Chapter 3

Wearable Human Motion and Heat Energy Harvesting System with Power Management

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Additional information is available at the end of the chapter

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Abstract

A combined human motion and heat energy harvesting system are under investigation. Main parts of the developed human motion energy harvester are flat, spiral-shaped inductors. Voltage pulses in such flat inductors can be induced during the motion of a permanent magnet along its surface. Due to the flat structure, inductors can be completely integrated into the parts of the clothes, and it is not necessary to allocate extra place for movement of the magnet as in usual electromagnetic harvesters. Prototypes of the clothing with integrated proposed electromagnetic human motion energy harvester are created and tested. Voltage of generated impulses is shown to be high enough to be effectively rectified with commercially available diodes and ready to be stored; however, efficiency depends on properties of controlling circuit. In order to increase the sustainability of the energy source and its stability, an option for combining a motion energy harvester with a human body heat energy harvester is also considered. Thermoelectric generator that harvests electricity from waste heat of human body is presented, and generated voltage and power are compared at different activity levels and ambient temperatures. Power generated with thermoelectric generator located on lower leg reached up to 35 mW with peak voltages reaching 2 V at certain conditions. A possible power management set-up and its efficiency are discussed.

Keywords: human motion energy harvesting, smart apparel, flat inductors, thermoelectric generators, microwatt power management

1. Introduction

Electronic devices are becoming smaller, lighter, and consume less power. These tendencies cause search for energy sources that will produce electricity using energy that is available in our surrounding environment (light, motion, heat, etc.) [1]. With such energy source, electronic device would become independent and there would be no need to periodically access the battery to change or charge it. It would also allow designing embedded systems, which will be protected from harmful environmental influence. Wearable electronic systems integrated in clothing elements are one of the device groups that need to be protected [1, 2]. Aims and tasks for such systems are security and monitoring of physiological parameters [3, 4], determination of location [5], and communication [6, 7]. At the moment, practically all such systems are based on integration of various sensors in clothing to gather information about surroundings and send it to remote receivers for data storage and processing, as well as to inform person about the changes in the environment or any harm or danger [3]. Powering of such systems is possible by using electrochemical batteries [8, 9], solar cells [10, 11], thermoelectrical elements [12], converters of mechanical energy (piezoelectric [1, 13], electrostatic [1], and electrodynamic [1, 14] energy harvesters). Cost of change or charging as well as necessity to access electrochemical elements are considered as major disadvantages. Mentioned alternative energy sources use various physical phenomena and can be combined to work together, optimizing work of wireless electronic devices. Mechanical energy harvesters are regarded as most perspective and universal energy source for wearable electronics according to various scientists [1, 15]. Multiple publications offer such harvesters for footwear [16], add-on for bags or purses [14], or as accessories [17]. In almost all cases, the construction of these harvesters considers either human body part direct force [16] or periodic motion [14] conversion into electric energy. Most of prototypes are three-dimensional devices [14, 18], which makes it impossible to implement them into clothing without changing its functionality and appearance.

Authors and other researchers have previously shown that it is possible to use flat spiral-shaped coils [19, 20] as inductors in electrodynamic harvesters and elements of electronic circuits. Another advantage of electromagnetic harvesters is their ability to work without direct contact between harvester elements, as it is necessary, for example, with piezoelectric harvesters; therefore, it is possible to implement them without changing shape, elasticity, and other mechanical properties of clothing [19].

It is possible to use different technological methods when designing wearable electronic elements [21, 22], which allows to make flexible and stretchable connections for components. One of the technologies that can be used for electronic connections is embroidery, which can be considered as one of the most perspective ways to make conductive structures in textiles and on the surface of clothing elements. It is possible to make structures (connections, resistive, and inductive elements) that preserves properties of fabric and only minimally changes clothing shape. Recently embroidery was suggested as a method to make inductive elements for resonant circuits [21].

Another perspective wearable energy harvesting method is the use of thermoelectric generators, which use waste heat as energy source. Due to rigidity, these harvesters are mainly used for such wearables as wristwatches [23, 24]. However, commercially available thermoelectric elements are available in various sizes; therefore, they can be used in clothing as well. The main advantage of these harvesters is that they provide direct current (DC), which can be generated in both high and low activities of a person who wears it.

Work [19] presents possibility to design clothing and human body part movement energy transformer, which generated electrical energy using motion of permanent magnet in parallel

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with flat spiral inductors. Design, properties, and performance of such generators as well as possibilities to implement these generators into various clothing elements are presented and discussed in the following parts of this chapter.

2. Analysis of electromotive force and energy generated in inductive elements in homogenous magnetic field

Proposed human motion energy harvester working principle is based on electromagnetic induction phenomenon, when electromotive force (EMF) ε and current I in closed loop is induced by changing flux of the magnetic field Φ_M.

Assuming wire inductance is negligible, self-inductive electromotive force (EMF) will not be generated. Induced EMF can be calculated according to Faraday's law: electromotive force is proportional to the rate of change of magnetic flux Φ_M:

$$\mathcal{E} = \frac{d\,\Phi_M}{dt} = \frac{d(BScos\alpha)}{dt} \tag{1}$$

Supposing that magnetic field is homogenous ($B = const$) and perpendicular to coil plane ($\alpha = 0$), rate of change of magnetic flux will be proportional to crossed area changing rate:

$$\mathcal{E} = B\frac{dS}{dt} \tag{2}$$

where ε is the electromotive force [V], B is the magnetic induction [T], S is the magnetic field crossed conductor loop area [m^2], and t is the time [s].

