



Piezoelectric generators: materials and structures

Dariusz Grzybek

AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics

Abstract: The article presents piezoelectric generators, which can solve the problem of power supply of wireless sensors nets in the monitoring systems of the structure parameters. The operating principle of these appliances is based on the conversion of mechanical energy, e.g. vibration to electric energy in piezoelectric materials. In the first part of this article, the basic groups of piezoelectric materials: ceramics, composites, polymers and monocrystals were discussed in the field of its application in generators. It focused on material constants, which have the biggest effect on energy conversion. In the second part, structures of generators, which are the most often presented in the literature were discussed. The article focused on the structure consisting of piezoelectric actuators connected with the cantilever beam as well as other structures containing piezoelectric actuators, which have different shapes. In the last part, the efficiency of energy conversion was discussed. It focused on the range of values of the obtained electric power from generators.

Keywords: piezoelectric materials, energy harvesting, piezoelectric generator, wireless sensors

1. Introduction

In many technology branches the parameters monitoring of structures, applications or environment, in which an appliance operates is necessary in correct operating of technical objects. Monitoring system contains often tens or hundreds of sensors. Heating, ventilation and air condition systems applied in buildings can be examples. Correct functioning of these systems is possible thanks to temperature monitoring in the particular places. In the case of big, multi-storey buildings, such monitoring is performed by installing a considerable number of sensors that must be powered. The application of conventional powering of these sensors requires the use of either kilometres of wire or hundreds of batteries. In the case of powering with batteries, there is a necessity to replace these batteries, which increases operating costs of monitoring system and makes the whole system non eco-friendly [25]. Among these types of applications, the most beneficial solution would be generating electric energy in a place where a sensor has been installed. In different scientific

centres, there is a research being conducted concerning appliances that generate electric energy from mechanical vibrations in a place where a sensor is installed. A promising line of research in this field is employing the natural properties of some materials to generate electric energy. Among these materials one can single out piezoelectric materials that enable conversion of mechanical energy to electric (direct piezoelectric effect) and from electric to mechanical (converse piezoelectric effect). A source of mechanical energy can be vibrations that are often generated in monitored processes and are usually adverse. Piezoelectric materials are the basis of construction of generator prototypes, whose target can be powering of sensors in wireless monitoring nets. The increasing of efficiency of generators designed so that more electric power can be generated, which is achieved by application of more and more advanced piezoelectric materials and by different generator designs. In this article, an attempt is made of the systematized presentation of piezoelectric generators referring to applied materials, design, and application.

2. Piezoelectric materials in the energy harvesting process

2.1. Piezoelectric materials applied in generators

For energy conversion in generators one can apply materials from every four basic piezoelectric groups. In most experimental research introduced in literature it is ceramics that have found a use, followed by composites, polymers and monocrystals.

Ceramic materials are most frequently used in piezoelectric generators design, as presented in the literature. First of all, PZT ceramic are used in generators. PZT is a mixed crystal of titanate and lead zirconate with the general formula: $(x)\text{PbTiO}_3-(1-x)\text{PbZrO}_3$ [10]. One can manipulate with properties of piezoelectric ceramics PZT by modification of the percentage content of particular compounds comprising mixed crystal, $x = (0-1)$. It enables production of ceramics PZT with different sets of material constants. There is no single ceramic PZT dedicated to generators design. Many PZT variations are used in generators as presented in literature, e.g. PZT-5H

[21], PZT-5A [25], PZT-PIC255 [16], PZT-APC 841[12], PZT-APC 850 [12], PZT-PPK11 [8].

Composites are materials composed of piezoelectric materials of different shapes, layers of adhesive, polymer film and appropriately formed electrodes. On bolt-on parts of these composite layers there are properly fitted electrodes. One can single out two types of composites, which can be applied in generators design: PFC (*Piezoelectric Fiber Composite*) and MFC (*Macro-Fiber Composite*). PCF comprises the circular piezoceramic fibers placed in the layer of adhesive and on bolt-on parts the polyimide film and electrodes (fig. 1a). MFC manufactured by Smart Materials Corp. are made of rectangular piezoceramic bars, separated by adhesive layers and the polyimide film and an electrode on the bolt-on part (fig. 1b). Generator using PFC is presented in [27], and MFC in [29].

