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RIGA TECHNICAL UNIVERSITY

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HUMAN ENERGY HARVESTER AS A PRACTICAL SOURCE FOR ELECTRONIC DEVICES

Summary of the Doctoral Thesis

RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
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Gorņevs, I. Human Energy Harvester as a Practical Source for Electronic Devices. Summary of the Doctoral Thesis. Riga: RTU Press, 2024. – 40 p.

Published in accordance with the decision of the Promotion Council “P-08” of 23 February 2024, Minutes No. 29.

NATIONAL DEVELOPMENT PLAN 2020

EUROPEAN UNION
European Social Fund

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This work has been partially supported by the European Social Fund within the Project No. 8.2.2.0/18/A/017, “Development of the academic personnel of Riga Technical University in the strategic fields of specialization”.

Cover picture by Ilgvars Gorņevs

https://doi.org/10.7250/9789934370595
ISBN 978-9934-37-059-5 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on May 24, 2024, at 15:00 at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12 Āzenes Street, Room 201.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree

Ilgvars Gorņevs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 5 chapters, Summary and Conclusions, 99 figures, 7 tables, and 5 appendices; the total number of pages is 168, including appendices. The Bibliography contains 133 titles.

ABBREVIATIONS

AC – alternating current;
DC – direct current;
MOSFET – metal-oxide-semiconductor field-effect transistor;
RMS – root-mean-square;
EM – electromagnetic;
TE – thermoelectric.

CONTENTS

INTRODUCTION

During the last decades, the reduction in the size of electronics made portable devices a part of everyday life, their functionality improved and diversified, changing people's habits as well. By connecting several smart devices in a mutual network, the Internet of Things was born, where these "things" are devices that are able to collect information with the help of sensors, process it, share it and even influence various processes, thus providing people with previously impossible detailed and extensive information, as well as providing various control options. Solutions designed to facilitate, improve, and even fully automate processes in various fields, such as logistics, security, health care, industrial processes, and environmental monitoring, emerged and developed rapidly [1]–[4]. As the number of individual devices increases, the challenge of providing electric power is becoming even more relevant as the development of batteries tends to lag behind the energy demands of smart devices in the still growing variety of tasks [5]–[7]. Providing a reliable power supply is especially important for devices dedicated to various safety and health purposes, such as electronic locks [8], [9] and emergency medical systems [10].

Regular battery replacement or recharging is resource-intensive, so it is more beneficial to manage and maintain multiple smart devices as infrequently as possible and, in the best case, achieve their completely self-sufficient operation. For this purpose, it is necessary to connect the devices to an external power source in such a way that their use is not limited. Researchers propose various solutions, in which a separate small generator, which converts, for example, the energy of ambient light [11] or vibration [12] into electrical energy, would be used to power the specific electronic device, say a sensor node. If we talk about a human as an object of study, then he himself must serve as a source of energy for the given systems. Of course, it has to be understood that simply telling a person to run a generator is impractical because it is physically cumbersome, so one has to try to use methods that will not be felt by a person and will not interfere with everyday routines. These methods are called energy harvesting or scavenging, as they are based on the idea of “scavenging” the remnants of energies from the processes and phenomena that would nevertheless happen. Without a doubt, having a power supply system that extends the life of the monitoring system while not creating a significant burden on a person's daily routine would make the long-term use of such devices less inconvenient. In this way, the spread and diversity of individual health monitoring systems would increase, potentially providing a higher level of detail for information about a person's health status and the factors affecting it.

Energy sources for harvesting can be characterized by the possibilities of controlling and predicting their operation [13]. Heat and mechanical energy can possibly be the most accessible and obvious forms of human energy. Heat is a constant by-product of our metabolism that passes through the surface of the skin into the environment, so it is more predictable, but mechanical energy is more controllable and manifests itself in many different ways: both as deliberate movements (walking, lifting an object) and unconscious ones (expanding the chest when breathing, swinging of the hand while walking, the impact of the foot on the ground). The use of thermal energy depends on the ambient temperature, as a temperature difference [14] or a relative change [15] is required to generate electricity, but the environment provides minimal restrictions for the manifestation of mechanical energy and one can choose between different sources of motion [2], [16], [17]. Although the range of options appears to be wide, the current choice may be limited not only by the user's convenience but also by the amount of electrical power and energy available, which is mostly relatively small and may therefore be insufficient for the expected power consumer. Of course, the consumption of the device can be reduced, for example, by limiting its range of tasks and using increasingly more efficient components, however, practical cooperation between energy harvesters and consumer devices may require an algorithm that will take into account the capabilities and limits of the specific power source [7].

The relevance of the Thesis topic is related to the challenges of using human energy harvesting as a practical power source for realistic operating conditions. Although energy harvesting has been extensively researched, it has not always found applications for powering low-power equipment. This may be due to insufficient energy generation, difficulties in storing it or ensuring stable operation, as well as problems related to incorporating energy harvesters into everyday accessories and clothing. By obtaining viable solutions for human energy sources, it would be possible to ensure a higher prevalence of integrated electronic systems in various everyday clothes and accessories that monitor environmental and human health parameters, making the given practice widely applicable and, therefore, easily accessible.

In order to successfully combine energy harvesters with smart devices, several inter-operating stages are needed, as not only the output power of the generator but also the electrical voltage must be adapted to the consumer, while it must be capable of operating with the limited and potentially variable energy availability of the harvester. Most studies are based on individual stages and the resulting insights may not be compatible with the creation of a unified framework. By carrying out a sequential study of the necessary stages, it will be possible to determine the existing possibilities and limits, as well as to decide the necessary steps for further research for the creation of a unified energy harvester and consumer system.

Summarizing the above-mentioned facts, the **goal of the Doctoral Thesis** is to research human motion energy harvesting to create a practically usable source of electricity for low-power electronic systems, investigating the development of its individual stages and using off-the-shelf elements.

In order to achieve the set goal, the following basic **objectives** are defined:

1. Summarize and review published solutions for motion energy harvesting and usage, determining their advantages and disadvantages.
2. Characterize the operating parameters of a non-inertial electromagnetic motion energy harvester.
3. Evaluate the AC voltage rectification capabilities of the said electromagnetic motion energy harvester.
4. Assess the use of commercially available low-voltage DC converters with the rectified signal of the electromagnetic motion energy harvester.
5. Evaluate the limiting factors for acquiring electrical energy and propose practical solutions.

6. Develop a monitoring algorithm of the accumulated energy for environmental or human physiological parameters measuring system made from off-the-shelf elements.
7. Practically check the applicability of the obtained human energy harvesting power source for the monitoring system.

Practical significance and **scientific novelty** of the Thesis:

1. A non-inertial electromagnetic human motion energy harvester is characterized by the dependence of its output energy on the design parameters.
2. The benefits and drawbacks of low AC rectification with MOSFET with fixed gate voltage have been experimentally assessed.
3. Prerequisites to use self-starting low-voltage DC converters for electromagnetic human motion energy harvesters have been identified.
4. An analytical model has been developed for the assessment of the effect of the smoothing capacity of the full-bridge rectifier on the first pulses of the obtained voltage in the case of a discontinuous input signal.
5. The impact of smoothing capacity on both the rectified signal value and the low-voltage converter performance under varying input signals resulting from real human motion energy harvesting has been experimentally confirmed using a voltage doubler and a full bridge rectifier.
6. The interaction of the generated power flow when combining motion and thermoelectric harvesters has been experimentally verified, and practical benefits have been evaluated through the use of separate low-voltage converters and a common energy storage element.
7. An operational algorithm has been developed for an off-the-shelf component-based environmental parameter measurement system based on available electric energy, supply voltage, and its own consumption to ensure continuous and full performance under variable generation conditions and regulate supply voltage.
8. The created and improved human energy harvesting system has been tested with the environmental parameters measurement system in realistic, controlled conditions, demonstrating its self-sufficient working capacity, and allowing to evaluate the validity of the development steps taken.

The following **theses** were formulated and demonstrated in the research:

1. For the DC low-voltage converter to load the motion energy harvester and diode rectifier according to a more efficient operating point, its input impedance and efficiency should be equally dependent on the input voltage in the expected value range, while for the rectified signal having a higher value during voltage dips is prioritized over solely focusing on the average or peak value.
2. In the case of short, intermittent AC voltage signals, the rectifier circuit achieves its maximum performance with a specific smoothing capacitance, which, in the examined circuit combinations, delivers up to a 10 % higher RMS value of the rectified voltage.
3. For the combined motion and thermal energy harvester, using separate, individually tailored low-voltage converters and a shared energy storage element can ensure

constructive interaction of generators, increasing the energy flow and reducing its deviation from 16 % for the motion harvester alone to 3 %.

During the research, the results were presented at the following international scientific conferences:

1. 11th European Conference on Renewable Energy Systems (ECRES 2023), Latvia, Riga, 18–20 May 2023, 'Enhancing the Performance of Human Motion Energy Harvesting through Optimal Smoothing Capacity in the Rectifier' (Gorņevs, I., Blūms, J.)
2. 7th European Conference on Renewable Energy Systems (ECRES 2019), Spain, Madrid, 10–12 June 2019, 'Towards the Creation of Fully Autonomous Wearable System for Subject's Microclimate Measurement and Data Transmission' (Blums J., Gornevs I., Jurkans V.)
3. 16th Biennial Baltic Electronics Conference (BEC 2018), Estonia, Tallinn, 8–10 October 2018, 'Performance Analysis of Low Voltage Converters for Completely Integrable Wearable Human Motion Energy Harvester' (Gorņevs, I., Blūms, J., Jurķāns, V.)
4. 16th Biennial Baltic Electronics Conference (BEC 2018), Estonia, Tallinn, 8–10 October 2018, 'Harvesting Electrical Power from Body Heat Using Low Voltage Step-up Converters with Thermoelectric Generators' (Jurķāns, V., Blūms, J., Gorņevs, I.)
5. 3rd Renewable Energy Sources, Research and Business Conference (RESRB 2018), Belgium, 18–20 June 2018, 'Energy Generation and Accumulation by Fully Integrated Human Motion Energy Harvester' (J. Blums, I. Gornevs, V. Jurkans)
6. 9th International Symposium on Flexible Organic Electronics (ISFOE16), Greece, 4–7 July 2016, 'Human Motion Energy Harvesters for Wearables' (Blūms, J., Terļecka, G., Gorņevs, I., Viļumsone, A)
7. International Conference of Young Scientists on Energy Issues, Lithuania, Kaunas, 29–31 May 2013, 'Investigation of Electromagnetic Harvester with Flat Structure and Low Voltage Rectifier' (Gorņevs, I., Blūms, J.)

