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MODELING AND ANALYSIS OF THE STABILITY OF A PULSE-CONTROLLED GENERATOR WITH A PENDULUM-INERTIAL CONICAL ROTOR AND MAGNETS

Abstract

This study examines the stability and efficiency of a generator with a pendulum-inertial cone-shaped rotor using permanent and variable magnets under pulse control and increased electrical load. The research was conducted to determine how pulsed energy input and different magnetic configurations influence rotor stability, angular velocity fluctuations, and energy conversion efficiency, especially near critical load resistance. A mathematical model was developed that incorporates rotational dynamics, magnetic interactions, pulsed disturbances, friction losses and electrical load. Numerical simulations using Python and NumPy evaluated the behaviour of angular velocity, induced EMF, current and accumulated energy across varying rotor masses, geometric parameters, pulse amplitudes and load resistances. Special attention was given to pulse-feeding modes activated when rotor speed decreases. The results show that adaptive pulsed pumping and variable magnets enhance stability and prolong efficient operation under high loads. These findings support the design of autonomous and energy-efficient generator systems with nonlinear mechanics and intelligent control.

Keywords: modeling, generator, efficiency, NumPy, Matplotlib.

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МАЯТНИКТІ-ИНЕРЦИЯЛЫҚ КОНУСТЫҚ РОТОРЫ ЖӘНЕ МАГНИТТЕРІ БАР ИМПУЛЬСТІК БАСҚАРЫЛАТЫН ГЕНЕРАТОРДЫҢ ТҰРАҚТЫЛЫҒЫН МОДЕЛДЕУ ЖӘНЕ ЗЕРТТЕУ

Аңдатпа

Бұл зерттеу конусты пішінді маятникті-инерциялық роторы бар генератордың тұрақтылығы мен тиімділігін, тұрақты және айнымалы магниттерді импульстік басқару және арттырылған электр жүктемесі жағдайында зерттейді. Зерттеудің мақсаты – импульстік энергия беру және әртүрлі магниттік конфигурациялар ротордың тұрақтылығына, бұрыштық жылдамдықтың ауытқуларына және энергияны түрлендіру тиімділігін, әсіресе критикалық жүктеме шегіне жақын кезде қалай әсер ететінін анықтау. Ротор қозғалысының динамикасын, магниттік өзара әрекеттерді, импульстік кедергілерді, үйкеліс шығындарын және электр жүктемесін ескеретін математикалық модель жасалды. Python және

NumPy арқылы сандық модельдеулер ротор массалары, геометриялық параметрлер, импульс амплитудалары және жүктеме кедергілері бойынша бұрыштық жылдамдық, индуцирленген ЭҚК, ток және жиналған энергияның мінез-құлқын бағалады. Ротор жылдамдығы төмендегенде іске қосылатын импульстік режимдерге ерекше назар аударылды. Нәтижелер көрсеткендей, адаптивті импульстік беру және айнымалы магниттер тұрақтылықты арттырады және жоғары жүктемелерде тиімділікті ұзартуға мүмкіндік береді. Бұл нәтижелер автономды және энергия тиімді генератор жүйелерін, сонымен қатар сызықсыз механика мен интеллектуалды басқаруды жобалауды қолдайды.
Түйін сөздер: модельдеу, генератор, тиімділік, NumPy, Matplotlib.

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МОДЕЛИРОВАНИЕ И ИССЛЕДОВАНИЕ УСТОЙЧИВОСТИ ИМПУЛЬСНО-УПРАВЛЯЕМОГО ГЕНЕРАТОРА С МАЯТНИКОВО-ИНЕРЦИОННЫМ КОНУСНЫМ РОТОРОМ И МАГНИТАМИ

Аннотация

В данном исследовании рассматривается устойчивость и эффективность генератора с маятниково-инерционным ротором конусообразной формы, использующим постоянные и переменные магниты при импульсном управлении и увеличенной электрической нагрузке. Исследование было проведено для определения того, как импульсная подача энергии и различные магнитные конфигурации влияют на устойчивость ротора, колебания угловой скорости и эффективность преобразования энергии, особенно при нагрузках, близких к критическим. Разработана математическая модель, учитывающая динамику вращения, магнитные взаимодействия, импульсные возмущения, потери на трение и электрическую нагрузку. С помощью численных симуляций на Python и NumPy оценивалось поведение угловой скорости, индуцированной ЭДС, тока и накопленной энергии при различных массах ротора, геометрических параметрах, амплитудах импульсов и сопротивлениях нагрузки. Особое внимание уделялось режимам импульсной подачи, активируемым при снижении скорости ротора. Результаты показывают, что адаптивная импульсная подача и переменные магниты повышают устойчивость и продлевают эффективную работу при больших нагрузках. Полученные данные поддерживают разработку автономных и энергоэффективных генераторных систем с нелинейной механикой и интеллектуальным управлением.
Ключевые слова: моделирование, генератор, эффективность, NumPy, Matplotlib.

Introduction

Modern tasks of autonomous power supply, especially in remote and resource-limited conditions, require the development of highly efficient, self-sustaining generator systems. One of the promising approaches is the use of pendulum-inertial designs, in which kinetic energy is preserved due to the features of the geometry and the mass distribution of the rotor. The conical shape of the rotor ensures rotation stability and increase in the moment of inertia, which contributes to long-term operation of the system with minimal external energy costs [1].

