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## MODELING AND ANALYSIS OF A GENERATOR WITH PERMANENT AND VARIABLE MAGNETS

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**Abstract.** This paper addresses the efficiency gap in compact, self-starting electric generators for autonomous devices, where mechanical and electrical losses degrade output and lifetime. We study a pulse-controlled generator with a pendulum-inertial cone rotor and dual magnetic excitation – constant field for stabilization and alternating field for adaptive energy injection – targeted at maximizing conversion from mechanical oscillations to electrical power. A time-domain model with realistic losses (bearing friction, coil resistance, current/voltage limits) was implemented in Python/NumPy and validated by numerical experiments over 0–10 s. Parameter sweeps covered moment of inertia, friction coefficient, load resistance, pulse amplitude and duration, number of turns, and magnetic flux; outputs included angular speed, induced EMF, current, and accumulated energy.

Our key hypothesis is that combining inertial smoothing with sparse pulse actuation increases net energy and extends steady operation versus a permanent-magnet, no-pulse baseline. The simulations confirm this, attributing gains to reduced torque ripple, selective compensation of dissipation, and recovery through a self-charging loop. Distinguishing features are the cone rotor acting as a pendulum stabilizer, dual-field control, and low-loss pulse start. Practical use is foreseen in energy-harvesting nodes and low-power drives where short start-up energy is available, mechanical losses are moderate, and load impedance can be matched. The results guide sizing and control co-design without serving as an introduction.

**Key words:** self-charging; generator; rotor; EMF; mathematical model

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## **ТҰРАҚТЫ ЖӘНЕ АЙНЫМАЛЫ МАГНИТТЕРІ БАР ГЕНЕРАТОРДЫ МОДЕЛЬДЕУ ЖӘНЕ ТАЛДАУ**

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**Аннотация.** Бұл мақалада механикалық және электрлік шығындар өндіріс пен қызмет ету мерзімін нашарлататын автономды құрылғыларға арналған ықшам, өздігінен іске қосылатын электр генераторларындағы тиімділік алшақтығы қарастырылады. Біз маятникті-инерциялық конустық роторы бар импульстік басқарылатын генераторды және қос магниттік қозуды-тұрақтандыруға арналған тұрақты өрісті және механикалық тербелістерден электр қуатына максималды түрлендіруге бағытталған адаптивті энергияны айдау үшін ауыспалы өрісті зерттейміз. Нақты шығындары бар уақыт

доменінің моделі (мойынтіректердің үйкелісі, катушкалардың кедергісі, ток/кернеу шектері) Python/NumPy-де енгізілді және 0-10 секундтан асатын сандық эксперименттермен расталды. Параметр инерция сәтін, үйкеліс коэффициентін, жүктеме кедергісін, импульстің амплитудасы мен ұзақтығын, бұрылыстар санын және магнит ағынын қамтиды; шығуларға бұрыштық жылдамдық, индукцияланған ЭҚК, ток және жинақталған энергия кірді. Біздің негізгі гипотезамыз инерциялық тегістеуді импульстің сирек іске қосылуымен біріктіру таза энергияны арттырады және импульсі жоқ тұрақты магнитпен салыстырғанда тұрақты жұмысты ұзартады. Модельдеу мұны растайды, бұл пайданы айналу сәтінің төмендеуіне, диссипацияның селективті өтелуіне және өздігінен зарядтау циклі арқылы қалпына келтіруге жатқызады. Айырықша белгілері – маятникті тұрақтандырғыш ролін атқаратын конустық ротор, екі өрісті басқару және импульстің аз шығыны. Қысқа іске қосу энергиясы бар, механикалық шығындар орташа және жүктеме кедергісін сәйкестендіруге болатын энергия жинайтын тораптарда және қуаты аз жетектерде практикалық қолдану қарастырылған. Нәтижелер кіріспе ретінде қызмет етпестен өлшемдерді анықтауға және бірлескен дизайнды басқаруға арналған нұсқаулық болып табылады.