Research stages of the Doctoral Thesis are reflected in various scientific publications.

1. **Gorņevs, I**., Blūms, J. 'Enhancing the Performance of Human Motion Energy Harvesting through Optimal Smoothing Capacity in the Rectifier'. *Sustainability* 2023, *15*, 13564. https://doi.org/10.3390/su151813564, SCOPUS.
2. **Gorņevs, I.**, Jurķāns, V., Blūms, J. 'Development of Wearable Multiple Source Energy-Harvesting System for Smart Clothing', *IEEE Access*, vol. 11, pp. 100284–100294, 2023, doi: 10.1109/ACCESS.2023.3313559, SCOPUS.
3. Blūms, J., **Gorņevs, I.**, Terļecka, G., Jurķāns, V., Viļumsone, A. 'Wearable Human Motion and Heat Energy Harvesting System with Power Management', in *Energy Harvesting*, R. Manyala, Ed., London, UK: InTech, 2018. doi: 10.5772/intechopen.74417.
4. Jurķāns, V., Blūms, J., **Gorņevs, I.** 'Harvesting Electrical Power from Body Heat Using Low Voltage Step-up Converters with Thermoelectric Generators', in *2018 16th Biennial Baltic Electronics Conference (BEC)*, Tallinn, Estonia: IEEE, Oct. 2018, pp. 1–4. doi: 10.1109/BEC.2018.8600958, SCOPUS.

5. **Gorņevs, I.**, Blūms, J., Jurķāns, V. ‘Performance Analysis of Low Voltage Converters for Completely Integrable Wearable Human Motion Energy Harvester’, in *2018 16th Biennial Baltic Electronics Conference (BEC)*, Tallinn, Estonia: IEEE Computer Society, Oct. 2018, pp. 1–4. doi: 10.1109/BEC.2018.8600954, SCOPUS.
6. Blūms, J., Terļecka, G., **Gorņevs, I.**, Viļumsone, A. ‘Flat Inductors for Human Motion Energy Harvesting’. *SPIE Proceedings*, 2013, Vol.8763: Smart Sensors, Actuators, and MEMS VI, pp. 876311–876318. ISSN 0277-786X. doi:10.1117/12.2016995, SCOPUS.
7. **Gorņevs, I.**, Blūms, J. ‘Investigation of Electromagnetic Harvester with Flat Structure and Low Voltage Rectifier’, in: *10th International Conference of Young Scientists on Energy Issues (CYSENI 2013): Conference Proceedings,* Lithuania, Kaunas, May 2013, pp. 206–213, ISSN 1822-7554.

Author's personal contribution to publications.

- In Publications 1, 5, and 7, the author undertook the formulation and implementation of the research idea, conducted a literature review, planned and conducted experiments, processed data and performed the interpretation and analysis of results, as well as drew conclusions. All co-authors contributed to the creation of publications and the implementation of various phases of the study, participating in the discussion of the research plan and analysis of the results, as well as helping to perform measurements.
- In Publication 2, the author carried out the development of separate parts of the study and helped advance the overall idea, plan, and realize measurements. The author ensured the processing, interpretation, and visualisation of the measured data, the characterization of methods and results, and the formulation of key conclusions. The author developed an essential part of the publication's text.
- In Publication 3, the author developed individual parts of the study and helped to advance the key ideas, plan, and realize measurements. Partial data processing, interpretation and visualisation were carried out, and the author contributed to the overall conclusions and the creation of the textual content.
- In Publication 6, the author assisted in the creation of the theoretical basis, research plan and conducting the measurements. He performed partial data processing and contributed to the creation of the final version of the text.
- In Publication 4, the author participated in the discussion of the research plan, methods, and results and assisted in measuring and interpreting the obtained results.

Latvian patent was obtained: “System and method for determination of human and environmental parameters and communication” (LV15580B, 20.12.2021), Juris Blūms, Ilgvars Gorņevs, Vilnis Jurķāns, Gaļina Terļecka.

Various stages of research work took place within the framework of the participation of European Regional Development Fund projects: “Synthesis of textile surface coating modified in nano-level and energetically independent measurement system integration in smart clothing with functions of medical monitoring”, in which the author worked on improvements in motion energy harvesting, and “Hybrid energy harvesting systems”, in which the author contributed in the research of the electrical performance of triboelectric generators [18]–[21], as a result of which insights were gained about the limitations of the use of the specific type of energy harvesting for the purposes of the given research.

The Thesis consists of an introduction, five chapters, a summary and conclusions, and annexes. Chapter 1 provides an insight into the various published technologies for harvesting human motion energy and their combinations, as well as an assessment of low voltage step-up converters and some prospects to use the generated electricity. Chapter 2 analyzes the motion energy harvester used in the research work offers a simplified mathematical model, and the rectification of the generated voltage is also examined. The chapter is based on the author's research published in [22]–[24]. In Chapter 3, converters of a specific operating principle for low voltage step-up are empirically evaluated; their comparison is provided under controlled and realistic working conditions, acquiring insights on the particular usage requisites. The chapter is based on the results of [25]. Chapter 4 offers and practically validates a mathematical model for characterizing the effect of the rectifier filtering capacity in the case of the given generated signal; the effect is also confirmed for the voltage doubler circuit. The main results of the chapter are published in [26]. Chapter 5 deals with the creation of a practical power supply and a consumer device, combining the insights and improvements of electrical performance identified during the research; the performance of the obtained system is evaluated in controlled yet realistic human motion conditions. The chapter is based on the author's papers [24], [26]–[28]. The main results and conclusions are summarized in the final section of the Thesis.

1. ENERGY HARVESTING: OPTIONS AND USE

The chapter examines the published options of obtaining electrical energy from involuntary movements – human motion energy harvesting – and boosting its voltage to a usable level, as well as evaluates the possibilities of practical application of the small amount of electricity. Among the principles of mechanical energy harvesting, the electromagnetic generation principle can be highlighted with its simplicity of development and potential diversity, which is why it was chosen for further research. It does not require an initial charge for generation like electrostatic harvesters [29], [30] and special materials like piezoelectric [31], [32] and triboelectric harvesters [33], [34]. Although the triboelectric generation principle is being rapidly developed and is considered promising due to the presented power densities, the physical processes behind it are yet to be fully understood, which was also reported in publications with the author's participation [18]–[20].

Studies have been published on electromagnetic generators of various designs for human motion energy harvesting, combined for higher electric performance in hybrid circuits with harvesters of other principles [35]–[37]. Some authors consider them more as theoretical sources, while others try to show the practical applications of such a source of electricity. In general, different trends can be observed in the research and testing of energy harvesters. Although numerous authors introduce controlled human testing conditions, such as moving on an electric treadmill [17], [36]–[38], uncontrolled motion testing is quite common [15], [39]–[42] and the repeatability and deviation of the results are very rarely mentioned [43]. Undeniably, free and inconsistent movements will be what the energy harvesters would mostly encounter, but they do not provide quantitatively comparable values in the course of experiments. There are also examples where energy harvester tests or optimization take place in conditions that do not correspond to the expected ones, so the actual test with human movements shows significantly worse results [40], [44].

The conversion of the generated voltage for storage purposes is mostly realized by a diode bridge rectifier or voltage multiplier if the initial level is not sufficient for the desired purpose. Many authors have published studies on energy harvesters that are also capable of charging the output capacitors to a sufficient voltage for low-power consumers in practical tests: electric wristwatches [40], desktop hygrometers [15], [38], digital temperature sensors [41], heart rate sensors [37], and for charging the lithium battery in the GPS device [36]. Presumably, consumer demonstrations are mostly for qualitative evaluation of the sufficiency of output parameters, as quantitative data on consumption and operational stability is usually not provided, also test conditions tend to differ from those used for harvester performance evaluation.

Looking at energy harvesters as potential power sources, it is more useful to evaluate their performance by comparing average output power, calculating it from the time needed to accumulate a specific amount of energy, because the publications often provide only peak values for the power; moreover, the numbers can also be exaggerated, for example, by using peak-to-peak voltage of the generated AC signal for power calculations [17], [36]. The average output power exhibited, for example, by hybrid energy harvesters during human walking is presented in a wide range: below a microwatt [44], [45], few microwatts [15], [40], several tens of microwatts [37], [41] and even a couple of milliwatts [38].

While the accomplishments in the examined scientific papers are broad and evident, numerous studies share common shortcomings:

- the experimental evaluation does not show the functional stability in the expected working conditions, therefore the obtained results may not consistently align with the practical expectations;
- little or no attention is paid to the efficiency of electricity conversion;
- when combining harvesters, their compatibility and individual contribution are not evaluated;
- limited attention is paid to how the tested power sources and consumers can cooperate in realistic environments, where dealing with, for example, an interrupted energy flow can be common.

When evaluating the collection of human movement energy as a potential power source, the shortcomings observed in the publications should be taken into account, therefore the research was chosen to be carried out in separate stages, which examine the functional parts of the power source to be implemented, guided by their mutual compatibility. The first step is to look at the possible improvements of the harvester itself so that its output signal is as high as possible and compatible with further voltage conversion requirements. Next, the most suitable voltage converter for a given harvester is evaluated along with its capabilities and limitations. Once individual system improvements have been made to obtain the highest possible performance under the given conditions, the combination with an additional human energy harvester has been tested. Finally, the hybrid harvesting system with a consumer capable of performing the tasks typical to monitoring devices has been assessed under the expected conditions of human motion. In addition, the use of off-the-shelf components demonstrates the practical feasibility of the system and a wider potential for use and future improvements.

