Chapter

Energy Harvester Based on Magnetomechanical Effect as a Power Source for Multi-node Wireless Network

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Abstract

This work is focused on the development of new kind of energy harvesters that could be used in various applications including industrial, aerospace, or customer markets. The main aspect to consider is transformation of different sources of energy (that in normal conditions is wasted such as temperature, vibration, shock, etc.) into the usable electric power. The goal was to prepare wireless subsystem based on energy-harvesting technology which will aid different areas. The energy-harvesting devices are shown as small harvesting devices with power output from 10 mW up to 5 W. Proposed solutions might be used in applications such as low-power microprocessor systems, ultrasonic continuous power supply for low-power wireless network systems, and multi-node harvester systems that allow to collect more electrical power for critical structural health monitoring (SHM) applications. The main purpose was to obtain from harvesters the sufficient values for supplying the chosen 32-bit microcontroller systems. Additionally possible application in mechanic for the other than magneto-based solid harvesters is described.

Keywords: magnetomechanical cross effect, smart magnetic materials, magnetostriction, Terfenol-D, magnetostrictive actuators, frequency response, energy harvesting, harvesters

1. Introduction

The chapter describes the results obtained in the field of energy harvesting (hereinafter referred to as EH, also known in the literature as power harvesting or energy scavenging). EH is a set of methods that allow obtaining electricity from sur-rounding sources, such as mechanical, thermal, solar, and electromagnetic energy, salinity gradients, etc. [1, 2]. Energy harvesting is the use of sources commonly found in the environment (the so-called background energy), which are undesirable and usually suppressed (e.g., noise, shocks and mechanical vibrations of devices and structures, electromagnetic smog, heat as a result of friction and combustion, current flow, cooling engines, etc.) or widely available (sunlight, wave energy, salinity differences, biochemical processes, e.g., in plants), as well as those related to human biology (movement, body heat, etc.), for example [3]. Currently, it is assumed that EH can be an effective source of "cost-free" energy (after omitting the installation costs) for powering low-power devices (e.g. electronic devices, sensor systems, etc.). Hence the growing interest in civil and military applications. The area of use of EH concerns numerous civil and military applications and includes such disciplines as medicine, transport (cars, aviation, pipelines), construction structures (bridges, buildings), mechanical structures, sports and rescue equipment, and many more.

Energy harvesting creates new opportunities today, especially in the field of the so-called self-powered microsystems. This is a consequence of the progress in the field of materials and technologies enabling the recovery of energy from the so-called background, i.e., from known sources, but so far omitted, which in turn was due to the low efficiency of transforming energy and the high cost of producing the necessary devices for this purpose (the so-called harvesters). The decreasing energy consumption of these microsystems is also of key importance, which causes power sources with a power of a mile or even microwatts to acquire practical significance and allow to eliminate traditional power systems using cable systems or batteries or accumulators. A particularly promising area of EH applications is systems for continuous monitoring of inaccessible structures or biomedical implants, as well as distributed systems for the detection of threats on large surfaces (e.g., fire protection systems in forests or detection of chemical or radioactive contamination). It is predicted that in the near future the power of EH systems will increase significantly and will also have significance in industrial power engineering. A better solution is to take energy from the surroundings unlimited in time. It is assumed that in the future EH will be a source of high-power energy by creating appropriately extensive harvester networks.

The paper describes the main directions of EH research based on magnetic transducers and characterized numerous own constructions, including harvesters with magnetic processing using the Faraday effect and modal resonance, with a large increase in voltage under the influence of coil movement, with a moving core of austenitic steel and magnetostrictive core. In particular, the construction, selected characteristics, and possible areas of harvester use are described. The issue of miniaturization of the harvester's construction and modification of the magnetostrictive core was undertaken. Magnetographic field measurements were also carried out outside the harvester. In addition, harvesters using mechanical shock and a dedicated inverter as well as a low-power electronic system were presented. A method has been developed for the use of harvesters and actuators for the wireless transmission of energy and information using Smart Ultrasonic Resonant Power System (the so-called SURPS system), an autonomous system of diagnostics of environmental and operating parameters' multi-degree-of-freedom (Multi-DOF) and the so-called wireless harvesting nodes. The directions for further research have been defined at the end.

Authors recommend energy-harvesting solution to go (**Figure 1**), as an indispensable development system in EH applications. This is a versatile device from Würth Elektronik demonstrating the capabilities of EH and power supplies based on various sources of energy. There are two built-in subassemblies for obtaining energy: using a thermoelectric effect and photovoltaic panel. The electronic site consists of a series of inverters dedicated to EH by linear technology and EFM32 Giant Starter Kit (Silicone Labs) equipped in addition to the microcontroller including LED display and light sensor. This harvester provides the option of changing the configuration of connecting [4–6] power sources. This solution shows a multitude of potential power options using EH, which will be described later in the work.

1.1 Influence of smart materials on energy harvesting

Describing smart magnetic materials and taking into account their properties, it is difficult not to undertake in their own research the issues of their application in

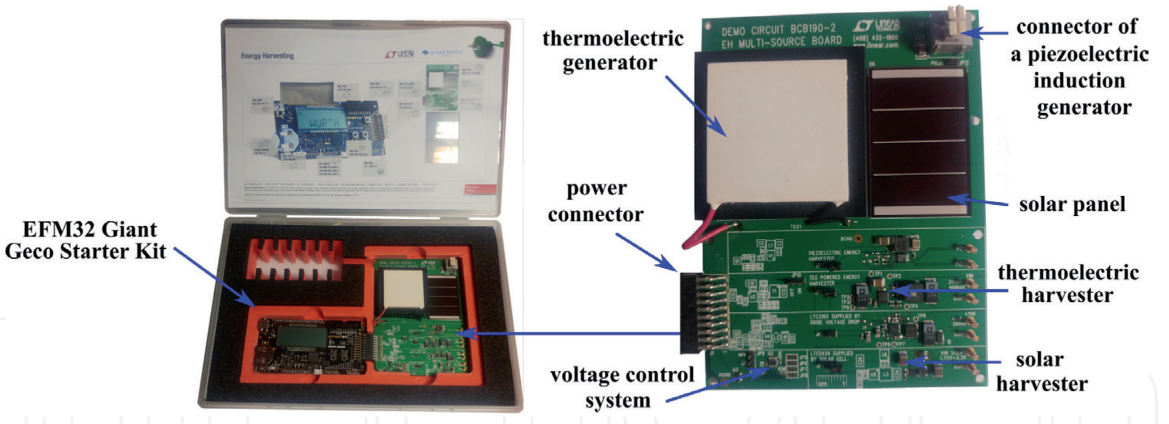

Figure 1.
Energy-harvesting solution to go.

the field of energy recovery (EH) and—as discussed further—wireless transfer of energy and information. It can even be said that the development of EH is possible thanks to the advances in science and engineering in the field of smart materials, including those stimulated by a magnetic field. From a wide group of them, materials with a giant magnetostriction (GMM) were considered to be particularly worth the attention and acceptance as an object of research in the field of EH. The GMM properties are crucial here. A typical example is Terfenol-D. Materials with gigantic magnetostriction can convert magnetic energy into mechanical and vice versa. Thanks to such properties, these materials can be used in the construction of sensors, actuators, and harvester. GMMs obtain much larger deformations (Terfenol-D up to 70 times) than traditional magnetostrictive materials, and to achieve this effect, not very high magnetic field strength H is required. There is also the opposite effect.

Relatively small deformations generate relatively high magnetic field and therefore the induced electric current (in comparison with other ferromagnets). A very important feature of these materials is the wide range of operating temperature, as well as their low inertia (small hysteresis loop field), which facilitates their use in various conditions. The Curie temperature for Terfenol-D is 653–693 K, while the working temperature can reach up to 473 K. Examples of GMM applications in the EH range include aviation, road transport, stationary mechanical structures, medicine, sports and tourism equipment, and many more. The aim of the research is mainly to increase the efficiency of converting mechanical energy into electricity, miniaturization of harvesters, and reduction of their price. Solid Terfenol-D, despite its many advantages, has several disadvantages that hinder its wider application in the field of EH. A significant drawback is, above all, the high brittleness, which is associated with low tensile strength. Another limitation is eddy currents of considerable value, which limits the effective frequency of operation of the devices to several kilohertz. An important parameter is also the price of Terfenol-D, which remains at the level of 1 $/1 g. These disadvantages are the reason for searching for new solutions. One of them is magnetostrictive composites, which can also be used in the construction of harvester.

1.2 Wireless energy and information transfer through energy harvesting

The use of harvesters increasingly requires solving the problem of unconventional energy and information transfer by solid, liquid, and gas media. Therefore, it was considered important to characterize the state of the art in this area and undertake own research. Smart materials in this case can be effectively used for wireless energy and information transfer using ultrasonic vibrations. Most often, piezoelectric and magnetostriction transducers are used for this purpose. There are many ways of wireless power transmission (WPT) using various couplings, e.g., inductive (most popular today since the pioneering work of N. Tesla), capacitive coupling, microwaves, optical coupling, and sound waves, including ultrasound. This last opportunity has been known for over 40 years. In 1970, the first paper [7] appeared, indicating the possibility of using ultrasounds not only for medical or engineering research but also as an energy carrier in transmission through solid bodies. The ease with which ultrasound passes through the solids was then observed. In 1998, using the given idea, a special heart stimulation electrode was patented for arrhythmia [8]. The biomedical application of ultrasound for energy transmission is intensively developed. Particularly noteworthy here is, for example, work [9], which shows the way of powering, using ultrasound, an actuator placed in the human body. The idea of this type of power lies in the fact that in the receiver, the energy of ultrasonic waves and vibrations caused by them are not converted back to the electrical voltage at all, but through the arrangement of vibrating elements—they directly supply the actuator. Other interesting studies in this area are described in [10, 11].

Much attention is devoted to energy conversion efficiency using piezoelectric transducers. The most frequently cited are works [12–14]. The last of them showed efficiency at the level of 50% in the transmission of ultrasound in the air at a distance of 70–80 m. Equally spectacular achievements are the Dutch team [15, 16]. Another interesting example is the transmission of data with the help of ultrasound over the plane [17, 18]. It should be noted that very intensively developed activities are aimed at mastering the effective transfer of energy and information through thick metal barriers, mainly using piezoelectric harvester. These works, initiated in the United States by Saulnier in 2006 [19], gained interest in the navy due to the possibility of sending energy and information through the thick walls of submarines. Particularly significant results were published in the dissertation of Lawry [20] and in a dozen or so publications after its defense, e.g., [21, 22]. The last two indicate that the state of knowledge allows the use of such relays on submarines today. The continuous supply of approximately 50 W of electricity, along with 12.4 Mbps of data through 2.5-inch (over 6 cm) metal walls, is an ideal system for use in submarines that require avoiding leakage and high safety. In [23], it is also pointed out that the system can also be used in ships, unmanned vehicles, armored personnel carriers, tanks, and airplanes.

Another large American project funded by the National Aeronautics and Space Administration (NASA) is research conducted by the team of Sherrit from the Jet Propulsion Laboratory. The research, begun already in 1998, concerned the possibility of generating and reading ultrasound signals using piezoelectric actuators and generators [23]. In 2005–2008 this technique was constantly improved. In 2005, the theoretical basis for energy transmission by flexible materials of thickness over 1.5 cm [24] using piezoelectric actuators was described and then—to improve efficiency—using special graphite “patches” attached with thin layers on both sides of the wall [25]. Obtained results were promising, and it was decided to do the first trials with use of mentioned above technology in the vehicles of the NASA. The team’s many years of work have been summarized in a comprehensive publication on the physical basis of ultrasonic harvesting [26] with the use of piezoelectric receivers and transmitters. Recently, a team led by Sherrit has developed a method for feeding the stepper motor through the metal wall of the vessel [27]. Thanks to the uniform power transmission, it is possible to continuously control the motor by the generated ultrasonic waves. Interestingly, this wave is not converted here to electricity and again to the mechanical energy of the engine, but the vibrating elements cause the motor to move directly by picking up ultrasonic waves. A broader literature analysis in the field of power transfer using ultrasound was carried out in [28].

2. Review of EH methods capable of supplying wireless harvesting nodes

Currently, there is a trend to create autonomous power supply systems for low-power consumer electronic devices (including the so-called toward zero-power information and communication technology (ICT)) or a variety of sensor systems and monitoring systems (e.g., structural health monitoring (SHM)), e.g., [6]. It is assumed that even the use of batteries in these cases is not an optimal solution, e.g., due to the troublesome replacement of batteries and their recycling.

The development of the physics of cross-field phenomena, in which one field (e.g., mechanical, thermal, magnetic) enables energy to be obtained in a different form (e.g., electricity), progresses very quickly and is supported by achievements in the field of material engineering. This results in the fact that there are an increasing number of materials usually called smart, which can be effectively used to build harvester.

The number of physical phenomena that produce electric current is significant, e.g., [29–32]. You can include here:

- Piezoelectric effect
- Reverse magnetostriction (Villari effect)
- Faraday electromagnetic induction phenomenon
- Thermoelectric effect (Seebeck effect)
- Static electricity
- Differences in superconductor parameters
- Pyroelectric effect
- Ionization using an electromagnetic field

EH can also be realized using double cross fields, for example, first heat and then electric current. The interdisciplinary nature of the issue, which is energy harvesting (physics of cross effects, material engineering, mechanics, electronics), stimulates the development of science and the economy. It should be emphasized that, despite numerous works undertaken mainly in the last decade in the research centers of the most developed countries, the subject of EH and the various smart materials used for this purpose is still very topical in terms of science and application. Leading economies and research centers allocate significant resources to basic and applied research in the field of EH.

