Influence of temperature on output load characteristics of polycrystalline silicon solar cells

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Abstract. Studies have been carried out of the effect of temperature on the load current-voltage characteristics of a polycrystalline silicon solar cell, which has been illuminated by solar radiation with a power of 80 mW/cm^2. It has been accepted that with an increase in the temperature of the solar cell, in the range of 25 - 90 ^{0}C, the efficiency decreases, from 16.6% to 13%, and the load factor of the current-voltage characteristic decreases. This is due to an increase in series resistance. The shunt resistance of the solar cell decreases. These variations in R_{ser} and R_{sh} are related with the modulation of photoactive layers of solar cells under the influence of solar radiation.

INTRODUCTION

Studying the photoelectric characteristics of solar cells at different ambient temperatures will make it possible to establish the energy depletions that comes in solar cells and determine the temperature range where photovoltaic modules consisting of solar cells with given parameters will operate effectively [1-8].

In [9-12], the temperature dependence of the open circuit voltage (V_{oc}) and the filling factor of the current-voltage characteristic (FF) was studied in the temperature range of 295–320 ^{o}K and found that the shunt resistance (R_{sh}) declines almost linearly with T, and its influence on the temperature coefficient dV_{oc}/dT is considerable for cells having less R_{sh} values. The series resistance (R_{ser}) also varies almost linearly with V_{oc}. A study [13-17] of thin-film solar cells made of hydrogenated amorphous silicon (a-Si:H) shows that dV_{oc}/dT also varies linearly with temperature (T). The short-circuit current (J_{sc}) rises linearly with temperature, mostly due to temperature-induced band gap reduction and reduced nonequilibrium charge carrier recombination. The temperature dependence of FF is not linear and has a maximum in the temperature range of 15 °C to 80 °C.

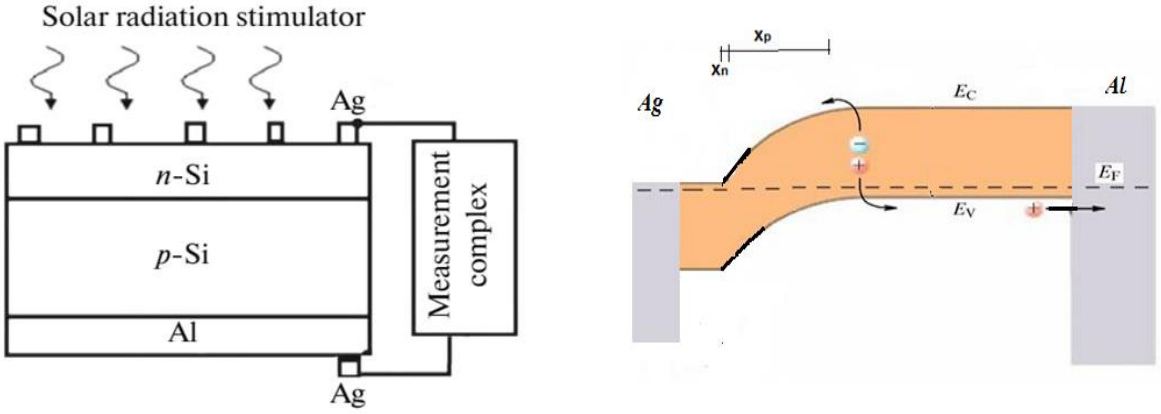
Temperature studies of the load current-voltage characteristics of a solar photovoltaic film based on amorphous hydrogenated silicon [18], under real solar illumination conditions (P_{rad}=870±10 W/m^2), showed that the temperature addiction of J_{sc} increases with two lines, explained by a transform in the generation-recombination mechanism, by increasing the lifetime of minority carriers. The decline in the open circuit voltage with rising temperature is interpreted by the exponential increase in the value of the reverse saturation current and the decline in the band gap of the semiconductor. FF declines with increasing temperature, which is probably due to a descend in R_{sh}. With increasing temperature, the value of R_{ser}, as well as R_{sh}, decreases. The large loss of power generation with enhancing temperature is mainly observed in the series resistance of the solar PV module. With increasing temperature, the loss of generated power across the shunt resistance increases sublinearly. In works [19-23], studies were carried out of the influence of temperature on the output parameters of various types of silicon-based solar cells. However, the output energy parameters were considered without taking into account changes in one of the main parameters that determine the effective conversion of solar energy by a photovoltaic device, such as R_{ser} and R_{sh}, and their changes with temperature.