If load resistance is much higher than resistance of winding, it can be assumed that there is no significant current flow, so generated voltage is equal to EMF. This is not optimal load condition and can be only used to characterize output voltage for ideal case. In reality, smaller load resistance leads to current increase, but it also decreases output voltage because every real generator has internal resistance (dependent on used materials, construction, etc.), which dissipates part of generated energy on itself. For this reason, it is possible to find the optimal condition for real generator, where load receives the highest energy. It happens when load resistance value is equal to internal resistance of generator. In such case, voltage on load and internal resistance is equal to half of EMF; they both share the same dissipated energy. Total energy available on the resistive load according to the Joule-Lenz law is:

$$W = \int Pdt = \int\frac{U^2}{R}dt \tag{3}$$

where U is the voltage on resistive load [V]; R is the resistance of the load [Ω]; $P = U^2/R$ is the instantaneous power [W].

By using analytical expression for spiral shaped, for example, Archimedean spiral, induction element, or element group, it is possible to apply Eq. (2) for specific instance. Generated EMF will depend on the magnet velocity v and shape of the inductor, which is crossed by magnetic field:

Shape	Induced EMF	Generated energy	Energy (rationed) according to theory	Energy (rationed) in experiments
Square	$\mathcal{E} = Bav$	$W = \frac{B^2 a^3 v}{R_1}$	*1*	*1*
Rhombic	$\mathcal{E} = B\,v^2\,2t \cdot tg(\alpha)$	$W = 0.94\,\frac{B^2 a^3 v}{R_2}$	0.94	0.93
Circular	$\mathcal{E} = 2rvB\sqrt{1-\left(1-\frac{vt}{r}\right)^2}$	$W = 0.66\,\frac{B^2 a^3 v}{R_3}$	0.85	0.79

Table 1. Results of theoretical calculations and experimental results for inductors with different geometrical shapes [25].

$$\mathcal{E} \sim \frac{\mathrm{dS}}{\mathrm{dt}} = \mathrm{f(v, shape)}$$

Ref. [25] shows analysis of power and energy for different shapes of flat inductor (square, rhombic, and circular) and theory is backed up with experimental data. Square and rhombic edge length *a* were considered equal to the diameter of round wire *2r* to obtain data in **Table 1**.

Theoretical analysis of different shapes shows that the highest energy should be obtained from square-shaped coil (magnet size is assumed to be equal to coil size). Experimental data for various sizes and shapes of inductors proved theoretical predictions. Relative energy and equations are shown in **Table 1**.

3. Experimental: motion energy harvester

3.1. Flat inductors

Flat inductors can be manufactured in various ways, many of which are related to types of clothing manufacturing technology. Here are some ways to produce flexible inductive coils for proposed harvesting:

1. Printed circuit board (PCB) technology on elastic substrate. This method can be used to create inductors of any shape with high resolution and also combine some parts of power management system on a flexible substrate (**Figure 1**). Since the final product is very thin, integration into apparel is easy and done without significant alterations, but the same reason creates significant coil resistance as copper tracks are long and usually thinner than 100 μm to keep the whole structure flexible. Even though longer conductor track produces higher voltage, larger internal resistance (over a hundred of ohms) reduces power output significantly.

2. Various shapes and sizes can be created by using embroidering by conductive yarns. The test structure (**Figure 2**) has the upper (needle) polyester thread and the lower (bobbin) conductive thread, which is a silver-coated polyamide thread Elitex 110 dtex/f34x2. The length of the tested square-shaped coil is 25 mm, and it consists of 19 windings. The main disadvantage as compared to PCB technology is the resolution as winding density is much lower which leads to lower generated voltages.

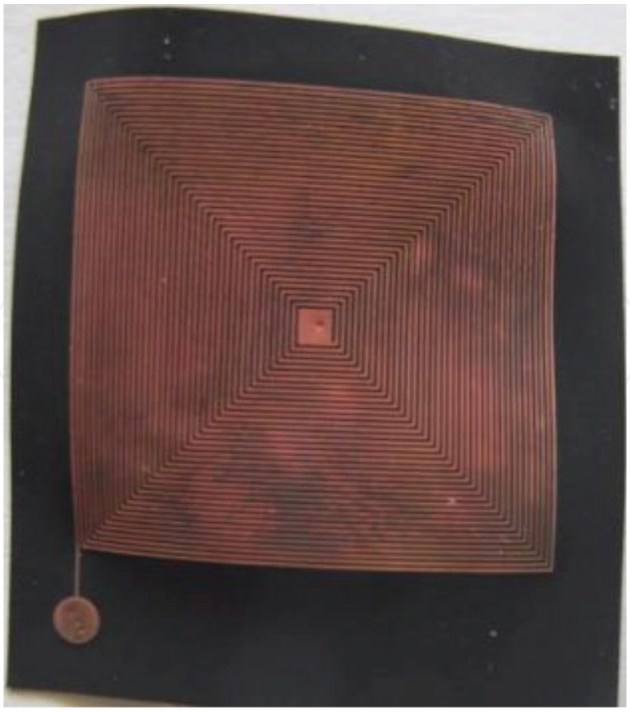

Figure 1. Flat spiral coil, made of 35 μm thick copper tracks and polyurethane substrate (created in *Fraunhofer Institute for Reliability and Microintegration IZM, Berlin, Germany*); length of an edge is 25 mm.