Due to scientific goals and interests, further work was focused on the use of methods increasing the parameters of harvester, mainly energy conversion efficiency, using the acquired experience in the field of magnetomechanical cross effects, smart materials, strength of materials and mechanical structures, and measurement methods. The extent of the subject matter required the imposition of restrictions. Therefore, magnetostrictive harvesters using GMM-type materials were recognized as key. Thanks to their application, instruments that were able to recover energy from sources not yet explored such as mechanical impact were obtained. An important limitation of the magnetic core harvester is its size and weight. Installing piezoelectric harvesters is a lot simpler than a magnetic core harvester that requires a complicated mechanical construction, premagnetization,

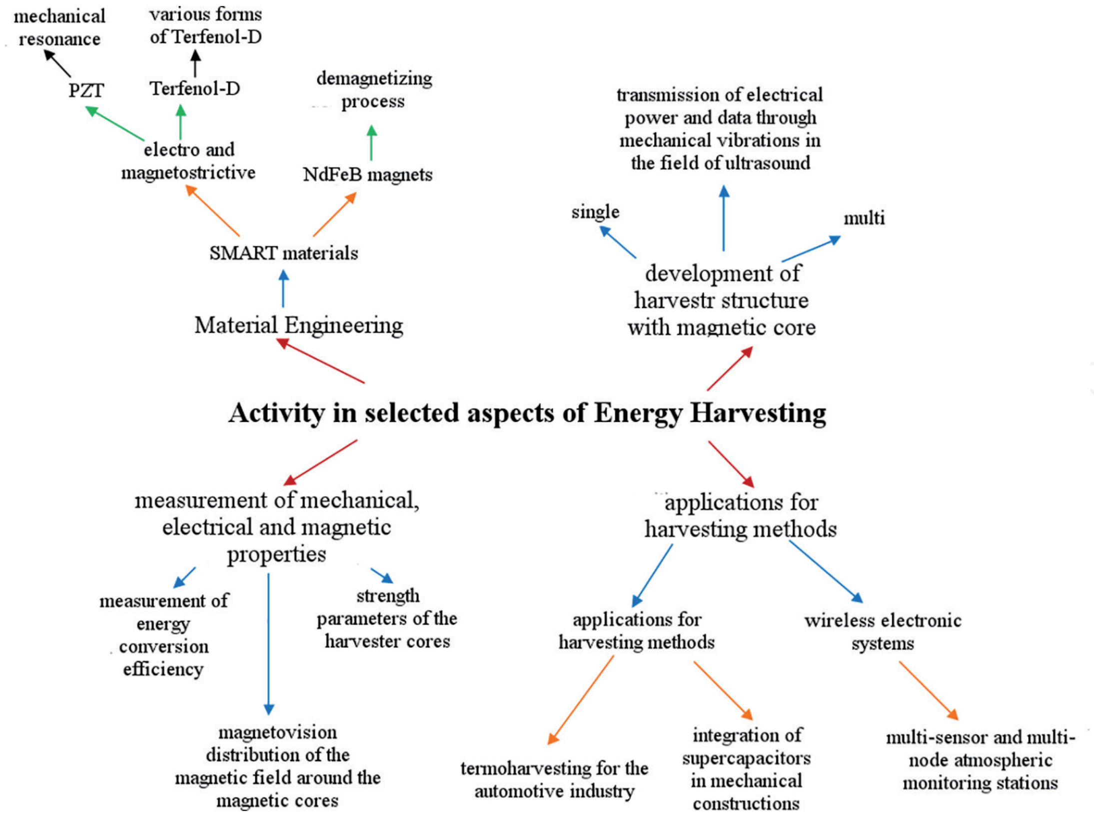

Figure 2.
Determining the dominant issues taken from energy harvesting.

and prestress. However, the current-voltage performance of magnetostrictive harvester is an order of magnitude larger than other types of harvester. That is why this type of harvester was considered to be particularly interesting. Further designs will include further miniaturization of the instruments. Current and future interests in this area are characterized by the graph presented in **Figure 2**. The following examples of implemented harvesting technologies are only briefly presented, the broader discussion of which will take place later.

In the field of low-power technique, the definition of harvester as the power supply of a single microprocessor was adopted, which after powering wirelessly sends data in accordance with its operating algorithm (program code) to the receiving and processing unit. A single harvesting system is a node in a larger structure managed from a central site. Individual configurations of harvester can make it easier to tune the harvesting power for specific phenomena that trigger its operation.

2.1 Harvester as an electric generator

The obtained power in laboratory harvesters became bigger; hence these devices were treated as (source) an electric generator. Due to the physical phenomenon used for the EH effect, construction, the principle of work, the conditions in which the harvester works, and characteristics of the source, harvesters can be divided, as follows:

- Constant voltage (e.g., harvesters based on a thermoelectric effect)
- Variable voltage (e.g., harvesters based on the Faraday effect, e.g., as Piezo patch)
- Impulse (e.g., solid-state harvesters, e.g., top core coil magnet (TCCM)

The pulse supply differs from the voltage-variable frequency of the occurrence of force and the instantaneous value of the generated current. Voltage supply is characterized by frequencies similar to the electricity in the electrical network (50/60 Hz). The generation of the voltage in the impulse supply occurs rarely and for a very short time, but the amplitude is very large. Due to the characteristics of the harvester circuits, they can be divided into:

- Current sources (Faraday generator, magnetostrictive harvesters)
- Voltage sources (Piezo patch type)

2.2 Types of electrical circuits due to the type of energy source

The essence of EH is to create new concepts of current generators, using cross effects, including more often magnetomechanical phenomena. It is assumed that

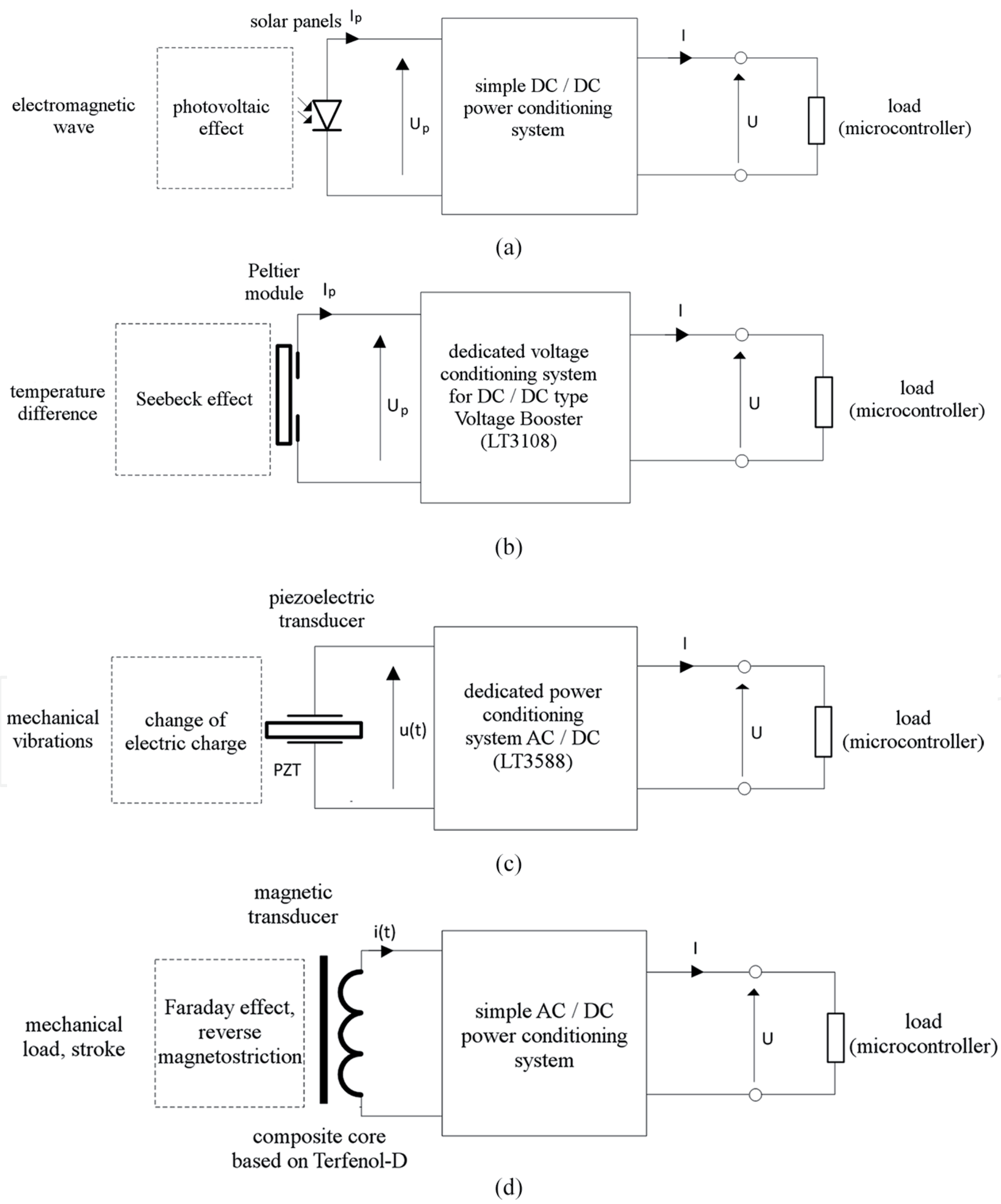

Figure 3.
Configurations of electrical circuits due to energy recovery from a specific source and converter: (a) solar, (b) temperature differences, (c) piezoelectric transducer, and (d) magnetic transducer.

even for small power and efficiency, it can be a valuable power source. The development of the technology of constructing harvester, with similar electrical parameters as chemical cells, may reduce the production of the latter for ecological reasons. As harvesters acquire energy in a nonparasitic manner, i.e., they process energy considered as a by-product ("junk") process, they increase the efficiency of the system as a whole.

Both electricity and electric voltage must have the parameters necessary to supply both the sensors themselves and the built-in processor with the transmitter adapted to it, as well as the communication unit. Another problem is the conversion and conditioning of the voltage/current from the generator (**Figure 3**) [33, 34]. Designing electrical circuits for harvester requires knowledge of the device's operating characteristics.

Only harvesters based on a thermoelectric or photovoltaic effect generate DC current. Harvesters recovering energy from vibration, magnetostrictive, and piezoelectric, as well as based on the Faraday effect, are on the other hand alternating current sources. Harvesters powered by impact impulse are a special case [35]. The generation of electricity in pulsed power takes place for a very short time, but the current amplitude is very high. Harvesters "powered" by mechanical shock generate a variable voltage waveform and are characterized by a strong current pulse, and in the generated signal, there are frequencies related to magnetic resonance of the core-coil system magnetostrictive core.

3. Magnetic-based effects of solid-state energy harvesters

Electricity can be generated by operating on a coil with a variable magnetic field. Such a field can be induced by another coil, in which a variable current flows, we are talking about the mutual induction of coils. This is how the transformer works. By definition, a harvester should be designed so that it does not require additional power supply. Materials that can be used to generate a variable magnetic field are:

- Permanent magnets (e.g., neodymium NdFeB), which are a source of constant magnetic field. In order to be able to recover energy through a coil, a source of an alternating magnetic field is necessary, which means movement of the magnet-coil system against one another.

- Materials with gigantic magnetostriction (giant magnetostrictive material—GMM): Work on new materials has led to the development of materials with gigantic magnetostriction, which undergoes the action of force, deforming, while generating a variable magnetic field. If harvesters based on these methods are subjected to mechanical vibrations, which are a side effect of a certain process, they can be considered a "free" source of alternating electric current, resulting from the appearance of a variable magnetic field generated in the coil, obtaining the best energy conversion parameters [36–40].

