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Article

A Robust Generator-Harvester for Independent Sensor Systems†

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Abstract: This work focuses on the research area of energy generation and harvesting for its transformation into electrical energy with the primary use of energy independent sensor systems in the power range P=10-10000W. These systems are applied in sensing quantities in the transport sector (bridge structures, transport infrastructure, and the others). The proposed theoretical harvester models describing the transformation of motion energy into electrical energy, also provides theoretical and experimental models. Results obtained in the design and construction of a robust motion generator with primarily linear geometry system technology are presented. The expected output electrical power of the harvester is variable and is designed based on the linear motion generated by the engine- compressed air, small fuel system, etc. The fundamental design of the generator core has been continuously numerically modeled and an experimental setup has been developed to analyze specific parts and variations in order to validate the concept and achieve the most suitable parameters with the selected construction materials. A scaled down version of the model principle was tested in experiments and then the parameters and results were compared with the predicted theoretical analyses.

Keywords*:* Harvesting; electromagnetic field; numerical model; renewable energy; linear motion; sensor systems

1. Introduction

In the recent period 2010-2020, the trend of energy saving, power system independence, energy processing efficiency and energy harvesting based on electromagnetic field principles [1] has spread to almost all industries. The field of energy harvesting or energy transduction science [2–4] does not deal with any processing and transformation of energy into electrical energy, but only covers a limited part of the principles [5–17] and corresponding device designs [18–25] for this conversion of unused forms of energy [26–30]. Other principles of energy conversion remain included in the field of electricity generation, such as the conversion of energy from flowing media - water, air, and the conversion of incident RF electromagnetic waves - photovoltaic systems into electrical energy [31–37].

The use of these scarce alternative power sources finds application mainly in mobile or wireless devices [38–44], sensor independent systems [2–4], autonomous devices where stable power supply is disadvantageous or impossible [3,4]. A requirement for the design and use of these principles in alternative power sources is mainly the estimation of the minimum operating time without connection to a stable/permanent (non-mobile) power distribution system. Harvesters, as an integral part of the concept and design, use some of the storage elements and devices such as electric storage batteries, capacitors or supercapacitors, inductors, etc., important to compensate for the time irregularity of the energy supply.

An interesting application area of harvesting is, for example, the use of the physiology of the human body as a source of energy to be transformed into electrical energy. This is then intended to power replacement devices and their electronics, as well as diagnostic medical devices from the produced motion, temperature, and behavior of the human body [17,40].

Then, for example, the concept of a robust harvester with its own motion energy source is shown in Figure. 1.

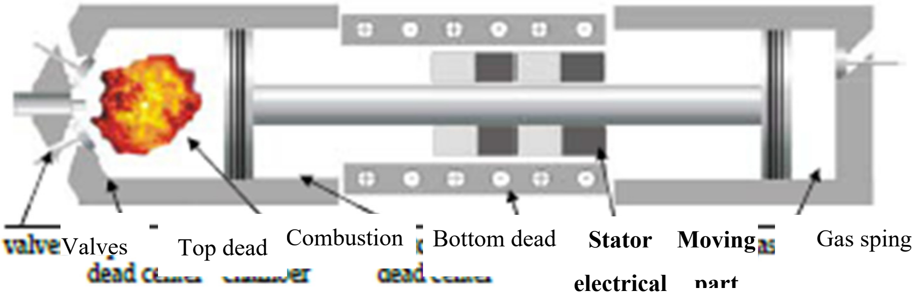

Figure 1. Schematic of the design of a linear combustion engine in combination with an electric generator [36].

In parallel, the research focuses on the design of conceptual solutions for the highly efficient conversion of motion energy into electrical energy. Figure 1 shows both the static electrical part and the motion part as an exemplary realization of the use of linear motion in a known way, in this case by the application of a linear combustion engine. The principle of solving the conversion of motion energy into electrical energy is based on the understanding and consistent use of the possibilities of Faraday's induction law [1], as shown in the works [2–4,38–44].

2. Overview of the Current Status

The subject of the study is focused on researching the concepts of efficient conversion of energy into electromagnetic, especially the solution of conversion of mechanical movement into electrical energy. These solutions are applied in devices from the field known as generators or harvesters. The study focuses on the range of conversion of instantaneous delivered/transmitted electric power in the range P=10 – 10,000 W. Currently published and edited works can be divided into several areas. The first is the area of design and solution of the electrical, electronic and electromagnetic part of the device, and prominent works are listed [5–17]. The second area of the solved problem is in the group of works focused on the topic of harvester/generator drives, mainly described as combustion parts of the engine [18–25]. An interesting group (the third) are works that deal with the design of both the combustion and electromagnetic parts of the generator [26–30]. A special group (fourth) consists of works and solutions of linear motion of the drive unit based on hydraulic transfer of dynamic energy to the motion element of the linear arrangement of the generator [31,32]. The specific part (fifth) of the published designs of the generator system (conversion of kinetic energy to electricity) is research dealing with control, modeling, simulation, measurement and evaluation of model parameters [33]. The first more detailed insight into the analysis and solution of the generator concept and more serious attempts to create a mathematical model and simulation of a hybrid engine is provided, for example, by the work [46], then [10] deals with the design of a purely electromagnetic part, i.e. electromagnetic conversion using a generator. Another direction of research leads to the design and solution of the combustion power unit of linear engines, in this case an engine with free pistons. Compared to a rotary engine with a crank mechanism, this has only one or two pistons connected on a common shaft [33,35] and precisely controlled detonation and dynamics of the moving mass. A linear motor with free pistons uses the movement of a common shaft, on which a linear electric generator is mounted [34], or a hydraulic piston mounted on a common shaft, which creates hydraulic pressure by the movement of the piston, further used [32]. Only a few works deal with the control of a motor with a hydraulic pump [31] and a simulation study of this assembly [47].

Among the first published works dealing with the design and testing of a linear combustion engine in connection with a generator, it is possible to mention a contribution from the University of West Virginia [35], in which its use is also considered for an electric power generator with an application for relatively remote locations, thanks to fewer moving parts, greater reliability, efficiency and compactness [5] compared to the concept with a rotary engine. The authors of works [7,12,48–50,23] are also dealing with similar proposals for the use of a linear combustion engine as an electric power generator to replace the application of the current concept of gasoline or diesel generators. One of the fundamental areas of application of linear generators in conjunction with a combustion engine with free pistons is automotive technology. The basic elements of a linear generator are a linear combustion engine or an engine with free pistons (free piston engine) and a linear electric motor generating electrical energy (linear generator). Next, the combustion chamber, which is equipped with valves, picture Figure.1. A piston moves in this chamber, which is connected via a piston rod (common shaft) to a piston on the opposite side functioning as a gas spring. In the middle of the piston rod is an electric generator/motor consisting of a movable part fixed on the shaft (rotor) and a fixed part fixed on the motor block ("stator"). Since there is no crankshaft with a flywheel and connecting rod to convert the sliding motion of the piston into rotary motion, there are reduced/minimum inertial forces and the linear motor is then just demanding to precisely control the detonation. The piston in the cylinder is closest to the valves in the top dead center and, conversely, in the bottom dead center when the opposite piston forming the gas spring is compressed, Figure 1. There are several principle arrangements of a linear internal combustion engine with a linear generator/electric motor that functions as a linearly arranged electric generator. Linear combustion engine with electric generator with one piston in the cylinder and one piston as a gas spring, Figure 1. A mechanical spring can also be used instead of a gas spring. In this mode, the internal combustion engine operates as a two-stroke, Figure 1 shows the positioning of the two separate units opposite each other to compensate for vibration, Figure 2.

Figure 2. The basic principle of two separate units of a linear combustion engine with one combustion chamber and a gas spring [36].

Another variant of the design consists in placing two separate pistons in the cylinder and in the central part forming a common gas spring in a single block, Figure 3. The combustion cylinders are in the outermost parts of the engine.

Figure 3. The basic principle of arranging two separate pistons in a cylinder with a common gas spring in the middle [36].

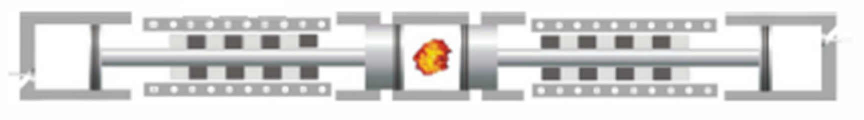

Figure 4. The basic principle of the arrangement of a linear combustion engine with a central combustion chamber in the middle [36].

By swapping the combustion and spring cylinder, the engine configuration is obtained, where gas springs are located on the edges with one combustion cylinder, which is located in the center of the engine block, Figure 4.

Figure 5. Schematic diagram of a linear combustion engine with a central combustion chamber and integrated gas springs [36].

