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doi:10.15199/48.2022.08.34

Impact of scale factor on performance of miniature DC power source based on wideband vibration energy converter

***Abstract**. This paper presents a miniature DC source based on a dual system of nonlinear vibration energy converters along with a converter of an induced voltage. The considered electromagnetic system converts vibrations into electrical energy using internal nonlinearity due to magnetic force dependent on relative position of a moving part. This results in a significant widening of the operating frequency band in comparison to linear system. Based on initial design, the output power and voltage were investigated as functions of the scale factor for the systems with the optimized winding. The result of the study is a construction of a DC power source that generates the output power of minimum of 2 mW (with maximum reaching 8.5 mW) over the frequency range between 15 and 40 Hz, proving the applicability of the system in powering of wireless sensor systems.*

***Streszczenie.** W pracy zaprezentowano miniaturowe źródło prądu stałego oparte o układ podwójny nieliniowych przetworników energii drgań wraz z przetwornicą napięcia. Zastosowane elektromagnetyczne układy przetwarzające drgania na energię elektryczną charakteryzują się dodatkową siłą wewnętrzną, co powoduje znaczne poszerzenie pasma częstotliwości pracy w stosunku do układów liniowych. Na podstawie początkowego projektu, przeprowadzono badania mocy oraz napięcia wyjściowego w zależności od współczynnika skalującego, z uwzględnieniem optymalizacji rozłożenia zwojów cewek. W wyniku badań zbudowano źródło prądu stałego generujące minimum 2 mW (max 8.5 mW) w zakresie częstotliwości od 15 do 40 Hz, co dowodzi możliwości zastosowania w zasilaniu bezprzewodowych systemów pomiarowych. (**Wpływ współczynnika skali na parametry miniaturowego źródła prądu stałego opartego o szerokopasmowy przetwornik energii drgań**)*

Keywords: vibration energy harvesting, electromechanical converters, nonlinear resonance, frequency response
Słowa kluczowe: pozyskiwanie energii z drgań, przetworniki elektromechaniczne, nieliniowy rezonans, odpowiedź częstotliwościowa

Introduction

In recent years, as a result of the increased interest of industry in wireless sensor networks, there has been a need for developing power sources that convert available ambient thermal, solar or vibration energy into electrical energy [1, 2]. The electromagnetic-type converters with nonlinear resonance operate over a much wider frequency range as compared to linear resonant systems and so they perform better in vibration energy harvesting system than the linear counterparts. The nonlinear parametric resonance occurs due to the existence of internal magnetic force caused by an interaction of moving permanent-magnets with ferromagnetic core or additional permanent magnets. In order to design such a system for the desired functional characteristics one needs to solve the coupled electromagnetic-mechanical problem [2, 3].

In the last few years, there have been several works published which relate to the issue of scaling the energy harvesting systems. Such approach enables understanding the relationship between the output power and the dimensions of these systems [4, 5]. In [6] the attention is focuses on determining the upper limit of the power density based on the available solutions from the literature. Another useful work [7] presents an analysis of dependence of the output power on the scale factor for a nonlinear electromagnetic converter with tubular structure. It has been shown that the output power is in proportion to the fifth power of the scale factor.

In our work, the effect of scale on the power and output voltage of a novel miniature DC power source will be investigated.

Miniature DC power source

The system proposed in this paper consists of two electromagnetic vibration converters with nonlinear internal resonance [8]. A single harvester (EH) is constructed from a plate spring attached on one end to the housing. The coreless yokes that include permanent magnets are mounted on another end. On the outer sides of the yokes the armature containing two coils connected electrically in parallel is placed as shown in Fig. 2. When such a system is mounted on a vibration source, the plate springs begin to bend and this causes mutual displacement between the yokes and coils and this induces the electromotive force in the armature coils. Due to the presence of additional permanent magnets that bring a nonlinear magnetic force affecting the dynamics of the system, a nonlinear parametric resonance occurs. As a result relatively high output power can be developed over a wide range of frequency. Figure 1 shows a kinematic scheme of considered system, for which a simplified mechanical dynamic model can be written as

$$m\ddot{y} + c\dot{y} + [k + k_{mag}(y)]y = F_{ext}(t) - F_e(y, \dot{y}) - F_g \quad (1)$$

where: y – relative displacement of yokes vs. coils, m – mass of yokes with magnets, c – damping coefficient, k – beam stiffness coefficient, k_{mag} – magnetic stiffness coefficient equal to magnetic force divided by displacement, F_{ext} – external force, F_e – electromagnetic force from the interaction of magnetic flux and coil current, F_g – gravitational force. Neglecting the effects of damping and the electromagnetic force and assuming a sinusoidal displacement variation of y in time (with magnitude y_{max}), the averaged steady-state resonant frequency of the nonlinear system is equal [1, 2]

