ANNOTATION

to the dissertation submitted for the degree of Doctor of Philosophy (PhD) in the educational program "8D06201 Radio Engineering, Electronics and Telecommunications"

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Improving the efficiency of solar cells under low solar concentration conditions with an adaptive cooling system

General characteristics of the work. This dissertation is devoted to increasing the efficiency of a low-concentration photovoltaic system based on polycrystalline silicon by increasing the reception angle and implementing an adaptive cooling system using Internet of Things technology.

The relevance of the dissertation theme.

Current research in concentrated solar cells aims to improve solar radiation conversion efficiency, reduce equipment costs, extend the service life of systems, and improve their performance in various climatic conditions.

Low-concentration photovoltaic systems represent the most promising approach, combining high efficiency and low cost. Low concentration systems using a Fresnel lens are generally referred to as traditional low concentration systems. They allow the use of readily available polycrystalline solar cells without the need for expensive multijunction technologies. However, their design still faces several challenges related to optics and cell cooling. One such challenge is the limited reception angle. Due to the limited area of the photovoltaic cell in concentrating systems, additional solar tracking systems are required to capture the maximum flux of solar radiation. However, this increases the design complexity and leads to additional energy costs. To ensure efficient radiation concentration on the photovoltaic cell at various incidence angles, depending on the sun's trajectory, it is necessary to widen the reception angle of the optical system. Implementing this approach reduces dependence on solar tracking systems and improves conversion efficiency.

Another important challenge is thermal management. When solar radiation is concentrated, the temperature of photovoltaic cells increases significantly, reducing their efficiency and accelerating their degradation. To prevent overheating, active cooling systems are used – most often using water or air. Active cooling systems require auxiliary components, which reduces the overall conversion efficiency. Therefore, to ensure optimal performance, it is crucial to regulate their operation according to the photovoltaic cell's temperature.

In traditional water-based cooling systems, the system is activated when a preset photovoltaic cell temperature threshold is exceeded, and cooling continues until a preset minimum temperature is reached. Water flow is maintained at a constant level, resulting in constant pump energy consumption. However, the cooling duration depends on both the solar radiation intensity and the photovoltaic cell connection configuration. Maintaining a constant water flow under low radiation conditions leads to excessive energy consumption, and under high radiation, a fixed flow rate does not provide sufficient heat removal.

Therefore, developing a low-concentration photovoltaic system based on polycrystalline silicon with optical elements providing a wide reception angle is a pressing challenge. This will reduce the tracker's turn-on frequency and enable the use of simple, single-axis tracking systems with minimal power consumption. Furthermore, integrating a water cooling system with Internet of Things technologies enables adaptive control of the cooling system, supporting wireless data transmission and real-time monitoring. This approach reduces operating costs and improves reliability and manageability, underscoring the relevance and demand for this research.

The purpose of the research

Improving the efficiency of low-concentration polycrystalline silicon photovoltaic systems through the use of wide-angle optical elements and an adaptive water-based cooling system.

To achieve this goal, it is necessary to solve the following tasks:

- Simulate a low-concentration photovoltaic system based on a flat concave lens and a Fresnel lens and investigate its optical parameters;
- Investigate the sun tracking system of a low-concentration photovoltaic system based on a flat concave lens and a Fresnel lens and compare it with traditional low-concentration photovoltaic systems;
- Simulate a Pi-shaped low-concentration photovoltaic system, investigate its optical parameters, and compare the output power with various low-concentration photovoltaic systems;
- Investigate the parameters of a low-concentration photovoltaic cell under different solar radiation levels and cooling modes, and develop an adaptive cooling system to improve efficiency.