In connection with the above, the main purpose of this study is to establish the effect of temperature on the main escape energy parameters of a solar cell constructed on polycrystalline silicon and to analyze the mechanisms of

photogeneration, considering the influence of temperature on the main parameters of the photosensitive structure of the solar cell, such as R_{ser} and R_{sh}.

EXPERIMENTAL RESEARCH

In this work, experimental studies of solar cells based on polycrystalline silicon (pc-Si) with an area of 2.00±0.02 cm^2 were carried out. PC-Si SC under "standard test conditions" (Standard Test Conditions (STC), P=100 mW/cm^2, T=25 °C), had an efficiency factor (efficiency) = 17%. Figure 1 shows the design of a pc-Si SC with the Ag-n-Si/p-Si-Al-Ag structure (a) and its energy band diagram (b). The energy value of the internal built-in potential of the homojunction was $eV_D \approx 0.890 \pm 0.01$ eV where $eV_D = eV_p + eV_n$: in the p-layer $eV_p \approx 0.885 \pm 0.002$ eV and in the n-layer $eV_n \approx 0.005 \pm 0.002$ eV, space charge region with $x_p \approx 260 \pm 5$ nm and $x_n \approx 1.5 \pm 0.1$ nm, $x_p/x_n \approx 170 \pm 5$.



(a) (b)

FIGURE 1. Design (a) energy band diagram and (b) of Ag-n-Si/p-Si-Al-Ag structural pc-Si solar cells

Experimental studies of the dark and light current-voltage characteristics of pc-Si SC were carried out on a complex for measuring the current-voltage characteristics of Oriel Sol 3A class AAA, using a solar radiation simulator Model - 94043A, in the temperature between 25 °C - 90 °C under normal lighting conditions (NLC), radiation power P=80 mW/cm^2. The illumination spectrum of the simulator corresponded to the spectrum of solar radiation at AM1.5 [24-27]. The power of the falling radiation was determined using a reference certified single-crystalline silicon solar cell from the manufacturer Newport Oriel (USA). The temperature was recorded using a TS/K temperature sensor. The current-voltage characteristics were recorded using a Source Meter Keithley 2400 instrument.

To study the spectral dependence of sensitivity, a research complex was used using a mirror monochromator ZMR - 3 and a combined digital device Sh - 300, which made it possible to study the spectral dependence of the studied photosensitive structure in the spectral wavelength range of monochromatic radiation from 300 nm - 2500 nm, with length accuracy wave ± 10 nm, current 0.01% and voltage 0.1%.

RESEARCH RESULTS

Figure 2 demonstrates the spectral dependence of the sensitivity (S is the external quantum yield) of the pc-Si SC. The SC had a spectral sensitivity range from 400 nm to 1100 nm. Figure 3 shows (on a logarithmic scale) the results of the dark current-voltage characteristic of pc-Si solar cells, curve A is the direct branch and curve B is the reverse branch of the current-voltage characteristic. The rectification coefficient (K) of the current-voltage characteristic of the pc-Si SC, the correlation of the forward current to the reverse one, at a fixed applied V=0.7 V was equal to $K=2*10^3$.