3. A thin copper wire can also be sewed on a fabric, for example, with zigzag stitch technology by using embroidering machine like SZK JCL 0100-585. Wires are much more fragile than threads, but this technology puts noticeably lower stress on the wire during production as the wire is supplied by a dedicated device and fixed to a fabric with zigzag stitch. The

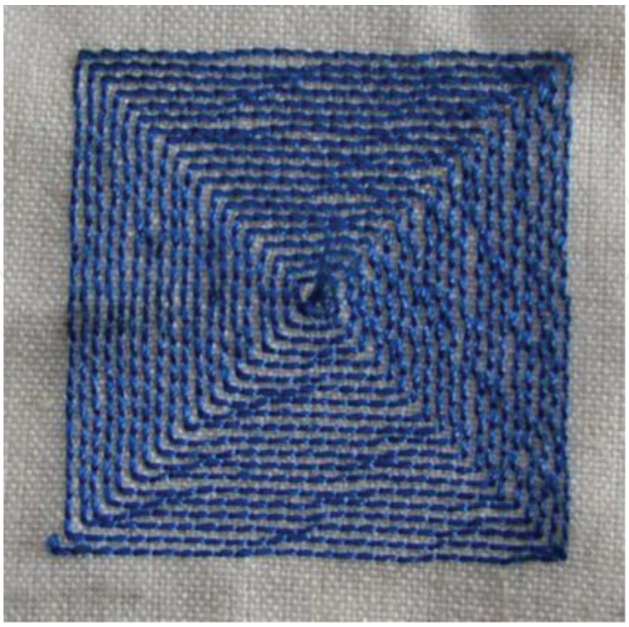

Figure 2. Embroidered flat square-shaped (length of an edge is 25 mm) inductor.

lower internal resistance is an additional advantage of such a method in comparison with the abovementioned. **Figure 3** shows Archimedean spiral with 25 mm diameter, 25 windings with a 0.2 mm copper wire. Stitching step must be adjusted carefully to protect the wire and its insulation layer from accidental damage by needle.

4. Coils can be made as a design element by machine production or handcrafting. Article [26] shows multiple examples of creation of inductors by crocheting (**Figure 4**) and knitting.

5. Manually made coils in Archimedean spiral shape [19] were the ones used in further discussed prototypes. All of them were 25 mm in diameter and winded using 0.22 mm copper wire, except coils mentioned in **Table 2**.

3.2. Number of flat inductors in the generator and its testing

To achieve maximal performance of the generator and acquire the highest amount of energy, it is necessary to place several inductors into elements of clothing in a way that magnet could induce electromotive force in several inductors sequentially. It is possible in such places where one part of clothing moves as fast and close to other parallel part as possible. Works [25, 27] analyze dependence of voltage impulses with regard to their placement to find maximal count of inductors that are allowed to be placed in clothing in path of movement of one magnet. By placing four inductors on magnet trajectory and analyzing relative increase of momentary power in respect to inductor placement, it was shown that it is reasonable to position two or three inductors so that their generated voltage impulses add with each other.

Figure 3. Copper wire sewed on a textile substrate (created in RWTH Aachen University – Institut für Textiltechnik, Aachen).

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Figure 4. Crocheted flat inductor [26].

Coil type	Internal resistance, Ω	Mean energy, μJ	Mean crossing time, s	Mean power, μW	Notes
Embroidered coil	8.3	2.21	0.075	29.84	Diameter 25 mm with 19 windings
Sewn coil with zigzag stitch technology	0.7	6.62	0.072	91.25	Diameter 25 mm, copper wire diameter 0.2 mm, 25 windings
Manually made coil	2.2	113.82	0.130	875.54	Diameter 30 mm, copper wire diameter 0.22 mm, 60 windings
PCB coil	116	4.31	0.146	29.62	Diameter 30 mm, 80 windings

Table 2. Experimentally defined performance of inductors created by different techniques.

Mechanical manipulator was used to compare different inductors, generated electromotive force, and overall energy. It provided controlled and repeatable conditions for tests of various inductors. Mechanical manipulator moved square-type permanent magnet ($Nd_2Fe_{14}B$, 0.2 T, 20 × 20 × 2 mm) along spiral flat inductors with controlled velocity. Voltage impulses were registered for each tested inductor on resistive load equal to inductors' internal resistance. Generated power and energy were defined using Eq. (3).

Table 2 shows experimental data of flat inductors that are made in various ways. It can be seen that embroidered coils have less windings compared to manually made coils as well as relatively high internal resistance. This is the reason why energy and power are low in comparison with others. The sewn coil energy and power values are smaller than those of the manually created coil, which is explained by the fact that such coils have two times lower number of windings, which cannot be increased by using manufacturing techniques.

Power from PCB technology coil falls behind manually winded coil as tracks are very thin, introducing significantly larger internal resistance, even though generated voltage is larger (up to 0.2 V for a single coil) due to larger number of windings. Manually made coils produce about 30 times higher power, but voltage reaches only 0.12 V on the load resistance.