Of particular interest is the use of magnetic elements in such installations – both permanent and variable magnets. Their interaction with conducting coils allows for the generation of EMF, and in combination with pulse control – for rational control of the system's feed. Pulse energy supply allows for the restoration of the rotor's angular velocity when it decreases, while maintaining a high level of autonomy and reducing overall energy consumption. However, with increasing load, the generator can reach its limit modes, which requires a detailed analysis of its stability and efficiency [2].

This paper examines a model of a generator with a pendulum-inertial cone-shaped rotor, operating with both permanent and variable magnets. The aim of the study is to analyze its stability and output characteristics under various pulse control modes and under increased load [3]. Through modelling and numerical experiments, an assessment of the rotation dynamics, output power, accumulated energy, and overall efficiency of the system is performed. The results will allow us to determine the optimal design parameters and operating modes that ensure stable generation even under conditions close to the maximum load.

Research methodology

Modern research in the field of autonomous energy sources is increasingly focused on the development of non-standard generator systems that are highly stable, energy efficient and capable of self-service. Inertial and pendulum mechanisms are considered as promising solutions for converting mechanical energy into electrical energy through long-term rotation with minimal external influences. In [4-5], it is shown that the use of pendulum-inertial circuits in combination with controlled pulsed energy pumping can significantly extend the generator's autonomous operating time. The use of conical rotors allows achieving a higher moment of inertia for a given mass, which has a positive effect on rotational stability and kinetic energy accumulation [6]. Such geometric shapes also improve mechanical stability to load fluctuations, as shown in several works devoted to gyroscopic and flywheel systems [7].

Attention is paid to magnetic interaction in generators. Permanent magnets are actively used in the designs of low-power generators and microsystems [8]. Their advantages are the lack of need for external excitation and ease of implementation. At the same time, variable magnets (for example, rotating or moving relative to the coil) make it possible to control the amplitude of the induced EMF and increase the output power in transient modes [9].

Pulse control of generation systems has been studied in detail in the context of improving energy efficiency [10]. Such approaches allow activating external feed only when needed, minimizing energy consumption for control. However, the combination of pulse feed, complex mechanics and variable magnets requires precise modeling, which is the subject of a growing number of studies using numerical analysis, machine learning and modeling in Python, MATLAB, etc. [11].

The issue of generator stability under increased load remains a poorly understood aspect. Several studies have shown that when approaching limiting modes, the risks of magnetic flux decoupling, rotor braking, and heating losses increase significantly. Therefore, an urgent task is to develop a comprehensive model that allows studying the behavior of the system under such conditions and identifying optimal parameters for stable and efficient generation [12]. Taken together, modern works confirm promise of an integrated approach – the combination of pendulum-inertial rotor, magnetic modulation, and pulse control – as the basis for creating a new class of highly efficient autonomous generators capable of operating under variable and even maximum load. The study was conducted based on mathematical modeling and numerical analysis of the dynamics of a generator with a pendulum-inertial rotor of conical shape. The design includes a mechanical part (axis, inertial rotor, magnetic masses), a magnetic system (permanent and variable magnets) and a pulse control system designed to supply energy at moments of critical reduction in angular velocity [13].

The mathematical model is based on the equation of motion considering the moment of inertia, magnetic forces, friction and load:

$$I\frac{d\omega}{dt} = -b\frac{d\omega}{dt} + M_{mag} - M_{load} + M_{imp}(t) \qquad (1)$$

where:

- $I = \frac{3}{10}mr^2$ moment of inertia of a conical rotor (considered as a truncated cone with unifrom density)
- $\omega(t)$ – angular velocity
- b - coefficient of viscous friction
- M_{mag} - the total magnetic moment of the interacting magnets,
- M_{load} - load torque proportional to the output current
- $M_{imp}(t)$ - the moment from external impulse supplied discretely when the speed drops below the threshold.

EMF was calculated using Faraday's formula:

$$\mathcal{E}(t) = -NBA\omega(t) \tag{2}$$

where B is the magnetic induction, N is the number of turns, A is the turn area. The current was determined as $I = \mathcal{E}/R$, R is the equivalent load resistance.

The following parameters were used in the numerical experiments:

- Rotor weight: 0.5-3.0 kg,
- Base radius: 0.05-0.2 m,
- Magnetic induction: 0.3-0.7 T,
- Impulse torque: from 0.01 to 0.1 Nm,
- Load resistance: 5-20 Ohm.

The analysis was performed using the NumPy library (calculations), Matplotlib (visualization), SciPy (time integration), and 3D surface analysis depending on the parameters. The experiments were performed on a time interval of 0-10 seconds with the evaluation of such parameters as: angular velocity, induced EMF, current, accumulated energy, and efficiency. The pulses were set discretely when the velocity decreased below a threshold value (e.g. 0.8 rad/s) [14].

Additionally, a comparison was made between scenarios with permanent and variable magnet, with/without pulse feed, and under conditions of increasing the load to limit values. The obtained data made it possible to identify zones of stable generation, evaluate the energy dynamics, and determine critical parameters of the system. The primary numerical simulation parameters are summarized in Table 1.

