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DESIGN AND CALCULATION OF A LINEAR RECIPROCATING GENERATOR FOR THERMOACOUSTIC ENGINE

This paper provides an overview of methods for the calculation and design of linear electric generators with permanent magnets for a single-stage thermoacoustic engine operating on the Stirling heat cycle. The proposed methodologies are grouped based on the type of approach used for the calculation. A detailed analysis of the proposed methods and assumptions is conducted, and conclusions are made regarding their feasibility for the design of electric generators with permanent magnets and solid magnetic core elements. The primary assumptions are related to the representation of parameters in the equivalent circuit of the magnetic systems. It is established that the majority of the methodologies do not account for the influence of eddy currents in the solid elements of the magnetic core. It is demonstrated that many approaches aimed at designing electric machines with permanent magnets can be adapted to linear electric generators. The designed linear generator is intended for use in a thermoacoustic device (TAD). The development of the TAD utilized well-established theoretical and practical advancements in the field of thermoacoustics. Several laboratory prototypes were also developed to refine the energy source, which will serve as the foundation *for a cogeneration thermal power plant of ultra-low capacity. This power plant will comprehensively produce both electrical and thermal energy for autonomous consumers.*

Keywords: linear generator, reciprocating motion, Stirling, permanent magnet generator, magnetic core, coil.

Introduction

Modern energy production technologies focus on developing systems that can provide electricity efficiently and sustainably while using as few resources as possible. A particularly important area of research is the creation of ultra-low power energy sources for autonomous systems, designed to operate on a wide range of fuels. These systems aim to ensure reliable energy supply for devices that work independently, reducing dependence on traditional power networks and improving overall energy efficiency One of the promising directions is the development of a thermoacoustic electrical energy source with linear generators featuring reciprocating motion, capable of operating using permanent magnets and inductive elements. Such generators convert the mechanical energy of reciprocating motion into electrical energy [1, p. 148].

One of the key aspects in the design of a linear generator is the stability of the magnetic flux generated by the permanent magnet [2]. Violation of this condition leads to the generation of electromotive force (EMF) in the moving element of the generator and increased heat dissipation due to eddy currents. This can reduce the efficiency of the device and lead to mechanical damage to the magnets, especially if they are made of certain materials.

Materials and Methods

A key requirement in the design of a linear generator is maintaining a constant magnetic flux produced by the permanent magnet [3, pp. 20–25; 4, pp. 3445–3462], as any fluctuations induce an EMF in the moving part, which in turn leads to the formation of eddy currents and subsequent overheating of the magnet beyond allowable limits. This issue is particularly critical for neodymium magnets, which are highly sensitive: even a 1 °C temperature increase results in an approximately 0.3 % decrease in residual induction and a 0.5 % reduction in coercive force. The magnet must be securely fixed in place to ensure that it does not shift or move inregions where the surrounding materials have different magnetic properties. At the same time, it is important that the magnetic flux produced by the armature remains stable and consistent in the solid ferromagnetic sections of the moving element, so that the generator can operate reliably and maintain proper energy conversion.. A linear generator is not very efficient and is limited in power to about 1 kW due to economic factors, but it is sufficiently suitable for ultra-low power energy sources. Further increasing its power significantly raises both the cost and mass, for instance, due to the growing cost of neodymium magnets. Therefore, it remains quite efficient for generating electrical power not exceeding 1 kW. Descriptions of this type of electrical machine and information about their design are provided in [5, p. 253].

Results and Discussion

The designed linear generator is planned to be used at °C. In the development of the Thermoacoustic Device (TAD), well-known theoretical and practical achievements in the field of thermoacoustics, previously discussed in [6, P. 60–66]; [7]; [8, P. 580–582]; [9]; [10]., were used. Various laboratory samples were also developed, on which the energy source was tested. This energy source will later form the basis of a cogeneration heat and power plant of ultra-low capacity. This power plant will simultaneously produce both electrical and thermal energy for autonomous consumers. Figure 1 shows the experimental laboratory energy source based on a one-stage ring TAD with a linear generator.