2. ELECTROMAGNETIC MOTION ENERGY HARVESTER

In order to assess the potential applicability of electromagnetic energy harvesters in creation of power sources, the generator itself must first be characterised. Such motion energy harvesters, as indicated by the analysis of published solutions, predominantly exhibit monolithic structures with internal volumes through which the magnetic field source moves [36], [39], [44]–[46]. However, if such structures are to be divided into individual components, a physically smaller and more human-adaptable energy harvester design can be achieved. The main advantage is the ability to use body parts that move along each other, like arms along the torso and legs along each other, thus eliminating the need for additional volume for magnet movement and avoiding constraints of the mechanical resonance, fitting which could be challenging due to the erratic nature of human movement.

An electromagnetic motion energy harvester using flat helical coils and a flat magnet is under investigation (Fig. 2.1 a–c). The harvester is characterized by a simplified mathematical model (2.1), which assumes the homogenous magnetic field can cover the whole generator. It shows the dependence of the electrical energy produced by a round coil of one winding on its radius, the electrical properties of the conductor used, the induction of the magnet and its movement speed. It is assumed that the harvester is loaded with a matching resistor –its resistance is equal to the internal resistance of the generator.

$$E = 0.665\,\frac{B^2 r^2\, v\, S_{\text{wire}}}{\pi\rho}, \tag{2.1}$$

Where

E – energy dissipated on the load, J;

B – magnetic field induction, T;

r – coil radius, m;

v – magnet movement speed, m/s;

S_{wire} – cross-sectional area of the coil conductor, m^2;

ρ – coil conductor resistivity, $\Omega \cdot m$.

Equation (2.1) describes the theoretically obtainable energy from the set of specific parameters of the energy harvester. Because the model is simplified, it is not intended for quantitatively precise values but rather for the assessment of relationships. From this, it can be concluded that in order to obtain a higher energy, the radius of the coil and the induction of the magnetic field should be primarily increased since the energy depends on the squares of these values. Since the magnetic field has to cover the entire size of the inductor, the size of the coil and, therefore, the amount of energy is limited by the magnet area, evidently, it is most useful to use a coil corresponding to the size of the magnet. To obtain a higher voltage, it would be necessary to use several windings, but as a result, the cross-section area of the wire S_{wire} will decrease and, therefore, the obtained energy will decrease. In order to increase the number of turns with a constant cross section, the width of the conductor must decrease, but the depth must increase, but this causes complications in the creation of coils due to the non-standard shape of the wire. For the solution of the given problem, one can choose fewer turns, therefore a thicker wire, but place several coils one above the other and connect them in series. As a result, the cross-section area of the wires crossed by the magnetic field will increase, but the connection in series will ensure that individual voltages of the coil layers add up. A parallel circuit would not be beneficial because even physically identical coils would generate different voltages when placed on top of each other due to the decreasing magnetic field, resulting in mutual loading within the generator itself. In practical conditions, the size is limited by the available space, but the number of coil layers is limited by the induction of the magnetic field.

To evaluate the potential of the energy harvester for the intended use, its prototype with coils on the sides of the jacket and magnets in the sleeve (Fig. 2.1 a–c) was practically tested by walking at a fixed speed. Several sets of coils are interconnected in such a way that the pulses generated by them overlap in a constructive way. Depending on available space, the performance of a given harvester can be improved by using multiple magnets in series with opposite polarity, resulting in an open-circuit voltage amplitude of up to 1.2 V. The generation is exhibited in the form of successive bursts of pulses, which are repeated in about 500 ms or more, each usually containing two asymmetric sinusoidal periods (Fig. 2.1 d). It is essential to ensure the proper placement of both harvester components in the garment so that, during movement, they cross each other as symmetrically as possible. Therefore, the performance also depends on the wearer's posture and gait.

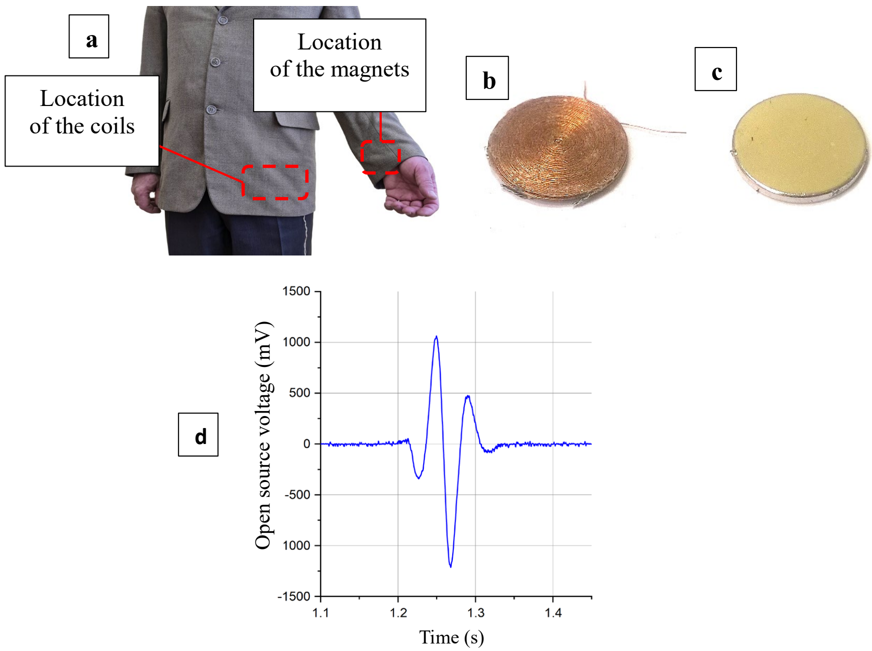

Fig. 2.1. Prototype of the electromagnetic motion energy harvester in a men's jacket (a), a single multi-layer coil (b) and a magnet (c) with a diameter of 20 mm, as well as an example of the open-circuit voltage obtained experimentally from hand movement in one direction (d).

The highest values of the obtained voltage amplitude are theoretically sufficient for a diode rectifier, but due to potentially higher efficiency, a low AC voltage rectifier with a fixed gate voltage MOSFET is evaluated. When supplied with a constant gate voltage close to its threshold level, MOS field-effect transistors exhibit variable current-voltage characteristics corresponding to those of diodes, surpassing conductivity of the parasitic body diode. The current-voltage curves for several field-effect transistors at different gate voltages were experimentally evaluated. The forward and reverse currents are limited by the applied gate voltage (Fig. 2.2), which results in an adjustable passive rectification element.

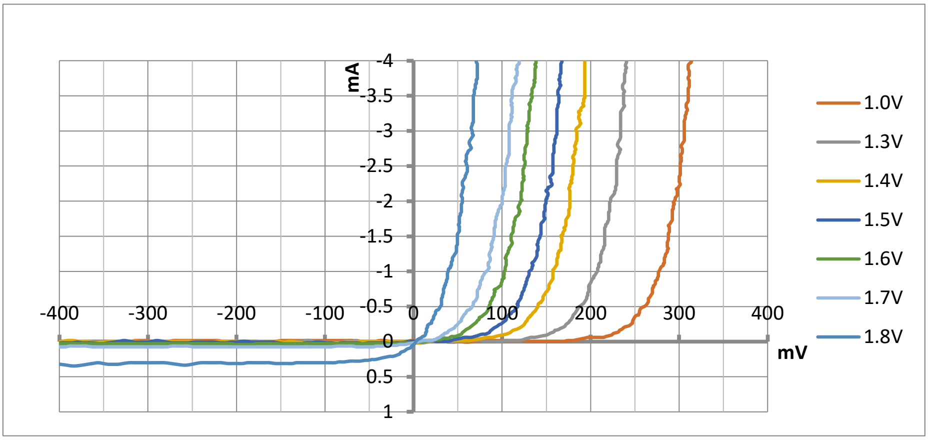

Fig. 2.2. Current-voltage curves of *IRF7832* MOSFET at various gate voltage.

In order to identify the advantages and disadvantages of using such an element compared to a Schottky diode, the forward current of the MOSFET rectifier was set to be three times higher, while the leakage current was ten times greater than of the selected diode model. Comparing the half-wave rectifiers of the given elements with a 220 mV amplitude input signal from an electromagnetic motion energy harvester and taking into account the leakage losses in the reverse direction, the MOSFET showed 11 % efficiency and the diode 3 %. Despite the gain, maintaining a constant gate voltage can prove to be challenging, especially when implementing a full-wave rectifier, so the given method is probably unreasonable for practical circuits, and a deeper study of the dependence of the current-voltage characteristic curve on other parameters, such as temperature, is required.

The experiment with the field-effect transistor as a passive rectifier showed that at low operating voltage level, it is more important to ensure a higher forward conductivity, while the elevated leakage from the reverse current is a secondary concern. Therefore the AC voltage rectification from the electromagnetic motion energy harvester was tested with Schottky junction diodes of higher conductivity and also leakage. A full-bridge rectifier is used to obtain both half-cycles of the signal, while decreasing reverse leakage. Measurements were made with a resistive load ranging from 10 Ω to 200 Ω. The efficiency increases with the load value as expected, but it begins to saturate above a load value approximately 6 times higher than the internal resistance of the harvester, reaching 68 % at an resistance ratio of 11.8. (Fig. 2.3).