Polymers are chemical substances consisting of multiple constituent parts: mers. Among polymers, the most significant is polyvinylidene fluoride – PVDF. PVDF is a semicrystal, consisting of a maximum of 50–60 % of the crystal phase [17]. In the 60s. of the XX century, piezoelectric properties of PVDF were discovered. PVDF is usually applied as a foil so that it can be freely shaped, in contrary to ceramics.

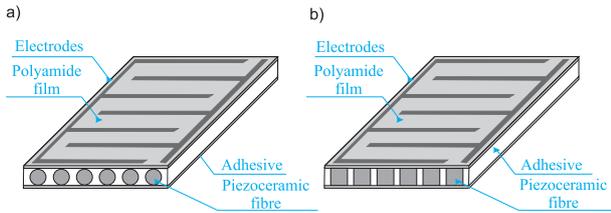


Fig. 1. Schema of PFC and MFC structures [13]
Rys. 1. Schemat budowy PFC i MFC [13]

Application of this polymer to powering a damage sensor is presented in [6], and energy harvesting from an acoustic resonator with beams made, e.g., from PVDF, in [15].

Monocrystals, devised a few years ago, are currently the most promising piezoelectric materials in the generators field of research, as they are very effective when it comes to energy conversion. One can single out two types of monocrystals that can be applied for generators: PZN-PT (Pb(Zn1/3Nb2/3)O3-PbTiO3) and PMN-PT ((Mg1/3Nb2/3)O3-PbTiO3). Use of PZN-PT-8% is presented in [16] and PMN-PT-33% in [18].

2.2. Material constants affecting energy conversion

The phenomenon of conversion of mechanic energy to electric one and from electric to mechanic one can be presented with the help of essential equations. These equations in the matrix notation are as follows [4]:

$$\begin{aligned} S_p &= s_{pq}^{(E)} T_q + d_{kp} E_k \\ D_i &= d_{iq} T_q + \varepsilon_{ik}^{(T)} E_k \end{aligned} \quad (1)$$

where S is the mechanical strain vector $(-)$, $s^{(E)}$ is the flexibility matrix determined for constant value of the electric field (m^2/N) , T is the stress vector (N/m^2) , d is the matrix of the piezoelectric constants (C/N) , E is the electric field intensity vector (V/m) , D is the dielectric displacement vector (C/m^2) , $\varepsilon^{(T)}$ is the matrix of the material permittivity constants determined for constant values of stresses (F/m) .

The second equation in (1) can be expressed in the expanded form:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11}^{(T)} & \varepsilon_{12}^{(T)} & \varepsilon_{13}^{(T)} \\ \varepsilon_{21}^{(T)} & \varepsilon_{22}^{(T)} & \varepsilon_{23}^{(T)} \\ \varepsilon_{31}^{(T)} & \varepsilon_{32}^{(T)} & \varepsilon_{33}^{(T)} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (2)$$

D is a vector with three components and T is a vector with six components. Based on (2) it may be noticed that:

- constant d_{33} joins third component of the electric induction (in direction of 3 axis) with third components of stress (in direction of 3 axis) – both components are parallel (fig. 2a),
- constant d_{31} joins third component of the electric induction (in direction of 3 axis) with first components of stress (in direction of 1 axis) – both components are perpendicular (fig. 2b).

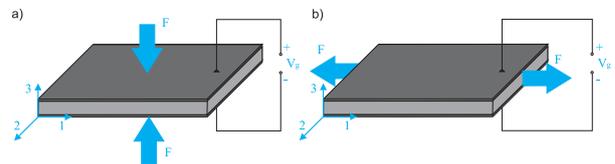


Fig. 2. Piezoelectric material action modes [1]
Rys. 2. Warianty działania materiału piezoelektrycznego [1]

The bigger values of the piezoelectric constant d are, the bigger efficiency of conversion from mechanic energy to electric will be.