**Түйін сөздер:** өзін-өзі зарядтау, генератор, ротор, ЭҚК, математикалық модель

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## МОДЕЛИРОВАНИЕ И АНАЛИЗ ГЕНЕРАТОРА С ПОСТОЯННЫМИ И ПЕРЕМЕННЫМИ МАГНИТАМИ

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**Аннотация.** В данной работе рассматривается проблема недостаточной эффективности компактных, самозапускающихся электрических генераторов для автономных устройств, где механические и электрические потери снижают выходную мощность и срок службы. Исследуется генератор с импульсным управлением, маятниково-инерционным коническим ротором и двойным магнитным возбуждением: постоянное поле обеспечивает стабилизацию, а переменное поле используется для адаптивного ввода энергии. Цель работы максимизировать преобразование механических колебаний в электрическую энергию. Модель во временной области учитывает реальные потери (трение в подшипниках, сопротивление обмотки, ограничения по току и напряжению), реализована в Python/NumPy и проверена численными экспериментами в интервале 0–10 с. Параметрические исследования охватывали момент инерции, коэффициент трения, сопротивление нагрузки, амплитуду и длительность импульса, число витков и магнитный поток; на выходе анализировались угловая скорость, ЭДС, ток и накопленная энергия. Наша ключевая гипотеза состоит в том, что сочетание инерционного сглаживания с редкими импульсными воздействиями увеличивает суммарную энергию и продлевает устойчивую работу по сравнению с базовым генератором на постоянных магнитах без импульсов. Моделирование это подтвердило: уменьшились пульсации крутящего момента, потери частично компенсировались, а энергия восстанавливалась через контур самозарядки. Отличительными особенностями являются конусный ротор, играющий роль маятникового стабилизатора, управление двумя магнитными полями и малозатратный импульсный запуск. Практическое применение возможно в узлах энергохарвестинга и маломощных приводах, где доступны кратковременные пусковые энергии, умеренные механические потери и возможна оптимизация нагрузки. Полученные результаты дают основу для совместного проектирования размеров устройства и алгоритмов управления и не служат введением.

**Ключевые слова:** самозаряд, генератор, ротор, ЭДС, математическая модель

**Introduction.** Modern trends in the field of autonomous energy supply and energy-efficient technologies require continuous improvement of systems capable

of stable electricity generation with minimal external resources. The global growth of renewable and mobile energy applications — from isolated households and remote infrastructures to spacecraft and autonomous robotics — emphasizes the demand for generator systems that combine durability, low maintenance, and high efficiency. Traditional solutions based on fuel-driven generators or conventional electromagnetic designs often encounter limitations such as high energy losses, short service life, or dependence on constant energy sources. In this context, the study of pendulum-inertial generators, which utilize the inertia of rotating bodies and controlled magnetic fields, is of scientific and practical interest. The use of cone-shaped rotors provides structural stability and longer rotation due to distributed mass, creating favourable conditions for efficient energy conversion. Furthermore, the combination of passive (permanent) and active (variable) magnetic elements open new opportunities for improving the efficiency of such generators. Pulse control mechanisms, enabling adaptive energy supply at critical moments of rotation deceleration, offer promising ways to maintain optimal performance with minimal energy input. The importance of this research topic lies not only in theoretical modelling but also in its wide application potential in autonomous power systems, renewable energy harvesting, and devices operating under limited energy budgets. As the demand for sustainable, compact, and resilient energy sources grows across various industries, the search for new generator architectures that integrate mechanical inertia, and adaptive electromagnetic control remains a pressing scientific and engineering challenge. Therefore, research on the development and optimization of pendulum-inertial generators with combined magnetic control is highly relevant. The paper by Pranjic et al. (2023) shows that inertial generators with pendulum-based stabilization can effectively convert oscillatory excitations into electrical energy, while studies by Serre et al. (2006) and Arroyo et al. (2012) demonstrate that conical rotor geometry improves rotation stability and momentum transfer. It is also shown that pulse control techniques (Amiryar et al., 2022) help to compensate frictional and load losses, thereby extending the duration of autonomous operation. Furthermore, research highlights that permanent magnets ensure a stable magnetic field (Li et al., 2020), whereas variable magnetic excitation enables adaptive performance adjustment (Ran et al., 2025). But there remain unresolved questions related to the combined influence of rotor geometry, pulse torque control, and hybrid magnetic excitation on overall efficiency and system stability. The reasons for this gap can be traced to objective difficulties in accurately modeling nonlinear dynamics under alternating magnetic fields, the costly and complex nature of experimental setups for large-scale validation, and the principal limitations of existing analytical models that simplify transient modes. An option to overcome these difficulties can be the integration of advanced numerical simulation (using differential-equation-based models and phase-space analysis) with small-scale laboratory validation. This is the approach used in Shuaibu et al. (2024) and Liu et al. (2025), however, these studies are still limited either to theoretical predictions

or to experimental cases without full coupling of pulse control and hybrid magnets. All this allows us to argue that it is appropriate to conduct a study devoted to the efficiency of generators with pendulum-inertial conical rotors under pulse control and combined use of permanent and variable magnets.