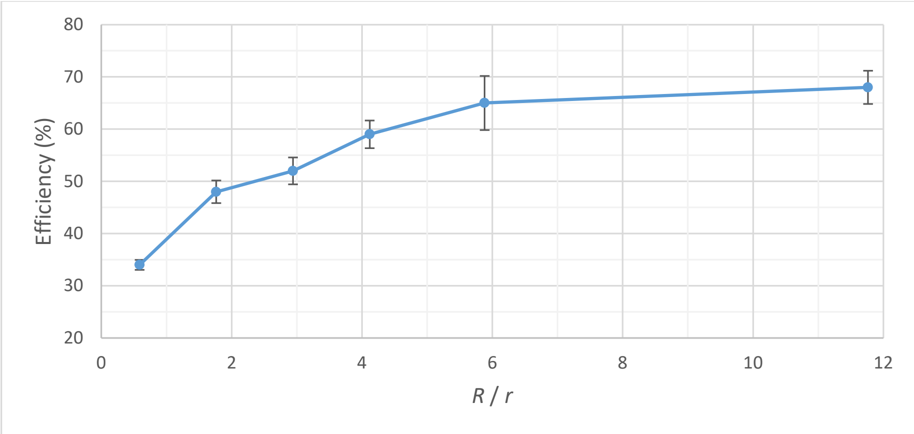

Fig. 2.3. The rectification efficiency of the electromagnetic motion energy harvester voltage vs the ratio of the load (*R*) and harvester resistance (*r*) when using Schottky (*DFLS120L)* full-wave rectifier.

It can be concluded that the parameters of the created motion energy harvester prototype are sufficient for an efficient use of off-the-shelf discrete rectifier elements, yet the output voltage of the best recorded performance – 169 mV on a 200 Ω load – will not be high enough to power electronic devices. The nature of intermittent generation would interfere with the use of a voltage multiplier, as the pauses between the bursts of voltage pulse (Fig. 2.1 d) will prevent charging enough multiplier stages to ensure a high voltage increase factor. However, the demonstrated rectification allows the use of low voltage DC converters.

3. PERFORMANCE ANALYSIS AND EFFICIENCY EVALUATION OF SELF-RESONANT VOLTAGE CONVERTERS WITH EM HARVESTER

The previously discussed electromagnetic motion energy harvester with a rectifier is the fundamental stage for creating a power source for real-world conditions. Further steps involve increasing the voltage to several volts usable in electrical circuits and accumulating obtained electrical energy.

In examining various existing options of power converters for low-voltage sources in Chapter 1 of the Thesis, a circuit with a transformer and transistor at the input was chosen, as it exhibits self-resonating switching without external power supplies, resulting in a high voltage boosting coefficient. Different commercially available converters are based on this principle, potentially simplifying the development and tuning of energy harvesting systems. However, they are intended for DC voltage, which in the case of a given energy harvester, after rectification, will be pulsating and intermittent, and due to natural conditions, with variable amplitude and period. Three commercially available models are selected for comparison of such self-starting low-voltage converters: LTC3108, EH4295 and EH4205 (Table 3.1). The choice was based on ultra-low, but different starting voltage, wide range of input impedance, possibilities to get 5 V output voltage and, of course, availability. The purpose of the comparison is not to check the specific models but to evaluate the applicability of the given conversion principle in the given operating mode, which differs from the manufacturer's intended use, depending on the input parameters of the converter. Thus, it is possible to determine the possibilities and prerequisites for the application of the given conversion principle to a non-inertial electromagnetic human motion energy harvester, as well as in cases of other harvesters characterized by intermittent and variable AC generation.

Table 3.1

Main Characteristics of the Chosen Converters According to Manufacturers' Data [47]–[49].

	Startup voltage	**Input impedance range**	**Efficiency range**
LTC3108	20 mV	2,5–6,5 Ω	5–40 %
EH4295	60 mV	700–1100 Ω	30–55 %
EH4205	75 mV	50–90 Ω	29–55 %

For the purpose of the experiment, an automated mechanical motion device was created to provide a constant motion input for the electromagnetic energy harvester, thus delivering steady generation. Its speed and period are tailored to the parameters of a particular person's hand movements, so that the results of measurements under controlled conditions are comparable to the results of real conditions (Fig. 3.1). Resulting generated impulse bursts are about 150 ms long with a repeating period of 660 ms on average.

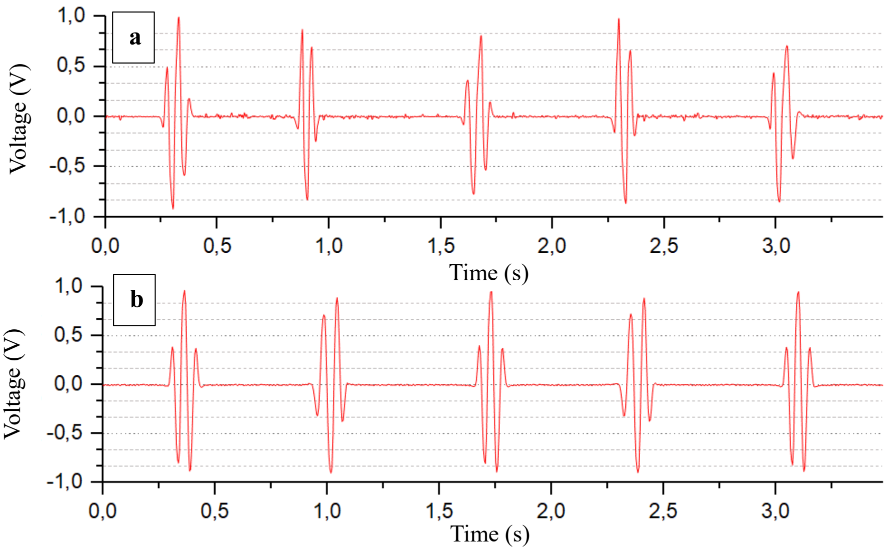

Fig. 3.1. Sample signal of the electromagnetic motion energy harvester with real human movements (a) and with the customized parameter mechanical manipulator (b).

An electrical circuit consisting of a motion energy harvester incorporated into a jacket, rectification elements with a filter capacitor, an interchangeable low voltage converter part and an output capacitor (Fig. 3.2) has been constructed to characterize the operation of the various converters. The output current and voltage of the harvester, as well as the voltage after rectifier and converter are measured. The full-wave rectifier tested in the previous chapter has been selected for the electrical circuit. For all low-voltage converters, a 1 mF filtering capacitor (*C1*) is chosen at the input, and a 1 mF (*C2*) capacitor is also used as the energy storage element.

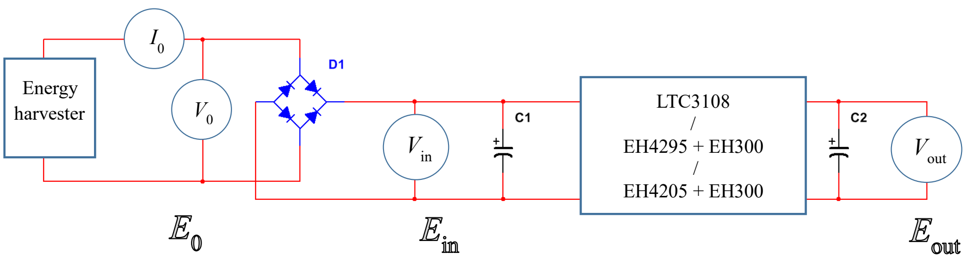

Fig. 3.2. Experimental measurements circuit with current and voltage measurement points (I_0, V_0, V_{in}, V_{out}). Symbolic representation of the total input electrical energy (E_0), input (E_{in}) and output energy (E_{out}) of the converters.

Performance testing of the motion energy harvester took place under controlled conditions using an automated mechanical manipulator and in real walking experiments in which a person with the harvester-equipped jacket walked at a steady pace down an approximately 80 m long corridor, turning around at the endpoints. Since the walking measurements are meant to compare the obtained voltage and efficiency trends and not the absolute values, repeated runs were not performed for each converter.

In both sets of measurements (with controlled conditions, where the input signal amplitude and period remained constant, and in real-world conditions, where uncontrolled variations in generated energy quantity occurred) the given low-voltage conversion principle was able to provide voltage boosting and accumulate electrical energy in the capacitor. The measurements revealed a consistent trend among input energy, output voltage, and efficiency between both sets of measurements. The obtained data suggest that the examined principle of conversion is successfully applicable with intermittent and varying input signals. Numerical results are presented in Table 3.2 along with the time period in which they were achieved. Possibilities for utilizing the accumulated electrical energy at the corresponding voltage were theoretically assessed: it was calculated that the best performance practically achieved with human movements (2.8 V, 3.8 mJ) would be sufficient for powering a low-consumption microcontroller, enabling it to perform various intensive operations. So, it is possible for the given harvesting system to become a viable power source.

Table 3.2

Comparison of Voltage and Total Efficiency Obtained under Controlled and Real Human Motion Conditions

Parameter	**Converter**	***Automated manipulator***		***Human motion***	
		Value	**Time**	**Value**	**Time**
Peak output voltage V_{out} (energy E_{out})	***EH4295***	**4.97 V (11.7 mJ)** (at η_0 =17.4 %)	282 s	**2.83 V (3.8 mJ)** (at η_0 = 11.1 %)	350 s
	EH4205	**4.66 V (10.4 mJ)** (at η_0 = 6.6 %)	350 s	**2.50 V (2,9 mJ)** (at η_0 = 4.7 %)	350 s
	LTC3108	**2.27 V (2.3 mJ)** (at η_0 = 1.3 %)	350 s	**1.02 V (0.5 mJ)** (at η_0 = 0.6 %)	350 s
Highest total efficiency η_0	***EH4295***	22.7 % (at V_{out} = **4.56 V**)	184 s	13.2 % (at V_{out} = **2.37 V**)	156 s
	EH4205	*9.7 %* (at V_{out} = **2.37 V**)	68 s	*5.8 %* (at V_{out} = **1.56 V**)	110 s
	LTC3108	1.3 % (at V_{out} = **2.27 V**)	350 s	0.6 % (at V_{out} = **1.02 V**)	350 s

The observed differences in the results under stable and naturally varying input signals and the diverse converter input parameters allowed for an assessment of their impact on the overall system performance. Therefore, when using the electromagnetic human motion energy harvester as a source for low-voltage converters of the given principle, several prerequisites must be taken into account. Not all of them can be evaluated with the data provided by the manufacturers, so a comparison under the expected operating conditions might be necessary:

- A rectification stage is required, which should provide the smallest possible voltage dip at the output during the generated pulses, but filling the generation pauses is of secondary importance for signal pulses lasting around 150 ms or longer.