The exemplary matrix d for piezoceramic PZT-5H is as follows:

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \quad (3)$$

The shape of matrix d (3) is the most often used for description of the piezoelectric materials, e.g. monocrystal PMN-PT-33% has the same matrix d [26]. Matrix d for composites is the same as matrix of the piezoceramic fibers [24]. The shape of matrix d determines the efficiency of the energy conversion in the piezoelectric materials for the multiaxial stresses.

The influence of the piezoelectric constant values d on the efficiency of energy conversion is visible in the values of the electromechanical coupling coefficient k [20]:

$$k_{33}^2 = \frac{d_{33}^2}{s_{33}^{(E)} \epsilon_{33}^{(T)}}, \quad k_{31}^2 = \frac{d_{31}^2}{s_{11}^{(E)} \epsilon_{33}^{(T)}} \quad (4)$$

In tab 1. there is a comparison of the energy conversion efficiency for the above mentioned piezoelectric materials.

Based on data presented in tab. 1 one can note that PZN-PT and PMN-PT monocrystals have the highest efficiency when it comes to energy conversion. Due to the fact that these monocrystals have been devised not long ago, composites or PVDF polymer are used in most research projects on generators ceramics. Ceramic materials are very effective when it comes to energy conversion, which is reflected with the high rates of electromechanical coupling coefficient. However, they are more fragile and more vulnerable to be worn out e.g. as a result of fatigue in comparizon to composites and polymers [1].

3. Structures of generators

3.1. Structures with actuators connected with the cantilever beam

The most often tested piezoelectric generator structures are designs, in which the basic element, apart from the piezoelectric actuator, is the cantilever beam. One can single out a few possibilities of the connection of piezoelectric materials to the beam:

- beam made of the base material, with no piezoelectric properties, on which there is one (unimorph) or two piezoelectric material layers (bimorph). Generator with two plates of PZT ceramics (bimorph) is presented in fig. 3a,

Tab. 1. Material constants of selected piezoelectric materials [2, 8, 11, 30–33]

Tab. 1. Stałe materiałowe wybranych piezoelektryków [2, 8, 11, 30–33]

Piezoelectric material	Constant			
	d_{33} [C/N]	d_{31} [C/N]	k_{33} [-]	k_{31} [-]
PZT-5H2	$593 \cdot 10^{-12}$	$-274 \cdot 10^{-12}$	0,75	0,39
PZT-5A4	$460 \cdot 10^{-12}$	$-195 \cdot 10^{-12}$	0,72	0,37
PZT-PIC255	$400 \cdot 10^{-12}$	$-180 \cdot 10^{-12}$	0,69	0,35
PZT-APC 841	$300 \cdot 10^{-12}$	$-109 \cdot 10^{-12}$	0,68	0,33
PZT-APC 850	$400 \cdot 10^{-12}$	$-175 \cdot 10^{-12}$	0,72	0,36
PZT-PPK11	$680 \cdot 10^{-12}$	$-350 \cdot 10^{-12}$	0,74	0,41
PFC	65–75 % of values for piezoceramics			
MFC (Smart Mat.)	$460 \cdot 10^{-12}$	$-210 \cdot 10^{-12}$	–	–
PVDF	$-33 \cdot 10^{-12}$	$23 \cdot 10^{-12}$	0,15	0,12
PZN-8%PT	$2900 \cdot 10^{-12}$	$-1450 \cdot 10^{-12}$	0,94	0,6
PMN-33%PT	$2820 \cdot 10^{-12}$	$-1334 \cdot 10^{-12}$	0,92	0,6

- beam with an additional element influencing the increase of stresses in the piezoelectric material layers. An example of generator with one piezoelectric layer and an additional element is presented in fig. 3b,
- beam without piezoelectric material layers with the additional setup containing a piezoelectric material.