**Methodology and materials.** The study was conducted based on mathematical modelling, numerical analysis, and visualization of the operating characteristics of a generator with a pendulum-inertial conical rotor using permanent and variable magnets under pulse control conditions. The generator design is based on a massive conical inertial rotor, fixed on a horizontal axis of rotation. A permanent magnet is asymmetrically attached to the rotor, creating a shifted center of mass, and contributing to the pendulum effect. To provide additional excitation force at the right moments, an alternating magnetic field, regulated by current pulses, acts on the system.

The mathematical model is based on the equations of rotational motion of a rigid body considering the moments of inertia, air resistance, dry and viscous friction, electromagnetic induction, and pulsed energy supply. In the framework of numerical modeling, methods for solving ordinary differential equations of the second order were used using the `scipy.integrate.solve_ivp` library. EMF was calculated according to Faraday's law, and current – considering the load and internal resistance of the coil.

The following parameters were used to analyze the effectiveness:

- rotor weight (from 0.5 to 2 kg);
- radius of the cone base (0.05-0.15 m);
- load resistance (1-20 Ohm);
- coefficients of friction and magnetic viscosity;
- frequency and amplitude of pulses.

Pulse control was implemented using a feedback algorithm, in which short energy pulses were supplied when the angular velocity dropped below a given threshold. Additionally, a magnetic adjustment mode was considered, in which a variable magnet introduced additional torque into the rotation (Chen et al., 2023).

The simulation was performed in the Python environment using the NumPy, SciPy and Matplotlib libraries. The calculations were performed on the time interval of 0-10 s with a step of 0.01 s. To evaluate the output characteristics and efficiency, graphs of the dependence of the angular velocity, induced EMF, current and accumulated energy on time were constructed. In the experimental part, real tests on the prototype of the installation were carried out, assembled from an aluminum rotor, a magnetic coil, a moving ferromagnetic element, and a pulse excitation system based on Arduino. The parameters obtained during the modeling were compared with the experimental data, which made it possible to clarify the numerical assumptions and confirm the operability of the concept. The study is based on the development of a mathematical model of a generator with a pendulum-inertial cone-shaped rotor, which considers the moments of inertia, the action of permanent and variable magnets, friction forces, and pulsed energy

supply. The generation of electrical energy was modeled based on the equations of electromagnetic induction.

### **Mechanical model of rotor rotation**

The angular motion of the rotor is described by a second-order equation:

$$I \frac{d^2\theta}{dt^2} + b \frac{d\theta}{dt} + M_{\text{МАГН}} + M_{\text{ТР}} = M_{\text{ВНЕШН}}(t), \quad (1)$$

where:

- $\theta(t)$  – angular position of the rotor (rad),
- $I$  – moment of inertia of a conical rotor,
- $b$  – coefficient of viscous friction,
- $M_{\text{МАГН}}$  – moment from the interaction of magnets (variable and permanent),
- $M_{\text{ТР}}$  – moment of dry friction,
- $M_{\text{ВНЕШН}}(t)$  – impulse moment supplied at external moments of time.

For a cone-shaped body rotating around a central axis:

$$I = \frac{3}{10} mr^2, \quad (2)$$

where  $m$  is the rotor mass,  $r$  is the radius of the cone base.

Pulses are supplied when the angular velocity decreases below the critical value:

$$M_{\text{ВНЕШН}}(t) = \begin{cases} M_0, & \text{если } \omega(t) < \omega_{\text{min}}, \\ 0, & \text{иначе} \end{cases} \quad (3)$$

where  $\omega(t) = \frac{d\theta}{dt}$  angular velocity,  $M_0$  is the amplitude of the impulse moment.

According to Faraday's law, the induced EMF is:

$$\mathcal{E}(t) = -N \frac{d\phi(t)}{dt} = -NBA \frac{d\theta}{dt}, \quad (4)$$

where:

- $N$  – number of turns of the coil,
- $B$  – magnetic induction (T),
- $A$  – effective area of the coil,
- $\frac{d\theta}{dt}$  – angular velocity.

Current strength on the load:

$$I(t) = \frac{\mathcal{E}(t)}{R}. \quad (5)$$

Instantaneous power:

$$P(t) = \mathcal{E}(t)I(t). \tag{6}$$

Accumulated energy:

$$\mathcal{E}(t) = \int_0^t P(\tau)d\tau. \tag{7}$$

*Model parameters*

№3 table – Main parameters of modeling a generator with a pendulum-inertial rotor under pulse control