By changing the design of the damping of the piston dynamics, a variant of the arrangement from Figure 5. is obtained. The pistons are placed against each other in the combustion cylinder and their rear part moves in the closed part of the cylinder forming a spring. Other configurations consist in the arrangement of the electric generator with respect to the method of obtaining the dynamic movement of the piston. For example, in Figure 6, the pistons working in the combustion cylinder are arranged on opposite sides of the common piston rod. Expansion in one cylinder causes compression in the opposite cylinder and vice versa. One of the cylinders still drives the electric generator in the middle.

Figure 6. Scheme of the principle arrangement of a linear combustion engine with combustion chambers on opposite sides [36].

Another more complex system that uses more effectively achieved dynamic parameters of the linear motor is shown schematically in Figure 7. Fuel is burned in the center of the cylinder and pressure is developed on the pistons, the edges of the cylinder act as a dynamic spring. The entire block can be shortened by placing the coils on the sides.

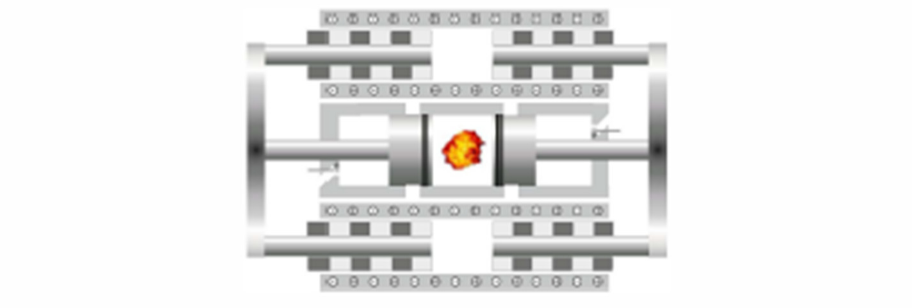

Figure 7. Scheme of the principle arrangement of a linear combustion engine with a central combustion chamber and linear generators branching to the sides [36].

The use of a linear internal combustion engine with an electric generator may be of interest in so-called series hybrid cars [6,9,20,13,51–55]. Another application is the deployment of this system as a range extender [56]. A summary of some of the recent developments for commercial use, especially in hybrid propulsion units, can be found in [57]. The requirements for a linear electric generator resulting from the basic analysis of the linear arrangement of an internal combustion engine with a generator with respect to the achieved output power for charging a traction battery Q=21 kWh and

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an electric drive of P=80 kW are published in [58].Other published works deal with the solution of deploying a linear generator for the conversion of mechanical vibrations of a car into electrical energy [8], the evaluation of the performance and quality of a linear microgenerator including testing for the use of energy from the mechanical propagation of waves with free pistons is dealt with by the authors of the work [11]. The paper [59] deals with the division of a linear internal combustion engine system coupled with an electric generator into three main subsystems and then the solution of the structural design and parameters of each of them. These subsystems consist of the combustion part of the linear engine, which converts chemical energy into kinetic energy, the linear generator, which converts kinetic energy into electrical energy, and a suitable air spring as an energy storage element that changes the motion characteristics of the piston. The authors of work [60] also approach the solution in a similar way, in which they also deal separately with individual parts of the system.

The design of the combustion part of a linear engine and a linear generator for burning hydrogen as a medium with a high density of volumetric energy concentration is dealt with in work [26], in which, in addition to hydrogen H_2, it is possible to burn a mixture of hydrogen and biogas. The principle of the combustion engine is considered to be diesel with homogeneous filling of the combustion space (Homogeneous Charge Compression Ignition - HCCI). The advantage of the HCCI principle is the use of lean explosive mixtures. The aim of this step is to reduce the formation of CO_2, make energy transformation more efficient and reduce the load by obtaining hydrogen from renewable sources as a replacement for classic fossil fuels. Numerical design and model, analysis of a linear engine with a generator (Free Piston Linear Generator - FPLG) for hydrogen combustion are dealt with by the authors in work [61]. Simulation using Matlab/Simulink and the finite element method (FEM) is used to design the system layout of a linear internal combustion engine with an electric alternator (Free Piston Linear Alternator - FPLA) and is described in [27]. The study of generator design with numerical simulation of combustion characteristics and finding ignition limits for a free-piston engine is carried out by the authors of work [62]. Furthermore, a group from the University of Newcastle and Beijing deals with numerical modeling, analysis of combustion and the process of spark-ignited FPLG, and comparison of test results [63]. A similar group deals with several other research topics. It is research focusing on the stable operation of the linear motor and the electrical characteristics of the generator, again using simulations and comparison with the measured results from the experiment [28]. Investigation of potential malfunctions during engine operation, such as missing a spark during ignition, fluctuations in individual engine cycles, and instantaneous changes in electrical load are provided by works [64]. The analysis of the operating characteristics of the FPLG during each phase of operation based on the results of simulation and experiment is published in the paper [21]. The overall control with a design for stable operation of a linear motor using cascade control and PID (proportional-integral-derivative) control units is presented in work [65], similarly [66]. The improvement of the output power thanks to the control by 7-10% is brought by the text of the contribution [67], the issue of resonant control is solved by the authors of the work [68]. Similarly, the focus on the experimental analysis of the characteristics of combustion and heat release when using a diesel engine with a free piston is solved by work [69]. A summary of FPLG design and control with regard to different types of linear generators, a description of their advantages and disadvantages is provided in text [70], the overall analysis of the combustion engine and linear generator is given in the work [30]. Analyses of the efficiency evaluation results using combustion chamber arrangements on both sides of a linear engine in these designs instead of an air spring on one side can be found in [71] and the theoretically achievable range for a slow-speed generator is given in [72].

Design problems in the combustion part of the engine

The basic concept of the energy conversion method depends on the use and design of a two-stroke linear combustion engine [73] or four-stroke [74]. Some works deal with the design, analysis or modeling of the combustion part of the system with a linear engine and generator [75,76], the thermodynamic model of a linear combustion engine is published in the work [77]. In [78], a parametric analysis of a two-piston linear internal combustion engine is presented that demonstrates, using a simple numerical model, the properties of a structure that is reduced to a forced oscillating mass-spring system under external excitation [79]. A numerical model analysis of a high-stiffness coil spring study is available [80], modeling and control of a free-piston generator is described in [81], and a simulation of a two-stroke engine with free pistons is in progress [82]. Another area of research and solution lies in the search for ensuring stable operation of combustion units [83] and its corresponding/optimal control [84]. The use of a linear Joule motor in combination with a linear generator is presented in the work [85] and their characteristics with respect to dry friction forces are discussed in the text [86].

The issue of the design of a purely electrical part

As a specific segment of research in the above mentioned method of power generation is the design of the electrical and electromagnetic part of the device or apparatus. A basic and detailed analysis of the concepts of linear machines suitable for use in linear arrangements of motors/generators, their concepts from the point of view of geometry (planar or tubular) can be found in the work [45]. The use of 3D modeling and simulation and then comparison with an experiment to study a linear generator, again in a planar or tubular design, is processed by the authors of the work [87]. Generators can be single-phase [88] in tubular arrangement or planar arrangement [89]. A comparison of a linear generator as a linear synchronous machine and a linear cross-flux machine is in the works [15]. Comparison and variation of parameters such as stator and rotor lengths relative to each other with respect to power density is recorded and analyzed in [90]. The work [91] includes the analysis and experiment of reducing the holding force with respect to the shape of the used permanent magnets. For example, the study [92] deals with individual sub-problems, investigations or simulations and further brings research conclusions for subsequent miniaturization by using the concept of a cylindrical double stator and improving the magnetic flux density in the gap. The text [93] deals with the study of radial and axial magnets using ANSYS, the simulation and experimental verification of equivalent circuit parameters and the evaluation of losses in the core using FEMM are dealt with by the authors of the text [16], the effect of the power converter on the construction of a linear alternator is covered by the work [94]. The evaluation of the problem of the range of the linear motor with the generator is solved by work [95], the investigation of the effects and force parameters from the pole extensions on the moving core of the generator is described in the text [96] and their solution is described in work [14] or a simplified analytical model is described in work [97].

Comparison, analysis, study of generator system links

The above-mentioned issue of the energy transformation method, harvesting, is also related to more general works, which include comparisons, for example, with other technologies such as microturbine, fuel cell, classical rotary internal combustion engine [36] as principles and technical solutions of harvesting and power generation, as well as, for example, comparison of output power depending on the change of operating parameters [98]. There are known studies dealing with different fuel applications such as propane-butane [37], diesel [99], FlexiFuel with an additional turbine on the exhaust [100]. Research on the parametric effects on generator design and its resulting efficiency is presented by the pole attachment power reduction techniques published by the authors in [15]. An earlier dissertation from West Virginia University focuses on the optimization of a permanent magnet AC linear alternator for use in conjunction with a linear internal combustion engine [101]. The relatively large work, consisting of three parts originating from Toyota's R&D center, is divided into research on the basic characteristics, presents the results of research on the design of a control system for the generator, and presents a new method for controlling the linear generator to improve the efficiency and stability of the system [102–104]. Several papers have been published in the German Aerospace Center's Institute for Vehicle Concepts in the topic area discussed. Works dealing with the concept, explanation, development and measurement results of a linear generator with an internal combustion engine with free pistons and integration into a vehicle are published in [105] and similarly in [106].