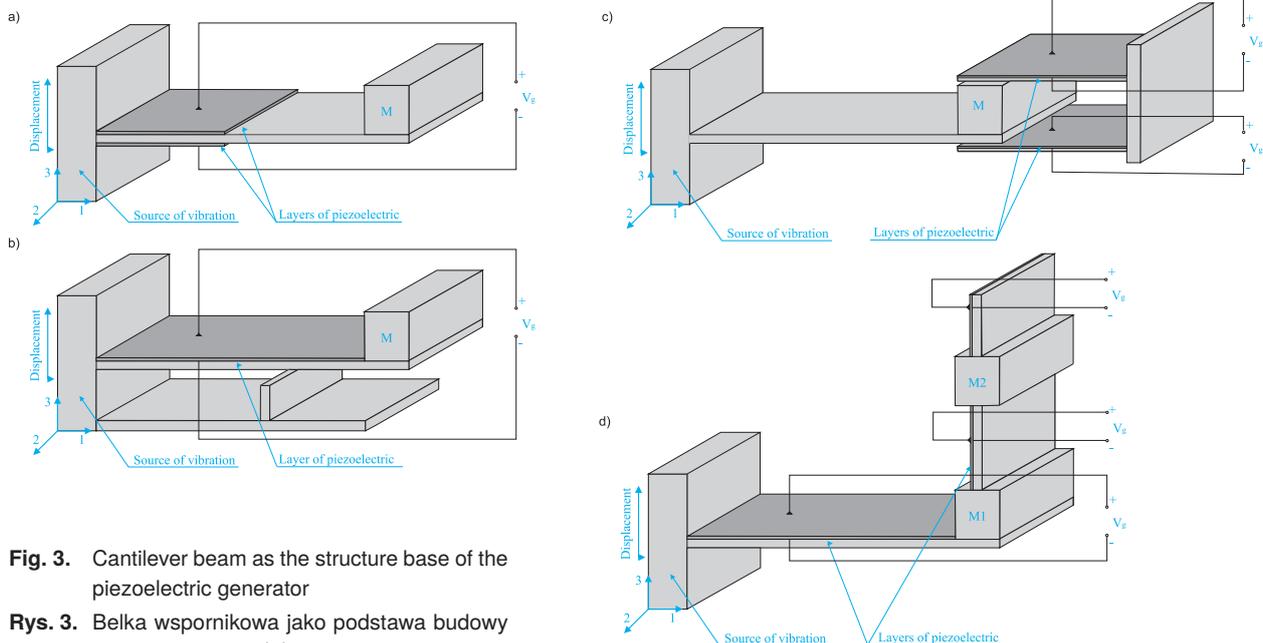


Fig. 3. Cantilever beam as the structure base of the piezoelectric generator

Rys. 3. Belka wspornikowa jako podstawa budowy generatora piezoelektrycznego

An example of a generator of this type is presented in fig. 3c,

- beam with an additional element [7], making it possible to install more piezoelectric layers (fig. 3d).

During beam bending, stresses appear in the piezoelectric material, on which electric charge builds up. An additional mass M installed at the end of the beam to increase stresses in the piezoelectric layers. Taking into consideration the fact that generators can power wireless sensors, generator structures should be small: about 1 cm^3 . It is to

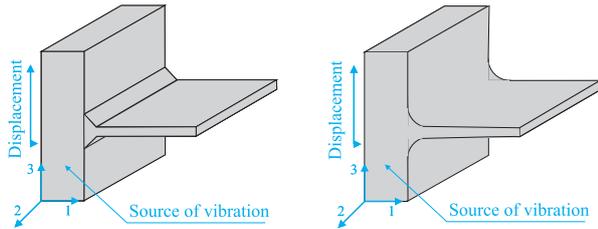


Fig. 4. Cross-sections of the beam in generators [5]

Rys. 4. Przekroje belki w generatorach [5]

be noted that in generator structures based on cantilever beams and the PZT plates, the direction of external forces action is perpendicular to the direction of polarization. Hence, the piezoelectric coupling is indicated by the coefficient k_{31} . The increase of stresses in the piezoelectric element can be acquired by various beam shapes: most often a rectangle, but also a triangle [8], as well as by various geometry solutions of beam fixing to the object which is a source of vibration (fig. 4).