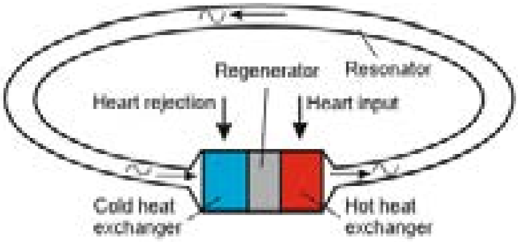


Figure 1 – Single-stage TAD

One of the key requirements in designing a linear generator is ensuring the stability of the magnetic flux produced by the permanent magnet. Any variation in this flux induces an electromotive force in the moving element, leading to the formation of eddy currents and potential overheating of the magnet. This issue is particularly critical for thermally sensitive neodymium magnets, where a temperature increase of just 1 °C results in a 0.3 % decrease in residual induction and a 0.5 % reduction in coercive force. In the proposed design, the magnet must be securely held in place so that it does not move relative to surrounding materials with different magnetic properties. At the same time, it is important to keep the magnetic flux produced by the armature stable and consistent in the parts of the moving element that are made of solid ferromagnetic materials. This ensures reliable operation of the generator and prevents unwantedfluctuations in performance.

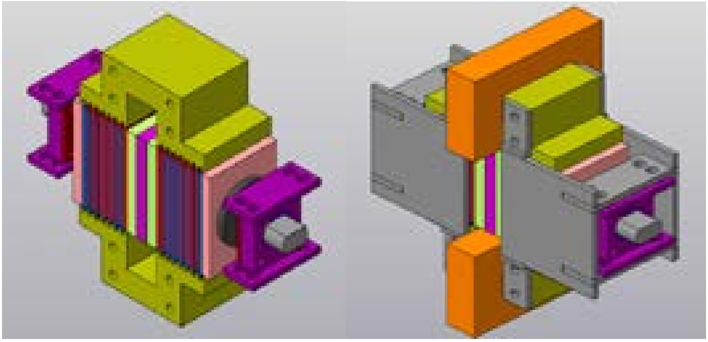
The SGL-0.1 prototype is specified as follows: it is a synchronous, two-pole generator with a permanent magnet located on the rotor. Each unidirectional stroke generates a complete EMF cycle, which corresponds to the maximum linear displacement of 4.21 mm-this value is equal to the tooth pitch of the moving element and ensures that the magnetic circuit undergoes one full change in relative alignment per stroke. Such coordination between the mechanical displacement and the magnetic geometry provides predictable periodicity of the induced EMF and minimizes harmonic distortions in the output signal. The nominal operating frequency of the generator is 50 Hz, achieved under conditions of stable reciprocating motion. The maximum linear speed of the moving element is 661 mm/s, which defines the upper operational limit for the generator while maintaining efficient electromagnetic energy conversion. Operating above this speed could reduce conversion efficiency and cause deviations in the generated EMF. The generator is designed to deliver a nominal electrical output power of 100 W, along with a mechanical conversion force of 302.4 N, which represents the effort required to transform the kinetic energy of the moving element into usable electrical energy. The rectified output voltage is 28 V DC, making the generator compatible with low-voltage storage systems and batteries, and aiſowing stable integration into autonomous or off-grid energy setups. At the generator terminals, the RMS phase voltage reaches 31 V under nominal conditions, ensuring reliable power delivery to connected loads. Maintaining this voltage and current stability is critical, as variations in speed, load, or magnetic alignment could affect the efficiency and performance of the generator. When paired with a 24-V nominal battery, ensuring efficient charging and compatibility with standard energy-storage configurations. The RMS phase current is 3.23 A under nominal loading conditions. Air cooling is utilized to maintain thermal stability throughout operation, and the generator is intended to work within power systems where the grid frequency does not exceed 60 Hz.