- Attention should be paid to the relationship between the input impedance and efficiency of the converter and the input voltage – the generator with a rectifier will be loaded accordingly, and the voltage will tend towards the region of the highest input impedance, which may be less effective for some parts of the system.
- To reduce passive rectification losses, the input impedance of the converter should be higher than the internal resistance of the harvester. Based on the efficiency measurements of the diode bridge used in Chapter 2, a load resistance of 2 to 6 times higher than the internal resistance of the generator is recommended – a higher value will introduce a relatively insignificant increase in the efficiency of the bridge but will reduce the input power of the converter.
- Instead of relying solely on the highest efficiency data of converters, for energy harvesters characterized by a strongly variable generated voltage, the expected voltage range after rectification should be determined, and a converter with a more stable efficiency in that range should be chosen.
- The efficiency of converters varies with the voltage on the storage element, so it must be assessed whether it considerably decreases before the required voltage value – in this case, the input voltage level of the converter must be increased, or a consumer with a correspondingly lower operating voltage must be selected.

4. OPTIMIZATION OF THE RECTIFIER BY THE SMOOTHING CAPACITY

As measurements from the previous chapter revealed, a significant part of total energy losses in the whole voltage conversion was introduced by the rectification phase. One possible solution would be to use lower voltage drop passive rectification elements or active rectification, but this does not reduce the voltage fluctuations and, thus, the voltage dips, which were observed to affect the effectiveness of the chosen low-voltage conversion principle. Consequently, efforts should be made to obtain not only a higher but also a more stable signal at the input of converters. Smoothness is provided by the filter capacitor after the rectifier, but it also has a noticeable effect on losses in the rectifier – as observed when comparing the results in Chapters 2 and 3, the same full-bridge circuit with a pure resistive load has a higher efficiency than the equivalent impedance converter with the filter capacitor. Therefore, the purpose of this chapter is to assess the effect of the smoothing filter capacitance on the rectifier circuit by using analytical and experimental evaluation.

The analysis methods of the capacitor effect available in the literature examine the cases of a continuous and stable signal, which does not correspond to the nature of the generation of the given motion energy harvester – the generated pulses are in the form of a set of pulses (a Fig. 3.1). Therefore, an analytical model was created for the assessment of the capacitance effect in a full-bridge circuit, it is intended to predict the values of V_{max} and V_{min} for the rectified signal between the first two pulses (Fig. 4.1). In order to simplify the model, it was aimed to determine the dependency of the given voltage values on circuit and signal parameters rather than their absolute values. Therefore, it is ignored that the filtering capacitor continues to receive power from the source a little after V_{max} is reached, which is possible due to the initially low load-to-source voltage difference, hence, the diodes would continue to conduct current. It is similar with the lowest voltage V_{min}, as it manages to reach a lower value V'_{min}. Since the discharge starts and ends slightly later, when looking only at the relative values, these effects partially balance each other out. The model is characterized by Equations (4.1)–(4.4).

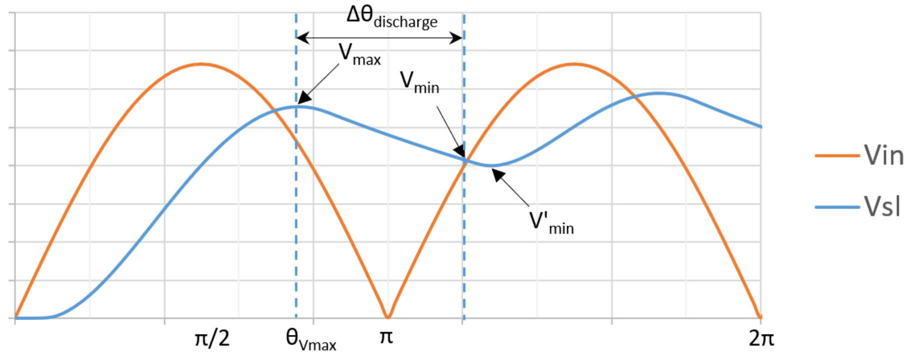

Fig. 4.1. The analyzed voltage characteristics, where V_{in} is input signal; V_{sl} is realistic output voltage; V_{max} and V_{min} are assumed maximal and minimal output voltage between two input

pulses; $V`_{\min}$ is the actual minimal output voltage between the two input pulses; $\Delta\theta_{\text{discharge}}$ is the assumed capacitor discharge region; $\theta_{V\max}$ is the maximal voltage reaching moment.

$$V_{\max} = \frac{V_{\text{in}} \cdot R_{\text{sl}}}{\sqrt{(r + R_{\text{sl}})^2 + (2\pi\, f\, C\, r\, R_{\text{sl}})^2}}\ , \tag{4.1}$$

$$V_{\text{dis}} = \frac{V_{\text{in}} \cdot R_{\text{sl}}}{\sqrt{(r + R_{\text{sl}})^2 + (2\pi\, f\, C\, r\, R_{\text{sl}})^2}} \cdot e^{-\frac{\theta - \pi + \text{ArcTan}\left[\frac{r + R_{\text{sl}}}{2\pi\, f\, C\, r\, R_{sl}}\right]}{2\pi\, f\, C\, R_{\text{sl}}}}\ , \tag{4.2}$$

$$V_{\min} = V_{\text{dis}} = V_{\text{in}} \qquad at\ \pi \leq \theta \leq 1.5\pi \tag{4.3}$$

$$C_{\text{limit}} = \frac{T}{5\, R_{\text{sl}}}, \tag{4.4}$$

where

R_{sl} – load resistance, Ω;

r – total circuit loses, Ω;

C – smoothing capacity, F;

f – input signal frequency, Hz;

V_{in} – the amplitude of the input signal, V;

$V_{\max}$ – the assumed highest voltage on the smoothing capacitor and load, V;

V_{dis} – the capacitor voltage during discharge, V;

θ – the signal phase angle, rad;

$V_{\min}$ – the assumed lowest voltage on the smoothing capacitor and load, V;

C_{limit} – the highest smoothing capacity for the model basal assumptions to be applicable, F;

T – the time between the repeated bursts of input signal pulses, s.

The model is solvable graphically and predicts that, depending on the signal frequency f, the resistive losses r and the load resistivity R_{sl}, there exists a capacitance value at which the lowest voltage $V_{\min}$ between pulses is maximized (Fig. 4.2). Depending on the characteristics of the circuit, this provides the highest mean of the rectified signal. The results have been tested in detailed computer simulations with non-linear rectification elements and also signal of different lengths, with the root mean square (RMS) value of the rectifier voltage correspondingly showing the highest value. It was observed that the additional losses in the circuit introduced by the nonlinear rectifier elements lower the optimal capacitance value, while multiple consecutive input pulses increase it. If the expected number of voltage pulses is small (2–5 sine wave periods), then the optimal capacitance is between the analytically obtained mean and $V_{\min}$ voltage peak capacitances. For a longer input signal, the capacitance value is above the analytically predicted value but does not increase linearly, for example, for a long set of 60 input signal periods, the capacitance is about 34 % higher than the analytically predicted $V_{\min}$ peak value. The results prove that the created analytical model can be used for predicting the range of optimal values of the smoothing capacity of the rectifier, replacing a time and resource intensive computer simulation. It was also applied to the voltage doubler circuit, for which, compared to the bridge circuit, the computer simulation showed an expectedly smaller correspondence of the optimal capacitance value to that predicted by the model, yet the existence of the optimal capacitance for a discontinuous input signal validates that the observed relationship exists across different circuits in which capacitors are periodically charged from zero using scarce voltage pulses.

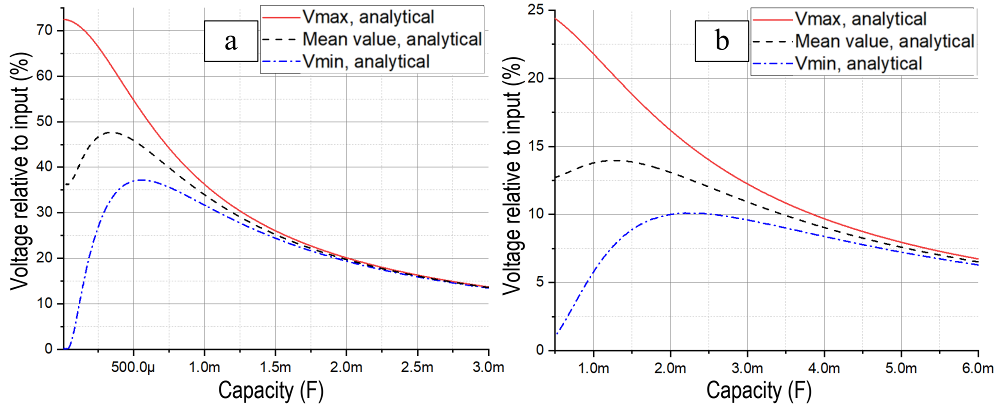

Fig. 4.2. Proposed analytical model results. Dependence of the highest (V_{max}) and lowest (V_{min}) voltage on the capacitance during the first period of the rectified sinusoid using the parameters of the tested electromagnetic energy harvester (Chapter 2) and different loads: 50 Ω (a) and 6.5 Ω (b).