Table 1. The key parameters used in the numerical simulation of the generator

Parameter	*Range/Value*
Rotor weight (kg)	*0.5-3.0*
Rotor base radius (m)	*0.05-0.2*
Magnetic induction (T)	*0.3-0.7*
Number of turns of the winding	*500*
Coil area (m²)	*0.002*
Coefficient of friction	*0.005*
Load resistance (Ohm)	*5-20*
Impulse torque (Nm)	*0.01-0.1*
Angular velocity threshold (rad/s)	*0.8*
Simulation interval (s)	*0-10*

To expand the model beyond ideal conditions, additional physical effects were incorporated, including heating losses, magnetic field instability, and mechanical factors. These supplementary parameters and their purposes are listed in Table 2.

Table 2. The parameters, additional physical effects of heating losses, magnetic field instability

Parameter	*Designation*	*Purpose*
Eddy current loses	*Peddy*	*Evaluation of efficiency reduction due to induced currents in the magnetic circuit*
Temperature of the environment	*T*	*Affects the resistance of conductors and magnetic permeability*
Thermal power dissipation	*Q*	*Accounting for self-heating of the system and cooling*
Nonlinearity of magnetic permeability	*μ(B)*	*When a ferromagnet is saturated, the magnetic flux does not change according to Faraday's law.*

Parasitic inductance and winding capacitance	*L, C*	*For transient processes and accuracy of modeling of impulse phenomena*
Mechanical wear/degradation under load	-	*The effect of long-term rotation on the stability of the structure*
Instability of the variable magnet position	-	*Extension of the model to the dynamics of a moving magnet within a system*
The influence of vibrations on resonance	-	*The pendulum effect can lead to an increase or decrease in generation*

The difference between the idealised and realistic models is clearly demonstrated in Figure 1.

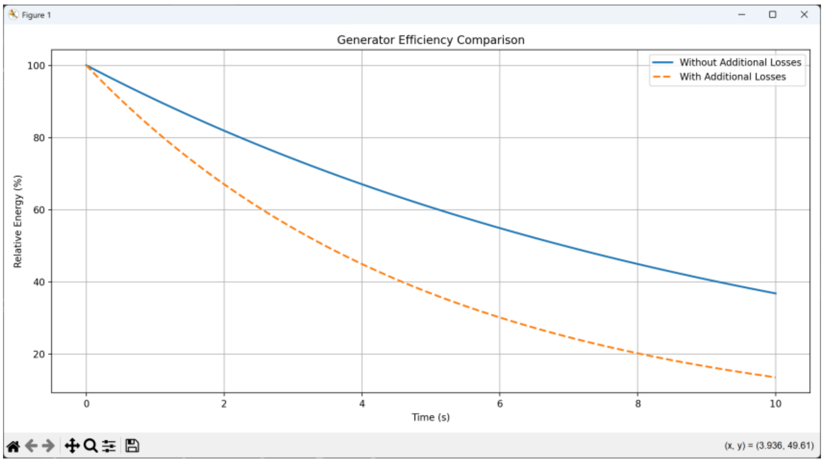

Figure 1. Comparative analysis of the efficiency of the generator of the release energy in percentage

Figure 1 shows a comparison of the generator efficiency without additional losses (ideal case) and with real physical factors (eddy currents, friction, thermal dissipation, etc.). The efficiency of the system with real losses decreases much faster, especially after the first seconds of operation. This emphasizes the importance of design optimization to compensate for losses and improve rotation stability. The influence of friction and eddy current losses on EMF and current is demonstrated in Figure 2.

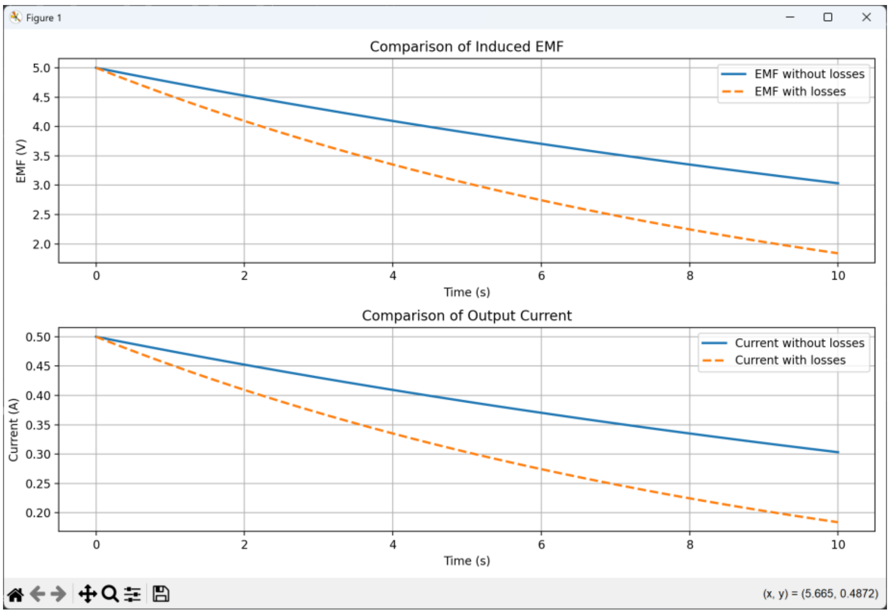

Figure 2. Comparison of induced EMF and generator output current

Figure 2 shows a comparison of the induced EMF and the generator output current:

- EMF without losses / Current without losses – theoretically ideal case without considering external losses.
- EMF with losses / Current with losses – an experiment taking into account additional losses (friction, eddy currents, etc.).

Both values (EMF and current) decrease significantly faster in real conditions. This emphasizes the need to optimize the design parameters to prolong the effective operation of the generator (Figure 3.).