3.3. Prototypes of clothes with energy harvesters

3.3.1. General considerations

Previously done tests with automatic magnet movement with constant parameters provide data for different inductor comparison, but the actual environment for proposed harvesters is far from constant. Multiple clothing prototypes were created for real-life results, two of them are described in the following sections. Both were tested on a person with different walking speeds.

Since the requirements for highest voltage and power are relative to the highest speed of the magnet's motion and as small as possible distance between the magnet and the inductor, the most suitable place is a sleeve and side of an outerwear. These positions are shown in **Figure 5**.

3.3.2. Prototype 1

Energy harvester with planar structure integrated into the men's insulated outerwear and generator is located at the anterior superior iliac spine level (**Figure 6**). The location of the inductive elements in the prototype 1 is marked in **Figure 5** by *1* and the location of the magnet is indicated by *2*. Insulated in outerwear, integrated electromagnetic human motion energy harvester contains two parts:

- The inductive element consists of three groups of spiral-shaped coil with identical direction of winding turns, which are connected in series (coil groups have 1 cm space between them and generated voltages gave the same polarity). Each coil group consists of five layers, placed one onto another with insulating layer in between, coils have 2.5 cm diameter and 50 windings.
- The second generator part is lightweight, small, and strong neodymium (Nd) magnet with double magnetic field structure and induction 0.26 T. An arc-shaped magnet is 1/6 from concentric circles with r_1 = 2.5 cm and r_2 = 4.0 cm.

The volume of the generator (coils + magnet) is approximately 4.63 cm^3. The total mass of the integrated elements is about 50 g.

The generator was tested by a wearer during the process of walking at fixed speeds (**Figure 6**). The typical shape of the pulses of generated voltage during the periodic motion of hands along the wearer's body are shown in **Figure 7**.

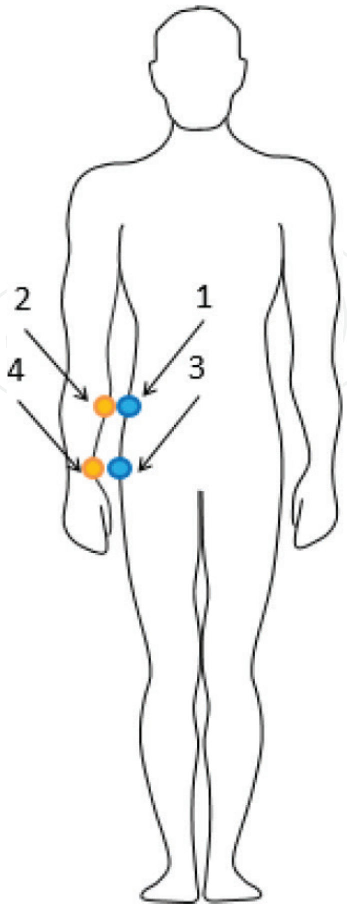

Figure 5. Positions of parts of electromagnetic harvester. 1 and 3 – Positions for flat inductors, 2 and 4 – For the permanent magnet.

The voltage generated during one full motion cycle of the magnet along the coil consists of two pulses. The full motion cycle—the period of double step—is formed for each arm from both forward and reverse movements. Some asymmetry of pulses connected with the trajectory of sleeve movement was observed. It was observed that during the movement of sleeve forward, trajectory of magnet is maximally close to the coils and voltage generated in pulse is higher (left pulse in **Figure 7**), while during movement of sleeve backwards, magnet is further away from them and generated voltage is lower (right pulse in **Figure 7**). Impulses are not symmetrical due to natural hand movement and clothing deformation.

The numerical data of harvester-relevant characteristics for the full walk cycle are shown in **Table 3**. Maximal mean power 0.50 ± 0.10 mW is observed at a walking speed of 6 km/h.

3.3.3. Prototype 2

In a men's jacket (prototype 2), energy harvester elements are integrated at the carpal joints level, maintaining symmetry (**Figure 5**, positions 3 and 4). The energy harvester's parts in the prototype 2 are the following:

- inductor array: three sets of coils are placed near to each other and connected in a series in a way that generated voltage for each set has opposite polarity;

Figure 6. Testing prototype 1 on treadmill.