A crucial parameter for the comparison of the efficiency of generators and their transformation characteristics, parameters for the choice of the downstream concept, is the quantity effective volumetric power density p_{efd} [W/m^3]. With this parameter it is very easy to compare the efficiency of a power source with respect to its volume, as for example shown in [40], Table 1. With this parameter it is possible to compare different concepts, designs, dimensionally different/non-measurable designs of power generators.

The research conducted on the above topic tries to use this parameter to select efficient and effective energy transformation principles that are later industrially applicable [107,108] and not just a theoretical example of energy transformation possibilities.

Table 1. The parameters of selected vibration generators [40].

Reference	Permanent Magnet type	Generator Body Size x,y,z [m]	Resonant Frequency f_r [Hz]	Amplitude mech. part A [m]	Output Power P_{out} [W]	Output Voltage U_{out} [V]	Load Resistance R [Ω]	Acceleration G, g = 9.81 [m/s]	Effective Power Density $[W/m^3]$
Beeby et al. [12], 2007	–	375 mm^3	52	–	2×10^{-6}	0.428 RMS	4000	0.06 g	≈6
Zhu et al. [13], 2010	FeNdB	2000 mm^3	67.6–98	0.6×10^{-3}	61.6–156.6 × 10^{-6}	–	–	0.06 g	≈30–80
Kulkarni et al. [11], 2008	FeNdB	3375 mm^3	60–98 40	1.5×10^{-3}	0.6×10^{-6}	0.025	52,700	0.398-4 g	≈0.2
Wang et al. [15], 2007	FeNdB	256 mm^3	121.25	0.738×10^{-3}	-	0.06	-	1.5 g	-
Lee et al. [17], 2012	FeNdB	$1.4 \times 10^{-4} m^3$	16	–	1.52×10^{-3}	4.8	5460	0.2 g	≈10
Yang et al., [16], 2014.	–	50,000 mm^3	22–25		13.4×10^{-3}	0.7–2.0	110	0.6 g	≈270
Elvin et al., [14], 2011	–	15,000 mm^3	112	–	4×10^{-6}	0.007	986	-	≈0.26
MG I [2], 2006	FeNdB	90, 40, 30 mm	20–35	50×10^{-6}–400×10^{-6}	70×10^{-3}	4–60 (300) p-p	7500	0.15–0.4 g	≈650
MG II [2], 2006	FeNdB	50, 27, 25 mm	17–25	50×10^{-6}–400×10^{-6}	19.5×10^{-3}	6–15	5000	0.1–0.7 g	≈60
MG III	FeNdB	50, 25, 25 mm	21–31.5	50×10^{-6}–400×10^{-6}	5.0×10^{-3}	1.0–2.5	600	0.05–0.4 g	≈15

MG IV	FeNdB	50, 35, 25 mm	21–31.5	50×10^{-6}–400×10^{-6}	8.0×10^{-3}	1.0–2.5	1200	0.05–0.4 g	≈18
*Lith. battery [19], 2018									$\approx 40 \times 10^{6}$
*supercap [20], 2010									≈3–5
*fuel									$\approx 4 \times 10^{9}$
*U_{235}									$\approx 9 \times 10^{16}$

3. Design of Electromagnetic Transformation Method of Renewable Energy

The first published work by world-class authors in the field of linear motion generation was published at West Virginia University [6], focusing on the engine and alternator section in Figure 8.

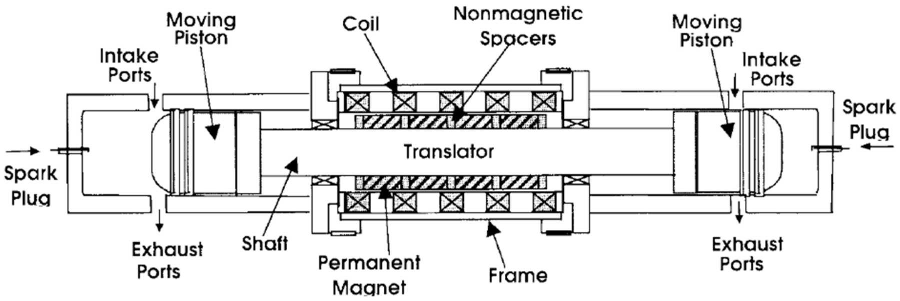


Figure 8. Schematic representation of a linear internal combustion engine coupled to an alternator [6].

The direct design of a linear synchronous generator, Figure 10, and the distribution of the magnetic flux density by finite element analysis is dealt with in [13]. The generator consists of a stator made of coils and a rotor made of permanent magnets in Figures 10 and 11.

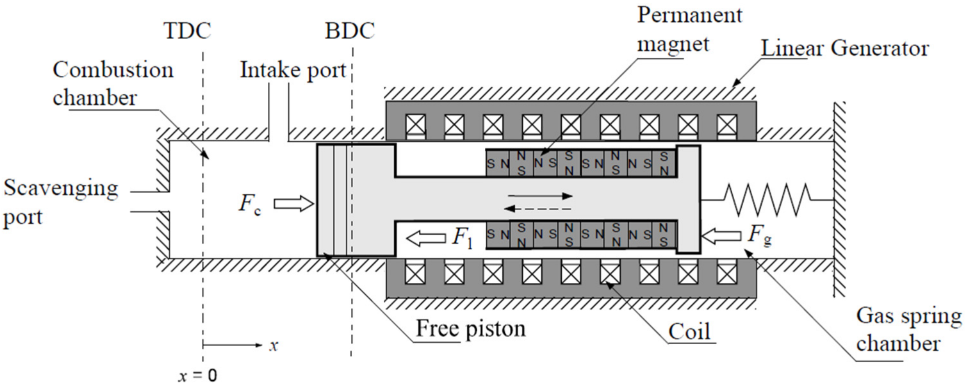


Figure 9. Schematic diagram of the linear alternator design [13].

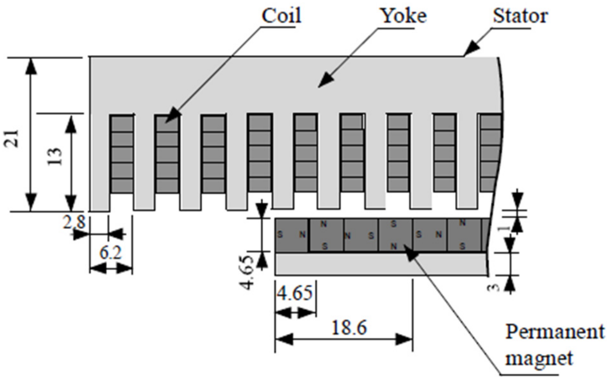


Figure 10. Enlarged view of the basic structure of the linear alternator and the location of the permanent magnets [13].

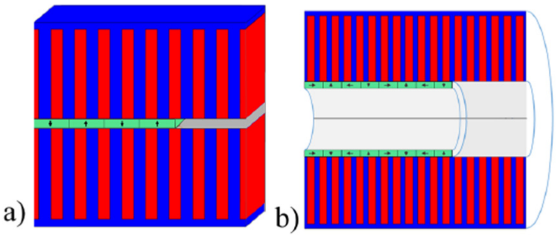


Figure 11. Concept of a) flat (planar) and b) circular (tubular) design [45].

Research involving the analysis of linear machine concepts that are applicable in linear motors and the division into concepts can be found in papers [2–4], in terms of the proposed geometry (planar or tubular) is mentioned in more detail in paper [45]. The use of 3D modeling and simulation, analysis and subsequent comparison with experimental models of a linear generator is available, for example, in authors [17,38–40]. Analysis and experiment for reducing the stator/rotor adhesion force with respect to the geometry of the arrangement, shape, distribution of the permanent magnets used is presented in [38]. Sub-problems, measurement or numerical analysis are addressed in the texts [13,17,40] and provide research recommendations for device miniaturization. The simulation and experimental verification of the replacement circuit parameters, rotor/stator core losses using FEM are dealt with by the authors in text [16], the evaluation of the influence of electrical parameters, load and drive dynamics is described in papers [11–15].

According to published works [17,40], the change in magnetic flux $\boldsymbol{\Phi}$ according to Faraday's induction

$$\underbrace{\oint_{\ell} \boldsymbol{E}(t)\cdot d\ell}_{\Phi} = -\int_{S} \frac{\partial \boldsymbol{B}(t)}{\partial t} dS + \oint_{\ell} \left(\boldsymbol{v}(t)\times\boldsymbol{B}(t)\right)\cdot d\ell \quad (1)$$

,

where $\boldsymbol{E}$(t) is the electric field intenzity vector, $\boldsymbol{B}$(t) denotes the magnetic flux density vector (induction), v(t) indicates the speed of the shift of the generator core position in time (instantaneous speed), S denotes the cross section of the magnetic flux regions , ℓ denotes the curve along the boundary of area S.