The structural constraints of the design include an inner shaft diameter of no less than 30 mm to ensure sufficient mechanical rigidity and space for auxiliary components. The overall axial length of the generator must not exceed 75 mm, ensuring that the device remains within the specified design envelope. The stator itself has an axial length of 128 mm, while the total length of the housing, including the bearing shields, is 72 mm. These compact dimensions make it possible to integrate the generator into mechanical assemblies with limited space, while still maintaining proper mechanical and magnetic alignment for efficient operation. The minimum air gap is set at 0.3 mm, ensuring both mechanical clearance and the magnetic coupling necessary for stable operation without excessive flux leakage.In the initial position of the generator, the tooth axes of the upper stator stack are aligned with the tooth axes of the outer upper part of the rotor, while simultaneously corresponding to the axes of the slots on the rotor's lower side. After passing through the winding, the flux moves into the right part of the stator, returns to the rotor, and completes its path at the magnet's south pole, following the route of least magnetic reluctance. It is critical that in the initial position, the lux through the lower stator package is minimal due to the higher magnetic resistance of its path.

When the moving element shifts to the left, the misalignment between the stator and rotor teeth decreases the flux in the upper stator package while increasing it in the lower package.

Theoretical studies, including computer simulations and numerical experiments, were conducted using ANSYS software. The linear generator, shown in Figure 3, incorporates a moving rotor that consists of a shaft (Figure 2); a square permanent magnet with an internal hole, magnetized horizontally; two steel 45 bushings at the magnet edges mounted on the shaft with a rectangular external profile; and rectangular laminations made from 0.5 mm thick electrical steel 2013.

Figure 2 – Laboratory sample of a single-stage TAD



а б

Figure 3 – Computer model of a linear generator

The moving rod, which is connected to the Stirling engine, displaces the moving element relative to a pair of The design incorporates «P-shaped» magnetic cores, each wound with coils. As the moving element travels upward, the magnetic flux coupled with the coils of the upper core increases, while the flux through the coils of the lower core decreases accordingly. The obtained results have been processed and subjected to correlation analysis using Excel software.

The results include the following parameters, calculated as follows:

Active length of each stator (rotor) package – $L_a = 44$mm;
Width of the rotor package at the teeth – 60 mm;
Number of tooth divisions on the rotor package – 7;
Distance between stator packages – 60.6 mm;
Number of teeth on one half of the stator package – $z_1 = 8$;
External dimensions of the magnet – 44×58 mm;
Magnet 45SH, residual induction – $B_0 = 1.32$ Тл; coercive force – $H_c = 10500$ А/см; coercive force of the magnet – $F_c = 10500 \times 0.7 = 7350$

The flux of the 45SH magnet (preliminary):

$$\Phi_m = S_m B_m / \sigma = [(0.058 \cdot 0.044 - \frac{\pi \times 0.02^2}{4})1.32]/1.05 = 0.00234 \text{ Wb}$$

.

Here: $S_m = 0.002552 - 0.00031 = 0.002244$ mm2 – magnet cross-section; B_m magnet induction; $\sigma = 1.2$– magnet scattering coefficient.

Constant component of magnetic conductivity of the air gap:

$$\lambda_0 = \frac{\mu_0}{\delta \cdot k_\delta} = \frac{4\pi \times 10^{-7} \times 0.533}{0.3 \times 10^{-3}} = 2.23 \times 10^{-3} \text{ (H/m2).}$$

Here: μ_0– magnetic permeability of air; $\delta = 0.3$mm - air gap; k_δ– Carter's coefficient.

Variable component of air gap conductivity:

$$\lambda_1 = \beta \times \lambda_0 = 0.62^2 \times 2.23 \times 10^{-3}/2 = 0.43 \times 10^{-3} \text{ (H/m2).}$$

Here: β – is the air gap conductivity pulsation coefficient. The cross-sectional area of the tooth-slot zone on one half of the stator package:

$$S_m = 7t_z \times L_a = 7 \times 4.21 \times 10^{-3} \times 0.044 = 0.00130 \text{мм2;}$$

Maximum conductivity along the path of the magnet flux through two air gaps:

$$\lambda 0_1{}^{-3}{}_{max} \text{ (H/m2).}$$

Minimum conductivity along the path of the magnet flux through two air gaps:

$$\lambda 0_1{}^{-3}{}_{min} \text{ (H/m2).}$$

Maximum magnetic resistance:

$$R \frac{1}{\lambda n_{min} \frac{1}{0.9 \times 10^{-3} \times 0.0013}{}_{max}} .$$

Magnet resistan

$$R \frac{1}{\lambda n_{max} \frac{1}{1.33 \times 10^{-3} \times 0.0013}{}_{max}} .$$

$$R_{magn} = \frac{F_c}{B_0 S_m} = \frac{7350}{1.32 \times 0.002552} = 2181890.$$

Simplified magnetic equivalent circuit of the linear generator is presented in Figure 14.