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k + k_{mag}(y_{max})}{m}} \quad (2)$$

The frequency f_{res} depends on the material properties of the system, as is the case in linear generators, but also on the nonlinear magnetic stiffness, which can in general be positive or negative. The system with positive stiffness coefficient causes "stiffening" of the system in the direction of motion, while the system with a negative stiffness coefficient makes the moving part more flexible in the direction of motion. This feature is utilised in this work for construction of a dual system.

Thanks to the coreless structure of the magnetic circuit of the converter, the designing of the system is significantly simplified and the possibility of shaping the variation of the magnetic force is provided. The magnetic circuits with opposite directions of magnetization of the magnets have the same values of the induced voltage but the signs of their magnetic stiffnesses are opposite. This makes the possibility of building a dual system with overlapping frequency bands, where the maximum power values of the component systems are reached at the frequency band limits.

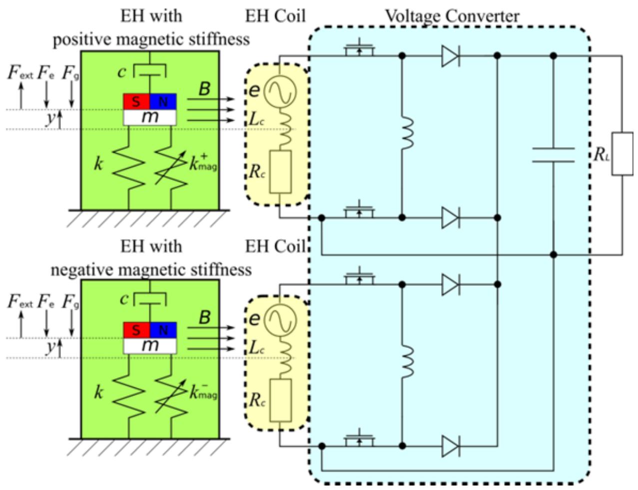

Fig.1. Scheme of ac/dc step-up voltage converter for dual system of electromagnetic energy harvesters

The considered vibration energy converters operate for the vibration signals in the range of 15-40 Hz and generate the voltages at terminal of the coils of up to 0.5 V. They can be used to supply e.g. the measuring devices using a microcontroller with a battery. Therefore, the voltage converter should be selected in such a way as to obtain a minimum output voltage of 2.5 V when using two Ni-MH batteries or 3.8 V when using three batteries or one Lithium-Ion battery. The value of this voltage is also important from the point of view of logical elements used to control the gate signals of switching elements. In case of use of a microcontroller and power MOSFET transistors controlled by logic signals, a higher voltage is of minimum 3.8 V is desired. Then, the microcontroller can be supplied with a voltage of e.g., 3.3 V. Due to the low input voltage, a boost converter with bridge rectifier will not be applicable due to a large voltage drops across diodes, even when using the Schottky diodes. Considering the above conditions, the bridgeless resonant AC-DC converter proposed in [9] and the bridgeless boost rectifier presented in [10] were taken into account here. Finally, the circuit shown in the Figure 1 based on one presented in [10] was implemented. To obtain the maximum efficiency of the converter all elements with possibly low energy losses were selected. The control unit will be based on a microcontroller with ultra-low power consumption (MSP430 family from the FR series with FRAM memory and current consumption in active mode is about 100 uA/MIPS). Additionally, in order to minimize the number of elements, the integrated internal comparators of the microcontroller are used to synchronise the signals controlling the switching transistors with the input signal of the generators. The Schottky diodes with low conduction resistance were used as rectifying elements. The switching elements will be power MOSFET transistors with low resistance and the possibility of controlling logic signals directly from the microcontroller. The converter in Fig. 1 operates correctly when the impedance of EH coils are low. Therefore, scaling procedure of the system regards only the designs with armature coils optimized for low impedance.