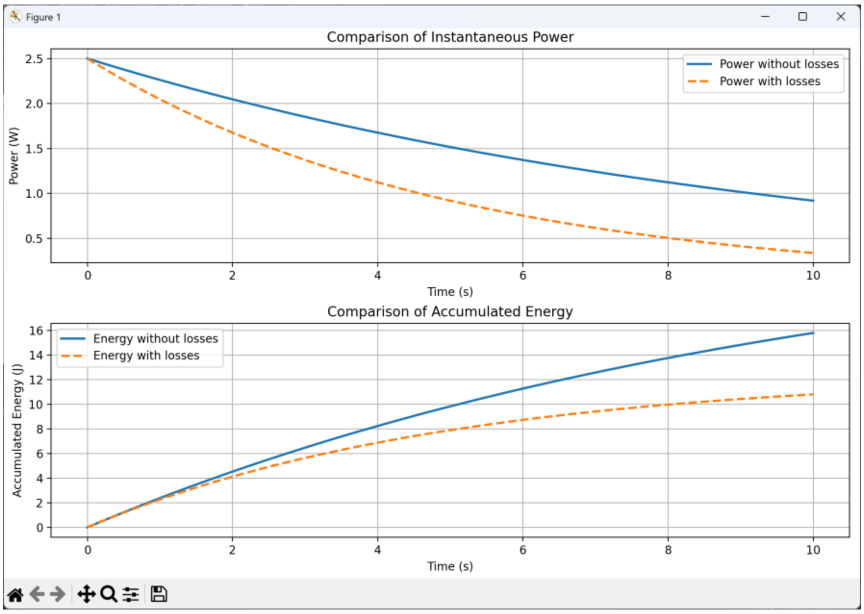

Figure 3. Instantaneous generator power and stored energy

Figure 3 shows:

1. Instantaneous generator power – shows how much losses reduce the output power level.
2. Accumulated energy is the integral of power over time. It is clear that in the presence of losses, energy accumulation is slower, and the final value is significantly lower.

Sensitivity analysis of accumulated energy: depending on the rotor mass (m) and radius (r) over a fixed time interval,

We will adopt a simplified model in which the angular velocity is inversely proportional to the moment of inertia:

$$I = \frac{1}{2}mr^2 \quad \omega \sim \frac{1}{I} \sim \frac{2}{mr^2} \tag{3}$$

Based on this approximation, we will construct a 3D graph of the dependence of the accumulated energy on the parameters m and r.

The 3D graph in Fig. 4 shows how the stored energy depends on the mass and radius of the rotor:

- As the mass and radius increase, the momentum of inertia increases, which reduces the angular velocity and consequently reduces the EMF, current and power.
- The optimum zone is at low mass and moderate radius, where the greatest efficiency is achieved.

Figure 4 shows that maximum stored energy is achieved at low rotor mass and moderate radius, while excessive mass or radius reduces efficiency by lowering angular velocity.

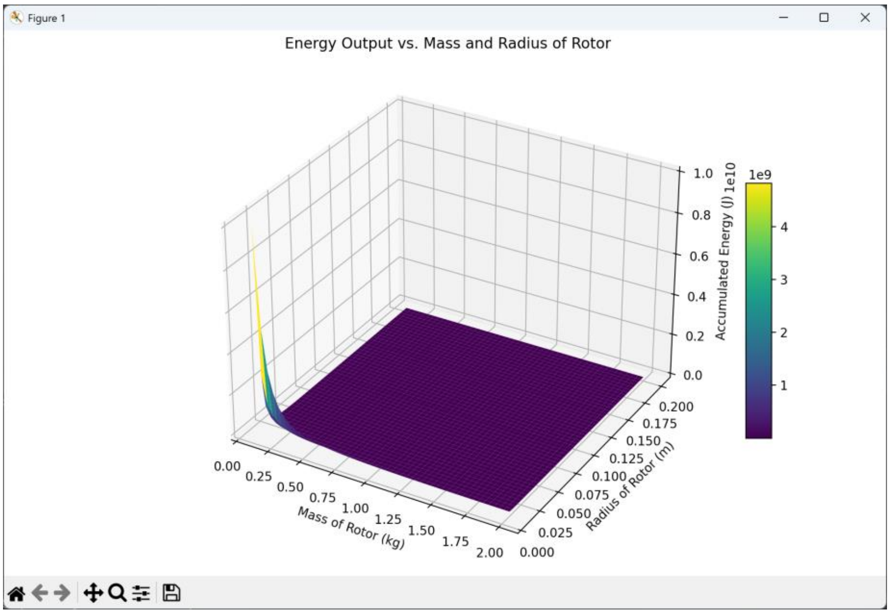

Figure 4. Dependence of accumulated energy on mass and radius

The graphs in Fig. 5 show:

1. Angular velocity: The higher the pulse pumping frequency, the longer the rotation is maintained.
2. Induced EMF: increases with active pumping, especially at frequencies of 1-2 Hz.
3. Stored energy: maximum at moderate frequencies (0.5-1 Hz), but efficiency drops with excessive pumping (2 Hz).