The research methods:

- Numerical simulation in COMSOL Multiphysics – analysis of transmission, reflection, and concentration of solar radiation in low-concentration optical systems with various incidence angles and based on various optical elements;
- Mathematical modeling in MATLAB – calculation of output power, concentration coefficient, and optimization of system geometric parameters;
- Optical analysis using ray tracing in COMSOL Multiphysics – evaluation of reception angles and optical efficiency for various lens and reflective surface configurations;
- Comparative analysis of the energy performance of the proposed low-concentration systems and traditional low-concentration systems based on simulation;
- Application of machine learning methods (XGBoost regression, linear regression, support vector regression, decision trees, and random forest) to estimate optical efficiency at various incidence angles.

The object of the research.

Low-concentration polycrystalline silicon photovoltaic system with adaptive cooling system.

The subject of the research.

Geometric parameters of optical elements used in low-concentration photovoltaic systems; the influence of concentrating components on the parameters

and output characteristics of a photovoltaic system; cooling processes and temperature distribution on the surface of photovoltaic cells.

The novelty of the work. The novelty and originality of the work lies in the fact that it is the first time:

- The use of a plano-concave lens, a Fresnel lens, and reflective surfaces in a low-concentration photovoltaic system was investigated. It was found that the use of such optics provides a significant increase in the concentration-acceptance product (CAP) compared to traditional systems.
- It was found that the use of a low-concentration photovoltaic system with a plano-concave lens, a Fresnel lens, and reflective surfaces reduces the use of the solar tracking system by increasing the reception angle.
- A low-concentration system based on a Fresnel lens and reflective surfaces with nine polycrystalline silicon solar cells was proposed. It was found that the optical solution allows the use of a single-axis tracker and produces more energy compared to a fixed, non-concentrated system.
- An adaptive cooling algorithm has been developed for a low-concentration PV system that, unlike traditional constant-flow approaches, adjusts the water flow based on solar radiation and cell temperature, thereby reducing cooling energy consumption.

The main provisions for the defense:

- The low concentration photovoltaic system with plano-concave lens, Fresnel lens and reflective surfaces shows a concentration angle product (CAP) value that is 2.9 times higher than that of the traditional low concentration photovoltaic system.
- Low concentration photovoltaic system based on plano-concave lens, Fresnel lens and reflective surfaces reduces the energy consumption of the sun tracking system by 27% compared with the traditional low concentration photovoltaic system..
- A low-concentration Pi-shaped system mounted on a single-axis solar tracker produces 2.2 times more energy than a fixed PV module.
- Adaptive cooling system control algorithm reduces system energy consumption by 12% compared to a traditional system.

Scientific and practical significance of the work.

The research is relevant given the growing demand for photovoltaic systems and the need to reduce operating costs. The developed optical solutions significantly improve the optical efficiency and acceptance angle of such systems, reducing the requirements for the accuracy and complexity of solar tracking systems and reducing their energy consumption. Particular attention is paid to the importance of using efficient cooling systems that ensure uniform temperature distribution across the surface of the photovoltaic cells and reduce their cooling time, thereby increasing the durability, operational stability, and overall efficiency of photovoltaic systems under conditions of variable solar radiation and temperature fluctuations.

The reliability and validity of the results.

The validity of the results of the dissertation work is confirmed by the presence of publications in foreign journals with an impact factor above zero.

The author's personal contribution. The author independently completed all aspects of the research, including the development and modeling of a low-concentration photovoltaic system in COMSOL Multiphysics, as well as the creation and optimization of an adaptive water cooling system. Output power calculations and numerical analysis of the system's characteristics were performed in MATLAB. Problem formulation and results discussions were conducted jointly with the research supervisors.