3.2. Structures with piezoelectric actuator of another shape

Energy conversion from mechanic to electric one is also made without using structures with the beam, only with the piezoelectric actuators. Stresses must be induced in a piezoelectric material to generate electric energy by an actuator, hence many structures have been designed that make it possible to generate these stresses. Actuator is presented in fig. 5a, made in the form of a piezoelectric stack. An example of such generator structure that extracts energy from the pressure pulsation in the hydraulic conduit is shown in fig. 5b. Increase of pressure causes bending of the membrane and induces stresses in the piezoelectric stack. The direction of the load from pressure is parallel to the direction of the piezoelectric polarization, hence the electromechanical coupling is defined by the coefficient k_{33} .

Actuators in generators can also have other structures than a piezoelectric stack, e.g., in [22] there is a generator

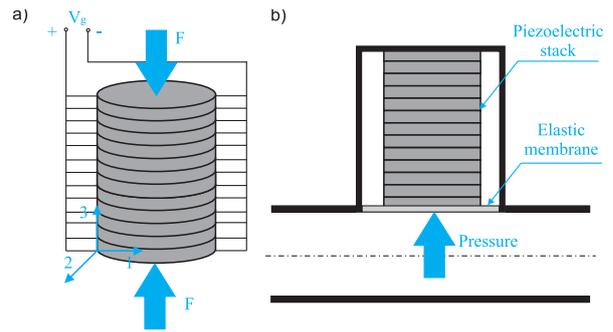


Fig. 5. Piezoelectric stack in generator [3]

Rys. 5. Stos piezoelektryczny w generatorze [3]

built in the form of a ring made from aluminium, inside of which there is a membrane from PZT 5H ceramics in the form of a circle. Deformation of the piezoelectric plate and generating the electric energy is a result of load applied to the bottom surface of the elastic membrane.

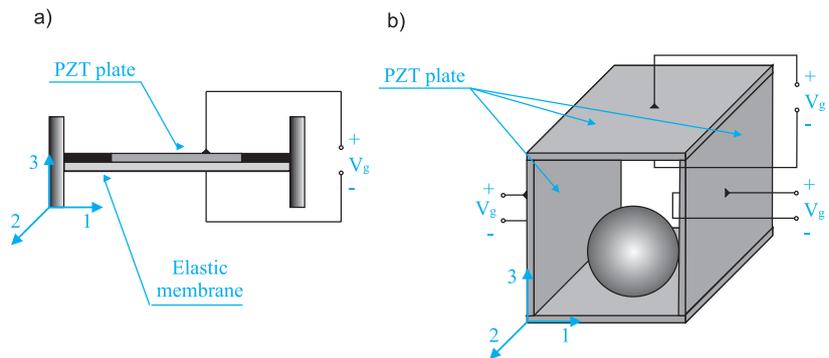


Fig. 6. Generators made from PZT plates [23]

Rys. 6. Generatorzy wykonane z płytek PZT [23]

In [23] there is a generator made of a cube made of the plate from PZT ceramic (fig. 6b). There is a ball inside this cube that hits the faces from PZT when activated by vibrations. As a result, stresses are generated in the walls which results with generation of the electric energy.

3.3. Electric systems of energy transfer

Three basic types of the electric systems can be singled out, which can be applied in generators:

- system consisting of the voltage AC/DC converter only,
- system consisting of two subsystems: AC/DC converter and the subsystem of voltage optimization for the receiver supplied,
- system consisting of two subsystems mentioned above and the electric power amplifier [14].

Relationships among these subsystems are presented in fig. 7.

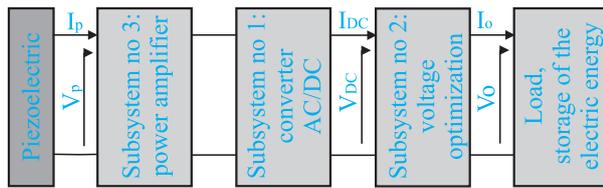


Fig. 7. Subsystems in energy harvesting systems [9]

Rys. 7. Podukłady w układach odzyskiwania energii [9]

An example of the energy harvesting system containing all three subsystems is presented in fig. 8.