Optimization of armature coils

The optimization was performed for several values of scale factor S applied to design variables of the system, namely 25 %, 50 %, 66.67 %, 75 %, 100 %, 125 %, 133.33 % and 150 %. These values are constrained by the dimensions of permanent magnets available on the market. It was assumed that the operation frequency is 35 Hz, the displacement amplitude of the permanent magnet yokes is equal to S x 15 mm, and the conversion ratio of the boost converter is assumed constant. Table 1 shows the scaled design variables (see Fig. 2).

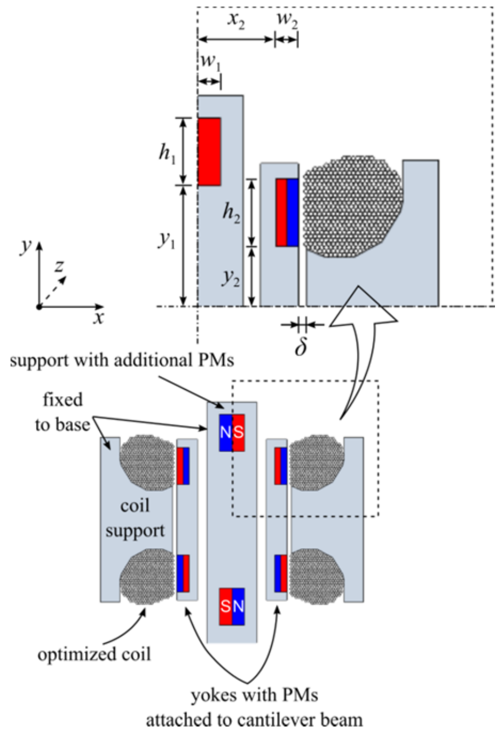

Fig.2. Cross-section of magnetic circuit

Table 1. Dimensions of initial magnetic circuit (for S = 100 %), where S is a scale factor

h_1	S x 9 mm
w_1	S x 3 mm
additional magnets length in z-axis	S x 18 mm
y_1	S x 16.6 mm
h_2	S x 9 mm
w_2	S x 3 mm
moving magnets length in z-axis	S x 18 mm
y_2	S x 8.6 mm
x_2	S x 10.4 mm
δ	1 mm

The optimization goal is to maximize the output power from the whole system considering the coil turn distribution in coil cross-section area as shown in Fig. 2. The design variables are the number of turns, wire diameter, length of the active part of the coil, and a load resistance of the system. The whole algorithm is described in details in earlier work of the authors [3]. The main idea is based on metamodeling using Kriging with sequential points grid densification around the optimum in order to reduce the optimization procedure execution time. In order to more accurately represent the flux associated with the coil windings a 3D analytical-numerical magnetic model derived from Biot-Savart law were used [11]. The resistance R_c and inductance L_c for a coil composed of separate turns is obtained from analytical formulas [12].

Figure 3 shows the effect of the scale factor S on selected design parameters of the system, i.e. wire diameter, length of the active part of the coil, number of turns, resistance and inductance of the coil, and load resistance. As it can be seen, the variations are complex not allowing for determination of simple empirical models. This is because for each value of the scaling factor S of the magnetic circuit dimensions the optimization of the coil winding distribution is performed.

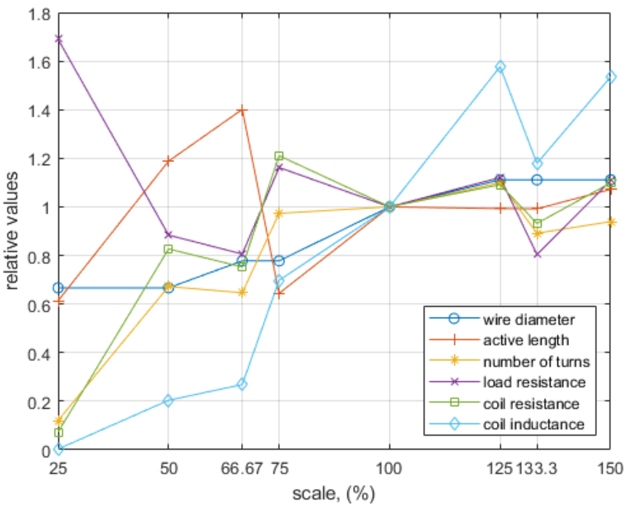

Fig.3. Relative values of optimized coil parameters for different values of scale factor

The dependence of the most important performance parameters of the system, i.e., power and DC voltage at the generator output is shown in Fig. 4. As it can be seen, the output power is proportional to approximately a 2.5 power of the scaling factor S.