The experimental test was carried out with a signal generator outputting interrupted sinewave, the parameters of which are close to the previously used electromagnetic motion energy harvester, paired with the corresponding full-bridge rectifier and the low-voltage converter as in the previous experiments (Chapter 3). The results confirm the existence of the modelled optimal capacity in the expected range, exhibiting the highest rectified RMS voltage (Fig. 4.3). The highest output power value of the used voltage converter is at a lower capacity value than the optimal one for the highest average voltage, this is consistent with the notably steep dependence of the efficiency of the given model on the input voltage described in Chapter 3 of the Thesis. Consequently, at a lower capacity value, wherein the RMS value had not yet decreased by more than 3 %, but V_{max} had notably increased according to the model, the converter was able to harness the advantages of higher peaks enough to overcome the effect of decreased RMS. At even lower capacity values, the power starts to quickly decrease due to the large voltage dips within rectified pulses, while at higher capacity values, the power descreases due to the general decrease of both voltage dips and peaks according to the model (Fig. 4.2 a).

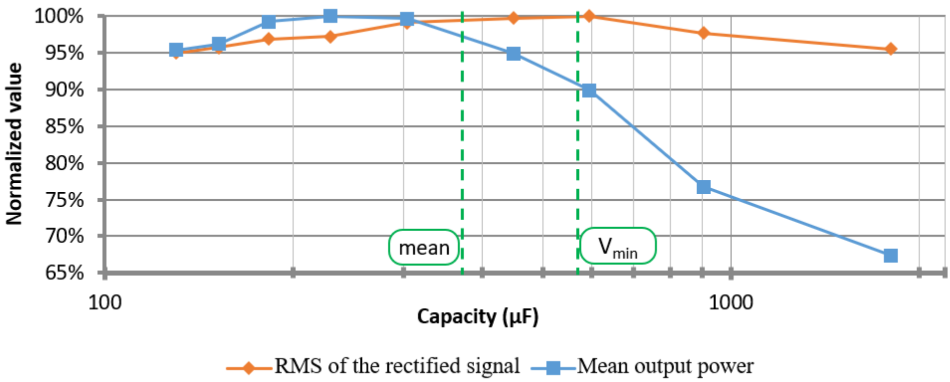

Fig. 4.3. Experimental data for the dependence of the rectifier voltage RMS value and the average output power of the *EH4205* on the filtering capacity of the rectifier bridge. The vertical dashed lines indicate the capacity predicted by the analytical model for the peaks of the lowest (V_{min}) and mean voltage (Fig. 4.2 a).

The voltage multiplier circuit for which the optimum capacity value was found by computer simulation has also been experimentally tested. Two multiplication stages were chosen, forming a voltage doubler. Higher number is impractical, since the harvester produces no more than two sine-wave-like periods per one movement (Fig. 2.1 d), meaning maximum four pulses to feed into the multiplier stages. Measurements were taken for a long, previously uninterrupted input signal and the one that has just started (Fig. 4.4), both sets consisted of the same number of rectified pulses. Numerically comparing these two conditions, it is shown that a higher, unfitting capacitance in the case of a short input signal causes a stronger RMS voltage drop than the predicted optimal capacitance would cause in the case of a long signal. The given effect is more pronounced for the average output power: using a 1.8 mF capacitance the output power with a long input signal is 0.9 % lower than with 2.7 mF, but with a short or interrupted input signal the average power is 1.9 % higher. So less is lost for a long signal than would be gained for a short signal. Therefore, the use of the optimized capacitance is also justified in circuits where the number of consecutive pulses of input signal can vary. It has been observed that the average output power decreases more rapidly at lower capacity values, while the rectified RMS value matches the one at higher capacity values than the optimal. That can be explained by the greater impact of the rectified voltage dips on the converter's operation, as they are more prominent at lower capacities. This result confirms observations and set prerequisites in the previous chapter.

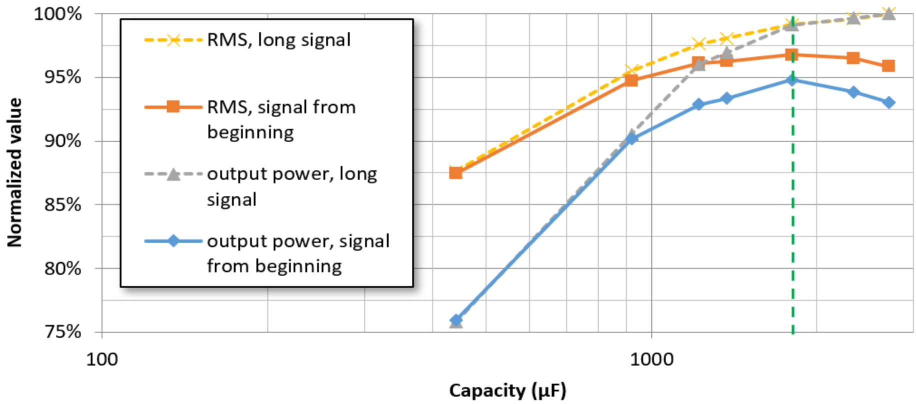

Fig. 4.4. Experimental data for the dependence of the rectifier voltage RMS and the average output power value of the *EH4295* on the filtering capacity of the multiplier. Comparing a long (stationary) signal and the one that just started. The vertical dashed line shows the capacitance predicted by the computer simulation to obtain the highest RMS voltage.

Under controlled conditions, it has been practically observed that by choosing an unfitting smoothing capacitance, the full-bridge circuit loses up to 5 %, and the voltage doubler circuit loses up to 10 % of the rectified RMS value, which consequently affects the operation of the connected low-voltage converter, reducing the average output power by at least 20 %. In order for the converter to obtain the highest benefit at the highest RMS values, the dependence of its input impedance and efficiency on the expected input voltage range should be as gradual as possible, which confirms the prerequisites set forth in the previous chapter. Overall, the results prove that the performance of the rectifier can be greatly improved by selecting the value of the filter capacitor, which can have an optimal value based on the input signal, source and load parameters.

5. DEVELOPMENT OF A LOW-POWER SUPPLY AND DATA MEASUREMENT SYSTEM INDEPENDENT OF EXTERNAL SOURCES

This chapter focuses on the completion and testing of low-power electric energy supply from energy harvesters based on the results and insights gained in previous chapters. Since the prerequisites for selecting a low-voltage converter for the electromagnetic motion energy harvester in Chapter 2 have been identified in Chapter 3, demonstrating that theoretically sufficient electrical energy can be obtained for consumers at the corresponding voltage, and improvements in the rectification stage are explored in Chapter 4, in this section, they are first combined to proceed with the practical assessment of the electrical energy source. Afterwards, the reduction of instability of the electric energy flow by combining two human energy harvesters will be evaluated, the development of a fitting consumer will be analyzed, and tests will be carried out under idealized yet realistic conditions.

Based on the previous conclusions, the most suitable of the tested low-voltage converters was selected in order to compare the voltage doubler rectifier with and without capacity optimization with the previously used bridge rectifier under realistic energy harvesting conditions (Fig. 5.1). Despite the significant scattering of results due to the nature of human movements, the average values showed the highest rectified RMS voltage for the voltage doubler circuit with the optimized capacitance.

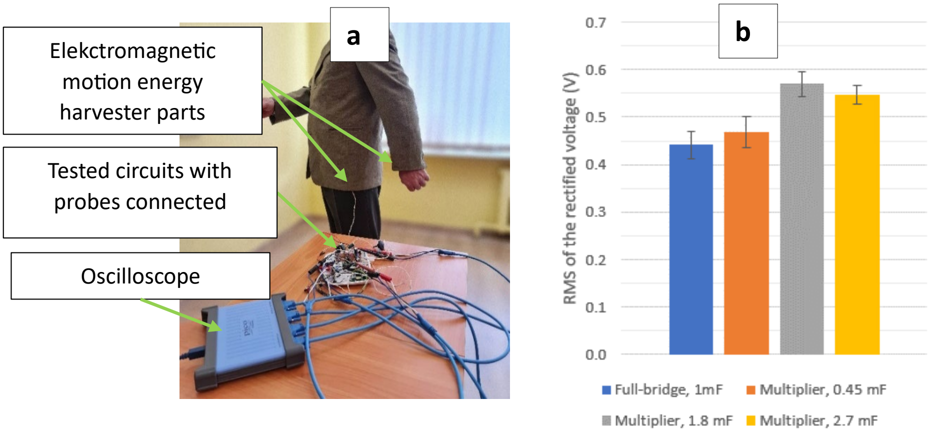

Fig. 5.1. Experimental setup in which a person mimics the typical hand movements during walking (a); RMS values of rectified voltage for all circuits (b).

In order to evaluate the influence of generation variability, the experimental runs that gave the most mathematically stable and the least stable energy accumulation results were identified for each rectifier option. Mutually comparing the two sets of opposite stability, a matching trend and very close relative results were obtained (Fig. 5.2). They show a higher agreement with the experiments under idealized conditions, which were also conducted using an automated motion device, than the average values, indicating an equal effect of the smoothing capacitance on both more and less consistent input signals. This confirms that the amplitude does not play a decisive role in the observed influence of the capacity as per the model in Chapter 4, proving the validity of the use of capacity optimization in cases of practically variable generation. When comparing operation under the same conditions, the voltage doubler with optimized capacitance exhibits approximately a 30 percentage points higher rectified RMS voltage value than the previously used full-bridge circuit, resulting in a 45 % higher input power for the low-voltage converter and twice the average output due to the efficiency gain.