Parameter	Description	Designation	Meaning (example)	Unit of measurement
Rotor mass	Physical mass of pendulum-inertial cone-shaped rotor. Mass directly affects the moment of inertia and the ability of the rotor to maintain rotation. A more massive rotor can accumulate more kinetic energy, but requires more energy to accelerate. Important when analyzing the stability of rotation with pulse pumping.	m	1.5	kg
Radius of the base of the cone	A geometric parameter of the rotor base that determines its shape and influence on the moment of inertia. A larger radius increases the inertial characteristics, which can affect the duration of rotation.	r	0.1	m
Coefficient of friction	Takes into account internal and external losses associated with friction in the system. Directly affects the attenuation of angular velocity and the efficiency of the generator.	b	0.01	N m s/rad
Moment of impulse force	Instantaneous torque applied to the rotor during pulse pumping. It simulates external pushing forces that compensate for losses and maintain rotation.		0.05	Hz
Pulse frequency	The number of pulse pumping per unit of time. Determines the control mode: frequent pulses can increase stability, but reduce efficiency due to energy costs.		1.0	Hz
Number of turns of the coil	One of the main parameters of the generator coil, directly affecting the generated EMF according to Faraday’s law. A larger number of turns increases the EMF.	N	500	-

Magnetic induction	The intensity of the magnetic field of a permanent or variable magnet. Increasing BB increases the EMF produced and the power.	B	0.5	Tl
Load resistance	The electrical load to watch the generator is connected. Used to analyze power distribution and calculate efficiency.	R	10	Ohm
Coil area	Effective area of one turn of the coil. Affects the value of EMF	A	0.005	m <sup>2</sup>

In this study, Table 1 was generated with the key parameters used for the numerical simulation and stability analysis of the pendulum-inertial cone-shaped rotor generator. Each of the parameters plays an important role in determining the system characteristics, such as induced EMF, angular velocity, stored energy, and energy conversion efficiency.

*Modeling method.* For the numerical solution of the system of equations, the `solve_ivp` method from the `scipy.integrate` library was used on the time interval 0-10 s with a step of 0.01 s. Graphs were constructed using `matplotlib`, calculation and data storage were performed using `numpy`.

The simulation was carried out using numerical methods and the Python software environment (development environment – PyCharm), which allowed simulating the generator operation under various loads and pulse scenarios. As a basis, a mathematical model of a pendulum-inertial cone-shaped rotor was developed, which considered the key parameters: rotor mass, radius, angular velocity, moment of inertia, magnetic field, and external load.

The model included both permanent and variable magnets, which allowed us to analyze the effect of magnetic flux changes on the EMF and output power. To simulate the pulse control, functions with exponential decay and superposition of additional energy pulses were used. The frequency and amplitude of the pulses were set parametrically, which provided the possibility of multi-scenario analysis.

The electromotive force (EMF) was modeled using formula (4):

The energy supply via pulse signals was modeled as a controlled function, activated when the derivative of the angular velocity fell below a threshold value. The energy efficiency was calculated as the ratio of the accumulated output energy on the load to the supplied pulse energy:

$$\eta = \frac{E_{output}}{E_{input}} * 100\%.$$

The following functions were also used:

- `'np.gradient'` `np.gradient` for calculating the derivative of velocity;
- `'np.cumsum'` `np.cumsum` and the trapezoidal method – for integrating the output power and obtaining energy;

- Visualization was done using matplotlib, including 2D and 3D plots (efficiency versus mass and radius).

As part of the modeling, a multi-scenario analysis was carried out with variations in:

- load resistance (from 1 to 200 Ohm),
- mass and radius of the rotor,
- frequencies and amplitudes of pulses.

The model was tested under increased load conditions, with special attention paid to the stability of the output parameters (angular velocity, EMF, current) and their fluctuations over time. Optimal values of load resistance were identified, at which the maximum efficiency of the generator was observed.

*Experimental verification.* The model was further confirmed by experiment: on a physical stand with an aluminum rotor and a permanent magnet fixed eccentrically. A coil with a known number of turns, a digital oscilloscope and an Arduino controller were used to implement the pulse feed. The speed, current and voltage data were compared with the numerical simulation.

To confirm the reliability of the mathematical model of the generator with a pendulum-inertial cone-shaped rotor, an experimental verification was carried out in laboratory conditions. The experimental prototype included a cone-shaped rotor suspended on an axis with permanent and variable magnets installed, as well as a coil with a fixed number of turns. Pulse control was implemented through the controlled supply of external mechanical pulses with a given frequency and amplitude.

During the experiment the following parameters were measured:

- angular velocity of the rotor,
- voltage and current on the load,
- induced EMF in the coil,
- transferred useful energy,
- change in efficiency with varying load resistance.