The simple concept, which has been tried before [2–4,17,40], can be applied to the electromagnetic part of the harvester and schematically illustrated as shown in Figure 12. The equation of motion of the arrangement of the electromagnetic part of the generator/harvester, the force field couplings and the linear motion of the moving part can be expressed according to the following form

$$m_m \ddot{x} + l_c \dot{x} + k x = f_{mag}(B,v,t) + f_{mech}(t) \tag{2}$$

Where m_m is the mass of the moving part of the generator system, l_c is the damping coefficient, k is the stiffness coefficient, x is the position of the body, $\dot{x}$ is the velocity of the moving part, $\ddot{x}$ is the acceleration of the moving part, f_{mag}, is the force acting on the moving part by interaction with the magnetic field, f_{mech} is the force of mechanical motion of the moving part the linear actuator.

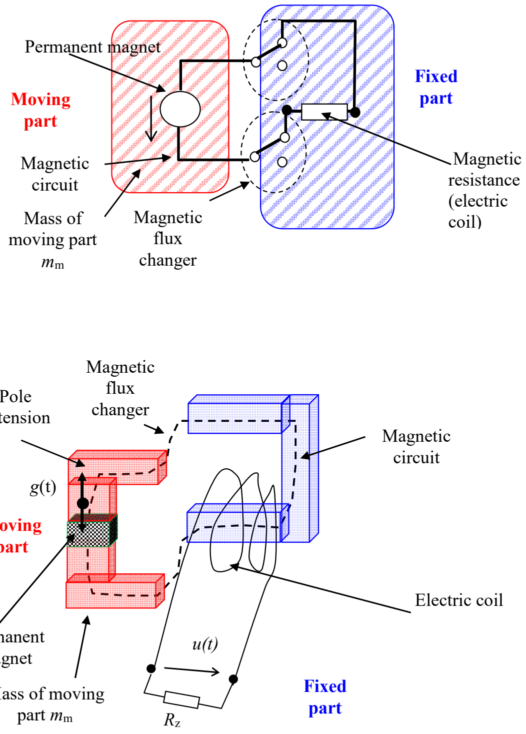


Figure 12. The principle of basic magnetic circuit design principle for a linear arrangement with one degree of freedom in the mechanical part, single-acting.

Then the induced voltage in the winding coil u(t) or u_1(t) u_2(t) is composed as

$$u(t) = u_1(t) + u_2(t),$$
$$u(t) = U_{mag} \left| g(t) \right| \tag{3}$$

Where U_{mag} is the maximum value of the induced coil winding voltage for a single-line arrangement (Figure 12) under the given conditions, g(t) is a function of the time dependence of the magnetic field corresponding to the system parameters and the dynamics of the moving part of the generator. The resulting induced voltage for the double-acting arrangement, Figure 13., changes with respect to the single magnetic circuit arrangement to the form

$$u(t) = U_{mag}\, g(t) \tag{4}$$

In order to achieve a concept with an efficient harvester yield with linear motion, it is necessary to accept the dynamic parameters of the system so that the conceptual design does not drastically reduce the energy conversion efficiency of the generator system right at the beginning of the design. As already compared with other motion/vibration harvester designs [40], the moving part of the electromagnetic part of the generator for the zenith linear actuator concept must have a mass parameter m_m of the moving part close to the minimum value (solution of relation (2)), Figure 14. In the case of the moving part of the generator model, the mass of the moving part must be close to the minimum. From the work [2], the instantaneous value of the electric current through the winding i(t) at the electric load at the terminals of the winding R_z can be derived and formulated.

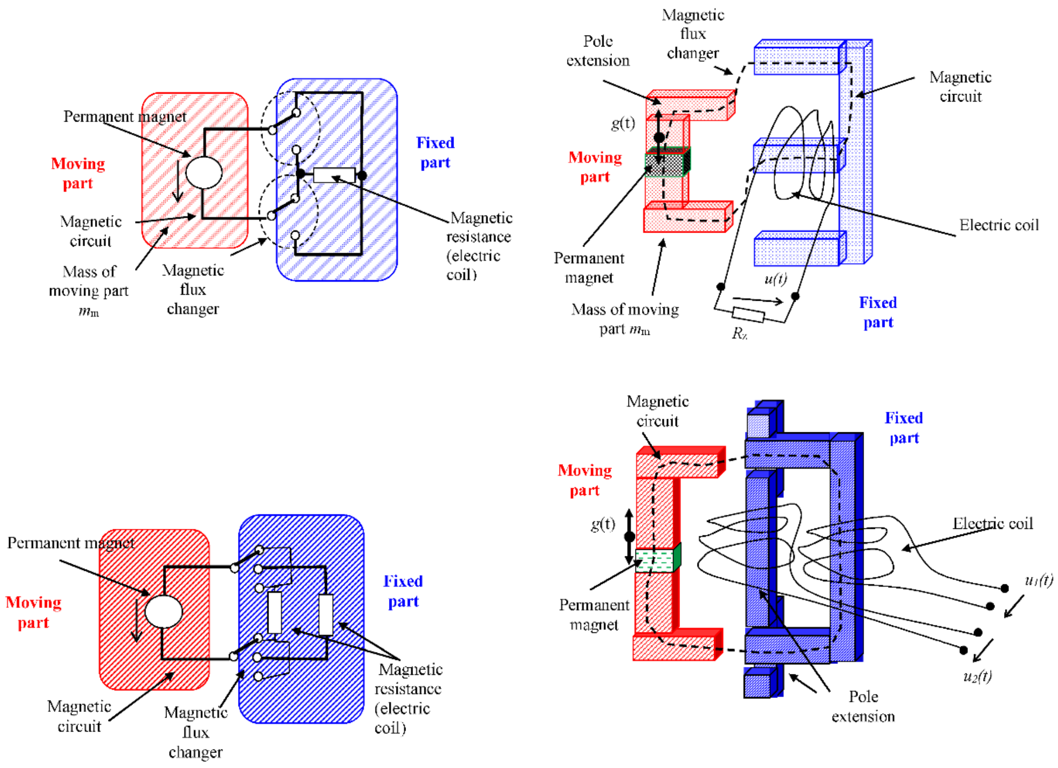


Figure 13. The principle of basic magnetic circuit arrangement for a linear moving system with one degree of freedom in the mechanical part, double-acting arrangement.

If the electromagnetic arrangement of a linear generator is considered, for example, as shown in Figure 14, it will be driven by the corresponding unit (internal combustion engine) in the dynamic non-volatile state (5), a general mathematical model of the form

$$m\,\ddot{z} + l_c\,\dot{z} + k\,z = F_z \tag{5}$$

where *m* is the mass of the moving part of the generator, l_c is the damping, *k* is the stiffness of the "rotor/stator" linear arrangement of the generator, F_z is the forces acting on the dynamics of the moving part of the generator.

$\ddot{z} = \frac{d^2 z}{d t^2}$ is the acceleration of the moving part $\dot{z} = \frac{d z}{d t}$ is the velocity of the moving part $\boldsymbol{v}$. The mass *m* includes the mass of the magnetic parts, the yoke and the mass of the attachment m_m, the force F_z is determined in the first view and depends on the masses of the moving part.

$$F_z = (m_m)\left(g_z + g(t)\right). \tag{6}$$

In this relation, the influence of changes in the external gravity g_z can be neglected, because conditions of rationally slow motions are considered and therefore the gravity of the reference system can be considered constant. Its magnitude of amplitude with respect to the function *g*(t) is an order of magnitude smaller. Then the force is expressed as

$$F_z = m_m g(t). \tag{7}$$

Faraday's law of induction (1) is used to formulate the principle and then the design of the active part of the generator, and to transform the motion energy of the system into electrical energy, through induction to the electrical voltage in the inserted conductor of the electric winding, its part is in the form

$$\oint_{\ell} \boldsymbol{E}(t)\cdot d\boldsymbol{l} = -\frac{d\Phi(t)}{dt}. \tag{8}$$