Magnetic flux of the magnet based on the equivalent circuit calculation –

$$F_{m1} = F_c / R_{перм} = \frac{7350}{2527192} = 0.00291 \text{ Bb}$$

Electromotive force (EMF) of open circuit in a single coil – 15.5 B.

Open-circuit electromotive force (EMF) with a margin for voltage drop – 17.5 Wb.

Number of turns in the coil - 286/

Coil cross-section – $20 \times 20 = 400$ mm2.

Copper fill factor of the slot – 0.85. Wire cross-section (preliminary) – 1.19 mm2.

Selection of the wire: PNET- $d_{wire} = 1.20$mm; $S_{wire} = 1.131$ mm2.

$$r_{\phi} = 2\rho \frac{w_k L_{sch}}{S_{np}} = \frac{2 \times 286 \times 0.172}{57 \times 1.131} = 1.52 \text{ Om.}$$

Coil inductance:

$$L_k = 0.5\lambda_0 S_n w_k^2 = 0.5 \times 2.23 \times 10^{-3} \times 0.0013 \times 286^2 = 0.1185 \text{ H.}$$

Inductive reactance of the coil:

$$X_k = 2\pi f L_{\phi} = 37.23 \text{ Om.}$$

The inductive reactance of a phase is determined by passing through two air gaps, since the coils in the phase are connected in opposite directions:

$$L_{\phi} = 0.5 \times 0.1185 \times 0.1924 = 0.0114 \text{ H;}$$

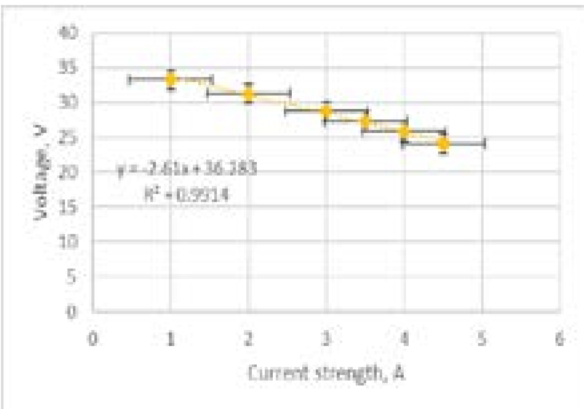


Figure-4 – Dependence of the change in voltage at the terminals of a linear generator on the increase in load current

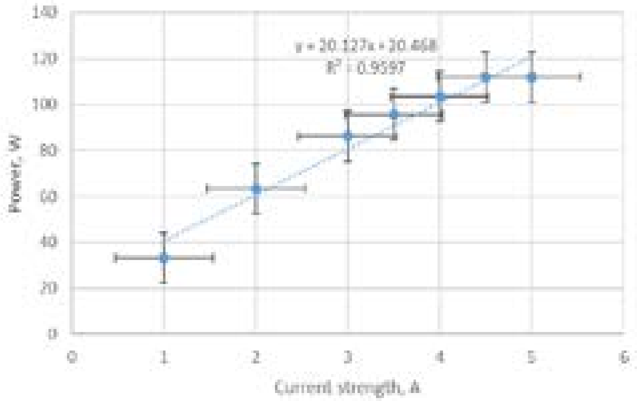


Figure-5 – Dependence of the change in electrical power at the terminals of the linear generator on the increase in load current.

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Conclusions

The linear generator is a rather complex electrical machine both in terms of design and calculation, as well as in operation. Its setup process is quite intricateFor electrical power generation above 1 kW, a three-phase synchronous generator with a rotating rotor offers higher efficiency. However, the use of permanent magnets significantly increases the cost of such generators, making them more expensive than other types. Another drawback is their relatively large mass, which can limit their applicability in compact systems. These generators are primarily employed for converting reciprocating motion, where the armature moves back and forth over a fixed distance and at a controlled speed, allowing effective transformation of mechanical energy into electrical energy. Despite all the drawbacks of the designed generator, it is important to note that it is ideally suited for a single-stage thermoacoustic engine operating on the Stirling cycle, which can be used as a power source.

