

Triboelectricity and construction of power generators based on it

Abstract. The topic of using triboelectrics as a promising source of energy has been actualized in this article. The data on the main types of generators in triboelectricity have been analyzed. The schematic solutions for the application of tribogenerators in various devices based on electronic modules of various manufacturers have been presented. The conclusion about the high efficiency of the use of tribogenerators in applied devices, when combined with other energy sources and accumulating it with super capacitors has been made.

Streszczenie: Artykuł dotyczy tematu wykorzystania efektu tryboelektrycznego jako obiecującego źródła energii. Przeanalizowano techniczne parametry głównych typów generatorów w tryboelektronie. Przedstawiono schematyczne rozwiązania w zakresie zastosowania trybogeneratorów. Wykazano dużą efektywność połączenia trybogeneratorów z innymi Źródłami energii i superkondensatorami dla akumulowania energii. **Efekt tryboelektryczny i generator, zbudowany na jego podstawie**

Keywords: harvesting technology, energy generator, triboelectricity.

Słowa kluczowe: efekt tryboelektryczny, źródła energii.

Introduction

Over the last decade the energy harvesting technology has been very intensively developed for self-powered mobile electronics. One of the most promising are systems that convert human-body motion to electricity. This was made possible due to reducing the power consumption of modern wearable electronic devices. There exist many of motion energy-harvesting techniques based on various physical principles: piezoelectric, triboelectric, electromagnetic, and electrostatic and others. However, unfortunately, the direction of mechanical movement, which can be harvested by a triboelectric [1] or piezoelectric [2] energy generator, is usually limited to a single direction. Therefore, the development of devices that do not depend on the direction of movement is very popular in the market [3]. In addition, due to small efficiency of each of transformation principles, many systems work simultaneously using multiple conversion methods.

The massive development of the world electronic technology follows a general trend of miniaturization, portability and functionality. The development of mobile phones is a typical example of miniaturization, from the transistors based on huge-size machines, to solid state MOSFET based on handhold cell phones or smart watches with communication functionality. Such small size electronic devices operate at ultralow power consumption, making it possible to be powered by the energy harvested from our living environment [1]. New technologies that can harvest energy from the environment as sustainable self-sufficient micro-power sources are a newly emerging field of nano-energy, which is connected with applications of nanomaterials and nanotechnology for harvesting energy to power micro or nano-systems. We have mainly utilized two physical effects for harvesting small-magnitude mechanical energies: piezoelectric and triboelectric ones. The first of these is described quite well in the literature [2], so the second type of transducers will be considered.

Related works

The triboelectric (from the Greek *tribos* - friction) effect is the process of the flow of electric charge from one material to another surface when they come into contact with each other. It is one of the types of so-called "contact electrification", when one body having a charge electrifies another, giving it this charge. Both bodies are electrified; Their charges are equal in magnitude and opposite in sign. For example, amber or ebonite can get an electrical charge by direct contact (friction) with the hair. Similar processes

occur in the interaction of glass and silk, rubber and fur, cellophane and polyvinyl chloride.

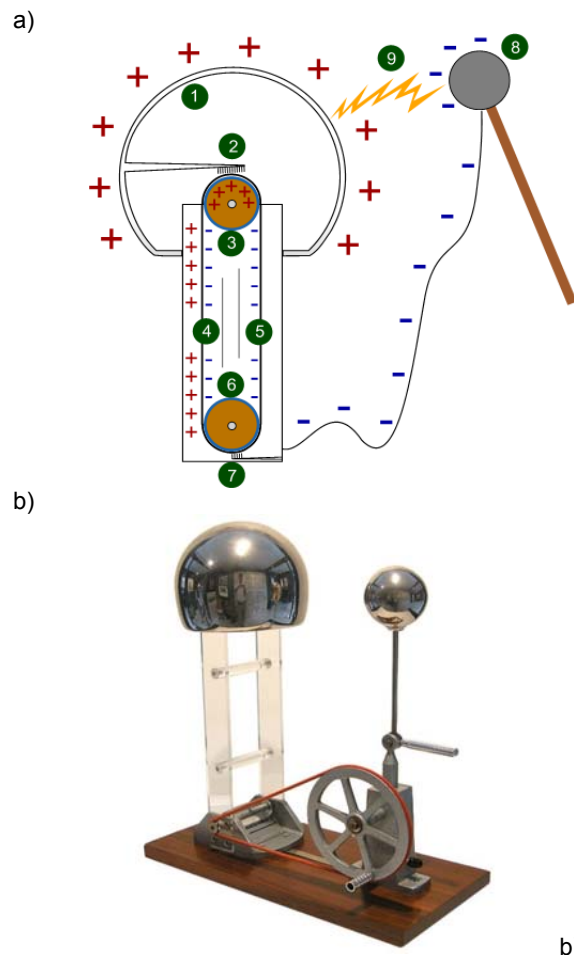


Fig. 1. The working mechanism (a) of Van de Graaf generator and real device (b). (1 - hollow metal sphere, 2 - upper electrode 3 - upper roller (for example an acrylic glass), 4 - side of the belt with positive charges, 5 - opposite side of belt, with negative charges, 6 - lower roller (metal), 7 - lower electrode (ground), 8 - spherical device with negative charges, 9 - spark produced by the difference of potentials.) [5].