As part of our own research, we selected a group of smart materials for harvesting applications and developed many solutions and harvesting methods predestined for the SHM [28, 41] application. The scope of works on magnetic harvester is presented in **Figure 4** [42]. Harvesters with a smart magnetic core can be used as:

- Impulse power supply operating under the influence of mechanical impact with energy adjusted to the size of the harvester core, conditioning its electrical power

- As an electric power transmitter operating under the influence of ultrasonic vibrations above 25 kHz, supplied either from an actuator or a specific technological process

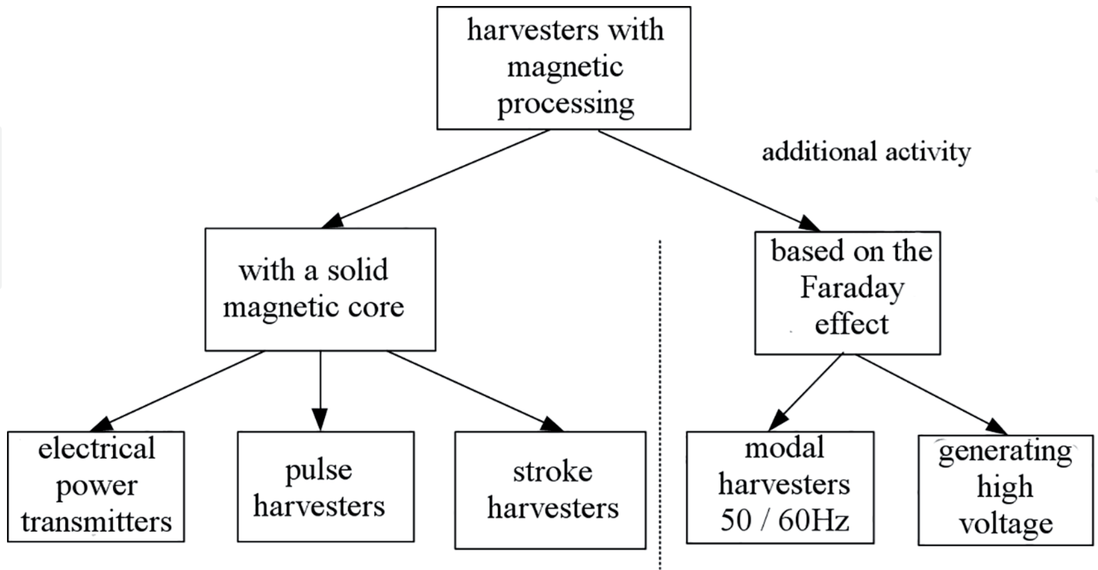

Figure 4.
Types of harvesters with magnetic processing.

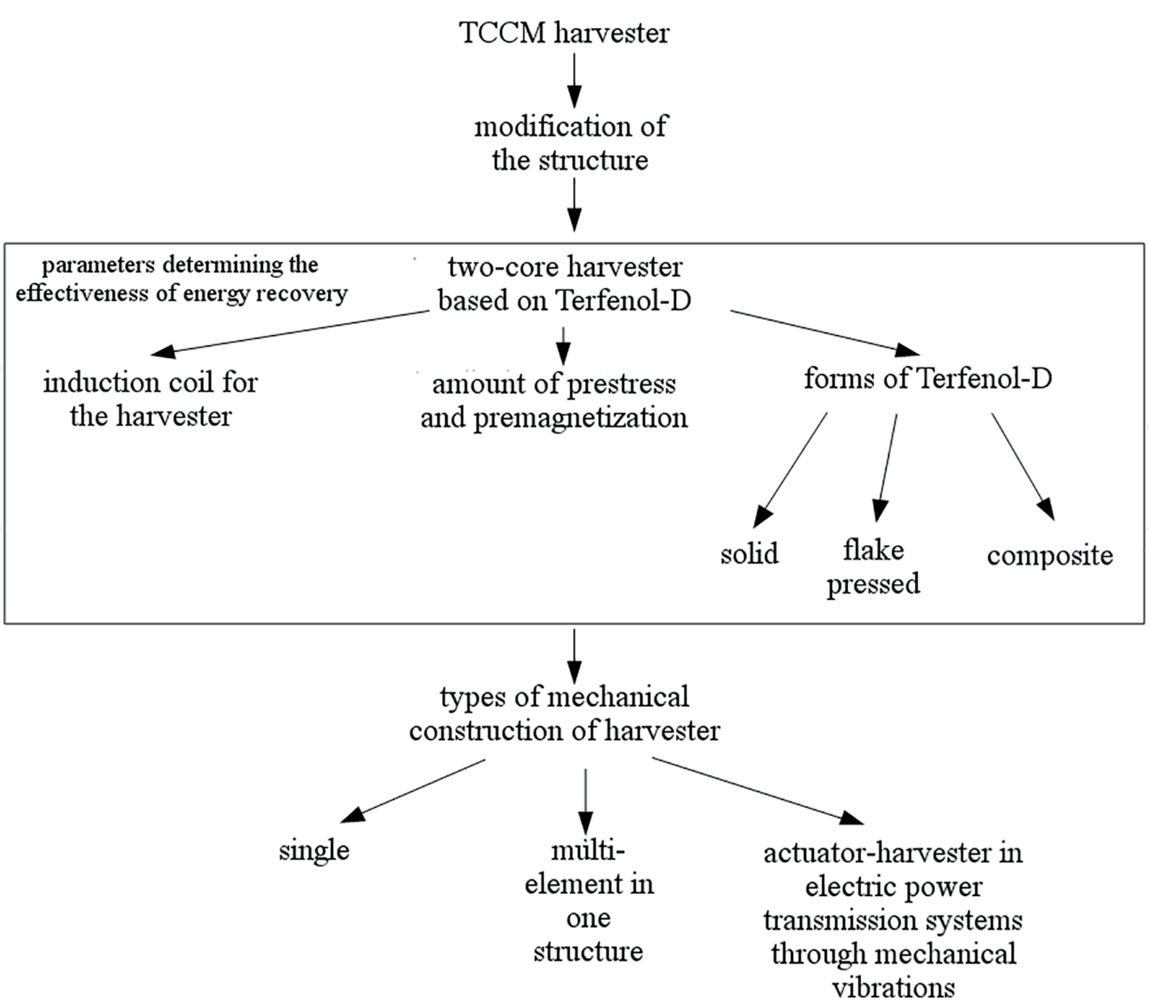

Figure 5.
Development of the next generation of harvester with magnetic core and their applications.

3.1 Harvester construction: core modification

In the next step, it was considered advisable to undertake the task of miniaturizing the harvester structure by modifying the harvester core. The magnetic circuit of the core consists of a set of permanent magnets coupled with magnetostrictive elements, which in turn are cores made of Terfenol-D, solid, as well as in the form of compressed flakes, which makes it possible to reduce eddy currents. Proper selection of parameters related to prestress and magnetization of the magnetostrictive material ensured the supply of the microprocessor even with much smaller dimensions than the one described in [33]. In addition to the typical design assumptions, it was necessary to formulate assumptions from the electrical and functional side, which would ensure a total possibility of working in the mode of actuator-harvester [33].

Previously, harvesters with magnetic processing have been described. The subgroup of magnetic harvester is top core coil magnet (TCCM) harvesters and its variants, double top core coil magnet (DTCCM) and TCCM model 2 [36]. In the work [36], it was shown that harvesters have low electric power yields in relation to dimensions and weight. Further work was aimed at developing a new harvester structure capable of miniaturizing the device without compromising performance and electrical efficiency. The schedule of work on the development of the structure is presented in **Figure 5**.

In order to develop a miniature harvester, the following assumptions were made:

1. As a core solid Terfenol-D must be used.

2. The core of Terfenol-D will be wrapped with foil, which will protect it against crumbling.

3. Alignment will be followed by a "cone-hole" pair.

4. An NdFeB magnet will be placed inside the coil, which will increase the obtained results with the Faraday effect under the influence of core magnetostriction.

Figure 6 shows a comparison of the TCCM structure currently developed based on two solid Terfenol-D cores. The fact that two external NdFeB magnets have been placed inside nonmagnetic oscillating cones is noteworthy.

The prestress of the core is determined by tightening the thread between the clamp and the body. A hole has been made in the aluminum cover in which a cylindrical-shaped ring is received, which receives vibrations. Between the clamp and the washer, there is a rubber ring, which acts as a shock absorber for transmitted vibrations and determines the prestress. By changing the mutual position of the clamp and body, the force at which the polyurethane ring is compressed is influenced, which acts on the core-coupled washer as shown in **Figure 7**.

The harvester body is made of steel; it acts as a seismic mass, affecting the core through a cone embedded in the hole at its bottom. A hole has been made in the body with a diameter suitable for the coil with magnetostrictive cores and a supply opening for the coil wires. The advantage of the body is that it shields the magnetic field from the magnetic circuit. All elements and assembly of the harvester are shown in **Figure 7**.

3.2 Review of prototypes of harvester with a smart magnetostrictive core

The above described only selected own works which allowed to create a palette of harvesters. The type of work and power range of the harvester are shown in the graph below (**Figure 8**):

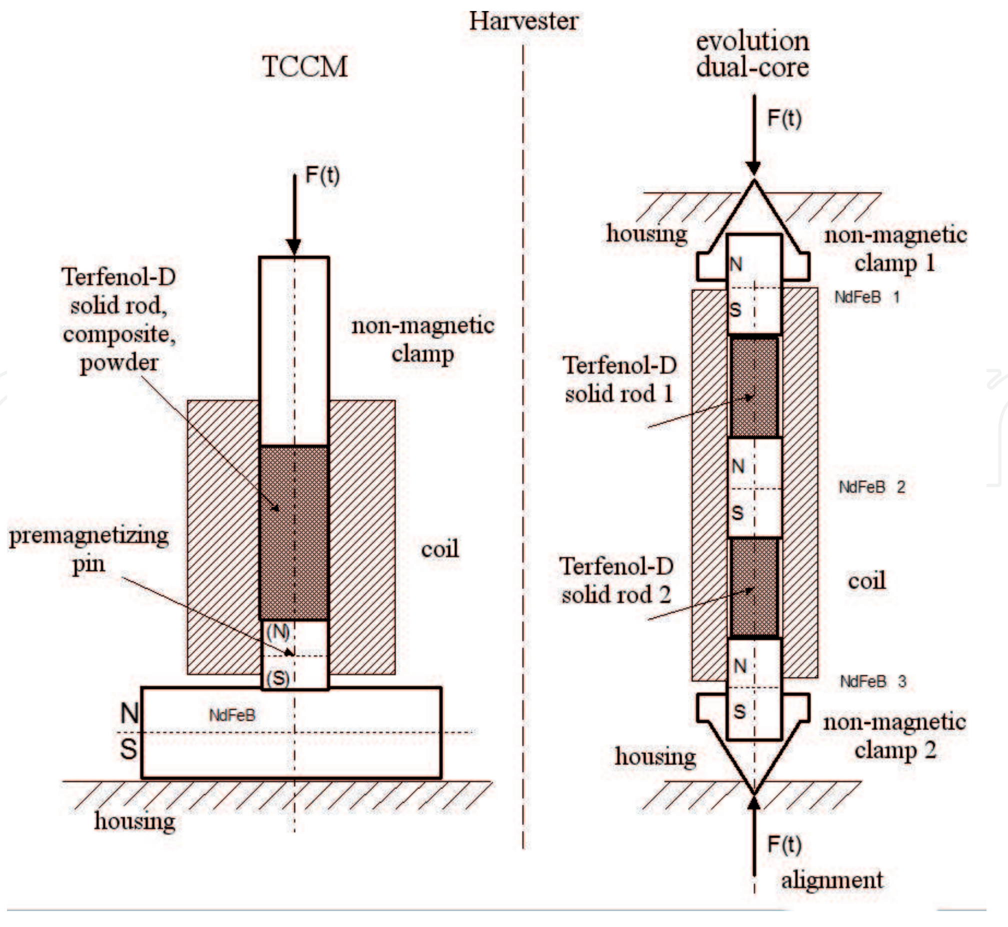

Figure 6.
Comparison of the structure of harvester construction developed in the Laboratory of Dynamics of WRUT.

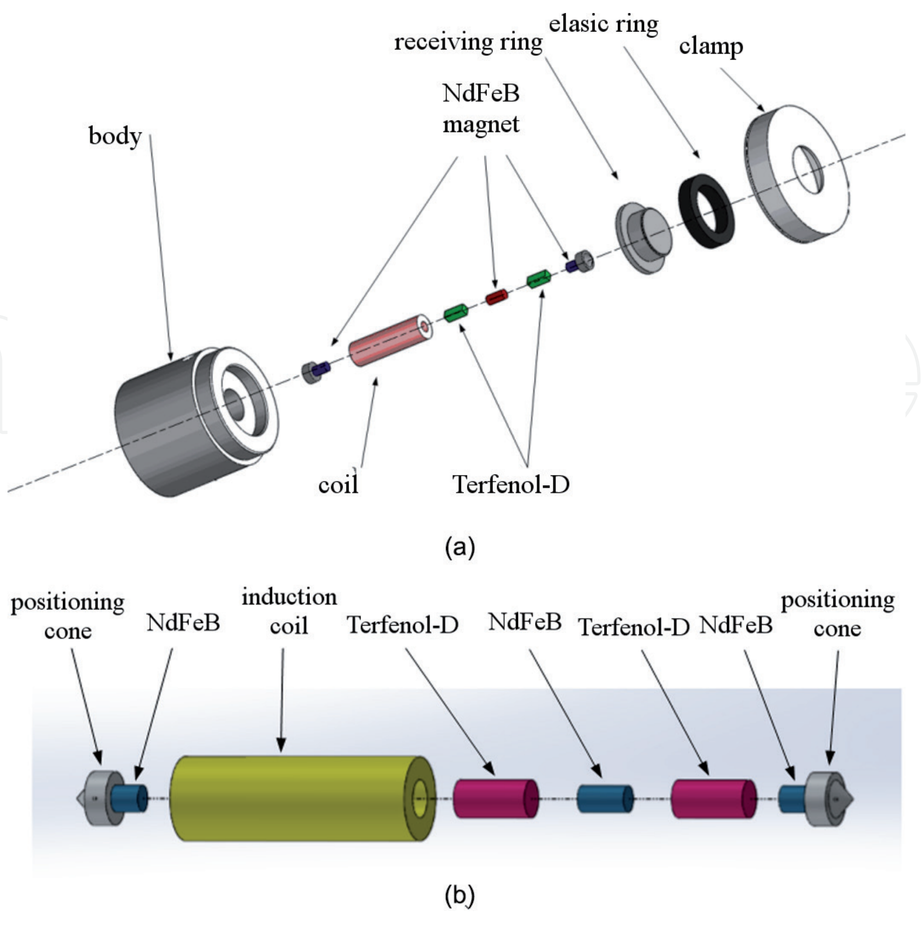

Figure 7.
List of all elements of the harvester: (a) main body, (b) coil with inner elements.