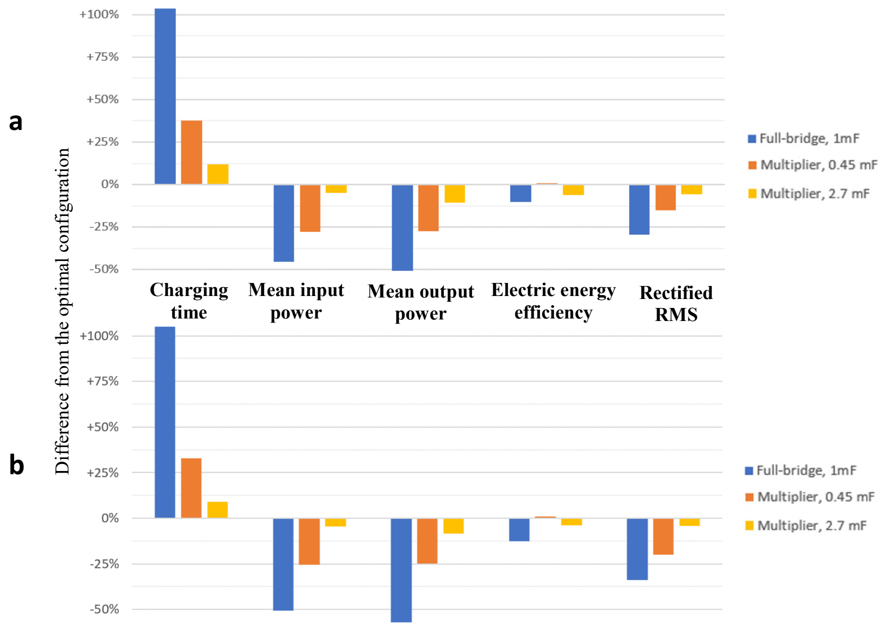

Fig. 5.2. Human motion experimental results of the most stable (a) and the least stable (b) input signal individually; data are normalized against the optimal circuit result in the human movement experiment.

In real-world conditions, a significant scattering of results has been observed, which can affect the reliability of a human energy harvester as a power source. This cannot be resolved either by improvements to the given harvester or by enhancements to the voltage converter efficiency; therefore, a different energy harvester has been selected for combining into a hybrid harvester, so the generation pauses of both generators do not overlap. In the publications reviewed in Chapter 1, combining is typically carried out for higher power acquisition; however, the primary objective in this study is the stability of energy flow, therefore, a thermoelectric harvester has been chosen, which, due to relatively slow body temperature changes, continues to generate power even after the human movement has stopped. The output voltage of both energy harvesters is matched by separate converters so that they can charge a common output capacitor (Fig. 5.3 a), thus the given system includes two individually optimized sources that can work together, complementing each other, and separately. The thermoelectric harvester is placed on the lower leg (Fig. 5.3 b) so that it does not affect human movements, while being exposed to greater air flow and remaining in stable contact with the skin. The thermoelectric harvester itself has not been discussed within the Thesis, rather in individual co-authored publications [24], [28].

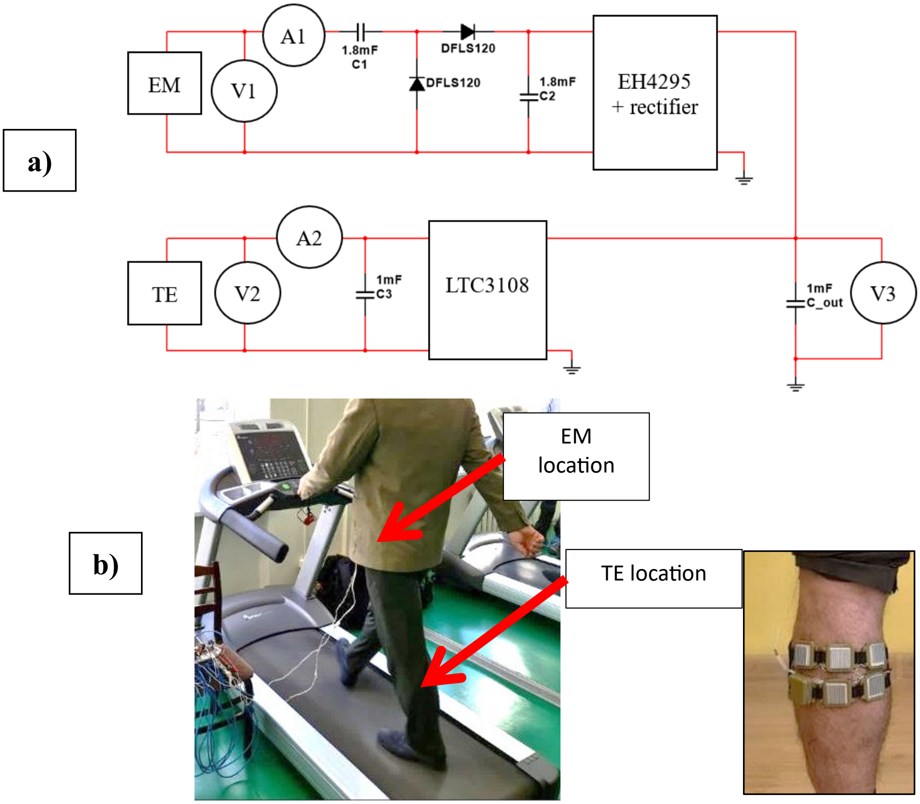

Fig. 5.3. Schematic for the combined electromagnetic (EM) and thermoelectric (TE) human energy harvester with voltage (V1–V3) and current (A1, A2) measurement points shown (a); experimental setup with locations of individual generators (b).

In walking experiments indoors at a fixed speed (Fig. 5.3 b)), it has been proven that in this connection the total generation is not only with a higher mean power output value but also with less variability than from the motion energy harvester alone (Fig. 5.4), 3 % and 16 % respectively. The given effect is explained by the instantaneous power balancing interaction, which occurs due to the parallel loading of both power sources through the common storage element. The effect requires harvesters of comparable mean power output with non-overlapping generation pauses and corresponding voltage converters to match the output voltages. However, it should be taken into account that the highest output voltage of individual sources may differ, so their contribution may not be relevant in the entire output voltage range, as can be seen in Fig. 5.4, where the thermoelectric harvester is unable to exceed 4.3 V, which may be important for the operation of the potential consumer. In general, it can be concluded that, although the given combining method uses more components than connecting harvesters directly or through a rectifier, it allows different sources to provide constructive interaction under practical generation conditions. Furthermore, a particular approach can potentially result in better performance from each individual harvester as they can be individually optimized.

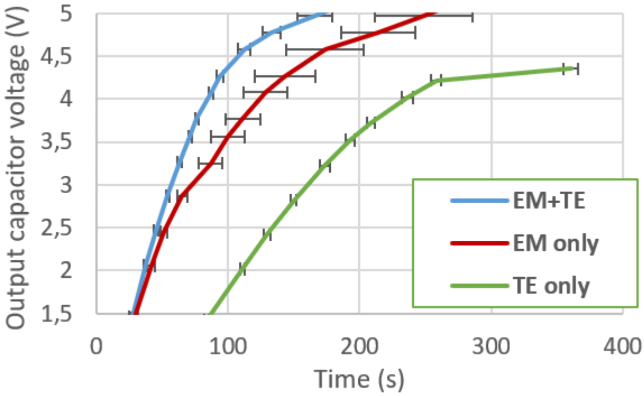

Fig. 5.4. Combined (EH+TE) and individual harvester performance during the treadmill experiments for the output capacitor (1 mF) voltage.

A consumer development has been examined for the practical usability assessment of the created harvesting system. It is designed to run its functions based on the necessary electric energy, which was determined experimentally for each main procedure, and the available electric energy on the storage capacitor determined by regular voltage measurements. The consumer is implemented using off-the-shelf components that provide greater configurability, can operate at a voltage below 2 V, and could utilize a broader harvested voltage range. The voltage monitoring function was chosen to be performed by the main microcontroller, an external temperature and relative air humidity measuring chip and a wireless communication chip are connected to it. The developed algorithm ensures that the operations proceed according to their consumption and the already available electric energy at the corresponding voltage (Fig. 5.5). External components' power is connected only when sufficient electrical energy has been accumulated for their initialization, performing certain measurements and sending data, as well as there is a reserve to safely maintain the system in a standby mode (Fig. 5.5, voltage monitoring A). Next, routine operations are performed according to the available energy (voltage monitoring B), thus their execution serves to control overall system consumption, helping to maintain the power supply voltage in the required range. In this way, the functionality of the system would not be disturbed even in cases of temporarily variable generation, and re-initialization would be required less often. A wireless reception device has been created for the evaluation of consumer communications and sensor measurements.

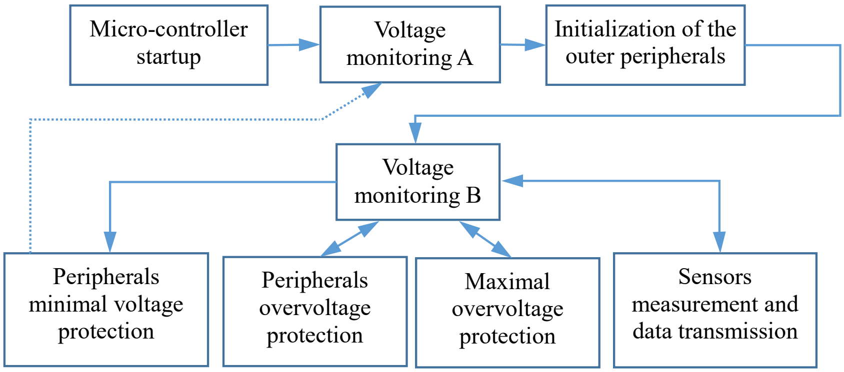

Fig. 5.5. Basic algorithm sequence.