The strength of this effect depends not only on the composition of the materials themselves, but also to some extent on the interaction of external factors: the humidity of

the medium, the surrounding temperature, the roughness of the surfaces of the contacting substances, and so on. The triboelectric effect, as the researchers have proved, does not arise from friction, as it was generally assumed before, but from contact of one material with another. Just one of these materials should be charged. Friction just leads to the appearance of the charge on the surface of rubbing materials.

This device (fig.1) consists of a rubber belt (or similar flexible dielectric material) moving along two rollers made from different materials, one of which is surrounded by a hollow metal ball [5]. Two electrodes (2) and (7) in the form of comb rows of sharp metal needles are located near the lower part of the lower roller and inside the sphere above the upper roller. The comb (2) is connected to the sphere, and the comb (7) is grounded.

The charging method is based on the triboelectric effect, so that a simple contact of dissimilar materials causes the transfer of some electrons from one material to another. Since the material of the tape and rollers can be changed, the accumulated charge on the hollow metal sphere can be positive (lack of electron) or negative (excess electrons).

The most suitable materials for creating such a generator can be chosen on the basis of a triboelectric table in which all materials are ranked by the magnitude and type of charge that appears on their surface during friction.

There are four fundamental modes of operation of triboelectric generators.

1. Vertical separation mode contacts

As an example, let us consider the simplest construction of TENG (Figure 2a) [1]. Two dissimilar dielectric films face each other, on the upper and lower surfaces of which electrodes are located. The physical contact of two dielectric films leads to the accumulation of an opposite charge on their surface. When the external force separates these two surfaces from each other (leads to an increase in the gap between them) a potential drop is created. If two electrodes are electrically connected to the load, the free electrons from one electrode will flow to the other electrode to create an opposite potential that balances the electrostatic field on the electrodes [6].

2. Lateral sliding mode

Let us consider a generator of similar structure, suitable for the mode of separation of contacts. When two dielectric films are in contact, the parallel sliding of two surfaces also creates triboelectric charges on both surfaces (Fig. 2b) [9]. In this case, the transverse polarization arises along the sliding direction, which leads to the flow of electrons to the upper and lower electrodes, and they completely compensate for the field created by the triboelectric charges. Periodic expansion and convergence of the two plates generate an alternating current at the output. This is a sliding mode of TENG. The slip can be a movement in a plane, a cylindrical rotation or a rotation of a disk.

3. Single electrode mode

In some cases, the objects that are part of TENG cannot be electrically connected to the load, since they are mobile, such as a person walking on the ground. In order to generate the energy in such a case, TENG with a single electrode was created. This variant corresponds to an equivalent circuit in which the electrode on the bottom of the TENG is grounded (Figure 2c). If the size of TENG is finite, then the approximation or removal of the upper and lower objects will change the local distribution of the electric field, under which the electrons between the lower electrode and the ground exchange are exchanging [10].

4. Free triboelectric mode

In nature, moving objects are naturally charged due to contact with air or other objects (for example, shoes on the

floor). As a rule, the charges remain on the surface for several hours.

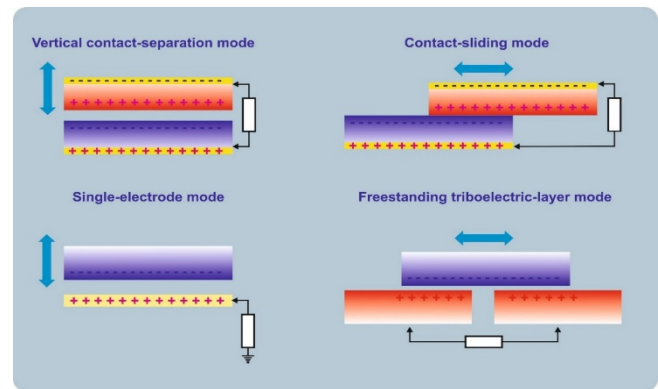


Fig.3. The four fundamental modes of triboelectric generators [1].