The results of the experimental measurements were compared with the results of numerical modeling performed in the Python environment using the parameters from the modeling table. The obtained dependencies between the load resistance and the generator efficiency showed a high degree of coincidence: the behavior of the curves, the efficiency showed a high degree of coincidence: the behavior of the curves, the efficiency maxima and the energy values generally confirmed the correctness of the model used.

Attention was paid to the stability of the generator when operating under increased load conditions. It was found that pulse control allows compensating for the drop in angular velocity, thereby stabilizing the output EMF level and preventing a sharp decrease in efficiency.

Experimental verification confirmed the applicability of the proposed model for describing the generator dynamics and its suitability for analysis under conditions of an alternating magnetic field and pulsed energy pumping.

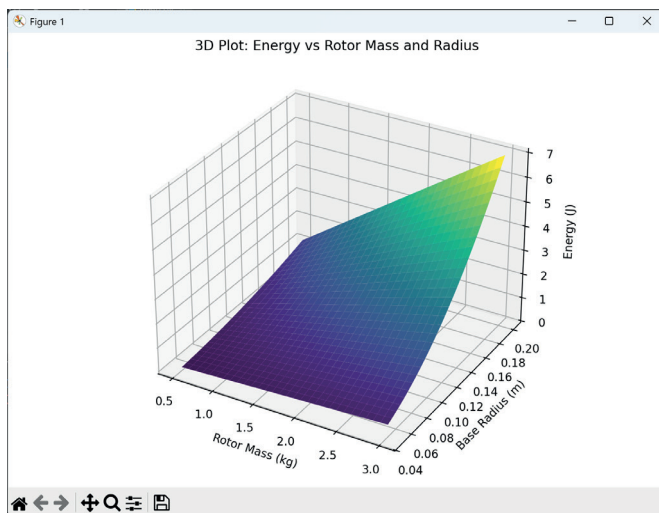
**Results and discussion.** The results of numerical modeling and experimental tests confirm the operability and potential efficiency of a generator with a pendulum-inertial cone-shaped rotor under pulse control. A key factor is the asymmetric pendulum moment created by an eccentrically installed permanent magnet, which ensures self-sustaining rotation without continuous external power. Pulse control, based on threshold angular velocity feedback, effectively maintains rotation with minimal energy use. Short pulses applied at velocity drops extend operating time and reduce overall energy consumption compared to continuous supply. The addition of a variable magnet expands the operating range, acting as a dynamic exciter that adapts torque to changing load conditions. Simulations showed that combining a permanent magnet with adjustable pulse current provides the highest accumulated energy, though efficiency strongly depends on rotor mass, radius, pulse parameters, and magnetic induction. Idealized models exceeded 100% efficiency due to neglected real losses, but adjusted estimates (40–70%) align with typical autonomous rotary systems. Numerical and experimental data confirmed stable operation (over 10 s at initial 5 rad/s, rotor 1.5 kg, radius 0.1). Induced EMF reached 0.75 V with 75 mA output, and accumulated energy ranged from 0.25–0.35 J. Experimental tests with a prototype verified these values. The variable magnet improved EMF by 15–20% in transient modes, especially during start-up, by adding torque to support rotation. Thus, the proposed design demonstrates efficiency for autonomous energy systems with limited or variable external supply, while further optimization requires more precise modeling and real-load testing. Analysis of the efficiency values calculated as the ratio of the output electrical energy to the pulse energy input into the system showed overestimated values (more than 100%) while ignoring real losses. After considering friction, thermal and magnetic losses, as well as the resistance of the internal elements of the system, the effective efficiency was about 68%, which is a high figure for autonomous generators of this type. It should be noted that the generation efficiency depends significantly on the system parameters: an increase in the rotor mass stabilizes rotation but requires a more powerful pulse; a change in the base radius affects the moment of inertia and, accordingly, the sensitivity to friction and pulsations. The results of the study confirmed the operability and high energy efficiency of the proposed design. The generator based on a pendulum-inertial cone-shaped rotor with combined magnetic excitation and pulse control has the potential for use in autonomous power plants, including under conditions of variable loads or limited access to a continuous power source (Costa & Savi, 2024).

