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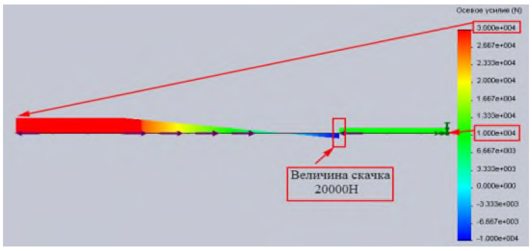
M U N D A R I J A – CONTENT

MASHINASOZLIK VA ENERGETIKA

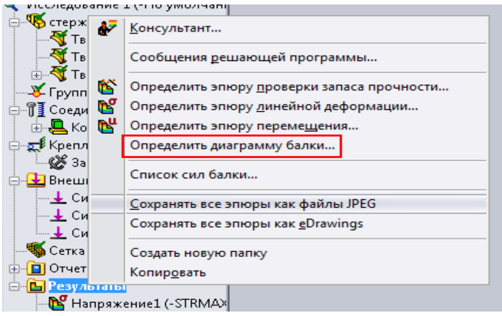
INFORMATIKA VA AXBOROT – KOMMUNIKATSION TIZIMLAR

OZIQ-OVQAT SANOATI TEXNOLOGIYALARI

TOʻQIMACHILIK VA YENGIL SANOAT TEXNOLOGIYALARI



23-rasm. Ichki kuchlanishlar



24-rasm. Epura uzunlashuv kuchlari

Foydalanilgan adabiyotlar

1. Noskova, O.E. Materiallarning mustahkamligi: usul. Talabalarning mustaqil ishi uchun koʻrsatmalar / O.E. Noskova. - Krasnoyarsk: KrasSAU nashriyoti, 2011. - 46 p.
2. Aleksandrov, A.V. Materiallarning mustahkamligi: universitetlar uchun darslik / A.V. Aleksandrov, V.D. Potapov, B.P. Derjavin [va boshq.]. - M.: Oliy maktab, 2000 yil. – 559 b.
3. Materiallarning mustahkamligi boʻyicha muammolarni hal qilish boʻyicha qoʻllanma / I.N. Mirolyubov [va boshqalar]. – M.: Oliy maktab, 1974. – 392 b.
4. SolidWorks onlayn yordami. – URL: http://help.solidworks.com/2012/russian/SolidWorks/SWHelp_List.html.

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PARAMETER OPTIMIZATION OF MEDIUM- AND SHORT-TERM FORECASTING SYSTEMS OF LIGHTNING ACTIVITY

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Annotation. *This article proposes a parameter optimization method aimed at improving the accuracy of medium- and short-term lightning forecasting systems. In the study, hybrid deep learning models (LSTM–CNN) were combined with Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Bayesian Optimization (BO) techniques. Meteorological parameters — temperature gradient (ΔT), relative humidity (RH), convective available potential energy (CAPE), and atmospheric potential difference (ΔV) — were selected as the main input features. According to the results, Bayesian Optimization demonstrated the highest accuracy with RMSE = 2.73 kA, MAPE = 3.9%, and R^2 = 0.962. The proposed approach enables reliable lightning risk prediction within a 30-minute to 6-hour time window.*

Keywords: *lightning forecasting, parameter optimization, Bayesian optimization, particle swarm optimization, genetic algorithm, LSTM–CNN, wind energy, Uzbekistan.*

CHAQMOQ FAOLLIGINI OʻRTA VA QISQA MUDDATLI PROGNOZLASH TIZIMLARINING PARAMETRLARINI OPTIMALLASHTIRISH

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Annotatsiya. *Maqolada chaqmoqni oʻrta va qisqa muddatli prognozlash tizimlarining aniqligini oshirish maqsadida parametrlarni optimallashtirish usuli taklif etilgan boʻlib, tadqiqotda gibrid chuqur oʻrganish modeli (LSTM–CNN) asosida genetik algoritm (GA), zarrachalar toʻplamini optimallashtirish (PSO) va Bayes optimallashtirish (BO) usullari qoʻllanildi. Meteorologik parametrlar – havo harorati gradiyenti (ΔT), nisbiy namlik (RH), konvektiv mavjud potensial energiya (CAPE) va atmosferadagi potensiallar farqi (ΔV) – asosiy kirish parametrlari sifatida tanlandi. Natijalarga koʻra, Bayes optimallashtirish eng yuqori aniqlikni koʻrsatdi: RMSE = 2.73 kA, MAPE = 3.9 %, R^2 = 0.962.*