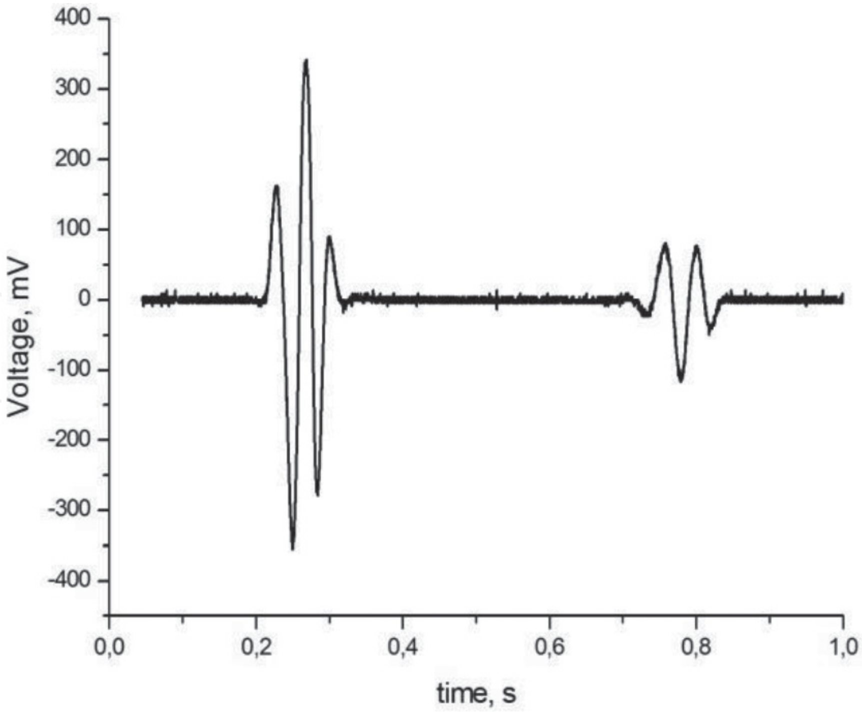

Figure 7. Prototype generated voltage pulses at walking speed of 6 km/h.

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Walking speed, km/h	Mean energy, mJ	Time of 1 walking cycle, s	Mean power, mW	Mean power density, mW/cm³
3.0	0.23	1.27	0.18	0.04
4.5	0.29	1.10	0.26	0.06
6.0	0.49	0.98	0.50	0.11

Table 3. Prototype 1 in use—Performance.

- magnetic field source: two round magnets with 20 mm diameter and 0.2 T magnetic induction.

Volume of the generator (coils + magnet) is approximately 4.95 cm^3. The total mass of integrated elements is 30 g. The voltage pulse generated is shown in **Figure 8** (**Table 4**).

3.4. Power management

As generated pulses have low amplitude, even such a simple and important task as rectification brings in some challenge. To verify usability of prototype 2, it was tested against typical full-bridge rectifier with DFLS120L Schottky diodes and resistive load (**Figure 9**), in which the values were changed (10, 30, 50, 70, 100, and 200 Ω). Voltage was measured before and after the rectifier (**Figure 8**) to get information about energy lost on the rectification circuit.

The most effective load for any generator is the one with value equal to internal resistance of the generator itself. This is because the energy on the load is the highest at these circumstances.

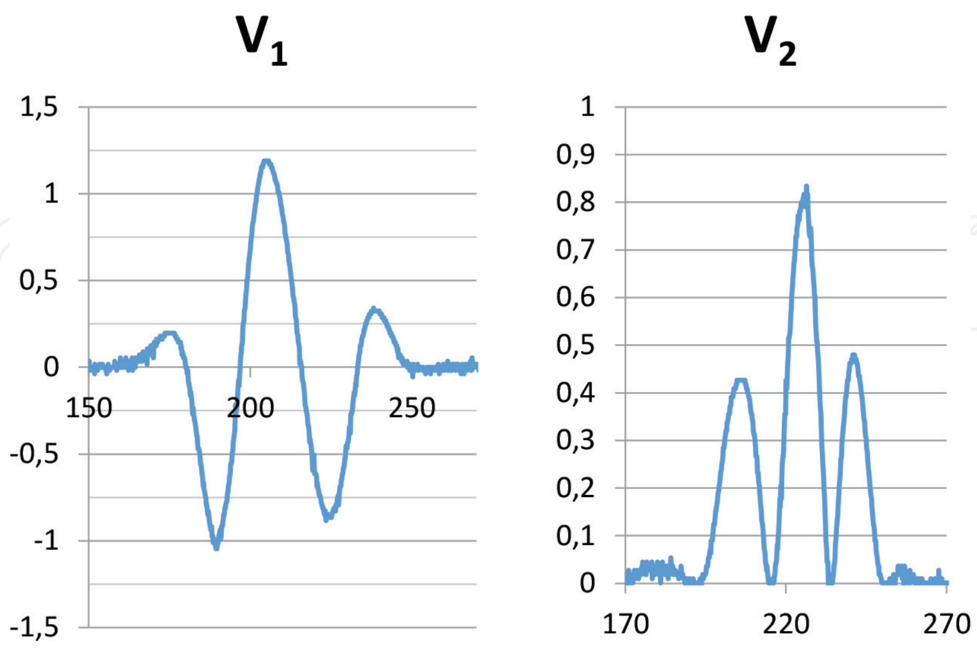

Figure 8. Voltage before rectifier (V_1) and on 70 Ω load (V_2); x axis — Time (ms), y axis — Voltage (V).

Walking speed, km/h	Mean energy, mJ	Time of 1 walking cycle, s	Mean power, mW	Mean power density, mW/cm³
3.0	0.24	1.35	0.18	0.036
4.5	0.30	1.28	0.23	0.046
6.0	0.49	1.11	0.44	0.088

Table 4. Prototype 2 in use—Performance.