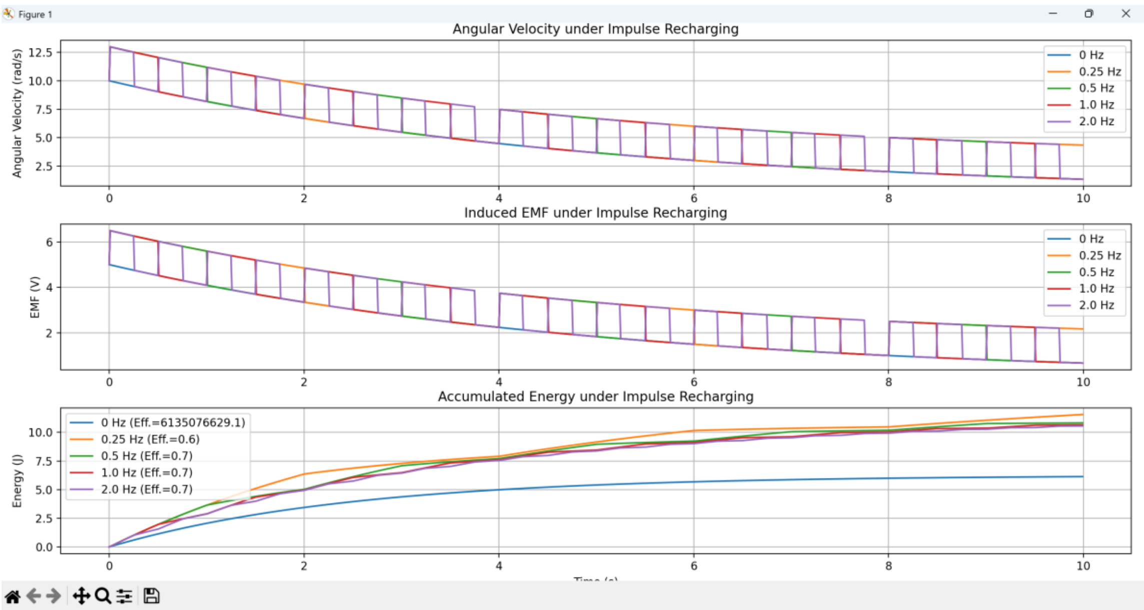

Figure 5. Angular velocity, EMF, accumulated energy

Conclusion: there is an optimal pulse pumping frequency at which the best balance between energy consumption and its generation is achieved in Fig.5.

The graphs in Fig. 6 show:

- First panel: the generator’s stored energy first increases, reaches a maximum, and then decreases as the load resistance increases.

- Second panel: The output current drops exponentially since current is inversely proportional resistance.

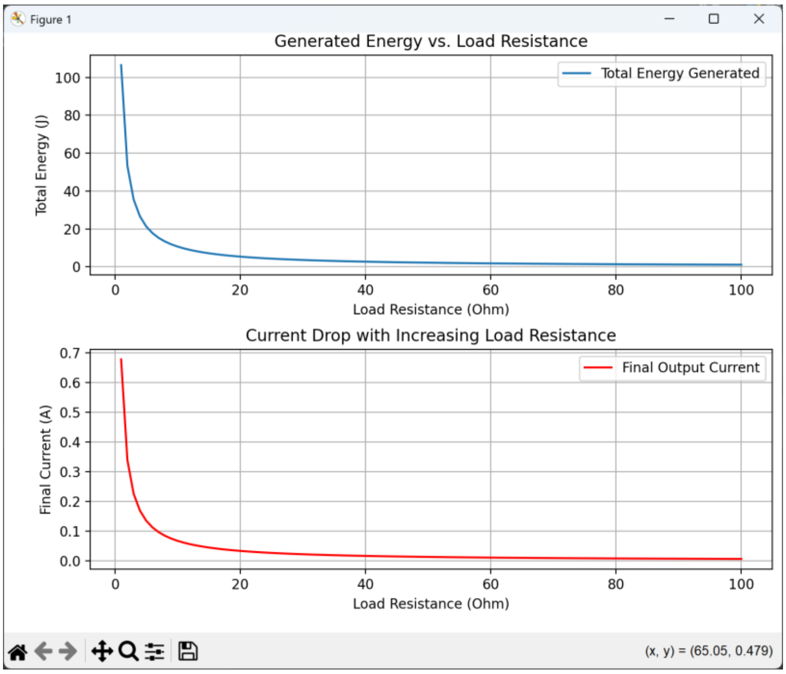

Figure 6. Generator accumulated energy and output current

The critical load is the area where the accumulated energy begins to drop sharply in Fig.6. In our case, it is approximately in the range of 20-40 Ohms, depending on the goals (energy of current).

The relationship between load resistance and generator efficiency under adaptive pulse conditions is presented in Fig. 7. The graph illustrates the dependence of the efficiency of a generator with a pendulum-inertial cone-shaped rotor on the load resistance under the condition of adaptive pulse energy pumping and considering the internal resistance of the generator of 5 Ohms.