If a thin conductor in the form of a closed loop is inserted into such a variable electric field, an electric current i(t) flows through it. Let us denote the current that flows through the closed loop without the presence of an external source of electric voltage as the induced current. The magnetic flux $\boldsymbol{\Phi}$ is generated by an external magnetic field. It is valid

$$u_T(t) = -\frac{d\Phi(t)}{dt} \quad . \qquad (9)$$

According to the principle of conservation of energy, the equation of state for the problem under consideration can be constructed. The kinetic energy, obtained by the motion of the generator core, can be written using the expression

$$W_k = \frac{1}{2} m_m v^2 \quad , \qquad (10)$$

$$W_p = m_m \, g(t) z \quad , \qquad (11)$$

where v is the mean velocity of the motion of the generator core. The energy stored in e magnetic field source (permanent magnet) is written in the form

$$W_m = \int_{V_M} \frac{1}{2} B_M H_M \, dV \quad , \qquad (12)$$

where B_M, H_M are the magnetic induction and intensity at the working point of the permanent magnet, V_M is the volume of the magnet. The energy, converted into heat, in the winding of the loaded coil (for our problem, an irreversible form of energy) is written in the form

$$W_T = \int_{V_{Jc}} \frac{1}{2} \frac{J^2}{\gamma} dV \quad , \qquad (13)$$

where γ is the specific conductance of the coil conductor, J is the current density vector , B is the magnetic induction vector, V_J is the volume of the electrically conductive components, V_{Jc} is the volume of the coil conductors. The energy that dampens the oscillatory motion of the generator core due to the electrical load on the coil terminals is written as

$$W_V = \int_{\ell} \int_{V_J} f_m \, dV \cdot \boldsymbol{n} \, d\ell = \int_{\ell} \int_{V_J} (\boldsymbol{J} \times \boldsymbol{B}) dV \cdot \boldsymbol{n} \, d\ell \quad , \qquad (14)$$

where f_m is the specific force acting on the motion part of the generator, $\boldsymbol{n}$ is the normal vector in the direction of the electric current flow i(t), dℓ is the displacement length due to the specific force. From expressions (10) to (14), the equation of state is obtained

$$m\,g\,dz - \int_{\ell} \int_{V_J} (J \times B) dV \cdot \boldsymbol{n} \, d\ell - \int_{V_{Jc}} \frac{1}{2} \frac{J^2}{\gamma} dV = \frac{1}{2} m \left(\frac{dz}{dt} \right)^2 \quad , \qquad (15)$$

$$\eta \int_{V_M} \frac{1}{2} B_M H_M \, dV = \frac{1}{2} m \left(\frac{dz}{dt} \right)^2 \quad , \qquad (16)$$

where dz is the deflection of the generator core, η is the energy utilization efficiency of the permanent magnet module. After adjusting and inserting the expressions for voltage and current, the relations (16)

$$m\,g\,dz - \int_{\ell} \int_{V_J} \left(\frac{I}{S_v} \boldsymbol{n} \times \boldsymbol{B} \right) dV \cdot \boldsymbol{n} \, d\ell - \int_{V_{Jc}} \frac{1}{2} \frac{\left(\frac{I}{S_v} \right)^2}{\gamma} dV = \frac{1}{2} m \left(\frac{dz}{dt} \right)^2 \quad , \qquad (17)$$

$$\eta \int_{V_M} \frac{1}{2} B_M H_M \, dV = \frac{1}{2} m \left(\frac{dz}{dt} \right)^2 \quad , \qquad (18)$$

where I is the maximum value of the amplitude of the electric current flowing through the coil conductor. Then

$$m\,g\,dz-\int\limits_{\ell}\int\limits_{V_J}\left(\frac{P}{U\,S_v}\boldsymbol{n}\times\boldsymbol{B}\right)dV\cdot\boldsymbol{n}\,d\ell-\int\limits_{V_{Jc}}\frac{1}{2}\frac{\left(\frac{P}{U\,S_v}\right)^2}{\gamma}dV=\frac{1}{2}m\left(\frac{dz}{dt}\right)^2 . \qquad (19)$$

By comparing relations (17) to (19), an expression is obtained from which the order of magnitude of the moving part (core) of the generator can be determined depending on the specified parameters.

$$m\,g\,dz-\int\limits_{\ell}\int\limits_{V_J}\left(\frac{P}{U\,S_v}\boldsymbol{n}\times\boldsymbol{B}\right)dV\cdot\boldsymbol{n}\,d\ell-\int\limits_{V_{Jc}}\frac{1}{2}\frac{\left(\frac{P}{U\,S_v}\right)^2}{\gamma}dV=\eta\int\limits_{V_M}\frac{1}{2}B_M H_M\,dV . \qquad (20)$$

According to relations (2) to (7), the addition of the braking forces gives the basic relation that characterizes the generator system

$$m\ddot{z}+l_c\,\dot{z}+k\,z=m_m g(t)-\int\limits_{V_J}(\boldsymbol{J}_v\times\boldsymbol{B})\cdot\boldsymbol{n}\,dV-\int\limits_{V_{Jc}}(\boldsymbol{J}_{circ}\times\boldsymbol{B})\cdot\boldsymbol{n}\,dV ,$$

$$m\ddot{z}+l_c\,\dot{z}+k\,z=m_m g(t)-\int\limits_{V_J}\left(\left(\boldsymbol{v}\times\boldsymbol{B}_{br}(t)\right)\times\boldsymbol{B}\right)\cdot\boldsymbol{n}\,dV-\int\limits_{V_{Jc}}\left(\frac{i(t)}{S_v}\boldsymbol{n}\times\boldsymbol{B}\right)\cdot\boldsymbol{n}\,dV ,$$

$$m\ddot{z}+l_c\,\dot{z}\,sign(\dot{z})\dot{z}+k\,z=m_m g(t)-\int\limits_{V_J}\left(\left(\dot{z}\times\boldsymbol{B}_{br}(t)\right)\times\boldsymbol{B}\right)\cdot\boldsymbol{n}\,dV-\int\limits_{\ell_{Jc}}\left(i(t)\boldsymbol{n}\times\boldsymbol{B}\right)\cdot\boldsymbol{n}\,d\ell , \qquad (21)$$

where ***B***br is the braking component of the magnetic induction vector, ***J***v is the current density vector of electrically conductive components due to eddy currents, ***J***circ is the current density vector in the coil winding, *i*(t) is the instantaneous value of the coil electric current. Then, the expression for the instantaneous value of the electric current supplied by the generator to the electrical load represented by the impedance *Z* with real component *R*v and *R*z has the form

$$i(t)=\frac{U_{mag}}{(R_v+R_z)}\left[\frac{4}{\pi}\sum_{n_o=1,3,5,\ldots}^{\infty}\frac{\boldsymbol{sin}(n_o\,\omega t)-n_o\,\omega\tau\,\boldsymbol{cos}(n_o\,\omega t)}{k_o\left[1+(n_o\omega\tau)^2\right]}+\left[\boldsymbol{tanh}\left(\frac{T}{4\tau}\right)-1\right]e^{-\frac{t}{\tau}}\right], \qquad (22)$$

where *T* is the period length of the signal, *R*v is the resistance of the real coil, *R*z is the resistance of the load at the output of the generator winding, *L*v is the load inductance *Z*, *t* is the time, is the angular velocity *ω*=2/T, is the time constant, *τ*=(*L*v)/(*R*v+ *R*z).

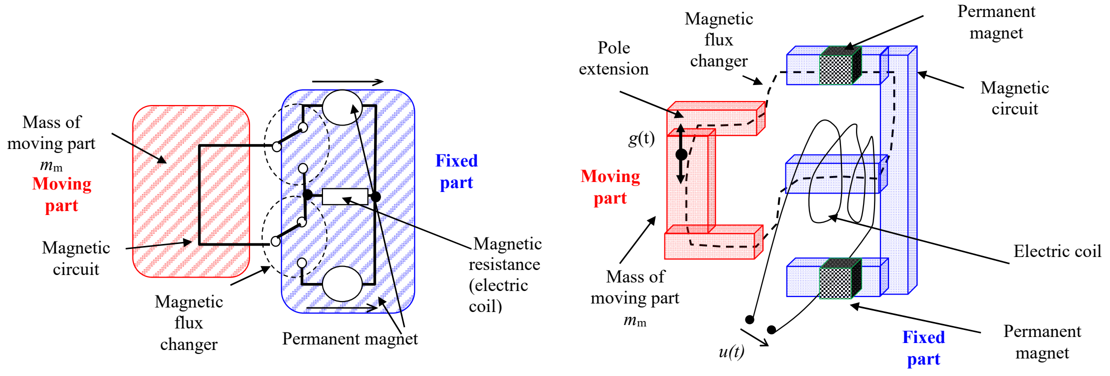
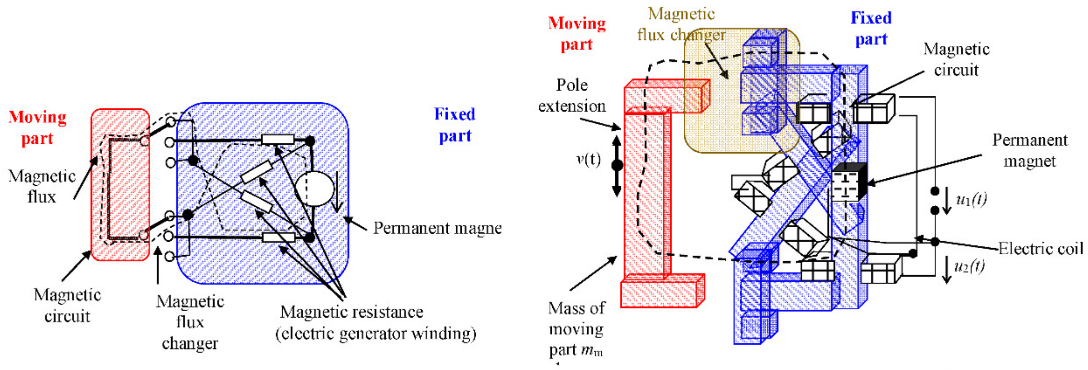


Figure 14. Schematic of a modified magnetic circuit for a linear motion system with minimization of dynamic losses, double-acting arrangement.