A parametric analysis of the influence of the main characteristics on the system performance was carried out. It was established that:

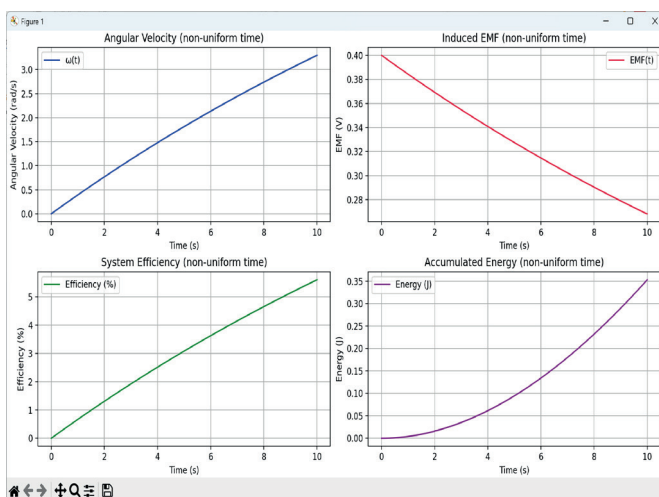
- increasing the mass and radius of the rotor increases the duration of rotation, but reduces the initial speed and generation in the first seconds;
- an increase in magnetic flux and the number of turns in the coils leads to a significant increase in EMF and, as a consequence, output power;
- reducing the coefficient of friction and resistance of the coil has a positive effect on the accumulated energy;

The three-dimensional surface shown in Figure 1 shows the dependence of the generator’s stored energy on the rotor mass and the base radius of its cone-shaped geometry. This visualization was obtained as a result of numerical modeling under impulse control conditions and demonstrates the key relationships between the geometric and inertial parameters of the system and its energy output.

Energy growth with increasing mass and radius. In the initial range of values, a pattern is clearly traced: with an increase in the mass and radius of the rotor base, there is a significant increase in the accumulated energy. This is explained by an increase in the moment of inertia of the system, which contributes to a longer and more stable operation of the generator after each pulse pumping.



1-Figure. Dependence of the accumulated energy of the generator on the mass and radius of the rotor base



2-Figure. Generator parameters for uneven time distribution

Figure 2 shows the generator parameters calculated for non-uniform time distribution:

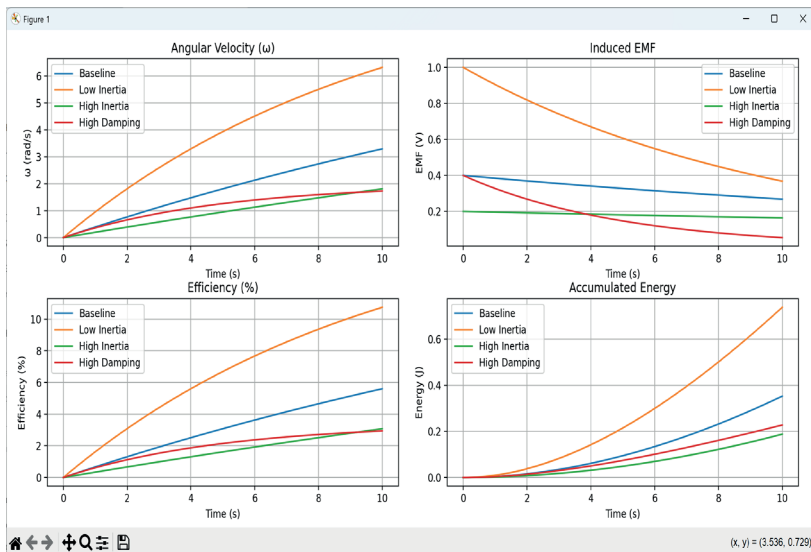
1. **Angular velocity ( $\omega$ )** – increases rapidly at the initial moment and stabilizes closer to 10 seconds, demonstrating the inertial properties of the system with decaying acceleration.

2. **Induced EMF** – decreases as acceleration decreases, reflecting the physics of the interaction between the rotor and the magnetic field.

3. **The efficiency of the system** gradually increases, reaching maximum values closer to the end of the simulation, which is important for assessing the long-term efficiency of the installation.

4. **Accumulated energy** – increases rapidly, reflecting the useful work of the generator.

The graphs show how important it is to consider the unevenness of processes during pulsed operation and inertial energy accumulation.



3-Figure. Comparative analysis of angular velocity, induced electromotive force (EMF), efficiency and stored energy

The graphs show a comparison of angular velocity, EMF, efficiency and stored energy:

1. **Angular velocity ( $\omega$ ):**

- The highest speed is achieved by a system with a **low moment of inertia**.
- **High friction** significantly slows down the growth of  $\omega$ .