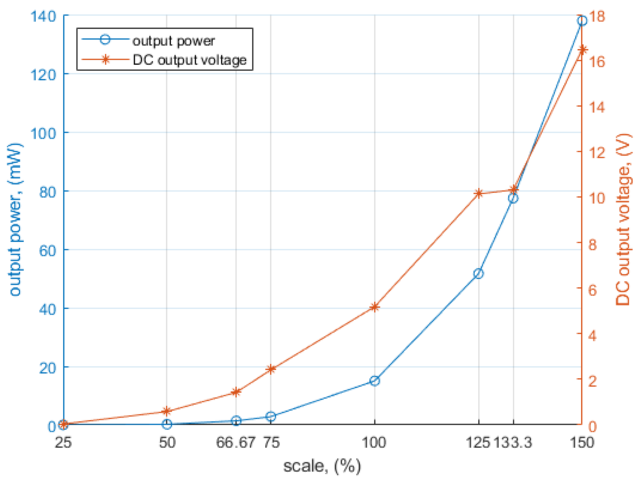

Fig.4. Output power and DC on-load voltage computed for different values of scale factor

Based on the presented results a 100 %-scale converter was selected for further study as a harvester with a positive magnetic stiffness coefficient, and a 66.67 %-scale one as a harvester with a negative magnetic stiffness coefficient, respectively. The scale of the latter was selected due to its operation at higher frequencies, which results in higher frequency of vibrations of a yoke and so a higher value of electromotive force induced. The parameters of these harvesters are summarized in Table 2, and their prototypes mounted on the laboratory test-stand are shown in Fig. 5.

Table 2. Optimization results for scale factors 66.67 % and 100 %

	Scale	
	66.67 %	**100 %**
Optimized output power, (mW)	1.40	15.04
R_c – coil resistance, (Ω)	1.87	2.48
L_c – coil inductance, (mH)	0.8	3
N – number of turns	311	481
D – wire diameter, (mm)	0.35	0.45
L – coil active length, (mm)	5.2	3.7
R_L – load resistance, (Ω)	1382.2	1715.2

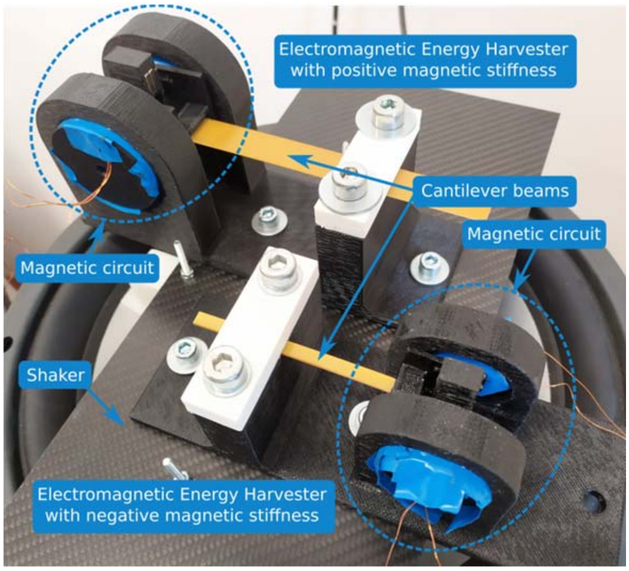

Fig.5. Dual system of electromagnetic energy harvesters on laboratory test-stand

Measurements of frequency characteristics

The laboratory test-stand in Fig. 5 consists of a dual system of electromagnetic vibration energy harvesters, a shaker powered from a programmable voltage source, an accelerometer placed on the shaker and a signal amplifier with conditioner. The entire measurement process is managed by a PC with data acquisition card. The frequency characteristics of the output power and steady-state voltage are obtained for the given rms value of the vibration acceleration and a specified frequency range.