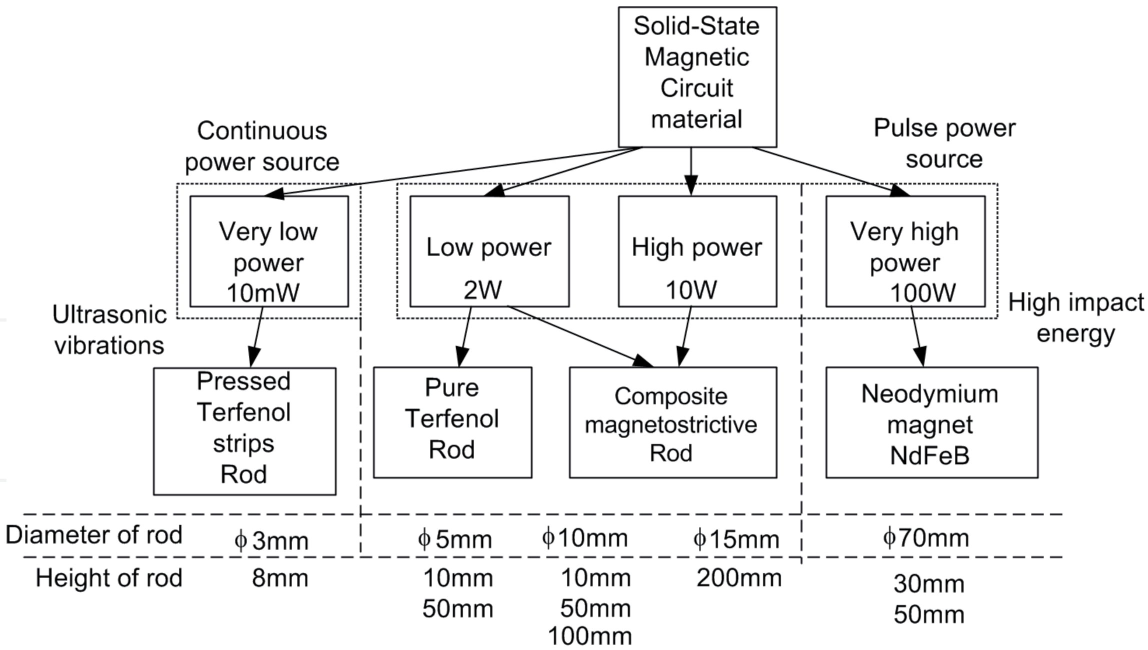

Figure 8.
The classification of harvesters due to the nature of work, power, and the core material.

Figure 9.
A view of prototypes developed in the Laboratory of Dynamics WRUT (a) and (d) low power harvesters, (b) high power harvester, (c) "Tactical grade" type harvester.

The electric power obtained by harvesters depends on the type of material and dimensions of the core. A separate group consists of solutions based on the method of

Harvester type	View from Figure 9	Dimensions [mm]	Mass [g]	Power in the impulse [mW]
Miniature	—	ϕ50 × 35	200	2000
Low power	(A, D)	ϕ50 × 50	300	5000
High power	(B)	ϕ50 × 150	1000	10,000
"Tactical grade"	(C)	ϕ80 × 250	1500	10,000

Table 1.
An overview of the prototypes of harvesters together with the most important parameters.

demagnetizing magnets, in which neodymium magnets subjected to strong mechanical stimulation, sometimes to its destruction, are used as the core. They differ in the amount of Terfenol-D used in the magnetic circuit and provide the possibility of screwing into the structure. The view of made harvesters is shown in **Figure 9** (**Table 1**).

4. Harvesters based on mechanical impact and electronic converters for small power applications dedicated for them

Generators of special characteristics are the explosive-driven ferromagnetic generators (EDFMG) producing an electromagnetic wave that arises as a result of immediate demagnetization of the magnet by a stroke following an explosion or other strong force impulse. The magnet then loses its magnetic properties but generates a strong pulsed magnetic field around it. During the impact it is possible to even destroy the magnet, but the amount of energy that will be induced in the coil is large, and it is enough to charge high-voltage capacitors with a large capacity. This issue is the subject of intense research, especially in the last decade, and their goal is applications, mainly military [43, 44].

One of the proposed methods of generating electricity directly from the impact was the impact demagnetization of NdFeB permanent magnets [35, 36]. Just as a spring has its constant, which is a measure of energy accumulated in it, the magnet has similar storage properties. Large diameter springs have large solid, strong magnets and have a high energy density. Permanent magnets containing components of rare earth have the highest energy density (see **Table 2**). This applies to the generation of electricity for the instantaneous supply of microprocessor systems from the impact demagnetization of permanent magnet-type NdFeB. Currently, NdFeB magnets are the most powerful permanent magnets. The advantages of NdFeB permanent magnets in impact harvesting:

- The largest—of all permanent magnets—BH energy, up to 600 kJ/m^3
- Strong magnetic flux at a surface of up to 2 T
- High hardness of the structure with simultaneous resistance to cracking

The disadvantages of neodymium magnets include:

- ○ Poor resistance to thermal changes—high temperature has a destructive effect on the BH parameter.
- ○ Oxidation of the outer layer of the magnet makes it necessary to use chromium as the outer layer.

Material	Energy density [kJ/m^3]	Bhmax MGsOe	Remanence kGs	Coercion kOe
N27	199–223	25–28	10.2–11.0	Min. 9.6
N30	223–247	28–31	10.8–11.5	Min. 10.0
N35	263–286	33–36	11.7–12.1	Min. 10.9
N38	286–302	36–38	12.1–12.5	Min. 11.3
N40	302–326	38–41	12.5–12.8	Min. 11.6
N42	318–342	40–43	12.8–13.2	Min. 11.6
N45	342–366	43–46	13.2–13.8	Min. 11.0

Table 2.
Magnetic parameters of permanent magnets NdFeB divided into classes.

Through the use of NdFeB magnets, harvesters feature the smallest possible external dimensions. The process of releasing energy through a surge load has become a determinant for the construction of a new generation harvester.

The limited availability and increasing price of rare earth elements are the reason for reducing their share in the composition of permanent magnets. At the same time, this is the reason for intensive research on improving the operational performance of magnets, with a significant reduction in manufacturing costs. On the other hand, you can see that, despite the popularity of the so-called neodymium magnets, not all of their capabilities have been noticed and fully used. There is little work on the use of NdFeB magnets as energy storage sources, which are used if necessary due to demagnetization as a result of mechanical impact. Due to the "longevity" of magnets, you can store "programmed energy" in them much longer than in typical alkaline batteries or accumulators. Of course, the amount of stored energy is much smaller than in typical lithium batteries, but in the case of energy recovered from magnets, there are no limitations in the type of leakage current, causing self-exhaustion of batteries. It is also possible to recycle magnets after fully demagnetizing them. Assumptions adopted during the construction of the impact harvester:

- Neodymium magnet with "stored" energy (BH) max can be treated as a warehouse with energy that can be used with impact demagnetization.
- The harvester can be stored in conditions much less favorable than typical batteries, even in seawater.
- The visible trend of reducing rare earth elements will result in a decrease in the cost of producing the harvester; however, a NdFeB magnet should be used as the method of standard.
- In the magnetic circuit, the simplest construction of the magnetomechanical magnetic circuit should be used (application of pre-pressure, magnetic screens).
- Energy "recovered" from a permanent magnet can be used to power a low-power sensor system.
- Electronics used in the input stage supplying microprocessor elements should have a minimum starting voltage of several mV.

There are examples of ferromagnetic generators which, thanks to the impact (explosion) against the neodymium magnet, obtain instantaneous powers reaching MW; however, in the energy-harvesting application, there is no need to destroy the magnet but only a "light" impact that would not cause its rapid destruction. The way to convert energy into electricity is to place the magnet in the induction coil, just as it is placed in it and other materials, e.g., in electromagnets or in the case of Terfenol-D [2]. Due to the wave phenomena resulting from the stroke, the coil must have a special construction, also due to the polarity of the NdFeB magnet. In the case of a wave transition, a large number of windings are not required (**Figure 10**).

Due to the pulsed energy release, too high inductance of the magnetic circuit causes the reduction of the recovered current due to the increase of the substitute output impedance. The winding should be permanently attached to the magnet. One of the most important information about a magnet that cannot be omitted is the shape and arrangement of the zero line. The winding should be made only at one of the poles, N or S. This means that the magnet should have the largest possible height to diameter ratio but at $ > 10 mm. Currently a 0.6 ratio is assumed to be the standard; however, there are solutions with a proportion close to 1. Be careful about the arrangement of the zero line, which shifts under the influence of demagnetization, and do not combine magnets in NSNS cascades, because the resulting relaxation of the NS transition results in a dramatic reduction in the performance of the magnetic circuit. A good chance to improve the performance of the recovered current is to use the Halbach matrix as the object to be demagnetized.

Harvesters using the mechanical impact phenomenon generate a variable voltage waveform. At the same time, it is characterized by a strong current impulse, and in the generated signal, there are frequencies associated with magnetic resonance of the core-coil system. Next, a new method of acquiring electric current is presented as a result of demagnetizing neodymium magnets in a circuit with a magnetostrictive core.

4.1 A dedicated low-power electronic system for impact harvesters

The use of a small number of coils around the magnet enables the "capture" of rapid change of the magnetic flux and the generation of electricity directly from the magnet impact. However, a very low voltage level at a very high current requires the use of specialized electronic transducers capable of delivering the

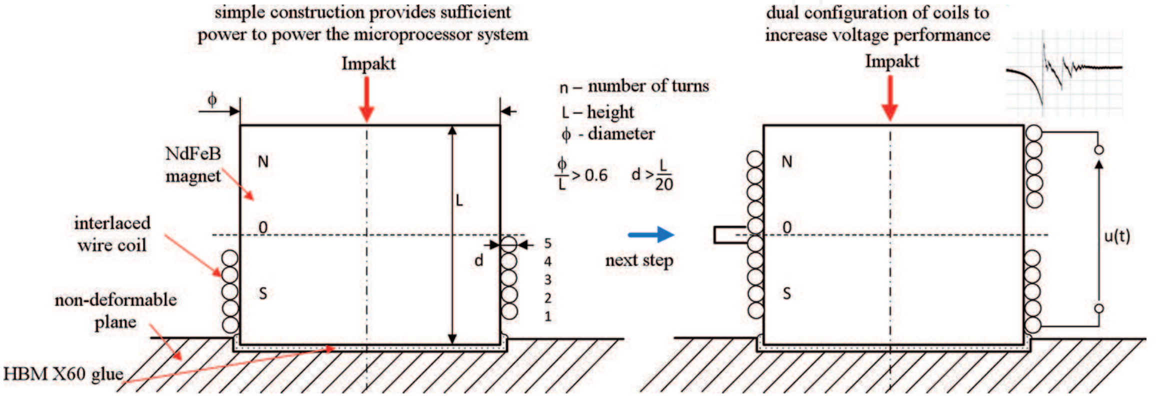

Figure 10.
The scheme of MFT harvester construction together with the description of the relevant parameters.