To increase the yield (efficiency) of the dynamic energy transformation, Figure 14., generated by the motion, the magnetic circuit layout concept according to Figure 15. can be used.



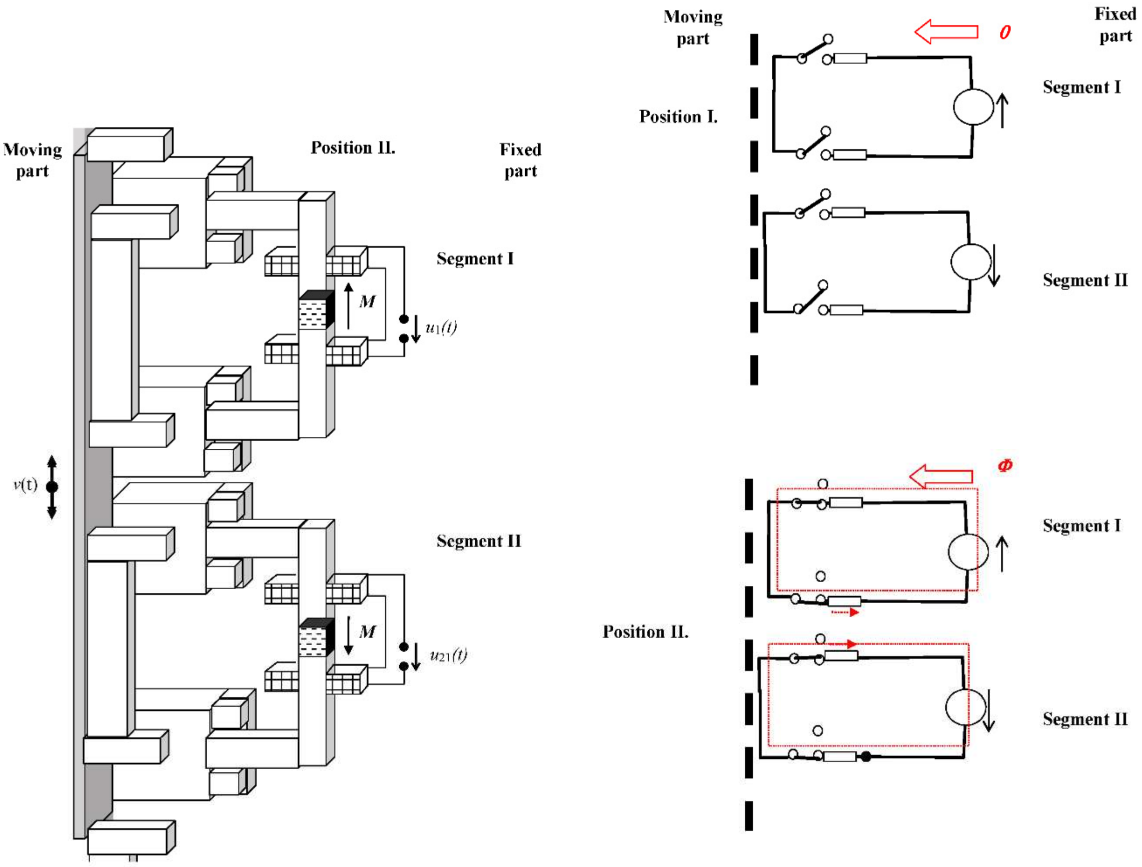
a) b)

Figure 15. Principle of modified magnetic circuit arrangement for maximum yield efficiency of linear motion system with minimization of dynamic losses.

In order to achieve high efficiency of converting motional energy of the generator into electrical energy using Faraday's induction law (1), the magnetic circuit arrangement schematically shown in Figure 14. will be used. Due to the magnetic circuit arrangement of Figure 15., the change in the mange flux dΦ/dx or dΦ/dt of Figure15. is multiply larger. Therefore, a significant magnitude of the induced electric voltage u(t) can be expected in a comparable electric generator winding. Then, in the proposed arrangement, Figure 14., Figure15., the resultant electric voltage u(t). A segment of the magnetic arrangement of the linear generator will be periodically repeated in its design, so the following text will deal with the necessary part of the periodic arrangement of the generator elements.

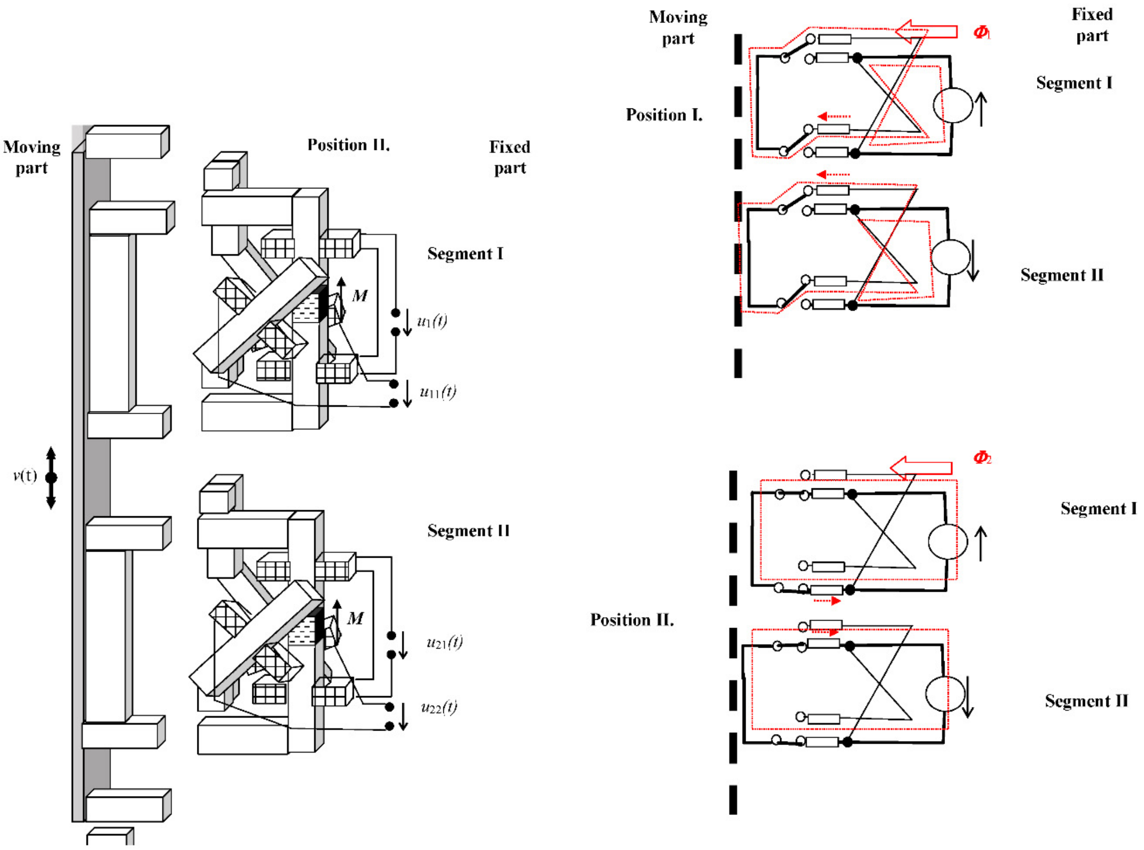
Then for the linear generator for the higher power harvester the basic segment, Figure 14, Figure 15, is concatenated as shown in Figure 16 and Figure 17. In order to achieve high power extraction the magnetic circuit arrangement of Figure 17. can be increased by the arrangement of Figure18.

The magnetic circuit layout and its efficiency is related to the arrangement of the transition of the moving part of the magnetic circuit to the circuit of the fixed part of the generator. The detail is shown in Figure 15 b) - magnetic flux changer. Figure 19. shows several arrangements of details of pole attachments for transferring magnetic flux through the air gap of the moving and static parts of the generator.



