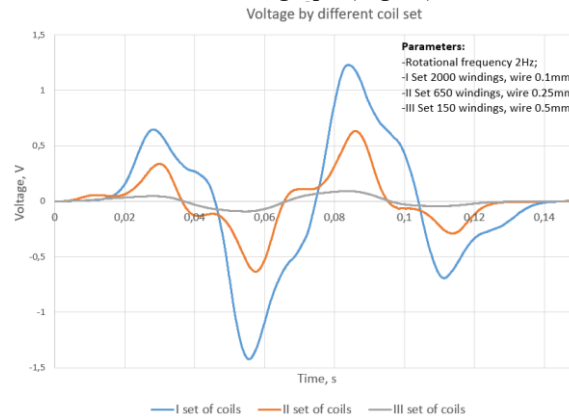


Fig. 7. Voltage from coil number 1 the three stator design variants.

It is important to mention that in one full rotation of harvester rotor there are four energy fluctuation in the coil while magnet crosses the coil.

4.2. Experimental results of coils with core inside

As already investigated, the highest voltage was generated by the first coil set, which had the highest number of windings and the lowest thickness of copper wire. To test the influence of metal core three simple cores were made from the same ferrous metal. The only difference between cores are diameter. Three types of cores were made with the following diameters: 2, 3, 4mm.

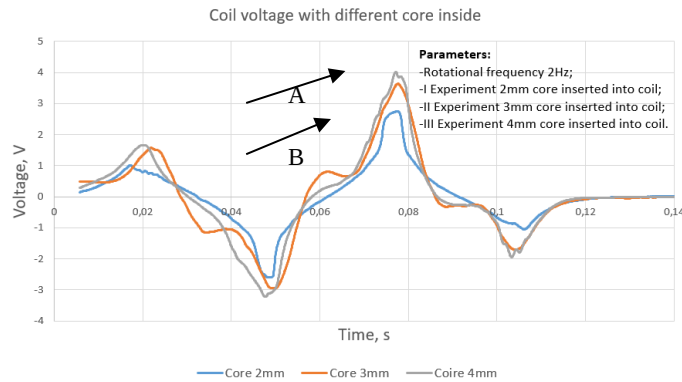


Fig. 8. Metal core voltage results.

From the graphical representation of the experiment can be stated that the increase of core diameter is directly to the increase of voltage generated by the coil. With the 2mm core total voltage generated at the 2 Hz is 2.62V, 3mm core – 3.64V, 4mm core – 3.83V. In the (Fig. 7.) can be seen that the coil without any core generated the 1.38V. This simple improvement lead the increase of 1.24 or 89.8% increase in voltage. Furthermore the thicker core leads to better results in voltage. The 4mm core increased the total voltage from 1.38V to 3.83V. It is 2.45V increase or 177.5%. From the other hand from the graph can be stated that additional metal in the core creates additional friction for stepper motor. For comparisment of 2mm core (A) and 4mm core (B) the thicker metal at the peak point creates a voltage swing, while the thinner metal core has much smoother voltage response.

Conclusions

This article presents the design, fabrication and validation of low-frequency 0.5Hz to 3.0 Hz electromagnetic energy harvester, build in the Mechanical faculty of Vilnius Gediminas Technical Univesity. The harvester was experimentally tested in two stages. The highest voltage by separate coil was achieved with the first stator variant (2000 windings of 0.12mm thickness wire. Coil generated the 1.38V at the rotational frequency of 2Hz. The increase of wire thickness cause in reduction of windings as a result the voltage was decreasing. The second stage of experiments was with metal core added into the coil. The biggest increase in generated voltage was from metal core. The 4mm core increased the total voltage from 1.38V to 3.83V. It is 2.45V increase or 177.5%

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