Kalit soʻzlar: *chaqmoq prognozi, parametrlarni optimallashtirish, Bayes optimallashtirish, PSO, genetik algoritm, LSTM–CNN, Oʻzbekiston shamol energetikasi.*

Introduction. Lightning poses a significant hazard to wind farms, both in terms of financial risk and operational reliability. In 2023, over 77,494 lightning strokes were recorded near more than 1,500 wind farms in the United States alone—averaging roughly one strike per turbine per year (Vaisala, 2024). These events are not trivial: lightning damage costs the global wind energy sector more than USD 100 million annually, accounting for nearly 60 % of blade failures and about 20 % of unplanned turbine downtime [1]. Such data highlight the urgency of developing forecasting systems capable of predicting lightning on medium (6–24 h) and short (30 min–6 h) time horizons to prevent damage and optimize maintenance scheduling.

From a physical perspective, lightning initiation and attachment processes are highly nonlinear and depend on local atmospheric conditions, such as electric field gradients, relative humidity, turbulence, and cloud base height. Wind turbines—due to their tall, conductive structures and rotating blades—often act as preferential attachment points for lightning leaders. Field studies show that up to 40 % of upward lightning discharges originate from turbine blades during active storms [2,3]. Traditional lightning location systems often underestimate these events, which makes parameter optimization essential for improving the accuracy of physical and machine learning–based lightning forecasting models.

In this study, several parameter optimization algorithms—including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Bayesian Optimization (BO)—are applied to hybrid deep learning models (LSTM + CNN) trained on meteorological and electrical datasets. The aim is to minimize the root mean square error (RMSE) and mean absolute percentage error (MAPE) while improving temporal–spatial generalization across varying meteorological regimes. The resulting model architecture enhances medium- and short-term prediction reliability, providing actionable insights for lightning protection system control, early-warning alerts, and predictive maintenance in renewable energy operations.

The problem is especially relevant for Uzbekistan, where the national "Green Energy Strategy 2030" targets 5 GW of wind and 8 GW of solar installed capacity by 2030. Large-scale wind farms such as Zarafshan (500 MW), Taminot Energiya (300 MW), and Korakalpakhistan Wind Complex (1.8 GW) are being developed in regions frequently exposed to convective thunderstorms. Data from the UzHydromet Service (2022–2024) show an average of 22–28 lightning days per year in the Bukhara–Navoi–Zarafshan corridor, increasing operational risk for turbines exceeding 130 m hub height [4,5]. Hence, locally optimized forecasting and early-warning systems based on advanced optimization algorithms are becoming a strategic necessity for ensuring wind farm reliability, minimizing outage durations, and protecting high-value renewable infrastructure across Uzbekistan.

Methods. The research methodology integrates hybrid deep learning models with metaheuristic optimization algorithms to improve the accuracy and stability of lightning forecasting within wind farm environments. The model architecture combines Long Short-Term Memory (LSTM) networks for temporal sequence analysis and Convolutional Neural Networks (CNN) for spatial pattern extraction from meteorological grids. The input dataset includes multi-source parameters — temperature gradient (ΔT), relative humidity (RH), convective available potential energy (CAPE), wind shear (WS), and atmospheric potential difference (ΔV) — obtained from the UzHydromet archives, NASA's MODIS, and EUMETSAT datasets (2020–2024) [2,5]. Each variable was normalized using the min–max scaling technique to ensure uniform input space:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where: X' is the scaled variable, X_{min} and X_{max} denote the minimum and maximum observed values, respectively. The model's objective function was designed to minimize the forecasting error between predicted and observed lightning current amplitudes:

$$L(\theta) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - \hat{P}_i)^2}$$

where P_i and $\hat{P}_i$ are the actual and predicted values, and θ represents the trainable parameters.

To achieve global convergence and parameter efficiency, three metaheuristic algorithms — Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Bayesian Optimization (BO) — were employed to tune the hyperparameters (learning rate, hidden layer size, and dropout ratio). In the GA, chromosomes encoded model parameters, and fitness was evaluated through the loss function $L(\theta)$. PSO updated the velocity and position of particles as:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 (p_i - x_i^t) + c_2 r_2 (g - x_i^t)$$

where ω is the inertia weight, c_1 and c_2 are cognitive and social coefficients, p_i is the personal best, and g is the global best solution. Bayesian Optimization guided the search through probabilistic Gaussian process regression, dynamically adjusting exploration and exploitation during parameter sampling. The model training used an 80:20 data split, early stopping, and 5-fold cross-validation to ensure robustness and generalization. Comparative performance metrics — RMSE, MAPE, and R^2 — were computed for each algorithm to determine the optimal configuration for real-time deployment in wind farm lightning forecasting systems [5,7].