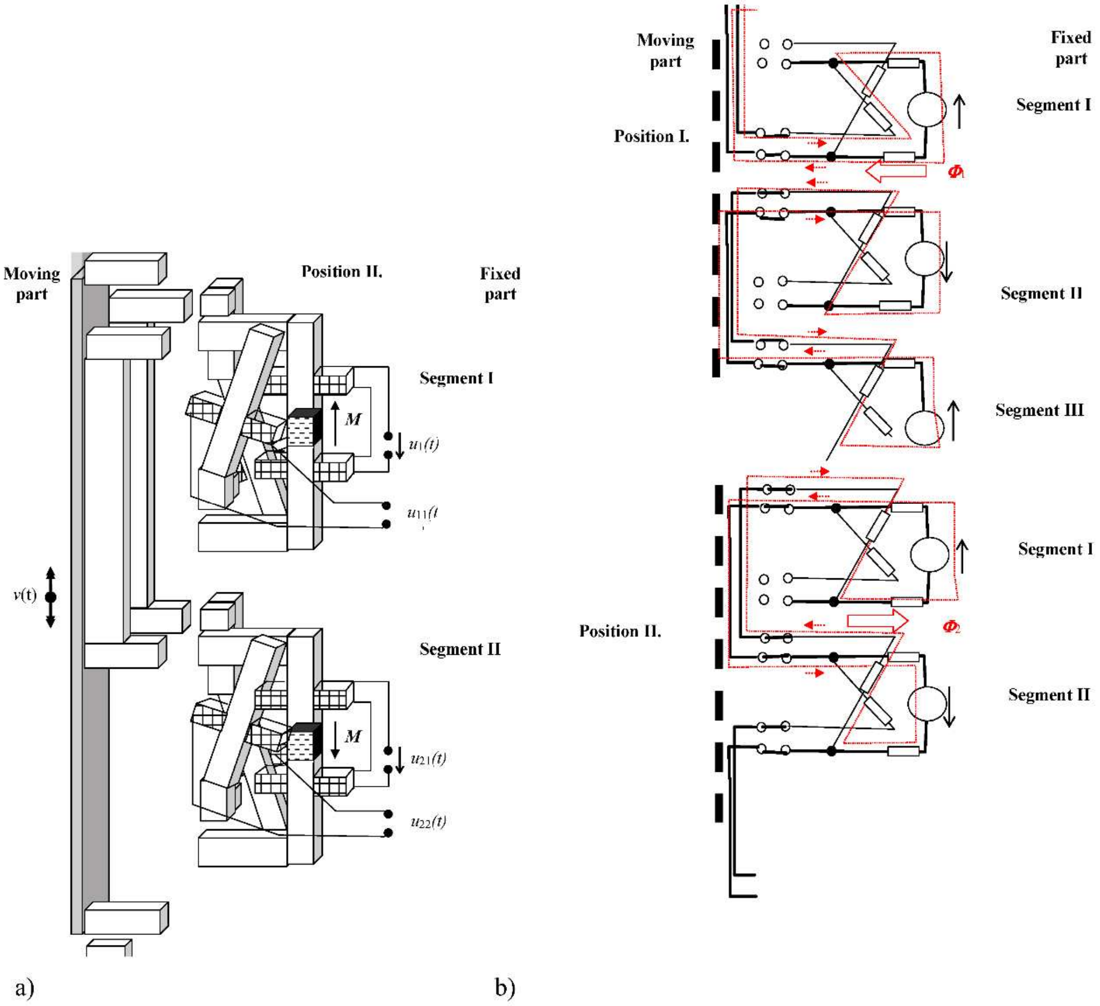
a) b)

Figure 16. Schematic of segment I and II of the single-acting magnetic circuit arrangement of the periodic structure of the linear motion of Figure 15. to achieve the maximum change in magnetic flux of the moving and fixed parts, a) principle geometrical arrangement, b) schematic of the symbolic representation of the magnetic circuit.



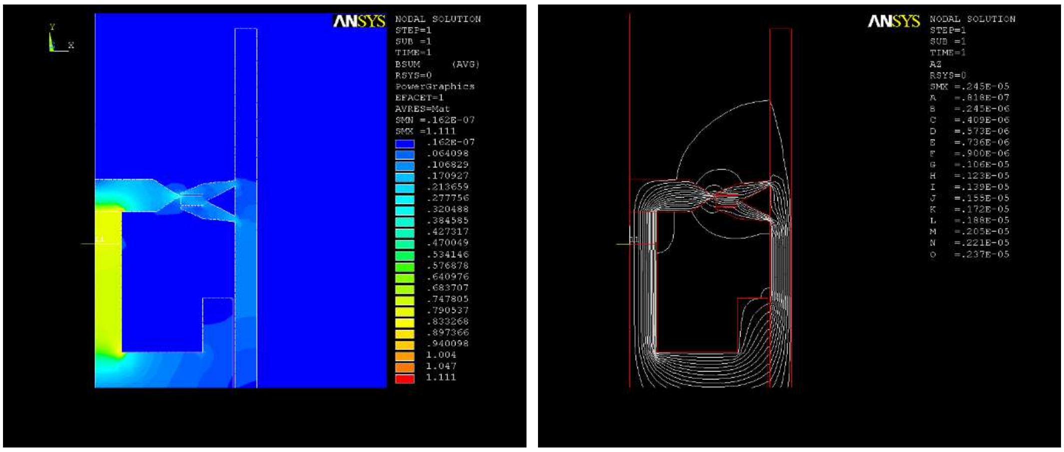
a) b)

Figure 17. Schematic of segment I and II of the double-acting magnetic circuit of a periodic structure of a linear motion to achieve the maximum change in magnetic flux of the moving and fixed parts, a) principle geometrical arrangement, b) symbolic representation of the magnetic circuit.



a) b)

Figure 18. Schematic diagram of segment I and II of the coupled double-acting magnetic circuit of the periodic structure of a linear motion to achieve the maximum change in magnetic flux of the moving and fixed parts, a) principle geometrical arrangement, b) diagram of the symbolic representation of the magnetic circuit.



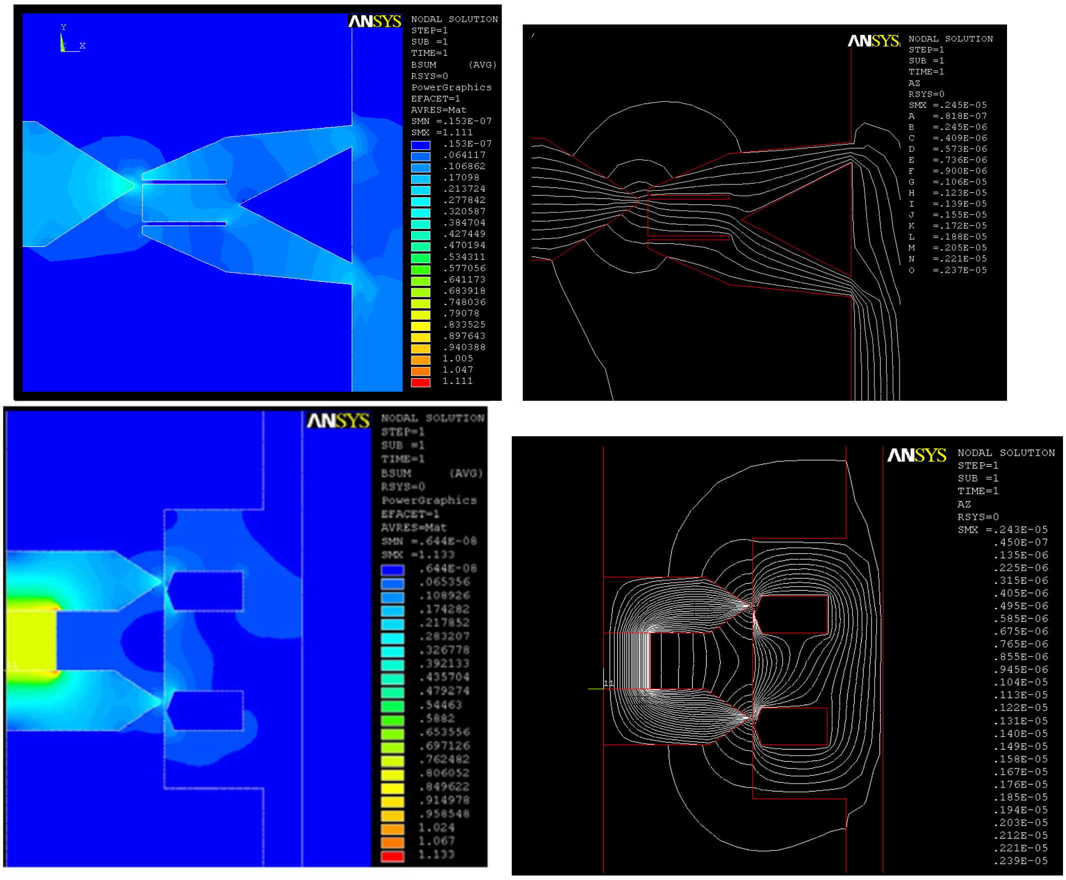


Figure 19. Examples of pole attachment geometry solutions, single or double acting model, Magnetic flux modulus *B* and fluxlines l in the design detail of a magnetic flux converter.

4. Experiments

According to the studies in the introduction of the text, an experimental concept of a generator with a renewable form of energy linear displacement driven generator (compressed gas) arrangement was proposed as shown in Figure 6.The concept uses two piston units Figure 20 b), Figure 20 c), driven by CO_2 or N_2, which are adapted from a CO_2 engine, Figure 20a). The power unit and the link to the electromagnetic generator is schematically shown in Figure 20 b). The theoretical properties of the magnetic flux transition from the moving to the fixed part of the magnetic circuit through air, Figure 19, was used in the design of the experimental embodiment, Figure 20 d) for the generator concept, both the single-acting embodiment of Figure 19 and the double-acting embodiment of Figure 17. Figure Figure 21. shows the single segment setup for the experimental verification concept of the single-acting generator design , Figure 16. Figure 22 a) shows the full setup of the experimental fixture with four segments, in the single-acting design, Figure.16, the setup for the load mode test Z_1=150Ω, Z_2= 1000Ω, Z_3= ∝ Ω. The time history of the instantaneous value of *u*(t) is shown in Figure 22 b).