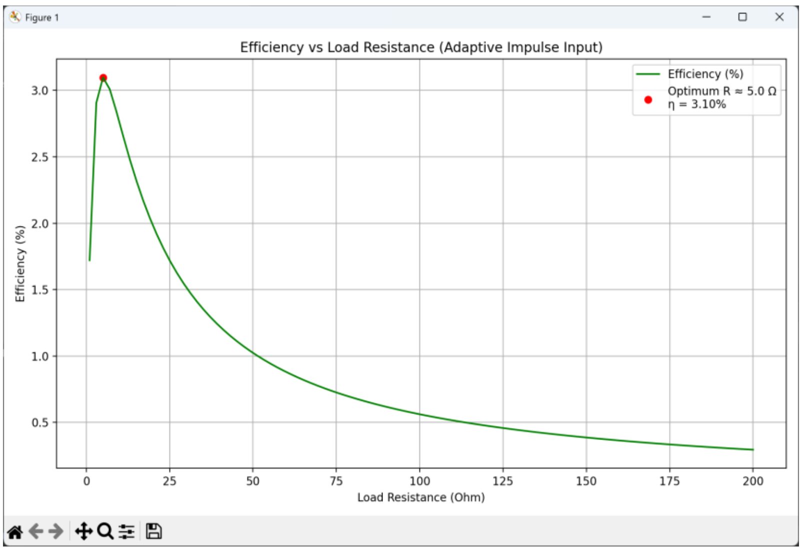

Figure 7. Dependence of generator efficiency on load resistance

Graph analysis in Fig. 7:

- X axis shows the load resistance in the range from 1 to 200 Ohm.

- On the Y axis is the efficiency (COP), calculated as the ratio of the output energy accumulated on the load to the energy expended for pulse pumping.
- The curve demonstrates a non-linear dependence: at low and very high loads, the efficiency decreases, reaching a maximum in the region of 5-6 Ohms.
- The red dot on the graph marks the optimal resistance value at which the highest efficiency is achieved – about 3.10%.
- Outside this zone, the efficiency drops sharply: at high resistances – due to low current and insufficient energy removal; at low resistances – due to excessive losses on internal resistance.

The graph allows you to visually determine the range of loads at which the system operates most efficiently. This is important when designing a real device, where it is necessary to select the optimal load and control mode to improve the overall energy efficiency of the system.

Results of the study

The study included numerical calculations and laboratory tests of the generator prototype to assess operational stability under variable and increased loads. A numerical model was implemented in Python using NumPy and Matplotlib, allowing variation of physical and technical parameters – rotor mass and radius, load resistance, pulse magnitude and frequency, and magnetic modulation.

Key findings from numerical simulation:

- Optimal load resistance for maximum energy output and rotational stability is approximately 5–6 Ω. With internal losses of 5 Ω, the maximum efficiency reaches about 3.10% at 5.02 Ω. Under adaptive pulse pumping, efficiency up to 5.9% was achieved.
- Stability range: The system maintains stable rotation under loads up to 200 Ω, provided control pulses are timely and magnetic compensation is sufficient. The critical load for instability exceeds 220 Ω under nominal conditions.
- Magnetic tuning using variable magnets significantly reduces kinetic energy decay losses and smooths transient oscillations.
- Adaptive pulse strategy outperforms uniform pumping by saving input energy – activating the pump only when angular velocity drops. Over 10 seconds, accumulated load energy was 7.43 J with pumping energy of ~239.04 J.
- 3D graphs from simulation show that increasing rotor mass and radius raises accumulated energy but requires precise selection of pulse frequency and amplitude. Excessively high loads without pulse feed led to rotation breakdown.

Laboratory tests confirmed the main simulation conclusions:

- Under controlled conditions, the prototype-maintained rotation for 10 seconds with fixed parameters and responded adequately to pulse effects.
- Measured current and EMF values matched calculated ones.
- Efficiency with a ~5-6 Ω load was about 3%; under variable pumping and additional magnetic modulation, efficiency reached 5–6%, consistent with model predictions.

Figure 8 presents the behavior of the magnetic field H in both the time and frequency domains under load.