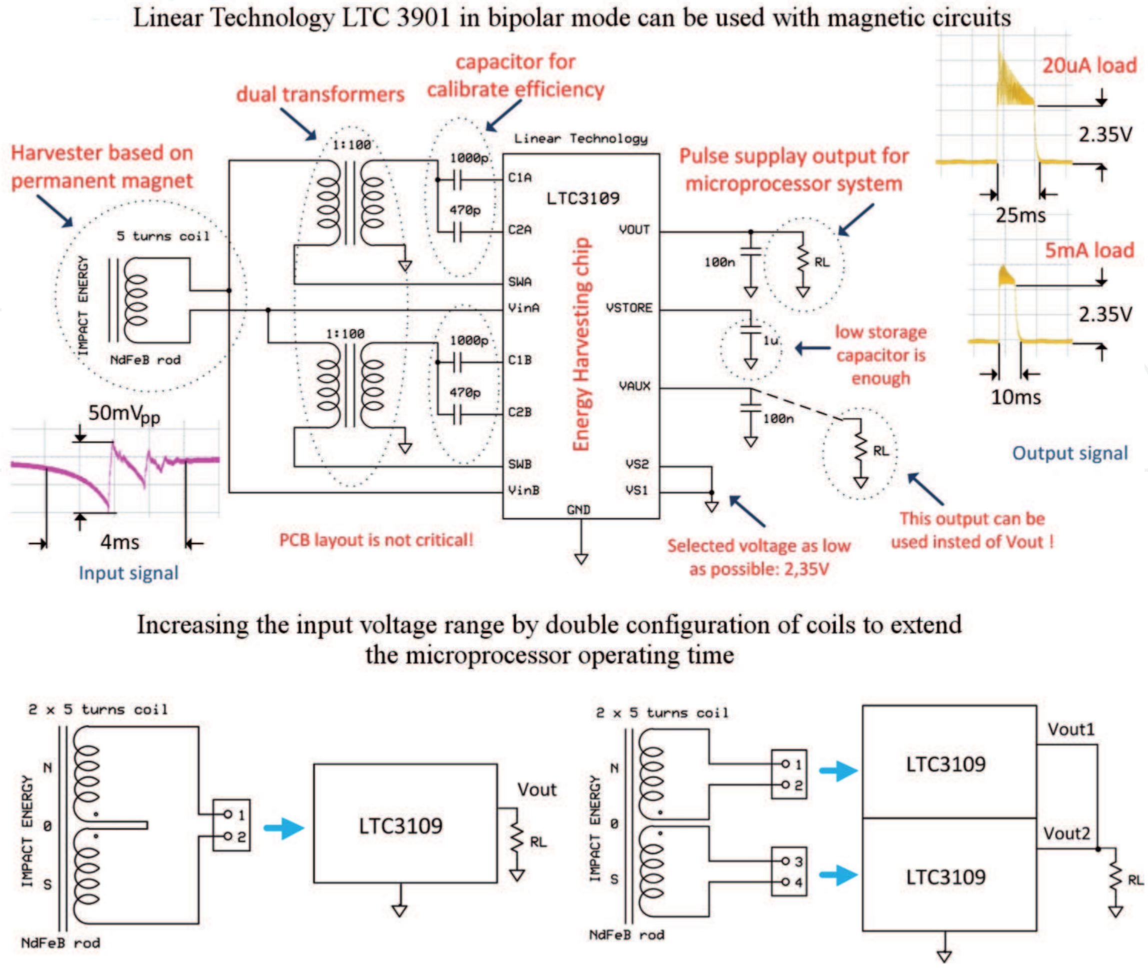

Figure 11.
Application of linear technology LTC3109 as a power conditioner for the microprocessor.

appropriate voltage level to power the microprocessor system. The linear technology LTC3109 system dedicated to thermoelectric applications operating in a bipolar configuration was used in an original way, which, as it turned out, enables voltage processing from low-impedance magnetic circuits. The obtained results demonstrated the usefulness of the system to resonant frequencies close to 70 kHz. The most important features of the harvester with the LTC3109 system are shown in **Figure 11**.

Thanks to the LTC3109 system, which enables the capacitor to be charged for the shortest possible time (the dynamic resistance parameter (ESR)), the operating time of the microprocessor is extended. It is estimated that the harvester subjected to a stroke with a 1 ms force impulse at the energy storage capacitor 100 nF manages to extend the microprocessor operating time to 6 ms. This effect is presented in **Figure 12**, and the view of the prototype impacts harvester system on **Figure 13**.

It should be borne in mind that the estimated efficiency of transforming the impact of the magnetization of the neodymium magnet to electric current is only 0.02%. Therefore, the key challenge is better transformation of energy, which requires changes in the harvester construction. An important aspect is the standardization of the harvester, in terms of their geometric dimensions, conditioned by the application requirements. It is possible to create their series of types, from miniature versions to powers of several watts, as well as relatively large ones (e.g., with neodymium magnets Ø100 mm diameter) for applications in, for example, mining. Further works should also consider the possibility of replacing relatively expensive neodymium magnets with their counterparts lacking rare earth elements.

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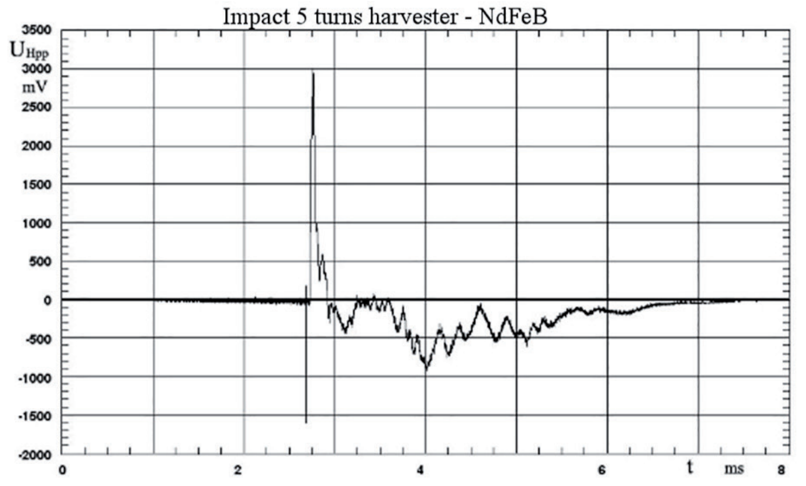
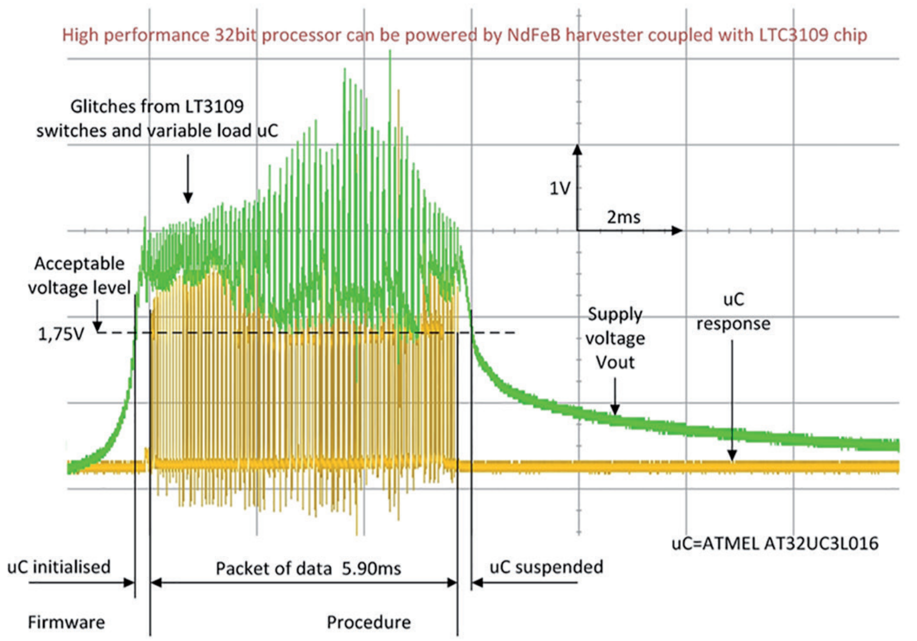


(a)



(b)

Figure 12.
(a) An example diagram obtained as a result of stimulation of a harvester by mechanical shock, (b) waveforms on the conditioner LTC3109, and microprocessor by Atmel together with a description of the parameters.

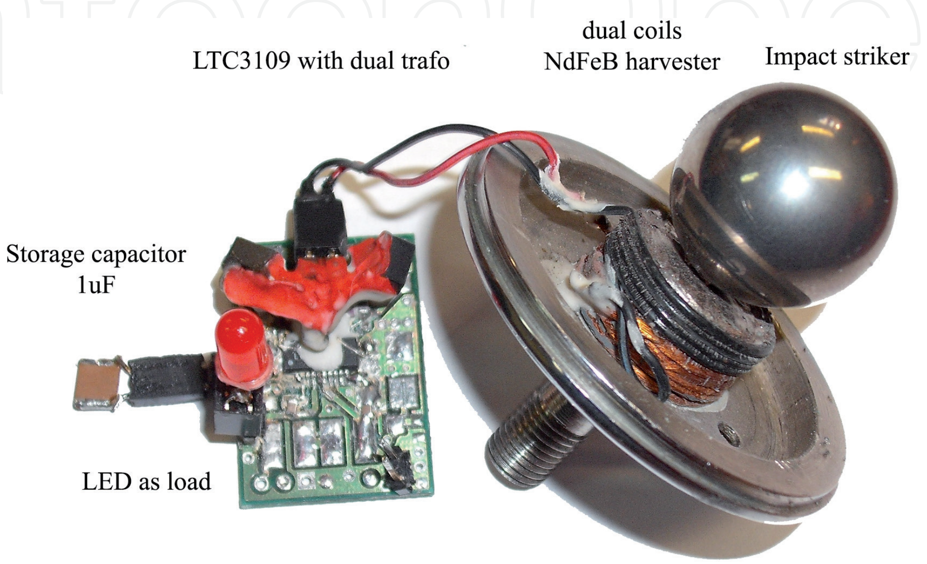


Figure 13.
View of the impact harvester with the ball as the element receiving the impact.

5. The use of harvester with magnetic processing for simultaneous transmission of power and information through the supra-acoustic wave

The use of smart materials for wireless power transmission (and information) proved to be practical, and the results obtained during the research indicated the high efficiency of this method. Following further work, the project of Smart Ultrasonic Resonant Power System (SURPS) was created, which provides for the possibility of such transmission via various media and through various transmitter-receiver configurations. Diagrams are shown in **Figure 14**.

The mechanism of energy transmission consists in "sending" mechanical energy through the actuator in the form of a pure, sinusoidal ultrasonic wave and then its "pickup" by the harvester through the magneto- or electrostatic material that is in it. In this way, energy (along with information) can be transmitted not only through different types of centers but also at different distances. The type of frequency modulation (FM) was used for transmission of information, which for the needs of various types of structures was modified so that the data transfer was less than the resonant frequency of the structure. This method worked well during laboratory tests, and a flow chart is shown in **Figure 14**. **Figure 15A** shows a schematic diagram of data sent by an actuator based on Terfenol-D (AT) or piezoelectric material (AP). **Figure 15B** in turn shows the signal that is obtained on a harvester with a core of magnetostrictive material. **Figure 15C** illustrates the result of the operation of the station with two magnetostriction rails and transducers from **Figure 16**. A sinusoidal carrier frequency with small harmonic distortion (in the below 23 kHz case) generated by an actuator for data transmission to a harvester-powered microprocessor is modulated in the "on-off" mode, that is, in some time fragments, the actuator does not work by temporarily disconnecting the power supply of the harvesting side. Due to the fact that the harvester power supply has been equipped with a bank of capacitors with a capacity of 0.5 s microprocessor operation without harvest rami support, satisfactory results have been achieved even when transmitting many bytes of information encoded in accordance with ASCII signs.

Simultaneous supply of the sensory system was obtained, based on an industrial 32-bit microprocessor system and data transmission in half-duplex mode at the speed of about 1000 bps with the recovery of energy from mechanical vibrations with an over-acoustic frequency. A technique for feeding the microprocessor system from harvester machines combined with various configurations at carrier frequencies depending on the natural frequency of the structure containing dedicated actuators and harvester units with electromagnetic and magnetostriction transducers was developed.

Figure 16 shows a view of the assembled rail system with magnetostriction transducers with the possibility of powering the microprocessor system on the harvester side and transferring data in both directions.

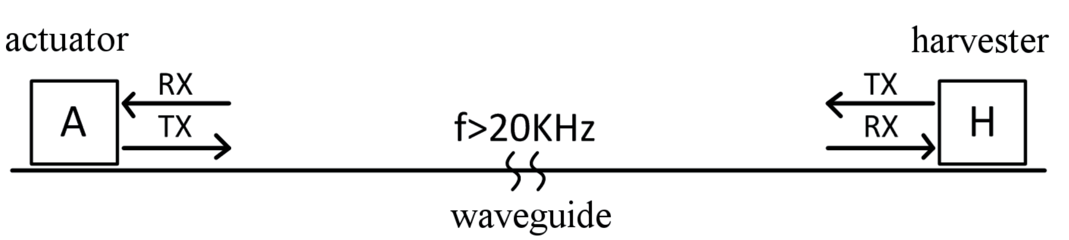


Figure 14.
A schematic diagram of power transmission through ultrasonic vibrations.