Approbation of the dissertation. The results obtained in the dissertation work were published, reported and discussed:

Publications with an impact factor on the Thomson Reuters database or in publications included in the international scientific database Scopus:

1. Orynbassar S., **Almen D.**, Mekhilef S., Kapparova A., Dosymbetova G., Nurgaliyev M., Saymbetov A., Ibraimov M., Kuttybay N., Yershov E., Koshkarbay N., Zholamanov B., Bolatbek A. Minimum solar tracking system for a Fresnel lens-based LCPV // Renewable Energy. – 2024. – Vol. 237. – 121607 (https://doi.org/10.1016/j.renene.2024.121607). (WoS: Impact Factor 9.1, Q1. Scopus: percentile 98 %)
2. **Almen D.**, Kapparova A., Yershov E., Orynbassar S., Dosymbetova G., Nurgaliyev M., Saymbetov A., Kuttybay N., Zholamanov B., Bolatbek A., Koshkarbay N. Output power analysis of low concentrated solar cells with Fresnel lens optics // Optik. – 2024. – Vol. 317. – P. 172088 (https://doi.org/10.1016/j.ijleo.2024.172088). (Scopus : percentile 85 %)
3. Kapparova A., Orynbassar S., Dosymbetova G., **Almen D.**, Yershov E., Saymbetov A., Nurgaliyev M., Kuttybay N., Algazin N. Modelling of the Pi-Shape Low-Concentrating Photovoltaic Solar Cells // IIUM Engineering Journal. – 2025. – Vol. 26, No. 2. – P. 81–95 (https://doi.org/10.31436/iiumej.v26i2.3175). (WoS: Impact Factor 0.7, Q3. Scopus : percentile 50 %)
4. Kapparova A., Orynbassar S., Dosymbetova G., **Almen D.**, Yershov E., Saymbetov A., Nurgaliyev M., Algazin N., Sharipbay A., Zhastalapova D. Modeling П-shaped concentrating optics for LCPV solar cells using Fresnel lens // Latvian Journal of Physics and Technical Sciences. – 2024. – No. 5. – P. 101–116 (DOI:10.2478/lpts-2024-0039). (WoS: Impact Factor 0.7, Q4. Scopus: percentile 37 %)
5. Orynbassar S., Kapparova A., Dosymbetova G., **Almen D.**, Yershov E., Saymbetov A., Nurgaliyev M., & Zholamanov B. Simulation of an active cooling system for low-concentrating photovoltaic solar cells // Acta Polytechnica. – 2025. – Vol. 65, No. 4. – P. 429–441 (https://doi.org/10.14311/AP.2025.65.0429) (WoS: Impact Factor 0.5, Q4. Scopus: percentile 32 %)

Patent for invention

1. Kuttybay N. B., Orynbasar S. O., Saymbetov A. K., Nurgaliyev M. K., Ibraimov M. K., Dosymbetova G. B., Bolatbek A. B., Koshqarbay N. Zh., Zholamanov B. N., Kapparova A. A., **Almen D. B.** Low-concentration photovoltaic system with minimal solar tracking, Patent for invention No. 37370, 2025, Republic of Kazakhstan, “National Institute of Intellectual Property”.
2. **Almen D.B.**, Ibraimov M.K., Nurgaliyev M.K., Saymbetov A.K., Burkit Sh.A. Adaptive Cooling System for Low-Concentrated Photovoltaic Systems.

Republic of Kazakhstan, “National Institute of Intellectual Property,” 2025. Copyright Certificate No. 62891.

The volume and structure of the dissertation. The dissertation consists of an introduction, four chapters, a conclusion, and a bibliography of 108 references. The work is 107 pages long, including 79 figures and 7 tables.

The first chapter examines the optical elements and cooling methods used in concentrator systems, including low-concentration photovoltaic systems.

The second chapter examines the general characteristics and output parameters of a low-concentration photovoltaic system based on a plano-concave Fresnel lens and reflective surfaces.

The third chapter is devoted to a low-concentration photovoltaic system based on a Pi-shaped Fresnel lens, examining its optical parameters and cooling system.

The fourth chapter examines the adaptive cooling system for a low-concentration photovoltaic system and its output parameters.

The dissertation work has been partially completed in accordance with the research work (R&D) plans: “Study of the efficiency of silicon photovoltaic converters with a new adapted cooling system under conditions of solar radiation concentration” for 2023–2025, individual registration number (IRN) AP19574454.