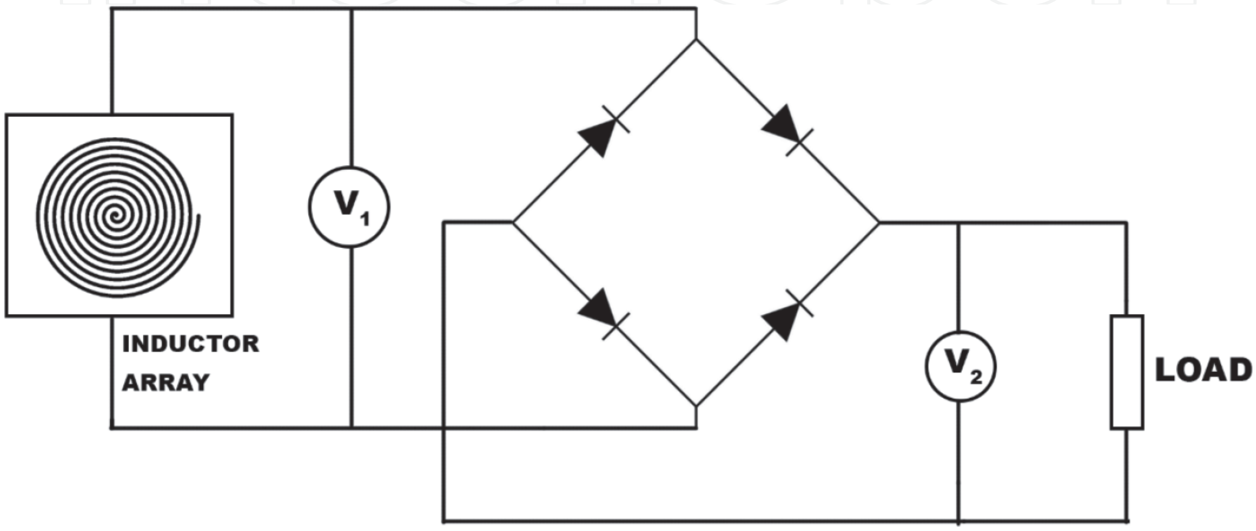

Figure 9. Measurement schematic. V_1 is measured voltage before rectifier (input voltage), V_2 is output voltage on the load.

As we have additional interface (bridge rectifier) between the load and the generator and it is changing its parameters depending on the generated voltage, multiple load values were tested. Internal resistance of the prototype 2 was 17 Ω, voltage measurements were done on the generator and load at the same time.

To evaluate generator effectiveness in prolonged period, 40 consecutive impulses were recorded during the normal movement of a test subject. True root mean square (RMS) values for every two impulses (1 s) of input and output voltages were calculated, resulting an average value and standard deviation of distinct measurements. By known load value, RMS current was calculated, that was used for generated power estimation as the current is the same for input and output. Each true RMS calculation was done for time period of a full second, thus numerically power from this RMS value is equal to energy. Results are provided in **Table 5**.

Standard deviation for voltage RMS measurements is small enough to consider average values for current measurements being true. Average power and energy is the product of RMS voltage and current on input and output. Efficiency increases with load resistivity because higher load value leads to smaller current in circuit, which decreases voltage drop on rectification elements, thus reducing wasted energy. On the other hand, it also decreases output power; accordingly, a trade-off must be chosen between efficiency and high enough output voltage and current as real-life load like sensors, batteries, and other systems will depend on that.

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	10 Ω	30 Ω	50 Ω	70 Ω	100 Ω	200 Ω
RMS on load (mV)	57.77 ± 1.14	98.65 ± 2.28	106.99 ± 2.24	133.59 ± 2.02	157.54 ± 3.43	168.83 ± 1.83
RMS on input (mV)	168.66 ± 1.64	204.01 ± 2.23	206.43 ± 2.71	227.87 ± 2.47	242.50 ± 4.54	247.7 ± 2.85
RMS current (mA)	5.78	3.29	2.14	1.91	1.58	0.84
Output power/energy for an impulse (μW, μJ)	166.84	162.19	114.47	127.47	124.09	71.26
Input power/energy for an impulse (μW, μJ)	487.13	335.43	220.86	217.44	191.02	104.55
Efficiency (%)	34	48	52	59	65	68

Table 5. Prototype 2 rectification experimental data. RMS calculated for time period of 1 s (two impulses).

4. Combination of the motion energy harvester with the human body heat energy harvester

Taking into account the fact that electromagnetic harvester will generate electricity only when a person that wears it is moving, its energy might be insufficient to continuously supply power to wearable electronic systems. To increase overall energy supply, it can be useful to combine energy harvesters that rely on different kinds of waste energy from human body. One of the kind might be thermal energy that can be converted to electricity using thermoelectric elements, for example, Peltier elements. Various studies [28–30] have shown that use of thermoelectrical generators may be a successful solution for harvesting energy for wearable electronic devices.

To evaluate possible gain of combining electromagnetic and thermoelectric generators, it was decided to build prototype using thermoelectric elements.

Thermoelectric harvester prototype with 5 Peltier elements was made to convert waste heat of human body into electrical energy (**Figure 10**). All five elements were connected in series to achieve higher generated voltage. System is mechanically connected using elastic strings to apply it to naked skin on arm or leg. Total surface area taken by Peltier elements is 4500 mm^2, which is optimal to cover forearm or lower leg.

Measurements were performed in two different environments:

1. Indoors—activities inside the building at 20°C ambient temperature, low air flow
2. Outdoors—activities outside at 5°C ambient temperature, wind speed approximately 3 m/s.

Generator was tested both covered with clothing and uncovered, during three levels of activity: "no activity"—the person is at rest, "low activity"—walking, and "high activity"—running.