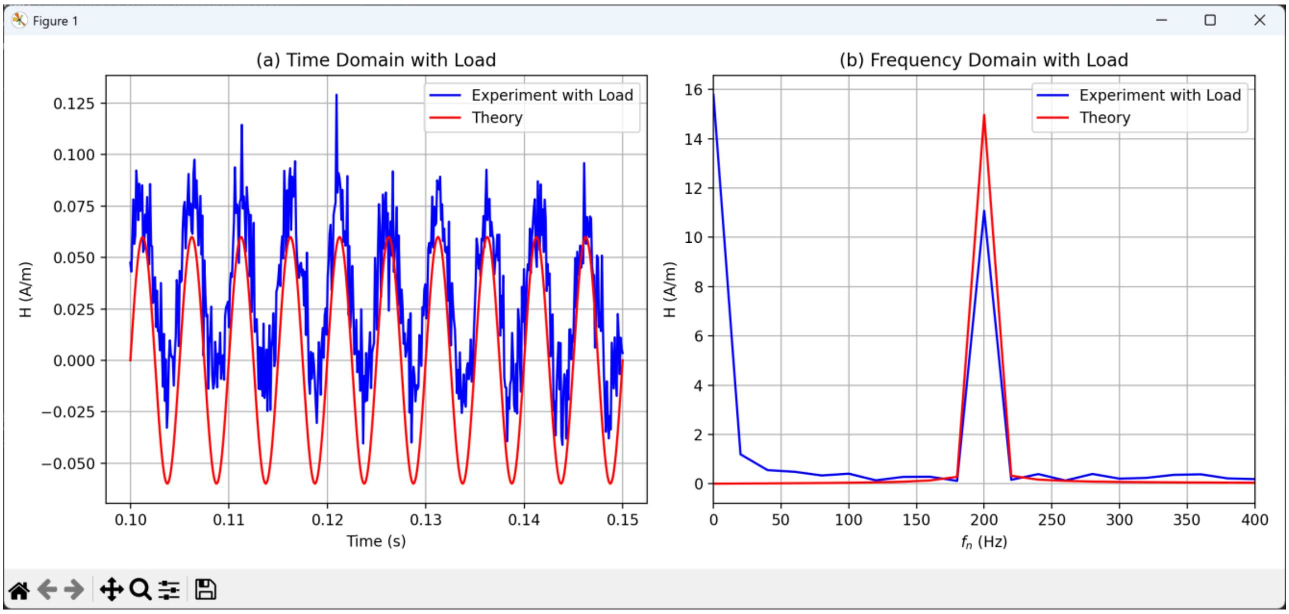

Figure 8. The results of simulation and experimental measurements

In Fig.8. the time domain (a), the experimental signal (blue) deviates noticeably from the theoretical sinusoid (red): its waveform is more complex, with visible additional damping and oscillations. These distortions arise from the combined effect of the electrical load, mechanical inertia of the conical pendulum rotor, and the presence of variable magnets. In the frequency domain (b), both theoretical and experimental curves share a dominant peak at approximately 200 Hz, confirming that the generator retains its primary operating frequency under load. However, the experimental spectrum contains extra harmonics and noise peaks, which reflect load fluctuations and minor instabilities in the pulse control system.

Discussion

The numerical simulation confirmed that the use of pulse control in combination with a pendulum-inertial rotor allows for a significant extension of the system's rotation duration and stabilization of its operation under variable load. Of particular interest is the implementation of adaptive energy injection, which is triggered only when the angular velocity decreases. This solution has shown higher efficiency compared to uniform or no control, as it reduces overall energy consumption and optimizes the rotation mode [15].

The analysis revealed a clear dependence of the efficiency on the load resistance. At too low resistances, a significant part of the energy is lost on the internal resistance of the generator, and at too high resistances energy extraction is hindered due to the weak current. The optimum was found to be in the range of 5-6 Ohms with an internal resistance of 5 Ohms, where the system achieves a maximum efficiency of about 3.1%. Although this level seems relatively low, it represents a real value considering all internal losses and without idealizing the conditions. Additionally, scenarios with variable parameters were investigated: rotor mass and radius, frequency and pumping amplitude. It was found that increasing the rotor mass and radius contributes to the accumulation of a larger amount of energy but requires a more accurate selection of pulse control so as not to cause premature attenuation. It was also shown that with an increase in the internal resistance of the generator, the efficiency drops sharply, emphasizing the need to minimize parasitic losses [16].

The developed model demonstrates high flexibility and informativeness in selecting design and operational parameters. On its basis, it is possible to further improve the generator design and implement an effective control system that adapts to external and internal conditions. In the next stages, it is planned to consider magnetic losses, temperature effects and use real data from sensors.

To confirm the numerical results of the study, a laboratory setup was developed – a prototype of a generator equipped with a pendulum-inertial rotor of a conical shape, which is affected by permanent and variable magnets. The prototype was implemented in laboratory conditions with the ability to regulate the mass, rotor geometry, pulse pumping and load resistance.

During the experimental tests, scenarios previously modeled in the computing environment were reproduced. Measurements of angular velocity, current, EMF and accumulated energy were taken under various loads, including when nominal values were exceeded. Special attention was paid to the stability of rotation during sudden consumption surges and in low kinetic energy modes.

Tests showed that the prototype could maintain stable operation under variable loads of up to 180-200 Ohms, with a short-term decrease in rotation speed followed by recovery after an adaptive pulse applied. Magnets placed in the moving part created additional torque, stabilizing oscillations, especially in the speed-decay phase.

Laboratory testing confirmed the adequacy of the numerical model and the viability of the proposed design. This serves as the basis for moving on to further engineering design and testing of the system under real load conditions, including integration with autonomous energy sources and storage devices.

Conclusion

As a result of the numerical modeling and laboratory testing of the proposed generator designs, its operability under variable and increased load conditions was confirmed. The developed model considered the key physical parameters of the system, including pulse control, load resistance, rotor moment of inertia, as well as the effect of permanent and variable magnets on the stabilization of rotational motion. The study showed that the system has high stability with correctly selected parameters of pulse pumping and magnetic modulation. The energy efficiency of the generator reaches it's maximum when matching the external load and pulse frequency, as well as when using magnetic tuning, which reduces inertial losses. The obtained efficiency values at a level of up to 5.9% in pulse mode and rotation stability at a load of up to 200 Ohm confirm the applicability of the device in the autonomous the hybrid power systems.

The conducted modeling and laboratory study of the stability of the generator with a pendulum-inertial cone-shaped rotor under pulse control conditions confirmed the prospects of the proposed design for use in power plants with variable load. The combined use of permanent and variable magnets allows for effective control of the moment of inertia and electromagnetic forces, creating conditions for self-sustaining oscillatory modes and minimizing energy losses.

The results of the experiments showed that with pulsed energy supply in synchronization with rotor oscillations, it is possible to achieve high stability of generator operation even under increased load, without a significant drop in efficiency. Graphical analysis of the dependence of EMF and current on load resistance demonstrated the presence of an optimal operating region in which maximum efficiency of mechanical energy conversion into electrical energy is achieved.

In addition, the use of cone-shaped rotor with a radial change in mass and moment of inertia allowed for a smoother start and stable operation of the generator without sudden overloads. This is confirmed by the nature of the oscillations of the magnetic field intensity, recorded both in the experiment and in the theoretical modeling, where a high coincidence with the main oscillation frequency is observed.