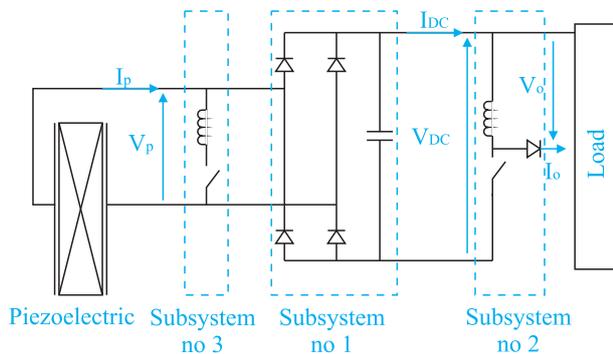


Fig. 8. Exemplary electric system of a generator [14]

Rys. 8. Przykładowy układ elektryczny generatora [14]

4. Applications of generators

4.1. Efficiency of electric energy generation

The effective electric energy generation depends on the following factors: piezoelectric material used, generator structure, electronic system of the control and storage of energy, and the generator size.

Influence of a piezoelectric material is reflected by material constants (d), mentioned above. Generator mechanical structure affects also the efficiency of energy generation in the case of the beam structure:

- most electric power is generated when generator has a resonant frequency nearing to the driving frequency of the object being the vibration source,
- amount of electric power generated is proportional to the additional mass M installed on a beam. However, increase of this mass is restricted by a necessity to keep the appropriate resonant frequency and the beam strength,
- amount of the electric power generated is inversely proportional to the value of driving frequency of the object being the vibration source, and to the resonant frequency of the generator [21].

The influence of the system of control and storage of energy bespeaks of the appropriate energy flow in three paths:

- power of the energy storage system,
- energy storage,
- power of the receiver, e.g. wireless sensor.

The influence of the generator size, especially made from a piezoelectric material on energy extraction efficiency is presented in fig. 9. On the whole, one can notice that the bigger are the generator sizes the more power one can generate. The excessively small sizes may result in the lack of electric energy to power the system of the control and storage of energy.

4.2. Amount of the electric power generated

The field of potential applications of piezoelectric generators in engineering is marked by the amount of the electric power that can be generated with these generators. In tab. 2, the maximum electric power amount is shown generated with generators along with the generator structure and size of the piezoelectric materials.

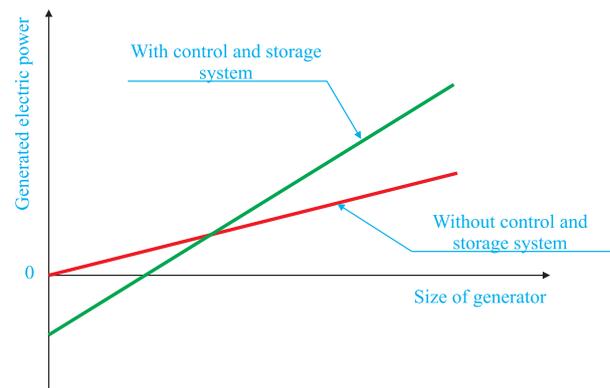


Fig. 9. Relationship between power and generator sizes [19]

Rys. 9. Zależność między mocą a rozmiarami generatora [19]

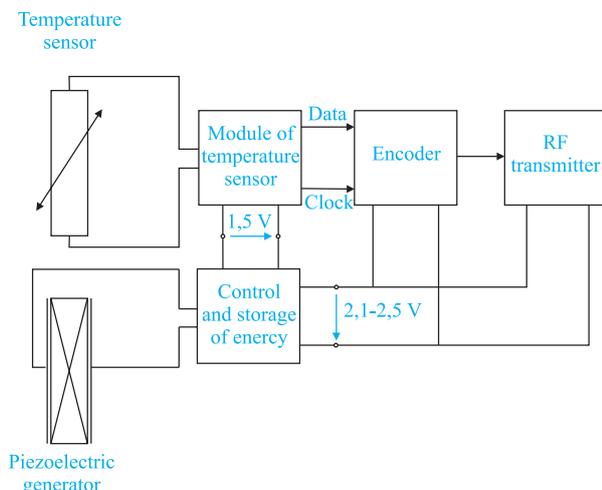
Based on data from tab. 2 one can state that the demand for power in potential applications cannot exceed several dozen mW, where one must take into consideration that the amount of the generated electric power depends on the vibration frequency of an object from which electric energy is extracted. The relatively insignificant amount of power restricts considerably the field of potential applications to powering of the miniaturized electronic devices with low power supply demand. The goal may be monitoring of the structure or industrial processes in hardly accessible places or/and in systems requiring the use of a big number of sensors. It will make cutting the operating costs possible and allow to create the eco-friendly technology (no waste discharged batteries).