If we take two identical electrodes coated with a dielectric layer, the size of the electrodes, and the distance between them, will be the same as the size of the object moving above them, the approach or removal of the object to one or the other electrode will lead to an asymmetric charge distribution in the surrounding, compensating by this the local distribution of the potential (Fig. 2d) [11].

Table 1. Triboelectric Series for Some Common Materials Following a Tendency To Easily Lose Electrons (Positive) and To Gain Electrons (Negative) [7,8].

Material name	Affinity nC/J	Material name	Affinity nC/J
Polyurethane foam	+60	PET (mylar) cloth	-40
Sorbothane	+58	EVA rubber	-55
Box sealing tape (BOPP)	+55	Gum rubber	-60
Hair, oily skin	+45	Hot melt glue	-62
Solid polyurethane, filled	+40	Polystyrene	-70
Magnesium fluoride (MgF2)	+35	Nickel, Copper	
Nylon, dry skin	+30	Polyimide	-70
Machine oil	+29	Silicones	-72
Nylatron (nylon filled with MoS2)	+28	Vinyl: flexible	-75
Glass (soda)	+25	Carton-sealing tape (BOPP)	-85
Aluminum		Olefins: LDPE, HDPE, PP	-90
Paper (uncoated copy)	+10	Cellulose nitrate	-93
Wood (pine)	+7	Office tape backing	-95
GE brand Silicone II	+6	UHMWPE	-95
Cotton	+5	Neoprene (polychloroprene)	-98
Nitrile rubber	+3	PVC (rigid vinyl)	-100
Wool	0	Latex (natural) rubber	-105
Steel		Viton, filled	-117
Polycarbonate	-5	Epichlorohydrin rubber, filled	-118
ABS	-5	Santoprene rubber	-120
Acrylic (polymethyl methacrylate)	-10	Hypalon rubber, filled	-130
Epoxy (circuit board)	-32	Butyl rubber, filled	-135
Styrene-butadiene rubber	-35	EDPM rubber, filled	-140
Solvent-based spray paints	-38	Teflon	-190

The motion of electrons between pairs of electrodes creates the alternating current. The moving object should

not directly touch the upper dielectric layer of the electrodes, so that it is possible to arrange the rotation mode of the object without direct mechanical contact. In this case, deterioration of surfaces can be dramatically reduced.

One of the options for implementing and using a triboelectric nanogenerator (TAGG) for mobile systems is presented in [12]. The generator consists of three layers - a kapton (films of polyimide developed by the chemical company DuPont), PTFE films (polytetrafluoroethylene or Teflon) and aluminum foils bent into a zigzag structure (Fig. 3). The carrier is a kapton film. If we combine this structure in the form of an accordion, we get a five-layer triboelectric nanogenerator. With physical dimensions of 3.8cmx3.8cmx0.95cm, we obtain five active layers connected in parallel. The short-circuit current of such a generator is 0.65 mA, and the voltage at open contacts is 215 V. The surface and bulk density of energy is 9.76 mW/cm² and 10.24 mW/cm³, respectively, with an applied force of 400N. The main advantages of this structure are light weight (7g), good scalability, ease way for manufacturing, mechanical flexibility (easy to bend even with fingers), ease of integration in smart clothes, virtually unlimited term of operation. The principle of the generator is shown in Fig. 3. If the deformation is removed from the described structure, the two polymer films are removed from each other. Let the potential of one of the electrodes = 0. Then the potential of the second electrode can be defined as:

$$U = \sigma \cdot d / \epsilon_0$$

where, σ - is the triboelectric current density, d - is the distance between the plates and ϵ_0 is the permittivity of the vacuum.

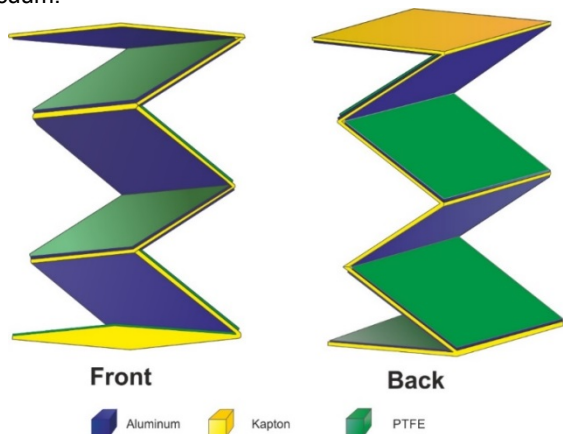


Fig. 3. The structure of a flexible multilayered TENG with five layers of units. The schematic view of a zigzag-shaped structure of the TENG [12]. (Polytetrafluoroethylene - PTFE).