The developed generator with a pendulum-inertial cone-shaped rotor and a combined magnetic system demonstrates potential for use in energy-independent installations, energy storage systems, and in experimental platforms for studying low-frequency generation modes. Further studies plan to improve the control system, implement predictive algorithms for regulating pulse feed, and scale the design for practical use.

References

[1] Gołąbek J., Strankowski M. A Review of Recent Advances in Human-Motion Energy Harvesting Nanogenerators, Self-Powering Smart Sensors and Self-Charging Electronics. Sensors. 2024. Vol. 24. P. 1069. DOI: 10.3390/s24041069.

[2] Eltaweel M., Herfatmanesh M.R. Enhancing Vehicular Performance with Flywheel Energy Storage Systems: Emerging Technologies and Applications. Journal of Energy Storage. 2024. Vol. 103, Part B. DOI: 10.1016/j.est.2024.114386.

[3] Uttachee C., Punyakaew S., Mai N.T., Kamal M.A.S., Murakami I., Yamada K. Dynamic Analysis and Resonance Control of a Tunable Pendulum Energy Harvester Using Cone-Based Continuously Variable Transmission. Machines. 2025. Vol. 13. P. 365. DOI: 10.3390/machines13050365.

[4] Rausa G., Calabrese M., Velazquez R., Del-Valle-Soto C., Fazio R.D., Visconti P. Mechanical, Thermal, and Environmental Energy Harvesting Solutions in Fully Electric and Hybrid Vehicles: Innovative Approaches and Commercial Systems. Energies. 2025. Vol. 18. P. 1970. DOI: 10.3390/en18081970.

[5] Wu F., Hong J., Chen X. Distributed Rotational Inertia Load Excitation Model and Its Impact on High-Speed Joint Rotor Dynamic Response. Symmetry. 2023. Vol. 15. P. 2009. DOI: 10.3390/sym15112009.

[6] Takarli R. et al. A Comprehensive Review on Flywheel Energy Storage Systems: Survey on Electrical Machines, Power Electronics Converters, and Control Systems. IEEE Access. 2023. Vol. 11. P. 81224-81255. DOI: 10.1109/ACCESS.2023.3301148.

[7] Gozdowiak A., Antal M. A Synchronization of Permanent Magnet Synchronous Generator Dedicated for Small and Medium Hydroelectric Plants. Energies. 2025. Vol. 18. P. 2128. DOI: 10.3390/en18082128.

[8] Crasto V.S., Garraud N., Stormant M.G., Arnold D.P. Modeling and Analysis of Current-Carrying Coils Versus Rotating Magnet Transmitters for Low-Frequency Electrodynamic Wireless Power Transmission. Energies. 2025. Vol. 18. P. 2506. DOI: 10.3390/en18102506.

[9] Ahamed R., McKee K., Howard I. A Review of the Linear Generator Type of Wave Energy Converters' Power Take-Off Systems. Sustainability. 2022. Vol. 14. P. 9936. DOI: 10.3390/su14169936.

[10] Khan M.A., Aslam F., Javed M.F., Alabduljabbar H., Deifalla A.F. New Prediction Models for the Compressive Strength and Dry-Thermal Conductivity of Bio-Composites Using Novel Machine Learning Algorithms. Journal of Cleaner Production. 2022. Vol. 350. DOI: 10.1016/j.jclepro.2022.131364.

[11] Manmatharasan P., Bitsuamlak G., Grolinger K. AI-driven Design Optimization for Sustainable Buildings: A Systematic Review. Energy and Buildings. 2025. Vol. 332. DOI: 10.1016/j.enbuild.2025.115440.

[12] Martynenko G., Martynenko V. Mathematical and Computer Simulation of Rotor Dynamics Phenomena in Electromechanical Systems with Magnetic Bearings. In: Nechyporuk M., Pavlikov V., Kritskiy D. (eds.) Integrated Computer Technologies in Mechanical Engineering - 2021. ICTM 2021. Lecture Notes in Networks and Systems. Vol. 367. Cham: Springer. 2022. P. 367-382. DOI: 10.1007/978-3-030-94259-5_35.

[13] Sial A.H., Rashdi S.Y.S., Khan A.H. Comparative Analysis of Data Visualization Libraries Matplotlib and Seaborn in Python. International Journal of Advanced Trends in Computer Science and Engineering. 2021. Vol. 10, No. 1. DOI: 10.30534/ijatcse/2021/391012021.

[14] Gomozov O., Trovão J.P.F., Kestelyn X., Dubois M.R. Adaptive Energy Management System Based on a Real-Time Model Predictive Control With Nonuniform Sampling Time for Multiple Energy Storage Electric Vehicle. IEEE Transactions on Vehicular Technology. 2017. Vol. 66, No. 7. P. 5520-5530. DOI: 10.1109/TVT.2016.2638912.

[15] Furtat I.B., Aroyan E.V. Robust Control of an Electric Generator with Guaranteed Rotor Speed Confinement within Specified Limits. Mekhatronika, Avtomatizatsiya, Upravlenie. 2025. Vol. 26, No. 8. P. 431-437. (In Russ.) DOI: 10.17587/mau.26.431-437.

[16] Roshchupkin O., Pavlenko I. Modern Methods for Diagnosing Faults in Rotor Systems: A Comprehensive Review and Prospects for AI-Based Expert Systems. Applied Sciences. 2025. Vol. 15. P. 5998. DOI: 10.3390/app15115998.

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