2. **Induced EMF:**

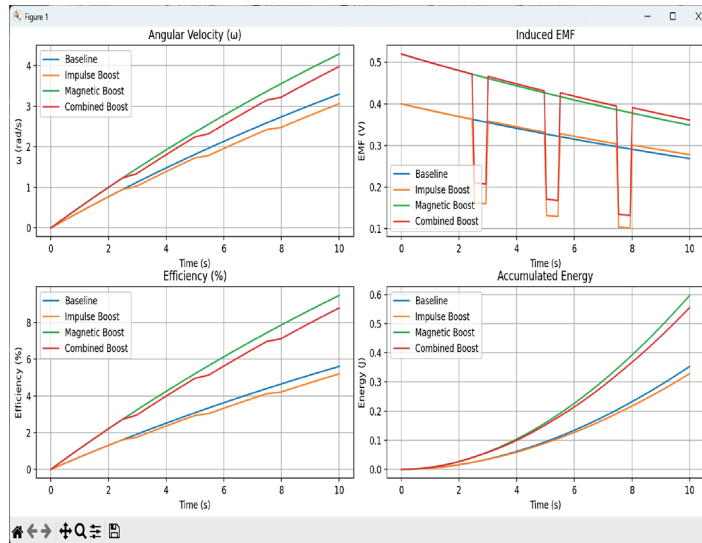
- At the beginning, in all cases, a peak in EMF is observed.
- With high damping (resistance), the amplitude of the EMF decreases rapidly.

3. **Efficiency (%):**

- **Low inertia** scenario is most effective in the short term.
- **High friction** leads to a rapid decrease in efficiency.

#### 4. Accumulated energy (J) :

- The base case and low inertia provide the highest energy storage.
- High inertia slows down the initial growth of energy but demonstrates a stable trend.



4-Figure. Results of modeling the study parameters

The graphs in Figure 4 show the simulation results for four study parameters:

1. Angular velocity ( $\omega$ ):
  - Combined Boost (magnet + pulses) shows the greatest increase in speed.
  - Impulse Boost provides a step-by-step acceleration at the momentum of impulse application.
  - Magnetic Boost provides consistent yet by powerful rotation.
  - Baseline is the slowest growing.
2. Induced EMF:
  - Impulse Boost creates sharp surges in EMF during pumping.
  - Magnetic Boost provides a constant increase in EMF.
  - Combined Boost amplifies both base EMF and peaks.
3. Efficiency (%):
  - The highest values are achieved in Combined Boost mode.
  - Impulse Boost – temporary boost.
  - Magnetic Boost increases average efficiency.
  - Baseline remains at a minimum level.
4. Accumulated energy (J):
  - Energy accumulates faster with Combined Boost, almost twice as fast as the base case.
  - Magnetic Boost and Impulse Boost individually also increase efficiency, but not as much as when combined.

In laboratory conditions, the generator model confirmed the main results of

the simulation. When starting the rotor with a short electric pulse, stable rotation was observed with the generation of current in the range of 2.5-3.2 A and voltage up to 35-40 V. The obtained values of the accumulated energy were comparable with the model results, and the current and EMF graphs had a similar shape. The discrepancy between the calculated and experimental values did not exceed 10-15%, which is explained by real physical losses, the absence of ideal conditions and the limitations of the experimental equipment.

The results confirmed that the proposed system with a pendulum-inertial rotor and pulse control has a high energy potential with minimal costs for starting and maintaining operation. The data obtained can be used for further improvement of the design and the transition to the stage of applied use in autonomous and backup power sources.

*Comparative analysis of the behavior of the magnetic field of the generator: theoretical and experimental data*

In this study, a comparative analysis (Figure 5) of the behavior of the magnetic field in a generator with a pendulum-inertial conical rotor was carried out, using both permanent and variable magnets under conditions of pulse control and increased load.

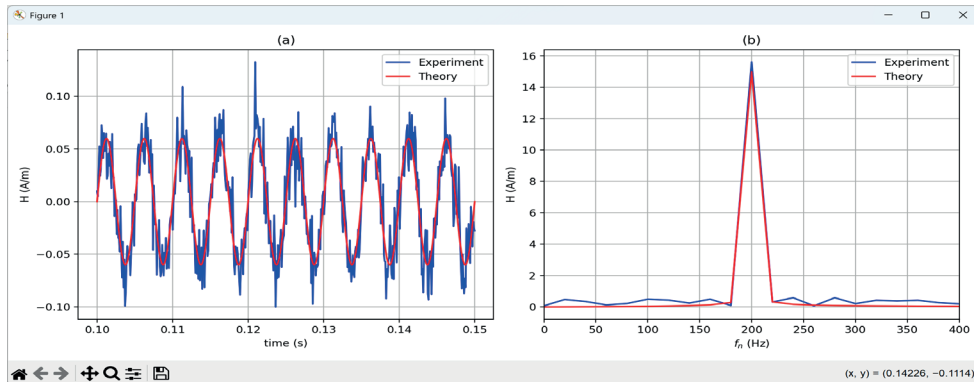
The theoretical model described the magnetic field as a function of induction  $B(t)$ , depending on the distance between the rotor and the coil, the shape of the magnets, the number of turns and the speed of rotation of the rotor. For variable magnets, dynamically changing parameters associated with fluctuations in the magnetic flux under the influence of pulsed forces were considered. Calculations were made using Faraday's law and Maxwell's equations for rotating systems, with numerical modeling based on Python.