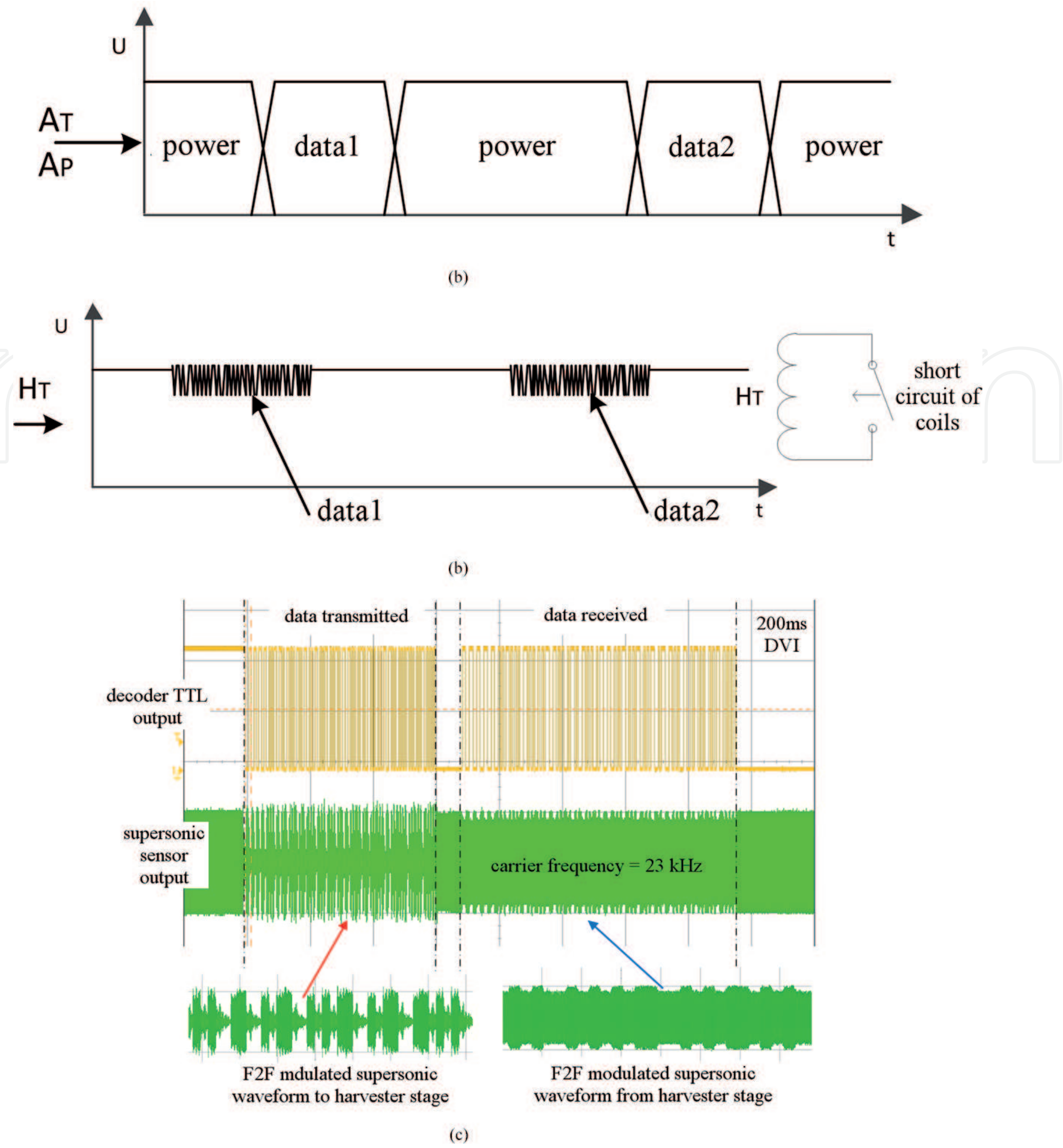


Figure 15.
Diagram of data sent (A) and received (B) by elements of the SURPS system. AT/P, actuator based on Terfenol-D/piezo material; HT, harvester based on Terfenol-D.

One of the main assumptions of the two rails' system was to set the required prestress, within a single structure, obtained by means of plastic elements, separately with each magnetostrictive transducer. This resulted in mutual mechanical coupling of the actuator and harvester and the possibility of adjusting the resonance frequency lying in the over-acoustic band.

Figure 17 shows the difference in the structure of the actuators based on magnetostriction and piezoelectric transducers. The characteristic differences relate to the way of generating the signal that powers the given actuator. In the case of magnetostrictive devices, in which the induction coil is loaded, the basic problem is to obtain a sufficient level of magnetostriction at a current that does not overheat the magnetic circuit with the core. Piezoelectric actuators require a voltage of 200VRMS, which is obtained through a bandwidth transformer with a primary winding matched to the power level based on the M-type metal-oxide semiconductor field-effect transistor (MOSFET) configuration in the H-configuration. During the development of the SURPS system, a structure of certain stages of electromagnetostrictive actuators and harvester was developed.

Based on the assumptions described above, as well as the current state of knowledge in the field of ultrasonic, wireless power transmission, a complete transceiver

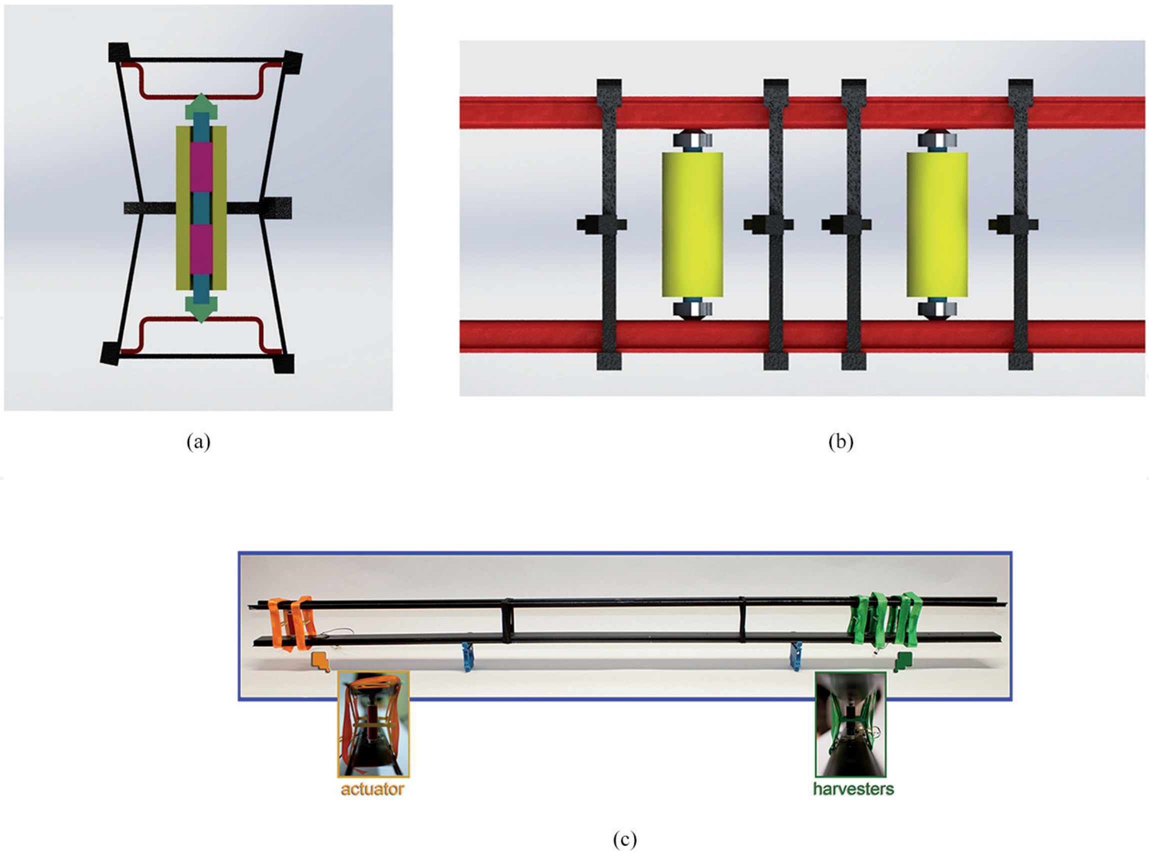


Figure 16.
View of the system of two rails with marked actuator and a unit recovering energy from mechanical vibrations (a) model, (b) real construction.

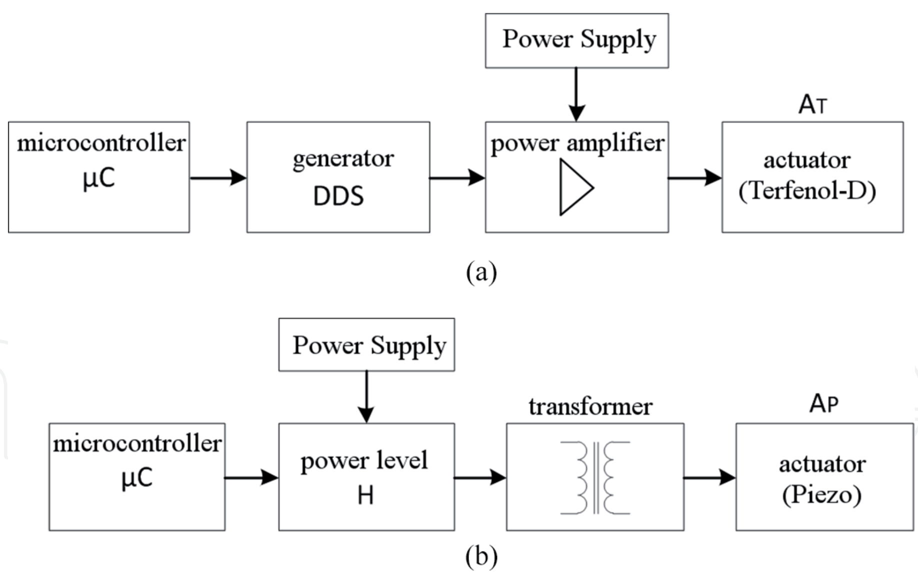


Figure 17.
Specification of the individual sections of the actuator: magnetostrictive (A), electrostatic element (B).

system was designed based on a suitable microcontroller, attendance modulators, as well as dedicated software.

The main features of the SURPS system are:

- Operation of piezoelectric actuators/harvester and magnetic processing.
- Finding and generating the resonance frequency of mechanical construction.

- Scanning of a given frequency range using the actuator-harvester system with real-time performance readout.
- Reading the current root mean square (RMS) voltage from the harvester.
- The system is equipped with the possibility of generating signals for two actuators generating vibrations of the same frequency but shifted in phase with each other.
- Data transmission between the actuator and return harvester sections (Tx, Rx).
- Frequency range from 0.1 to 50,000 Hz, 0.1 Hz (used direct digital synthesis generator (DDS) Analog Devices AD9851).

Figure 18 shows the frequency response of the mechanical structure of **Figure 16**. It is noteworthy that the highest performance (highest voltage) is in the over-acoustic range (above 20 kHz). The "SW" zone means an acceptable range of resonance frequencies lying near 20 kHz. On the characteristics with a dashed line, the 2.5 V voltage value is marked to guarantee the start of the microprocessor system. The points "A" and "B" marked on the waveform correspond to the most favorable ranges of carrier frequencies; it means that there are more frequencies capable of powering the system, and depending on the needs, the desired ranges of carriers can be selected. It is also possible to work more microprocessors connected to the same harvester but activated by a strictly defined frequency. The latter option allows the described solution to be used in SHM applications.

As a model microprocessor system, a Silicon Laboratory solution called Gecko with a 32-bit Cortex-M3 processor with the designation EFM32TG840 was used. In all applications, this type of set was used, and the solution had to guarantee the ability to supply this system as typically industrial with simultaneous half-duplex transmission (data transmission in one direction at a time in a bidirectional channel).

Data transfer is carried out using our algorithmy which we called frequency double frequency amplitude modulation (F2F-AM). As a result, the flow of information is much lower than the resonant frequency caused by ultrasounds or the structure itself and can get up to 1000 bps. Higher information flow rates can be obtained by using other types of frequency modulation.

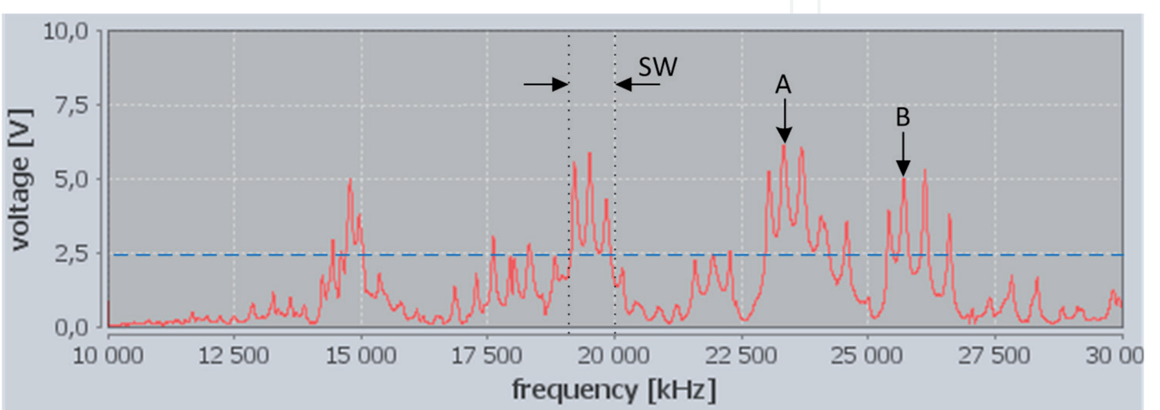


Figure 18.
The frequency response of the double bus system.