A wireless system for temperature measurement of the electric motor was proposed in [28]. A piezoelectric generator built of 3 PZT-PKG 11 discs was used for providing power to sensor. The generator used made it possible to

Tab. 2. Values of the electric power for selected piezoelectric materials [21, 16, 12, 27, 29]**Tab. 2.** Wartości mocy uzyskane dla wybranych piezoelektryków [21, 16, 12, 27, 29]

Generator structure	Type of piezoelectric material	Piezoelectric dimensions [mm]	Generated power [mW]
Beam	PZT-5H	6.5 × 3.2	19
Beam	PZT-PIC255	55 × 15 × 0,1	30
Beam	PZN-8%PT	55 × 15 × 0,1	40
Beam	PZT-APC 841	–	52
Beam	PFC z 250 μm PZT	1405 × 15 5 × 0.00032	0.11
Beam	MFC	265 × 145 × 0.25	6.6
Beam	PVDF	1715 × 22 × 0.00004	0.03

reach 12 mW. A commercial NTC sensor with low power demand (1.25 mW) was chosen for temperature measurement. For encoding and data transmission the M-RT4-433 RF radio module (Solutions Inc.) requiring powering of 6 mW was used. The control and storage of energy module required 2.5 mW at the time of activation. The system schema is shown in fig. 10.

**Fig. 10.** Wireless system of temperature measurement [28]**Rys. 10.** Bezprzewodowy system pomiaru temperatury [28]

5. Summary

Not every type of piezoelectric generators was presented in this article, because it is currently a rapidly developing branch of science. A considerable number of scientific articles prove it, particularly in the past few years. One can notice three basic directions of generator development in the field of increasing the amount of the generated electric energy:

- in materials science, it is a development of new materials developed either as a synergic connection of the applied piezoelectric, e. g. PFC or FMC or by devising new materials, e.g. PZT-PT or PMN-PT,
- in mechanics, it is a search for more efficient structure solutions, e.g., beam structure with additional elements,
- in electronics, it is an optimization of the electric system to achieve a more effective transfer and storage of the generated electric energy.

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AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Department of Process Control.

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Generatory piezoelektryczne: materiały i konstrukcje

Streszczenie: W artykule przedstawiono generatory piezoelektryczne, które mogą stanowić rozwiązanie problemu zasilania bezprzewodowych sieci czujników w systemach monitorowania parametrów konstrukcji. Zasada działania tych urządzeń opiera się na konwersji energii mechanicznej (np. drgań) na energię elektryczną w materiałach piezoelektrycznych. W pierwszej części artykułu omówiono podstawowe grupy materiałów piezoelektrycznych: ceramiki, kompozyty, polimery i monokryształy w zakresie ich zastosowania w generatorach. Zwrócono uwagę na stałe materiałowe, które mają największy wpływ na konwersję energii. W drugiej części artykułu przedstawiono konstrukcje generatorów, najczęściej spotkane w literaturze. Omówiono konstrukcje z piezoelektrycznymi aktywatorami połączonymi z belką wspornikową jak również inne konstrukcje z piezoelektrycznymi aktywatorami o różnych kształtach. W ostatniej części zwrócono uwagę na efektywność przetwarzania energii w zakresie uzyskiwanych wartości mocy elektrycznej.

Słowa kluczowe: materiały piezoelektryczne, pozyskiwanie energii, generator piezoelektryczny, czujniki bezprzewodowe

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Dariusz Grzybek, PhD

Dariusz Grzybek works in AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Department of Process Control. He deals with control of MIMO systems and application of smart materials in processes control.

e-mail: dariusz.grzybek@agh.edu.pl