The experimental data on the dependence of the maximum output power from the load resistance indicate that the optimum is at the $R_L = 1 \text{ M}\Omega$. When a similar generator is embedded in the heel of the shoe, the power output is sufficient for powering several serial LEDs.

Today, the maximum energy density of triboelectric generators is 1200 W/m² or 490 kW/m³ with an efficiency of ~ 50-85%. As shown in [1], when optimizing the TANG parameters, these parameters can be increased by a factor of 10.

Based on the rate of development of triboelectric nanogenerators (only in one, 2013 year, their energy efficiency increased by 5 orders of magnitude [1]). It can be concluded that this kind of converters of mechanical energy into electrical is today the most efficient, and the most dynamically developing [13]. Of course, like any technology,

it has certain drawbacks. For example, a high TANG resistance results in low output currents. However, this is not critical, and can be easily overcome.

Energy harvesting system

To connect the primary converters (triboelectric, piezoelectric, photoelectric, etc.) to the load, special electronic circuits, called *Energy Harvesters*, have been developed. They allow to match the large output resistance of converters with low load resistance. Many of them (for example, tribo and piezoelectric) have an output voltage of hundreds of volts (and current in units or tens of microamperes), and for the supply of modern mobile electronics one needs some volts (typically 3.3-5 volts) and tens or hundreds of milliamps of current. The conversion of voltage (decrease or increase) is the main task of such converters. In addition, it is necessary to compensate for "throws" and voltage surges associated with the specificity of the conversion of the energy of human motion into the electric current.

In the case of long-term rest, you also need to provide the final system with a backup power source (for example, a Li-Ion battery that must also be charged). To solve such a complex set of tasks, many manufacturers of analog electronics produce specific microcircuits and/or modules, a short list of which is given in Table 2.

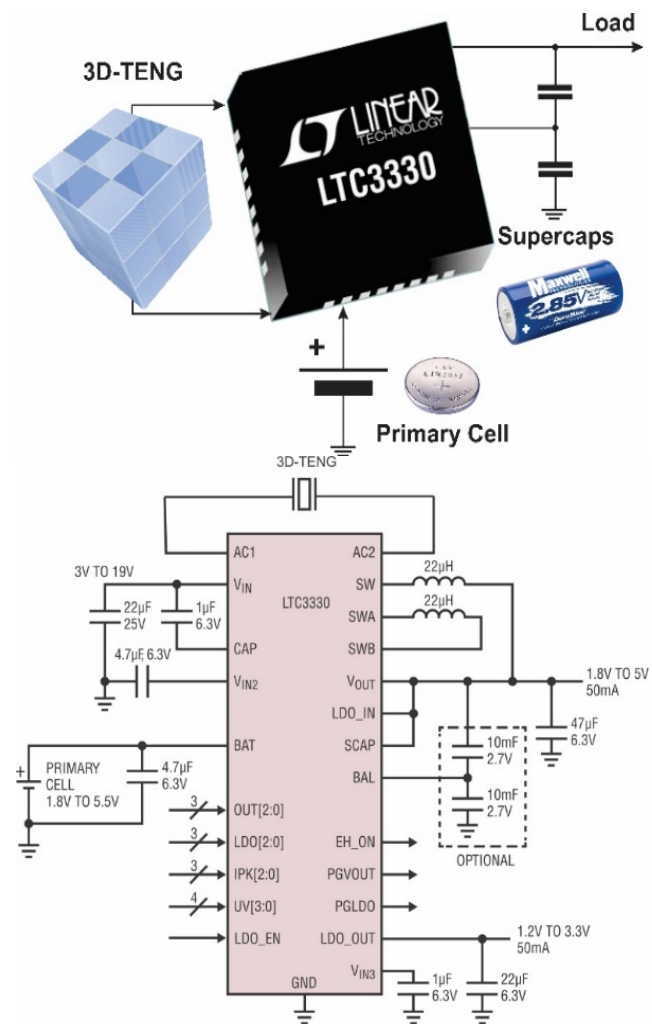


Fig. 4. Simplified (a) and more detailed (b) schematic of connection of 3D TENG to LTC3330 energy harvester circuit.

Let us consider the operation of the power management system using the example of the LTC3330 chip from Linear Technology [14]. In the presence of at least one current source, this chip provides power to the load from it instead of the battery CR2032 (which serves as a backup power source) (Fig.3).