Consumer functions with energy harvesters as a power source have been experimentally verified by a person walking at a fixed speed indoors. It has been demonstrated that it is possible to partially use stored electrical energy along with the currently generated power to initialize the microcontroller, immediately entering a low-consumption mode and relying on configuration and memory stability at temporarily caused lower voltage. This gives the opportunity to start up with the generated power, which is only slightly above the system consumption before the initialization, but for safer and more wide-range operation, a separate voltage monitoring unit is desirable. Guided by the available electrical energy and operation consumption, the created algorithm enables both safe operation at interrupted or weak generation by reducing the frequency of operations (Fig. 5.6 e and g), and useful voltage limitation at strong generation by performing more operations (Fig. 5.6 f). The application of the proposed algorithm allows the use of components with lower energy efficiency and harvesters of limited power generation, relying on the stored electrical energy and a wider working voltage range. This is confirmed by experimental measurements in which all regular operations are also performed with one of the two energy harvesters (Fig. 5.6). Walking was done indoors on a fixed-speed treadmill as presented before in this chapter. The movement was paused when the output voltage saturated, then resumed after its decrease rate dropped or was approaching 2 V. The proposed algorithm makes better use of the slow generation change provided by the thermoelectric energy harvester, allowing the system to function longer after the end of the motion and to resume operation faster after the resumption of motion, avoiding re-initialization.

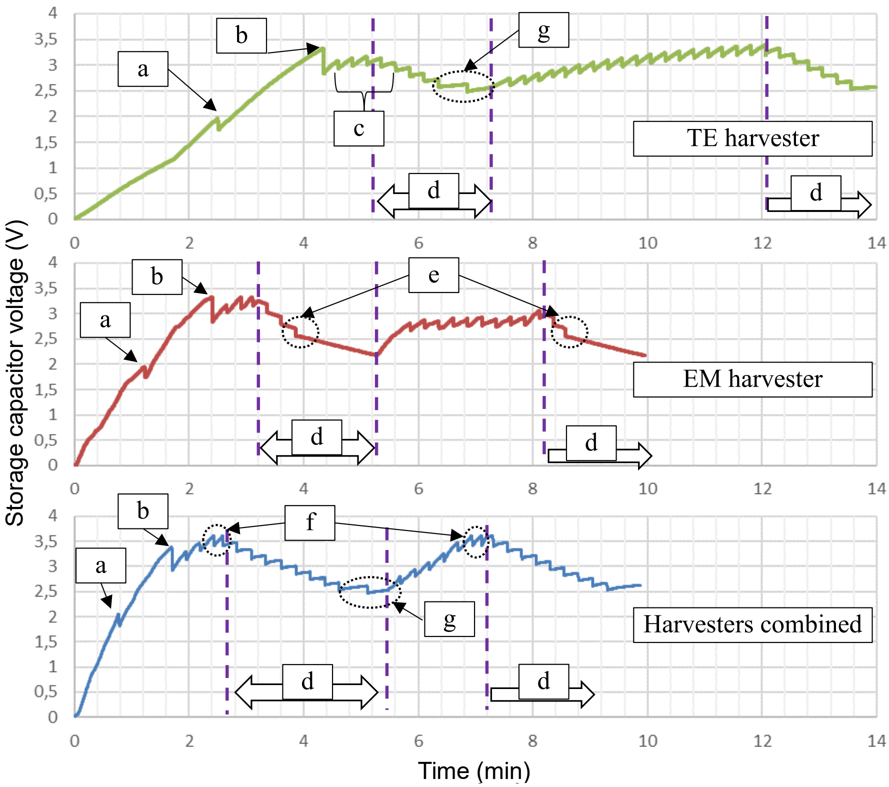

Fig. 5.6. Storage capacitor voltage during walking on a treadmill: consumer startup after the connection (a), initialization of the peripherals (b), sensors measurements and data transmission cycles (accordingly on all graphs) (c), walking pauses (d), last measurement and transmission in the predefined voltage range (e), peripherals overvoltage protection cycles (f), decreased operation frequency due to the predefined low-energy level (g).

The performance of the created power source from human energy harvesters was experimentally confirmed – 10 minutes, more than half of which are without movement, providing continuous power to the electronic system for monitoring environmental parameters and for the overall production using only off-the-shelf components. Relevant numeric data of the operation comparison between individual and combined harvesters is summarized in Table 5.1. No-load average power exhibits 97 ± 3 μW while charging the output capacitor to 4.3 V when walking at 4.5 km/h, which at the given speed exceeds the performance of the majority published hybrid human energy harvesters employing electromagnetic principle. In addition, the study provides generation stability evaluation and corresponding improvements (comparison details in Appendix 2 of the Thesis). The tested consumer, compared to many used in other authors' studies, is designed according to the potential functionality of an integrated smart device, its power consumption has been estimated and the overall functionality tested under the same generation conditions as harvesters alone, providing comparable reference values.

Table 5.1

Consumer Operation Comparison Between Individual and Combined Harvesters

	TE harvester	**EM harvester**	**Harvesters combined**
Time until the system startup (s)	150 s	78 s	50 s
Total time until the first data measurement and transmission cycle (s)	261 s	147 s	102 s
Sustainable pause-to-initial-motion ratio	38 %	63 %	105 %
Count of measurement and data transmission cycles during the first period without walking	6	3	9

SUMMARY AND CONCLUSIONS

In the Doctoral Thesis, the generation of electrical energy from involuntary human movements using the principle of electromagnetic induction has been studied. This method is primarily chosen because it does not require special construction methods or materials, making it easily adaptable to various working conditions. The operation of a specific structure of the harvester is characterized, the prerequisites for boosting the voltage to a usable level are determined, and a method for optimizing the rectification stage is proposed. Finally, the results of the research and gained insights are practically combined to improve the performance of the created low-power source and evaluate it practically. Among the improvements, the creation of a hybrid energy harvester was tested to upgrade individual operating parameters, which could not be achieved with individual improvements of the given electromagnetic harvester. A system for measuring environmental parameters has been created for the evaluation of the practical use of the obtained power source; the system adjusts its consumption to accommodate the variable available electrical energy.

The obtained results justify both the proposed harvester improvements and the developed consumer algorithm, as the ability to generate sufficient electrical energy from human energy harvesters alone was experimentally confirmed. This was validated over a 10-minute period with movements and extended pauses, providing power supply to the electronic system for sensor measurements and data transmission. Harvesters, their voltage converters and the consumer are made using only off-the-shelf components. The resulting system parts are individually characterized and, based on the results, matched to each other for higher overall performance. The system is tailored and tested under realistic conditions, characterizing the generation stability. The research provides an extensive insight into the practical aspects related to obtaining the electric energy of human motion for the creation of a power source using the principle of electromagnetic generation. The generation results are comparable or even exceed the existing published solutions, therefore the aim of the work is considered to be achieved.

Main results

1. Taking into account the characteristics of the electromagnetic generation principle for a flat coil, a clothing-integrated motion energy harvester has been characterized and improved without the need for mechanical resonance, providing up to 68 % electrical efficiency on a resistive load with a Schottky diode full-bridge rectifier.
2. Among several options a low-voltage converter was identified, which with the studied electromagnetic motion energy harvester provides charging of a 1 mF capacitor to 2.8 V in 350 s under real walking conditions, accumulating 3.8 mJ of energy.
3. An experimental evaluation was carried out to determine the prerequisites for self-resonant low-voltage DC converters to work with the generated intermittent and varying AC input signal; the results can be used both for the selection of the most suitable parameters and for the assessment of the needed improvements.
4. A mathematical model has been developed for assessing the smoothing capacity influence on the full-bridge rectifier output voltage for a discontinuous input signal,

allowing to predict the existence of the optimal capacity and its value depending on the generator and load parameters.

5. The rectifier filtering capacity influence on the obtained RMS value has been experimentally proven for an intermittent AC signal with different rectifiers, revealing a distinct peak nature and, depending on the circuit, reduction of the RMS value by up to 10 % comparing to the optimal level.
6. The rectification stage was tailored specifically for the studied harvester-converter combination, and its contribution was confirmed under the influence of natural generation variability, demonstrating a doubling of the output power compared to the full-bridge rectifier circuit previously used in this research.
7. To ensure higher stability of the generated power, the motion energy harvester has been combined with a thermoelectric harvester of comparable output power under similar operation conditions, experimentally assessing the electrical interaction of the generators and the individual contribution to the overall performance.
8. The resulting power-generating system has been tested under realistic human motion conditions, demonstrating greater power output (97 μW vs. 63 μW of the motion harvester alone) and improved stability and repeatability (deviation of 3 % vs. 16 %). The performance of the given hybrid harvester structure, generation conditions and principles is comparable or superior to solutions published by other authors.
9. The capability of the created energy harvesting source has been experimentally verified by powering a custom consumer assembled from off-the-shelf parts, which measures temperature and relative air humidity and provides wireless data transmission. Short walking pauses do not affect the continuous operation of the system due to the implemented adaptive algorithm, that adjusts power consumption with function timing and ensures keeping the supply voltage in the required range.

The **main conclusions** of the Thesis

1. A non-inertial electromagnetic human motion energy harvester generates short, sequential bursts of voltage pulses, which limits the use of multiplier circuits for voltage boosting; however, when employing DC low-voltage converters, a two-stage multiplier as a rectifier proves advantageous over a full-bridge circuit.
2. The rectification stage for small bursts of pulses can be optimized since, depending on the signal frequency and circuit parameters, there exists a value of smoothing capacitance at which the highest RMS value of the rectified voltage is achieved.
3. The naturally varying generation of the harvester has minimal impact on optimizing the rectifier through capacity selection, nevertheless, it does complicate choosing fitting low-voltage converter parameters; therefore, it is advisable to select converters with least dependence of input impedance and efficiency on the input voltage within its expected range.
4. To ensure the addition and balancing of power from various energy harvesters, individually tailored voltage converters must be used with their outputs connected in parallel across a common energy storage element, where each harvester can provide close mean power and a voltage higher than what is required by the consumer.

5. Algorithm, when designed for the combination of a low-power consumer and an energy harvester, can ensure maintaining the supply voltage within the necessary range and allow the use of less energy-efficient components by performing operations according to the available and needed electric energy and the respective voltage.
6. There are no generally accepted standards for the comparison of harvesters. It complicates the assessment of energy harvester-consumer systems and their selection for practical purposes, therefore the test methods chosen in the work investigate individual stages of development in their intended working conditions, while the criterion of stage compatibility is selected for the evaluation of the results.

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