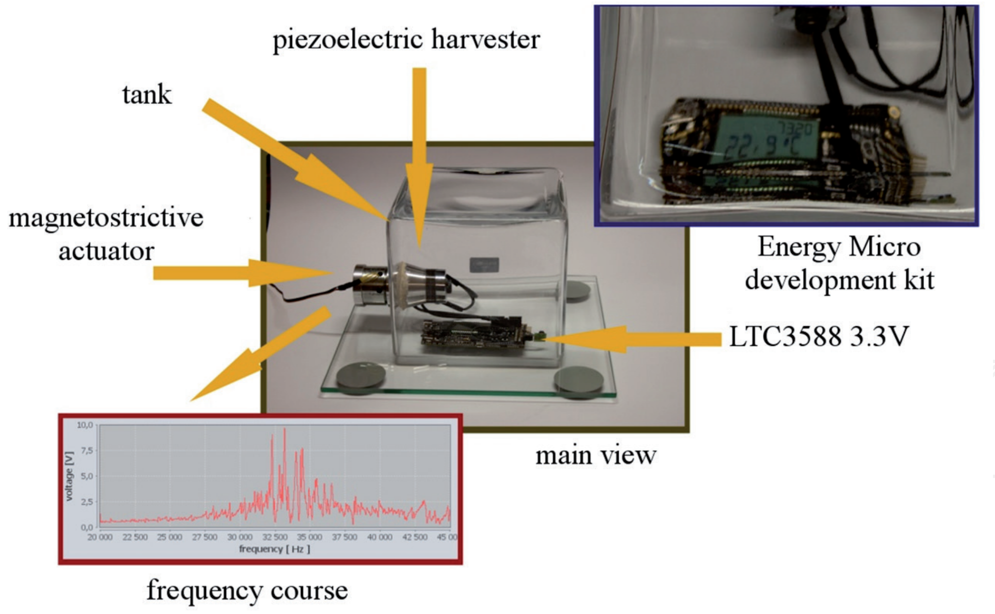


Figure 19.
View and frequency response of the system for simultaneous power transmission through the wall of a hermetic glass container with a wall thickness of about 10 mm.

Thanks to the observations made, it was found that the use of solutions based on the SURPS system developed under the author's guidance enables the transmission of energy over long distances without using cables but only through inaudible mechanical vibrations. However, the location of the harvester in different types of construction cannot be arbitrary. It is closely related to the medium in which the transmission takes place, as well as the length of the ultrasonic carrier wave.

A prototype of a simultaneous supply and data transmission system to the microprocessor sensory system was also created by the hermetic tank wall as a result of ultrasound wave stimulation, which is shown in **Figure 19**. Although its structure is similar, the frequency responses differ due to the different resonant frequency of the piezoelectric harvester. In this case, the actuator was a broadband magnetostrictive actuator. Behind the harvester, a piezoelectric cone transducer with a natural frequency of 38 kHz is placed.

6. Autonomous system of diagnostics of environmental and operating parameters named Multi-DOF

Multi-node harvesting systems for simultaneous energy recovery from many sources, including:

- Multi-node harvesting structures based on miniature harvester machines with magnetostrictive cores
- Wireless monitoring of the parameters of the harvesting node using micro-electro-mechanical systems' (MEMS) sensors for SHM applications (**Figure 20**)
- Microprocessor systems powered from harvesting sources
- Autonomous monitoring system Multi-DOF

Figure 20.
View of a single electronic wireless node powered from a harvesting source.

In the field of low-power technology, the definition of harvester as a single microprocessor power supply (μC) was adopted, which after wireless feeding sends data in accordance with its operating algorithm (program code) to the receiving and processing unit. A single harvesting system is a node in a larger structure managed from a central site. Individual configurations of harvester can allow tuning the harvesting power supply to specific phenomena that trigger its operation. **Figure 21** shows a schematic diagram of a harvesting structure consisting of several harvesters activated as a result of an external stimulus.

Harvesters which in their principle of work use cross effects, more and more often are based on magneto-mechanical phenomena. It is assumed that even in the case of low power and efficiency, they can be a valuable source of power supply.

Multi-node harvesting structure can be used in structural health monitoring (SHM) applications to recover an electric power from the wasted energy generated mostly from vibrations. Magnetic harvester also might be used as a power source in SHM systems which are monitoring large mechanical structures. Our latest system presents this solution. It uses 14 MEMS sensors which designated 14 degrees of freedom (DOF) (3D accelerometer, 3D gyroscope, 3D magnetometer, barometric pressure sensor, microphone, temperature T, humidity R, light intensity). The structure of the system was shown in the **Figure 22**. The software designed by authors allows to monitor the parameters provided by 14 sensors via web page or

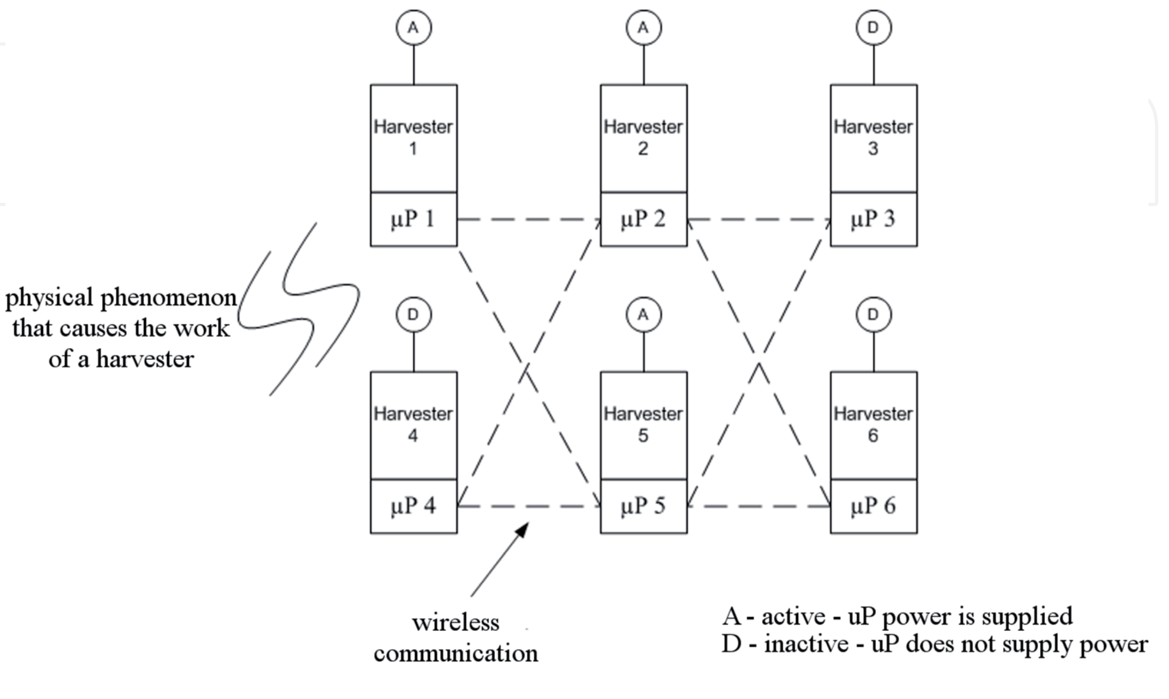


Figure 21.
Activation of harvester by physical phenomenon.

in service mode. The software is designed to support such systems as ADIS16488 module and other components of one of the most precise Analog Devices iMEMS 2016 (IMU). In order to process data received from the 14DOF sensors, which include not only measuring the certain physical value but also monitoring the level of recovered energy, the proper microprocessors had to be chosen (an important factor is a power consumption).

Figure 23 shows three typical sources of low-frequency energy harvesting: mechanical shock wave (**Figure 23A**), low-frequency mechanical resonance (**Figure 23B**), and energy transmission though ultrasonic resonant vibrations (**Figure 23C**). Properly selected conditioning circuit provides the harvesting system with a useful current and voltage capabilities. The creation of a wireless node to measure certain physical quantities and to monitor the level of recovered energy

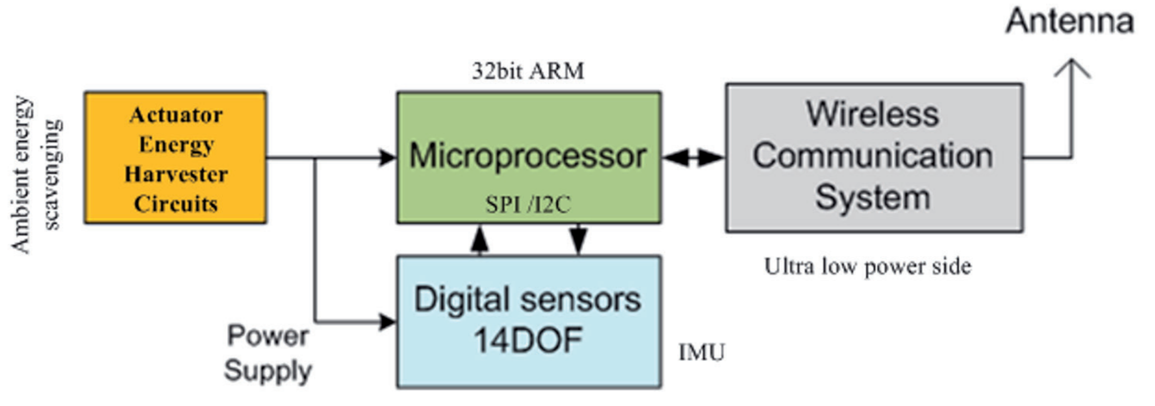


Figure 22.
The structure of a wireless harvesting system with a 14DOF block.

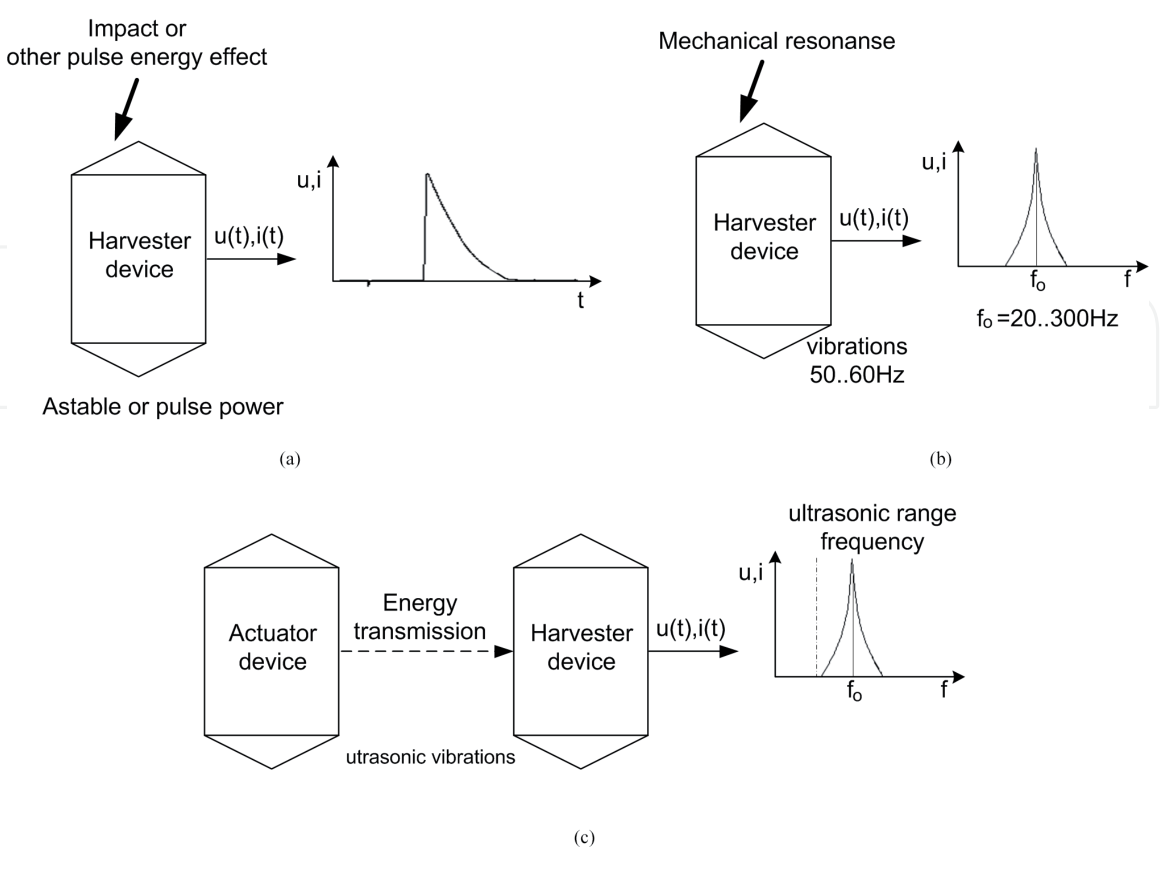


Figure 23.
Energy-harvesting sources and their power requirements: (A) mechanical impact, (B) low-frequency mechanical resonance, and (C) energy transmission by ultrasonic vibration.