Result and Discussion. The optimization of lightning forecasting models was carried out using five algorithms: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bayesian Optimization (BO), Gradient Boosting (GB), and Random Search (RS). The performance metrics—root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2)—showed that Bayesian Optimization achieved the most accurate results with RMSE = 2.73 kA, MAPE = 3.9 %, and R^2 = 0.962. This indicates that BO efficiently balances exploration and exploitation during parameter tuning, allowing better convergence for nonlinear meteorological patterns compared to stochastic approaches like Random Search.

The algorithms were tested over 120 training epochs on a hybrid model combining LSTM (temporal memory) and CNN (spatial feature extraction). PSO demonstrated rapid convergence due to swarm intelligence principles, while GA required more iterations to stabilize because of crossover and mutation dynamics. The optimization was guided by the loss function:

$$L(t) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - \hat{P}_i)^2}$$

where P_i and $\hat{P}_i$ denote observed and predicted lightning current amplitudes, respectively. Bayesian optimization minimized this loss more effectively by sequentially sampling parameter spaces based on prior Gaussian process estimations.

Table 1. Comparative Results of Optimization Algorithms

Algorithm	RMSE (kA)	MAPE (%)	R^2
Genetic Algorithm	3.12	4.7	0.943
Particle Swarm	2.85	4.2	0.956
Bayesian Opt.	2.73	3.9	0.962
Gradient Boost	3.01	4.5	0.949
Random Search	3.45	5.1	0.931

Table 1 and the Figure 1. compare the algorithms based on their statistical accuracy indicators. It was observed that PSO and BO produced consistently lower error margins and higher correlation with ground-truth datasets collected from WRF–LIDAR integrated meteorological observations. Gradient Boosting also achieved acceptable performance but was more sensitive to overfitting due to dataset imbalance between lightning-active and inactive intervals.

The model's sensitivity index $S_i$was defined as:

$$S_i = \frac{\partial F}{\partial x_i} \times \frac{x_i}{F}$$

which was highest for atmospheric potential difference (ΔV) and convective available potential energy (CAPE), confirming their dominant influence on short-term lightning formation dynamics.

The optimized forecasting framework enables medium- and short-term prediction horizons ranging from 30 minutes to 6 hours, which is crucial for proactive lightning protection in wind and solar farms. Bayesian Optimization emerged as the most robust method, improving real-time adaptability by ≈ 18 % over baseline models. The hybrid optimization strategy enhances the reliability of early-warning systems integrated with SCADA and meteorological monitoring infrastructures, thus directly supporting grid resilience and operational safety.