To compensate for the transient processes, two supercapacitors with a capacity of 10 mF are connected to the output of the LTC3330 chip. They work on the principle of conventional capacitors, only with a very large capacity (if

necessary, you can increase their number) [15]. Today, samples with a capacity of more than 3,000 Farad (for example, Nichicon, Maxwell Technologies, PowerStor/Eaton) are available in the market. The main advantages of ionistors, supercapacitors or ultracapacitors are high specific capacitance (8-10 Wh/kg and up to 10,000 W/kg), a very short charging time (1-10 seconds), almost unlimited charge-discharge cycles and work (1 million or 30,000h), a very high discharge current (> 2500A) and a wide operating temperature range (-40 to 65 ° C).

Roadmap and applications of Nanogenerators (2013-2022)			
For Mega power source		Electricity generated by air flow, tires (hybrid)	Electricity generated by road and ocean wave
If-powered system integrated with current technologies		Ecological environment and climate wireless monitoring and sensing	Flexible electronics, touch screen technology, vital signs monitoring
Self-powered sensors integrated with current nanodevices		Water, chemical sensing, gas/oil/water pipe monitoring, optoelectrochemical sensing	In-vivo blood glucose monitoring, Human body health monitoring network
Working as active sensors	Bridge vibration monitoring	Infrastructure/traffic/earthquake monitoring	Microfluidic, in-vivo/in-vitro and medical bio sensing
Power source for low-consumption devices	Higher output, 3D integration. Harvest energy in water, with	NG/battery power pack, hybrid NGs harvesting mechanical, thermal, chemical energies	Power sources for small portable devices, like cell phone, MP3, sensor networks, mini-robotics; medical and bio-species monitoring
	2013-2015	2015-2017	2017-2019 2019-2022

Fig. 5. Proposed technology roadmap for nanogenerators (2012) [(Wang, 2014)].

Table 2. Specifications of some commercially available energy-harvesting modules

Type of energy harvester	Product code	Output voltage range	Compatible sources	Manufacturer
Multipurpose energy harvester	IC-744885	2.35–5 V	Solar cell, electromagnet, piezoelectric, thermoelectric generator	Wurth Electronics, Germany (http://www.we-online.com)
Energy harvester (Multipurpose)	Ener Chip EH CBC5300	3.6 V maximum	Photovoltaic cell, piezoelectric material, thermoelectric converter, etc	Cymbet Corporation, USA (http://www.cymbet.com)
Energy harvesting power management	SAE101A	1.9-3.3V	Solar-Powered Internet of Things (IoT) Device Kit	Cypress Semiconductor (http://www.cypress.com)
Universal energy harvesters	EH301A, EH300, EH301, EH300A	1.8–5.2 V	Piezoelectric, electromagnet, solar, THERMOELECTRIC	Advance Linear Devices, CA (http://www.aldinc.com)
Ultralow Power Energy Harvesting PMU with MPPT	ADP5091	1.5V - 3.6V	DC power from PV cells or TEGs	Analog Devices, USA (http://www.analog.com)
Ultra-low power boost converter with battery management and autonomous power path multi-plexing	bq25505, bq25570, bq25504	$V_{IN} \geq 330$ mV	Ultra-low power boost converter with battery management and autonomous power path multi-plexing	Texas Instruments, USA (http://www.ti.com)
Nanopower Buck-Boost DC/DC with Energy Harvesting Battery Charger	LTC3330 LTC3331	3.0V to 19V Buck DC/DC	Piezoelectric, Solar, Magnetic	Linear Technology, USA (http://www.linear.com)
915MHz RF Powerharvester™ Receivers	P1110 P2110	0-4.2V	Directed or ambient RF energy	Powercast, USA (http://www.powercastco.com/)
Ultra-low power energy harvester and battery charger with embedded MPPT and LDOs	SPV1050	1.8 V and 3.3 V output	PV cells and TEG harvesting sources from 75 mV up to 18 V.	STMicroelectronics, USA (http://www.st.com)
Energy-Harvesting Charger and Protector	MAX17710	1.8V, 2.3V, or 3.3V LDO	Complete Power-Management IC Dedicated to Energy Harvesting	Maxim Integrated (http://www.maximintegrated.com)

Conclusions

Today's portable electronics needs efficient and affordable power supplies. One of the most promising propositions is a triboelectricity. The main advantage of this type of energy is the cheapness and the possibility of fixing into moving mechanical objects and systems. Particularly relevant will be the creation of special generators on triboelectricity, which are adapted to a specific energy supply system. Especially promising are triboelectric generators based on nano technologies, made using 3D printing technology. The effectiveness of the operation of such a system will be significantly increased, in the case when it will appear as an additional one and control will be carried out through specialized electronic modules. The number and capabilities of these modules on the present day are widely represented on the market of electronic components and their list continues to be expanded.

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