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ТЕРМОАКУСТИКАЛЫҚ ҚОЗҒАЛТҚЫШҚА АРНАЛҒАН СЫЗЫҚТЫҚ КЕРІ ГЕНЕРАТОРДЫ ЖОБАЛАУ ЖӘНЕ ЕСЕПТЕУ

Бұл мақалада Стирлинг циклі бойынша жұмыс істейтін бір сатылы термоакустикалық қозғалтқыш үшін тұрақты магниттік сызықтық электр генераторларын есептеу және жобалау әдістеріне шолу жасалады. Ұсынылған әдістер қолданылатын есептеу тәсілінің түріне қарай топтастырылған. Ұсынылған әдістер мен болжамдарға егжей-тегжейлі талдау жүргізілді, олардың тұрақты магниттері мен магниттік ядроның қатты элементтері бар электр генераторларын жобалау үшін қолданылуы туралы қорытындылар жасалды. Негізгі болжамдар магниттік жүйелердің эквивалентті схемасындағы параметрлерді ұсынумен байланысты. Көптеген әдістер магниттік ядроның қатты элементтеріндегі құйынды токтардың әсерін ескермейтіні анықталды. Тұрақты магнитті Электр машиналарын жобалауға бағытталған көптеген тәсілдерді сызықтық электр генераторларына бейімдеуге болатындығы көрсетілген. Әзірленіп жатқан сызықтық генератор термоакустикалық құрылғыда (ТАД) пайдалануға арналған. ТАД-ның дамуы термоакустика саласындағы *жақсы қалыптасқан теориялық және практикалық жетістіктерге сүйенді. Сондай-ақ, ультра төмен қуатты когенерациялық жылу электр станциясының негізі болатын энергия көзін жақсарту үшін бірнеше зертханалық прототиптер жасалды. Бұл электр станциясы Автономды тұтынушылар үшін электр және жылу энергиясын кешенді түрде өндіреді.*

Кілтті сөздер: сызықтық генератор, кері қозғалыс, Стирлинг, тұрақты магниттік генератор, магниттік өзек, катушка.

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ПРОЕКТИРОВАНИЕ И РАСЧЁТ ЛИНЕЙНОГО ВОЗВРАТНО-ПОСТУПАТЕЛЬНОГО ГЕНЕРАТОРА ДЛЯ ТЕРМОАКУСТИЧЕСКОГО ДВИГАТЕЛЯ

В данной статье представлен обзор методов расчета и проектирования линейных электрических генераторов с постоянными магнитами для одноступенчатого термоакустического двигателя, работающего по циклу Стирлинга. Предложенные методики сгруппированы в зависимости от типа используемого подхода к расчету. Проведен детальный анализ предложенных методов и допущений, сделаны выводы о их применимости для проектирования электрических генераторов с постоянными магнитами и твердыми элементами магнитного сердечника. Основные допущения связаны с представлением параметров в эквивалентной схеме магнитных систем. Установлено, что большинство методик не учитывают влияние вихревых токов в твердых элементах магнитного сердечника. Показано, что многие подходы, направленные на проектирование электрических машин с постоянными магнитами, могут быть адаптированы для линейных электрических генераторов. Разрабатываемый линейный генератор предназначен для использования в термоакустическом устройстве (ТАД). Разработка ТАД опиралась *на хорошо зарекомендовавшие себя теоретические и практические достижения в области термоакустики. Также было создано несколько лабораторных прототипов для совершенствования источника энергии, который станет основой когенерационной тепловой электростанции ультранизкой мощности. Эта электростанция будет комплексно производить как электрическую, так и тепловую энергию для автономных потребителей.*

Ключевые слова: линейный генератор, возвратно-поступательное движение, Стирлинг, генератор с постоянными магнитами, магнитный сердечник, катушка.

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