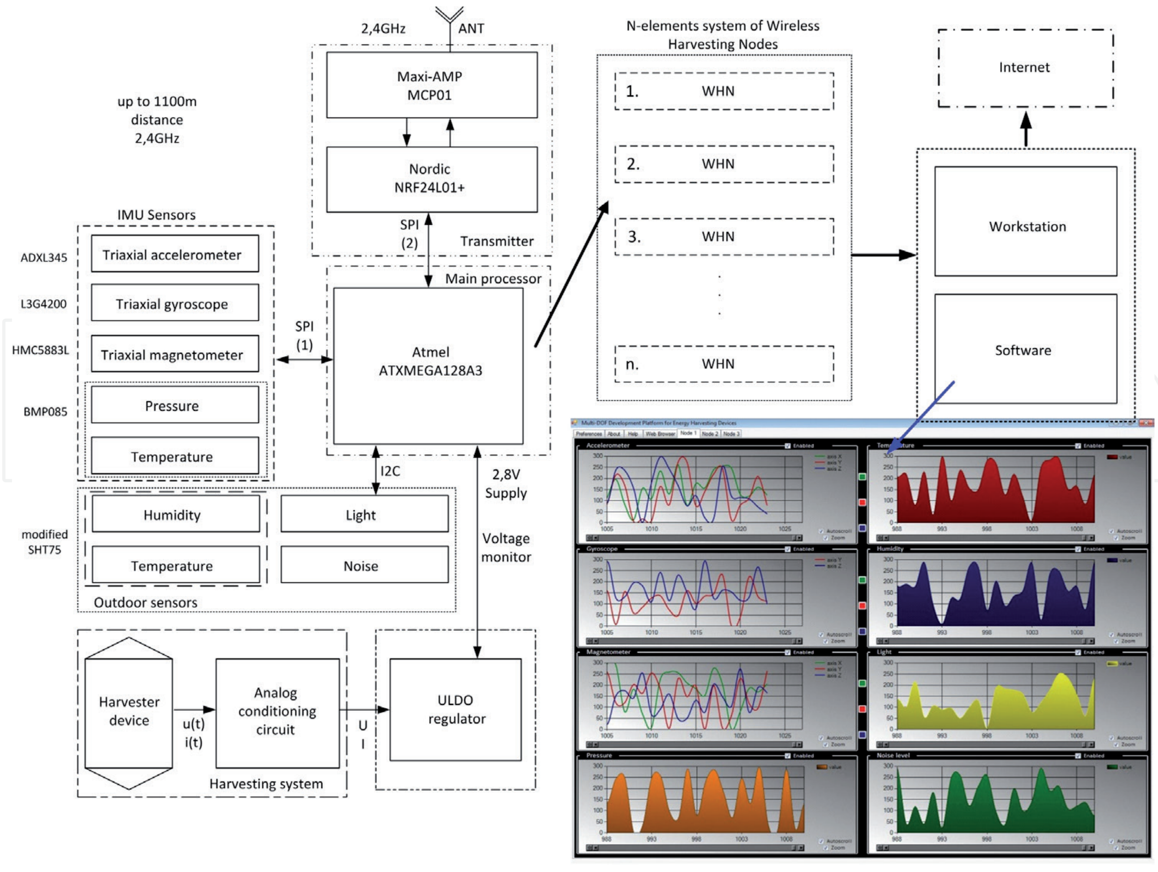


Figure 24.
Prototyping of the multi-DOF wireless sensor platform: main communication station and the Multi-DOF software.

requires selection of an appropriate hardware platform such as a microprocessor and wireless transmission system. The use of smart materials in wireless power transmission turned out to be effective. For this purpose, a SURPS system for simultaneous power and data transmission was developed. It ensured transmission through various media (solid, liquid) and with various transmitter-receiver configurations [X].

After matching the sensor-microprocessor configuration with a suitable energy harvester, the whole packets, together with a wireless communication system, were placed in the nodes. Due to the fact that every node is equipped with the same wireless communication system, different types of sensors can be easily substituted or put together by the user, thanks to the dedicated software shown in **Figure 24**.

Properly selected conditioning circuit provides the harvesting system with a certain current and voltage output. The creation of a wireless node to measure certain physical quantities and to monitor the level of recovered energy requires selection of an appropriate hardware platform such as a microprocessor and wireless transmission system.

7. Conclusions and final remarks

The essence of EH is to create new concepts of current generators, using cross effects, including more often magnetomechanical phenomena. The use of smart materials for wireless power transmission (and information) proved to be practical, and the results obtained during the research indicated the high efficiency of this method.

A technique for powering the microprocessor system from harvester machines combined with various configurations at carrier frequencies depending on the natural frequency of the structure containing dedicated actuators and harvester units with electromagnetic and magnetostriction transducers was developed. Satisfactory results have been achieved even when transmitting many bytes of information encoded in accordance with ASCII characters. Simultaneous supply of the sensory system was obtained, based on an industrial 32-bit microprocessor system and data transmission in half-duplex mode at the speed of about 1000 bps with the recovery of energy from mechanical vibrations with an over-acoustic frequency.

Thanks to the observations made, it was found that the use of solutions based on the SURPS system developed by the authors enables the transmission of energy over long distances without using cables but only through inaudible mechanical vibrations. However, the location of the harvester in different types of construction cannot be arbitrary. It is closely related to the medium in which the transmission takes place, as well as the length of the ultrasonic carrier wave.

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References

[1] Roundy S, Wright PK, Rabaey JM. Energy Scavenging for Wireless Sensor Networks: With Special Focus on Vibrations. New York: Springer; 2004

[2] Roundy S, Steingart D, Frechette L, Wright P, Rabaey J. Power sources for wireless sensor networks. In: Karl H, Wolisz A, Willig A, editors. Lecture Notes in Computer Science, nr 2920. Springer Berlin Heidelberg; 2004. pp. 1-17

[3] Mitcheson PD, Yeatman EM, Kondala Rao G, Holmes AS, Green TC. Energy harvesting from human and machine motion for wireless electronic devices. In: Proceedings of the IEEE. Vol. 96. 2008. pp. 1457-1486

[4] Kompis C, Aliwell S. Energy Harvesting Technologies to Enable Remote and Wireless Sensing; 2008

[5] Green PL. Nonlinear Energy Harvesting, Rozprawa Doktorska. Department of Mechanical Engineering, University of Sheffield; 2012

[6] Energy Autonomous Systems: Future Trends in Devices, Technology, and Systems. 2019. Available from: http://www.catrene.org/web/about/EAS_ExecutiveSumm_v7CAT.pdf

[7] Murry EJ. A unique system for transmission of ultrasonic energy over fibrous bundles. Ultrasonics. 1970;**8**(3):168-173

[8] Sherman ML, Castellano TM. Ultrasound energy delivery system and method, US patent 5,735,280; 1989

[9] Denisov A, Yeatman E. Stepwise microactuators powered by ultrasonic transfer. Procedia Engineering. 2011;**25**:685-688

[10] Ozeri S, Shmilovitz D. Ultrasonic transcutaneous energy transfer for powering implanted devices. Ultrasonics. 2010;**50**(6):556-566

[11] Mazzilli F, Thoppay PE, Praplan V, Dehollain C. Ultrasound energy harvesting system for deep implanted-medical-devices (IMDs). In: 2012 IEEE International Symposium on Circuits and Systems (ISCAS); IEEE. 2012. pp. 2865-2868

[12] Ottman GK, Hofmann HF, Bhatt AC, Lesieutre GA. Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. In: IEEE Transactions on Power Electronics. 2002. pp. 669-676

[13] Ishiyama T, Kanai Y, Ohwaki J, Mino M. Impact of a wireless power transmission system using an ultrasonic air transducer for low-power mobile applications. In: 2003 IEEE Symposium on Ultrasonics; IEEE. 2003. pp. 1368-1371

[14] Li P, Wen Y. Energy harvesting transducer by collecting electromagnetic energy based on ultrasonic horn. In: IEEE International Conference on Information Acquisition; IEEE. 2006. pp. 550-555

[15] Roes MGL, Hendrix MAM, Duarte JL. Contactless energy transfer through air by means of ultrasound. In: IECON 2011—37th Annual Conference on IEEE Industrial Electronics Society; IEEE. 2011. pp. 1238-1243

[16] Lomonova E, Roes M, Duarte J, Hendrix M. Acoustic Energy Transfer: A Review; 2013

[17] Kural A, Pullin R, Featherston CA, Lees J, Naylon J, Paget C, et al. Wireless power transmission using ultrasonic guided waves-electric circuit measurement and simulation. Key Engineering Materials. 2012;**518**:445-454

[18] Kural A, Pullin R, Featherston C, Lees J, Naylon J, Paget C, et al. Wireless electric power transmission using ultrasonic guided waves. In: Energy Harvesting. 2012. Available from: http://eh-network.org/events/eh2012.php

[19] Saulnier GJ, Scarton HA, Gavens AJ, Shoudy DA, Murphy TL, Wetzel M, et al. P1g-4 through-wall communication of low-rate digital data using ultrasound. In: 2006 IEEE Ultrasonics Symposium; IEEE. 2006. pp. 1385-1389

[20] Lawry T. A High Performance System for Wireless Transmission of Power and Data through Solid Metal Enclosures, Rozprawa Doktorska; Rensselaer Polytechnic Institute; 2011

[21] Lawry TJ, Wilt KR, Ashdown JD, Scarton HA, Saulnier GJ. A high-performance ultrasonic system for the simultaneous transmission of data and power through solid metal barriers. In: IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. 2013. pp. 194-203

[22] Lawry TJ, Wilt KR, Scarton HA, Saulnier GJ. Analytical modeling of a sandwiched plate piezoelectric transformer-based acoustic-electric transmission channel. In: IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. Vol. 59. 2012. pp. 2476-2486

[23] Sherrit S, Mukherjee BK. The use of complex material constants to model the dynamic response of piezoelectric materials. In: Proceedings Ultrasonics Symposium; IEEE. 1998. pp. 633-640

[24] Sherrit S, Badescu M, Bao X, Bar-Cohen Y, Chang Z. Efficient electromechanical network model for wireless acoustic-electric feed-throughs. In: Smart Structures and Materials. International Society for Optics and Photonics; 2005. pp. 362-372

[25] Sherrit S, Doty B, Badescu M, Bao X, Bar-Cohen Y, Aldrich J, et al. Studies of acoustic-electric feed-throughs for power transmission through structures. In: Smart Structures and Materials; International Society for Optics and Photonics. 2006. pp. 617102

[26] Sherrit S. The physical acoustics of energy harvesting. In: 2008 IEEE Ultrasonics Symposium; IEEE. 2008. pp. 1046-1055

[27] Sherrit S, Walkemeyer P, Bao X, Bar-Cohen Y, Badescu M. Acoustic mechanical feedthroughs. In: SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring; International Society for Optics and Photonics. 2013. p. 86920P

[28] Mirosławski M. Stan prac z dziedziny Energy Harvesting w Laboratorium Dynamiki; stan wiedzy z dziedziny bezprzewodowego, ultradźwiękowego przesyłu energii na świecie, Rap. Tech., Instytut Materiałoznawstwa i Mechaniki Technicznej Politechniki Wrocławskiej, Wrocław; 2013

[29] Beeby SP, Tudor MJ, White NM. Energy harvesting vibration sources for microsystems applications. Measurement Science and Technology. 2006;**17**(12):R175

[30] Mitcheson PD, Green TC, Yeatman EM, Holmes AS. Architectures for vibration-driven micropower generators. Journal of Microelectromechanical Systems. 2004;**13**(3):429-440

[31] Beeby S, White NM. Energy Harvesting for Autonomous Systems. London: Artech House; 2010

[32] Torah R, Glynne-Jones P, Tudor M, O'Donnell T, Roy S, Beeby S. Self-powered autonomous wireless sensor node using vibration energy harvesting.

Measurement Science and Technology. 2008;**19**(12):125202

[33] Kaleta J, Kot K, Mech R, Wiewiórski P. Ultrasonic energy harvesting system based on magneto- and electrostrictive actuators. In: The 7th International Symposium on Mechanics of Materials and Structures, Conference Proceedings; Augustów, Poland. 2013. pp. 133-137

[34] Ghemari A. The usage of selected methods of Energy Harvesting in mechanics; construction and applications [Master thesis]. Wrocław: Politechnika Wrocławska, Wydział Mechaniczny; 2010

[35] Kaleta J, Lewandowski D, Wiewiórski P, Mech R, Liberda M. Power generating by high pulse mechanical stimulation of magnetic coupled NdFeB and Terfenol-D. In: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring; International Society for Optics and Photonics. 2010. p. 76440U

[36] Kaleta J, Lewandowski D, Liberda M, Mech RP, Wiewiórski PK. Energy harvester with high pulse mechanical stimulation. In: 27th Danubia-Adria Symposium on Advances in Experimental Mechanics. Wrocław: Wrocław University of Technology; 2010

[37] Kaleta J, Kot K, Rikitatt M, Wiewiórski P. Multid. of wireless sensor system based on iMU-MEMS technology supported by energy harvesting methods. In: 4th International Conference on Integrity, Reliability & Failure; Funchal. 2013

[38] Bomba J. Investigation of GMM actuator as a communications system. In: Communications System Application of GMM. 2006. na prawach rękopisu

[39] Bomba J, Kaleta J. Sprawność przekształcania energii w materiałach o gigantycznej magnetostrykcji. In: IX Krajowa Konferencja Mechaniki Pękania. 2003. pp. 47-54

[40] Lewandowski D. Solid State Magnetic Phenomena Harvesters and their Power Conditioners for Low Power Applications. Berlin, Germany: Harvesting & Storage Europe; 2013

[41] Kaleta J, Wiewiórski P. Rapid demagnetization of neodymium magnets, due to mechanical shock, as a pulse power supply for microprocessor system. In: International Conference on Integrity, Reliability & Failure; Funchal. 2013

[42] Energy Harvesting: Downloads. 2019. Available from: http://www.energyharvesting.pl/download.html

[43] Holt TA. Explosively-Driven Helical Magneto-Cumulative Generators, Praca Magisterska. Texas Tech University; 2002

[44] Lee J, Choi JS, Ryu JH, Kim CH. Maximizing the energy output of explosively-driven ferromagnetic generators. Electromagnetic Phenomena. 2003;**3**(3):11