Table 6 represents both open circuit voltage (U_{OC}) and power (P) at balanced load:

Measurements reveal that even in quite difficult for the heat exchange conditions (indoors, covered, no activity) with generator based on 5 Peltier elements, it is possible to generate voltage up to 55 mV, which is enough to convert it to higher voltages with Step-Up converter, for example, LTC3108 manufactured by Linear Technology. This means it is possible to get continuous

Figure 10. Thermoelectric generator on lower leg.

	Indoors				Outdoors, cold weather			
	Covered		Uncovered		Covered		Uncovered	
Type of activity	U_{OC}, V	P, mW	U_{OC}, V	P, mW	U_{OC}, V	P, mW	U_{OC}, V	P, mW
No activity	0.065	0.05	0.09	0.1	0.145	0.28	0.34	1.5
Low activity	0.11	0.21	0.172	0.41	0.195	0.51	0.43	2.45
High activity	0.14	0.42	0.26	0.93	0.234	0.74	0.46	2.97

Table 6. Performance of the thermoelectric generator.

50 μW power from the generator all the time while it is on a wearer. This power is enough to power devices such as wearable wireless sensors for physiological signal monitoring [31].

If conditions are good for generator (outdoors, uncovered, high activity), it is possible to obtain up to 3 mW power, which could be enough for activities such as wireless data transmission. This is contributed by both higher temperature difference between skin and air as well as good airflow, resulting in higher heat transport through Peltier elements.

Most probable results that should be expected for person with moderate activity during the day would be 0.1–0.2 mW on average, which is typical power consumption for high-performance general purpose microcontrollers [32].

Power generated by both electromagnetic and thermoelectric harvesters are similar, therefore both can provide comparable energy to be stored to single capacitor or battery. Taking into account the discontinuous nature of each generator, storing energy in the same element might result in less interruption in the supply of energy.

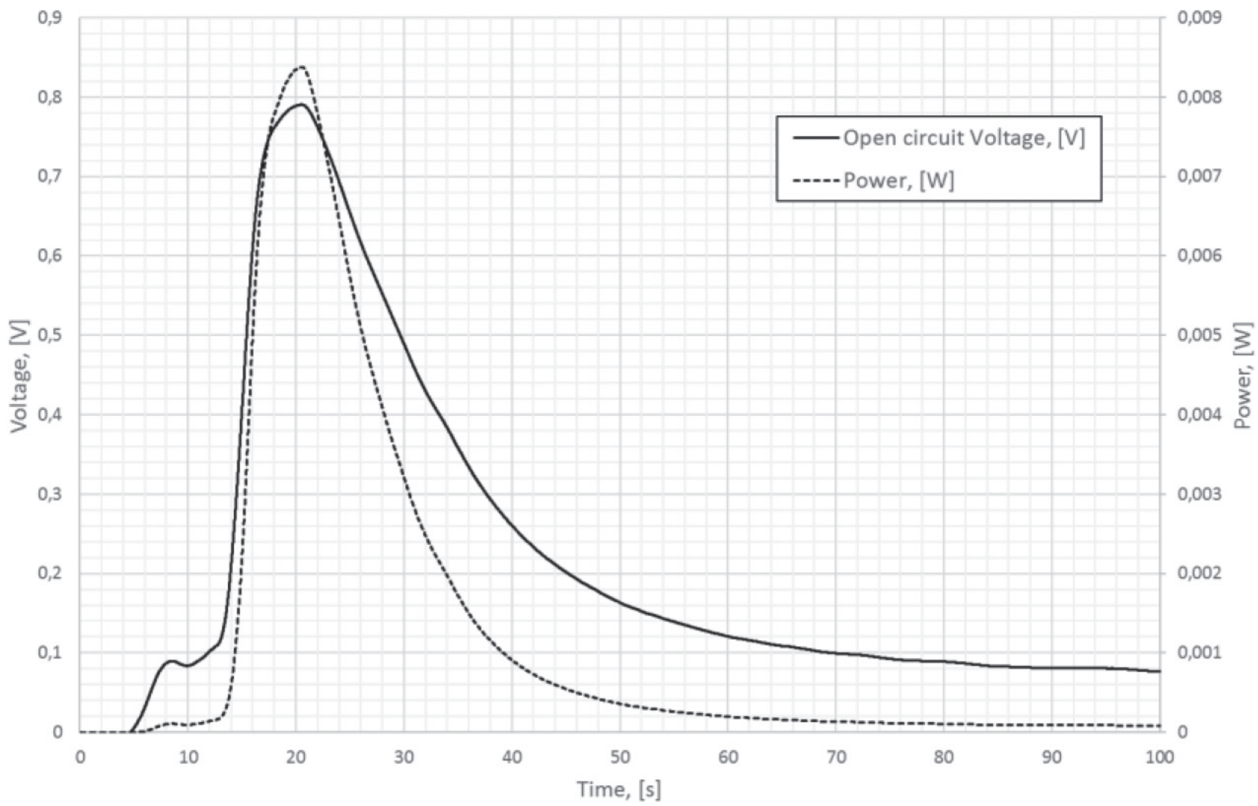

Figure 11. Open circuit voltage and power generated by thermoelectric generators during putting on.

An interesting moment of such thermoelectric generator that could be quite useful is the moment of putting it on—when generator, that has ambient room temperature, is exposed to warm skin, at least 10°C difference between sides of Peltier elements is produced. The generated voltage and the power developed by Peltier elements at this time are shown in **Figure 11**.