Figure 6 shows the frequency characteristics of the voltage on an electronic converter load equal to 1500 Ω for a miniature DC source based on system of dual electromagnetic energy harvesters. As it can be seen, the higher the vibration acceleration is the higher output voltage and the wider frequency bandwidth are. This performance could not be reached in linear systems, which operate in resonance only for a certain value of the frequency. Unfortunately, in the generator under consideration, the voltage hysteresis phenomenon [2] which detracts from its performance intensifies at high acceleration values. This means that the maximum voltage value of about 3.5 V is reached only at decreasing vibration frequency. For a vibration acceleration of 12.5 m/s^2, the voltage jumps to a value of approximately 3.3 V only at a frequency of 28 Hz when increasing the vibration frequency. The solution of the problem could be tightening of the overlapping frequency bands when designing transducers with positive and negative magnetic stiffness. In addition, future prototypes should consider increasing the output voltage beyond 30 Hz, even at the expense of reducing the output power and considering minimum requirements of particular powered devices or battery recharging modules.

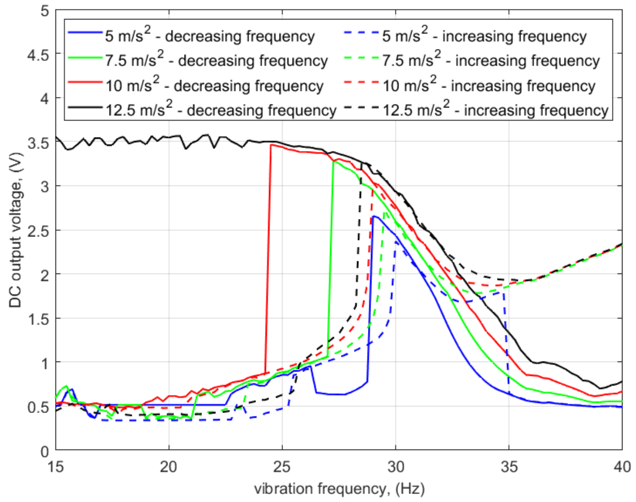

Fig.6. Measured frequency characteristics of DC output voltage for dual system of electromagnetic energy harvesters with voltage converter

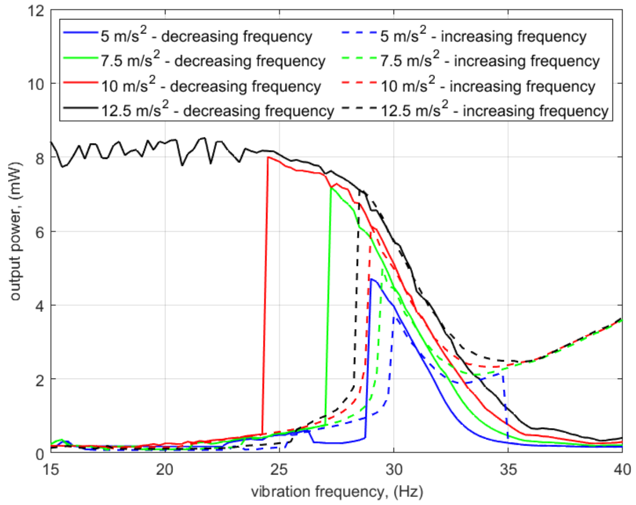

Fig.7. Measured frequency characteristics of output power for dual system of electromagnetic energy harvesters with voltage converter

In support of the above, Figure 7 shows the dependence of the output power on the voltage converter load as a function of the vibration frequency. The maximum power is obtained in the range between 15 and 25 Hz (with decreasing frequency) and is equal to about 8 mW. However, the circuit with a negative magnetic stiffness coefficient contributes more to power generation beyond 35 Hz, despite its smaller size compared to the former.

Conclusions

In this work, the effects of the scale factor on the output power and voltage of a miniature DC source harvesting electrical power from mechanical vibrations was presented, performing independent optimizations of the coil winding distribution for the considered values of the scale factors. In the manufactured prototype, circuits with a scale factor of 66.7 % and 100 % were used. This resulted in dual system of energy harvesters with similar maximum output voltages. The measured frequency characteristics showed a potential for broadband mechanical vibration energy harvesting using the proposed concept. In our future works, the attention will be concentrated on maximization of the voltage and power preserving the size of generator. Additionally, to ensure a stable voltage that charges the battery a closed-loop voltage control system should be implemented.

This work was funded by the National Centre for Research and Development, Poland, grant number TANGO-V-A/0023/2021-00.

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