Φ $B,$

M

$u_1(t)$

$u_{11}(t$

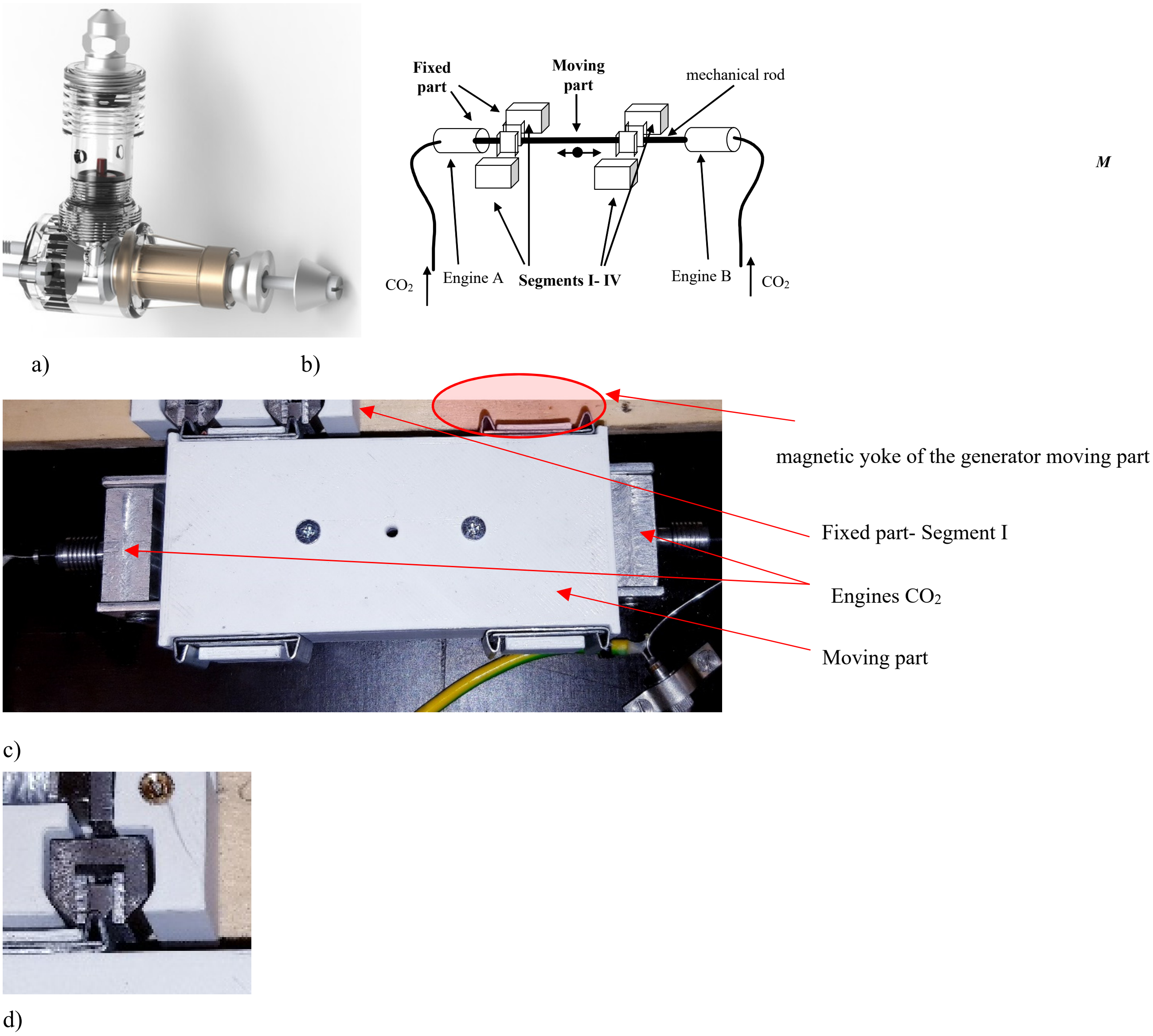


Figure 20. Linear generator drive unit, a) CO_2 engine, b) unit arrangement c) experimental arrangement, d) detail of the pole adapter – flux converter of Segment I (concept from Figure15.).

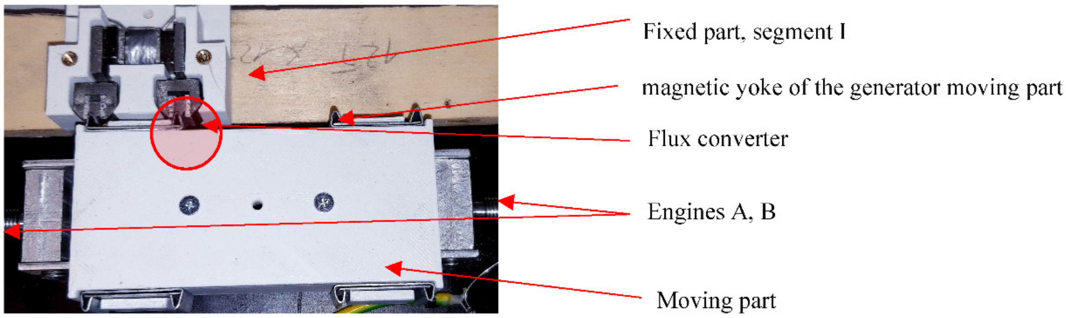
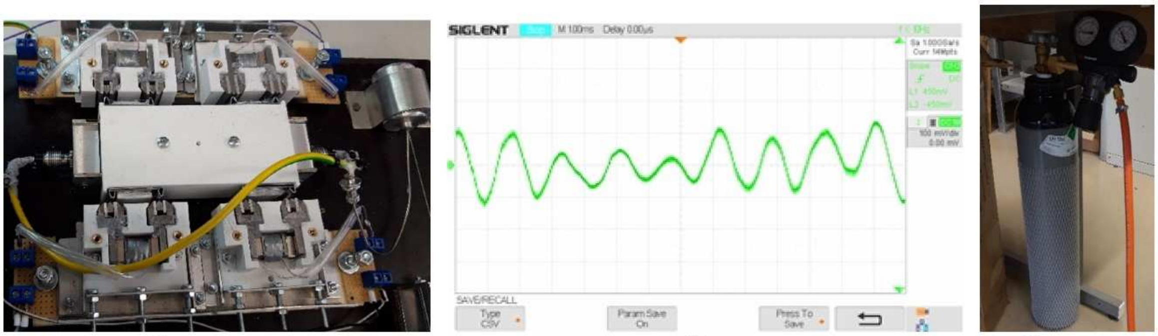


Figure 21. Experimental part of the verification of the principle arrangement of the harvester.



a) b) c)

Figure 22. Experimental fixture for verifying the layout of the harvesting thresher; a) simple concept from Figure 16 b) generator coil output waveforms (Z=∝ Ω), c) N_2 storage tank for driving the experimental generator.

The windings of the coils with turns N_1, N_2,...N_4 of the experimental preparation of the tested generator are connected in series in one sense of polarity of the output voltage on the coil. Figure 22 b) shows the time waveform of the generator output at idle for a simple single-acting variant of the magnetic circuit arrangement. The coil of the Segment I had a number of turns N_1=1000, the linear motion speed was v=4 m/s and the unit was driven by compressed gas N_2 at pressure p=10 bar, Figure 22 c). A comparison of the measurements for one module of concepts I to III of Figures 16 to 18 is shown in Table 2.

Table 2. Comparison of basic measurements of the conceptual layout I- III.

Measurement HV	*type I	**type II	***type III
U_0[V]	0,2	0,3	0,8
U_z[V]@Z_1=150W	0,01	0,02	0,5

*type I ….. According to Fig.16. **type II …. According to Fig.17. ***type III ….. According to Fig.18.

5. Conclusions

Based on our experience with numerical models and subsequent experiments with a microgenerator as a source of a renewable form of energy, we proposed the concept of a powerful generator excited by linear motion, such as a linear piston engine driven by compressed gas. The concept has been modified to achieve high efficiency in converting the motion energy into electrical energy.

Experiments on a scale model showed the feasibility of implementing such an energy conversion system as a harvester and at the same time using a renewable form of energy. The numerical model and the analysis of the model parts significantly accelerated the geometrical design of the arrangement of the key parts of the ectric generator. The selected variants of the magnetic circuit layout were experimentally verified.

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Author Contributions: PF and JZ contributed to the theoretical part, numerical modeling, and design of the experiments, and they also co-wrote the paper; ZS, JD conceived and designed the experiments that allowed partial verification of the effects; and TK with RK modified the manuscript graphically and participated in evaluating the experiments.

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