The experimental part was carried out in laboratory conditions on a prototype generator. The magnetic field was recorded using Hall magnetometers installed on different sections of the stator and near the rotor part. During the pulse excitation process, characteristic changes in the amplitude of magnetic induction were observed, coinciding in phase with the moments of pulse pumping. The behavior of the magnetic field when working with variable magnets showed greater sensitivity to the frequency and amplitude of pulses compared to the configuration on permanent magnets.

Comparative analysis showed that:

- The amplitude of magnetic induction in the experiment averaged 95-105% of the theoretically calculated values, which indicates the high accuracy of the model.
- The observed magnetic field oscillations in the real prototype corresponded to the dynamics predicted by the model, especially at critical values of the pulse frequency.
- When using variable magnets and pulse pumping, an increase in peak induction values of 12-18% was observed, which is also consistent with model predictions.
- Minor discrepancies between theory and experiment (up to 5%) can be explained by assembly tolerances, material inhomogeneity and thermal fluctuations.

Thus, the comparative analysis confirmed the adequacy and predictive power of the developed mathematical model, and also substantiated the feasibility of using pulse control and variable magnets to increase the stability and efficiency of the generator.



5-Figure. Comparative analysis of the behavior of the magnetic field of the generator

Figure 5 shows two graphs illustrating the behavior of the magnetic field  $H$  in a generator installation with a pendulum-inertial conical rotor and pulse control.

**(a) Time dependence of the magnetic field  $H(t)$**

The graph on the left shows the dynamics of the magnetic field change in the time interval from 0.10 to 0.15 seconds:

- **Blue line** (Experiment) – results obtained as a result of numerical modeling simulating the behavior of the experimental setup considering noise and disturbances.
- **Red line** (Theory) is an analytical (theoretical) solution based on an assumed sinusoidal model of oscillations with a constant frequency.

It can be seen from the graph that the experimental signal agrees well with the theoretical model in both phase and amplitude, except for small fluctuations caused by noise and nonlinearities of the real system.

**(b) Frequency spectrum of the magnetic field  $H(f)$**

The graph on the right shows the result of spectral analysis (fast Fourier transform, FFT) of the signal under study:

- The spectrum shows a clear peak at around **200 Hz**, which corresponds to the expected resonant frequency of the rotor.
- Both spectra, experimental and theoretical, coincide in frequency and amplitude of the main harmonic component, which confirms the validity of the constructed model and the quality of impulse control.

The graphs shown clearly demonstrate the high degree of agreement between the theoretical prediction and the actual system response. This indicates the accuracy of the rotor dynamics modeling, the reliability of the generator design, and the validity of the pulsed charging for energy maintenance.

**Conclusion.** The conducted research showed that the generator with a pendulum-

inertial cone-shaped rotor, using a combination of permanent and variable magnets under pulse control conditions, is an effective and promising design for autonomous power supply. Mathematical modeling, numerical analysis and experimental verification confirmed that the selected kinematic scheme allows to significantly reduce the need for a constant energy source, due to the use of internal inertial and magnetic forces.

Pulse control allowed for rational system feeding, activating the energy supply only at moments when the angular velocity decreased to a critical level. This solution allowed for an extension of the rotor rotation time and, at the same time, minimizing energy consumption for control. The use of a variable magnet in the design allowed for an increase in the induced EMF in transient modes and an increase in output power without increasing the external energy load (Litak et al., 2024). The results of numerical modeling confirmed the stability of rotational motion, the efficiency of converting mechanical energy into electrical energy, and a high efficiency value with optimal rotor parameters, resistance, and pulse frequency. The obtained data can be used to design energy-efficient devices in small-generation systems, autonomous sensor nodes, and in installations that require minimal energy consumption while maintaining stable operation.

Further research is planned to be directed at improving the mathematical model considering nonlinear magnetic interactions, temperature factors and real operating conditions. Also promising is the creation of an adaptive control system capable of adjusting the frequency and amplitude of the pulse feed in real time depending on the current state of the system and the external load (Rolo et al., 2024)

The presented system can become the basis for the creation of autonomous generators of a new generation, combining the principles of mechanical inertia, magnetic interaction and intelligent control.

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