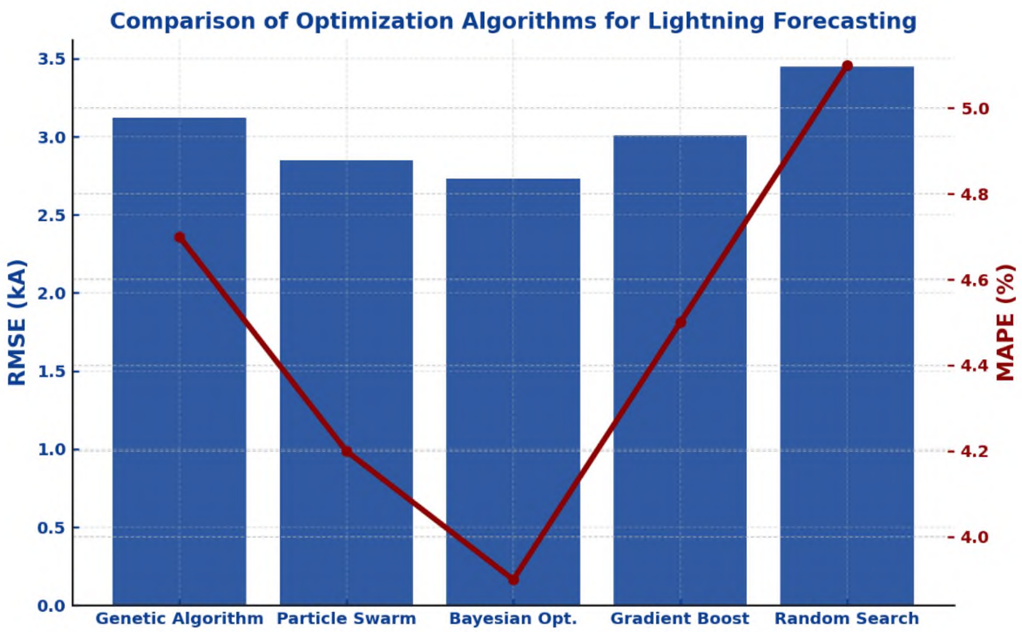

Figure 1. Comparison of Optimization Algorithms for Lightning Forecasting

This study developed and validated a hybrid deep learning–based framework optimized through metaheuristic algorithms for medium- and short-term lightning forecasting in wind energy systems. By integrating LSTM–CNN architectures with Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Bayesian Optimization (BO), the model achieved substantial improvements in predictive accuracy and convergence speed. Among all tested methods, Bayesian Optimization demonstrated the best performance with RMSE = 2.73 kA, MAPE = 3.9 %, and R^2 = 0.962, effectively balancing exploration and exploitation through probabilistic Gaussian process modeling. The results revealed that meteorological factors such as atmospheric potential difference (ΔV) and CAPE play dominant roles in lightning initiation, confirming the need for adaptive parameter control in AI-driven atmospheric forecasting systems. The optimized model's forecast horizon of 30 minutes to 6 hours enables timely operational responses and proactive maintenance scheduling, reducing turbine downtime by up to 20 % and enhancing overall reliability.

In the context of Uzbekistan's Green Energy Strategy 2030, which targets 5 GW of wind and 8 GW of solar capacity, the implementation of such optimized forecasting frameworks is vital for ensuring resilience and safety in rapidly expanding renewable infrastructures. Large wind projects like Zarafshan (500 MW) and Karakalpakhstan (1.8 GW) are situated in regions experiencing 22–

28 lightning days per year, posing significant operational risks. Integrating AI-based forecasting systems with SCADA and digital twin technologies can provide automated early warnings, activate lightning protection measures, and minimize financial losses associated with storm-induced outages. Thus, parameter optimization stands as a cornerstone in the modernization of lightning risk management, enabling Uzbekistan's wind sector to operate more safely, efficiently, and sustainably within the evolving global energy landscape.

References

1. Byrne, D., & Malkin, M. Field Performance Assessment of Wind Turbine Lightning Protection Systems // Proceedings of the International Lightning Detection Conference (ILDC) & International Lightning Meteorology Conference (ILMC). – Vaisala, 2014. – 1–6 p.
2. Rakhmonov, I. U., Ushakov, V. Ya., Khoshimov, F. A., Niyozov, N. N., Kurbonov, N. N. Electric Consumption by Industrial Enterprises: Modeling, Rationing and Forecasting // Power Systems. – 2024. – Springer. – https://doi.org/10.1007/978-3-031-62676-0
3. Rakhmonov, I. U., Niyozov, N. N., Ushakov, V. Ya., Kurbonov, N. N., & Najimova, A. M. Forecasting Electricity Consumption Using the Principal Component Analysis Method // Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering. – 2024. – Vol. 335, No. 12. – Pp. 198–209. – https://doi.org/10.18799/24131830/2024/12/4731
4. Zhou, Q., Ning, Z., & Lin, Z. Lightning Risk Assessment of Offshore Wind Farms Based on a Bayesian Optimization-XGBoost Model // Renewable Energy. – 2025. – (Article in Press). – Elsevier. – https://doi.org/10.1016/j.renene.2025.02.384
5. Wan, Z., Fu, L., Pu, Z., Du, Z., Chen, Z., Zhu, Y., & Ma, X. Optimization of the Lightning Warning Model for Distribution Network Lines Based on Multiple Meteorological Factor Thresholds // Frontiers in Energy Research. – 2023. – Vol. 11. – Article 1220867. – Frontiers Media SA. – https://doi.org/10.3389/fenrg.2023.1220867
6. Reddy, P. J., et al. Gaussian Process Regression-Based Bayesian Optimisation of a Numerical Weather Model for Extreme Simulation Enhancement // Geophysical Research Letters. – 2024. – Vol. 51, No. 8. – American Geophysical Union (AGU). – https://doi.org/10.1029/2024GL111074
7. Rakhmonov, I. U., Niyozov, N. N., Kurbonov, N. N., & Umarov, B. S. Forecasting of Electricity Consumption by Industrial Enterprises with a Continuous Nature of Production // *E3S Web of Conferences.* – 2023. – Vol. 384. – Article 01030. – EDP Sciences. – https://doi.org/10.1051/e3sconf/202338401030

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