As we can see, peak power and voltage can be observed for about 10 seconds. Amount of generated voltage and power depends on ambient temperature, skin temperature, speed of putting the generator on, and several other factors. Power generated during this process fluctuates between 3 and 35 mW and voltages between 0.5 and 2 V. This can be quite useful energy, because start-up process of voltage converters that do not use external power source will be very slow if converter is being operated with lowest input voltages. For example, ultralow voltage step-up converter and power manager LTC3108 should be able to charge its output capacitor about 10 times faster if input voltage is 500 mV instead of 100 mV. It means that self-powered wearable electronic device will gather energy to start work much faster when using this advantage.

5. Discussion

Produced prototypes proved possibility to integrate human motion energy harvester into apparel without compromising its usability and characteristics. According to [33], this was the main problem of published energy harvesters developed for human motion energy harvesting.

As prototype 1 had thicker construction because of the materials and thermal insulation layer, harvester showed more stable results and higher generated energy than prototype 2. Thicker and more robust construction provides less free movement of individual garment parts, creating more distinct trajectory for harvester elements.

Considering necessity for integration into apparel, proposed flat inductor system has multiple advantages over other harvesters: flexibility, variable size, and harvester elements are located in different places and direct contact is not necessary, energy is harvested from human natural movements, and so on. Proposed harvester does not rely on inertia and can be used in broad movement frequency diapason with unchanged efficiency.

Since harvester parts are not meant to be enclosed in any rigid housing, there is no need to allocate any space for magnet movement like it is in traditional cylindrical coil construction [14], flat coils with magnetic suspension [34], or with the magnet moving through the coil [20]. Power density is considerably higher than for other electromagnetic harvesters summarized in [1], but most of them rely on inertia and thus have resonant frequency, which is high (e.g., P/V = 2,2 mW/cm^3 at f = 320 Hz).

As human movement nature is individual and changes on many occasions, the same harvester can show different results for another clothing, user, or simply during time. Systems relying on inertial movement, for instance, MEMS, have much more stable performance. Prototype 1 shows 20% deviation in results, while prototype 2 up to 30%, invariance increases with faster walking pace. Generated energy is dependent on various factors, many of them are uncontrollable, for instance, specific walking features, pace, body load, and so on.

Comparing with other published electromagnetic harvesters, proposed harvester can generate high enough voltage to be rectified with off-the-shelf diodes with efficiency above 50%. On an average, peak output voltage is below 1 V, but such values can also be further used for low-power management systems, for example, voltage boost converter LTC3105 from Linear Technology starts up from 0.25 V (then works from 0.225 V) and can be programmed to load the harvester in a way to get the most effective power output. Such converter will start up on rectified pulses above 250 mV as they have relatively low frequency, it may give enough power at appropriate output voltage like 3.3 V for direct usage, but the most perspective objective is further accumulation in a battery or a capacitor. Some short activities like body or environmental parameter measurements might be powered directly, but it is unlikely due to unavoidable power losses in all power management steps.

Thermoelectric elements have several advantages when compared to electromagnetic motion harvesters: it generates electricity even when the person is not moving; relatively high voltages (up to several Volts) can be generated when system is applied to a person; generated electricity is direct-current (DC) type, therefore no rectifying is needed. These advantages make thermoelectric generators very beneficial addition to electromagnetic motion harvesters because (1) system that is powered by harvesters can be powered continuously, because thermoelectric generators will supply power, when it is not generated by movement; (2) startup, which is most difficult moment for every low-power harvesting system, can be done much faster and easier because higher energy generated by thermoelectric generators during putting on the wearable; and (3) generated DC voltage can be used as a bias voltage or additional power source to improve efficiency of rectifier used for electromagnetic generator.

6. Conclusion

The combination of human motion and heat energy harvesting systems is under investigation. The electromagnetic human motion energy harvester which consists only of flat elements and can be completely integrated into the apparel is under discussion. Main parts of the developed human motion energy harvester are flat, spiral-shaped inductors. Voltage pulses in such flat inductors are induced during the motion of a permanent magnet along its surface. By not using common method of magnet moving inside the coil but applying the proposed method with magnet and coil moving in parallel planes, new possibilities are created because such kind of movements precisely coincide with the relative motion of one part of apparel along the other. It is not necessary to keep hollow place for the movement of the magnet as in usual electromagnetic harvesters, because the parts of harvester are placed in separate elements of apparel. Due to the above-mentioned properties, the mean power density of developed harvester exceeds the values given for three-dimensional harvesters with traditionally used cylindrical coil. The prototypes of the clothing with integrated electromagnetic human motion energy harvester with flat inductors were tested. The power developed by the harvester during the walking with a speed of 6 km/h was up to 0.5 mW, which is suitable for powering wireless sensors. The voltage generated by the proposed harvester is shown as ready to be rectified with off-the-shelf diodes for further power management steps.

Thermoelectric harvester is proposed as addition to electromagnetic harvester. Combined system benefits not simply from extra power but from possibilities to differentiate power flow, for example, less powerful harvester can be used as independent source for control or power management system for the main harvester. As thermoelectric harvester does not fully depend on human movement, it can provide great support for motionless periods, creating more complete power harvester system.

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