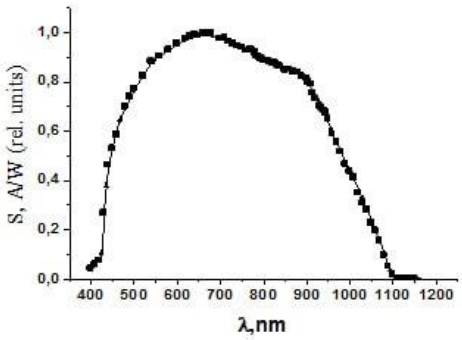


FIGURE 2. Spectral dependence of the sensitivity of pc-Si solar cells

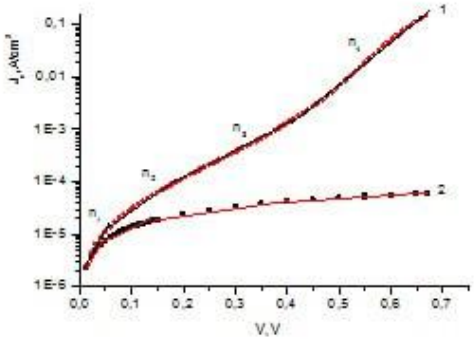


FIGURE 3. Dark current-voltage characteristic of pc-Si solar cells: 1-direct branch, 2-reverse branch

Research of the direct branch of the current-voltage characteristic [28-30] made it possible to estimate the value of the built-in potential of the pc-Si SC, which has a value of V_b=0.9±0.03 eV. The energy value of the internal built-in potential of the homojunction eV_D≈0.890±0.01 eV determined from Figure 1 (b) and the value of the built-in potential of the pc-Si SC V_b=0.9±0.03 eV have almost the same value, within the experimental error. From the direct branch of the current-voltage characteristic [31-33], the options of charge carriers in the high-resistivity region beside the space charge were also estimated: $p_0=2.8*10^{10}$ cm^{-3}; $\mu_n*\tau_n=3*10^{-8}cm^2/V$, where p_0 is the concentration of holes in the photoactive part of the pc-Si SC; μ_n - electron mobility; τ_n - is the lifetime of electrons.

Below are the results of experimental researches of the light load current-voltage characteristic of a pc-Si SC (radiation power AM 1.5, P=80 mW/cm^2), in the temperature between 25 °C - 90 °C. The short circuit current (J_{sc}) (Figure 4) decreases slightly with increasing temperature, with a temperature coefficient $(\Delta J_{sc})/\Delta T=1.045*10^{-5}$%. The open circuit voltage (V_{oc}) (Figure 5) decreases with increasing temperature with a temperature coefficient $(\Delta V_{oc})/\Delta T=1.7*10^{-2}$%.

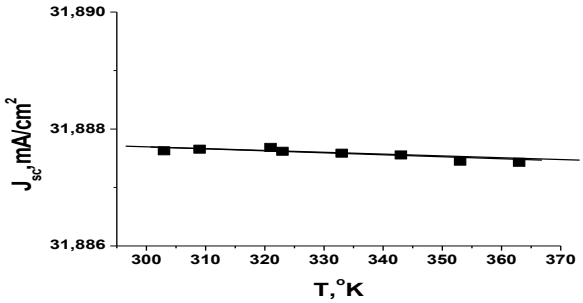


FIGURE 4. Temperature relation of short circuit current J_{sc} pc-Si solar cells

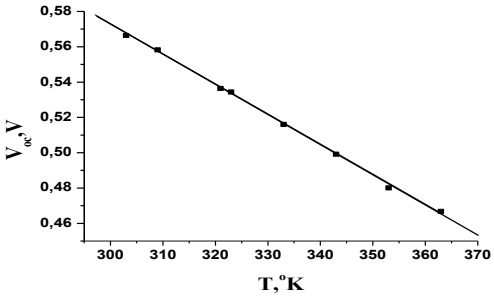


FIGURE 5. Temperature relation of open circuit voltage V_{oc} of pc-Si solar cells

The photocurrent at the point of maximum power ($J_{max}(T)$) (Figure 6) decreases with increasing temperature with a temperature coefficient $(\Delta J_{max})/\Delta T$=0.03%/deg. The voltage at the spot of maximum power ($V_{max}(T)$) (Figure 7) falls with increasing temperature with a temperature coefficient $(\Delta V_{max})/\Delta T$=0.37%/deg. The maximum output power ($P_{max}(T)$) (Figure 8) decreases with rising temperature with a temperature coefficient $(\Delta P_{max})/\Delta T$= 0.38%/deg. The filling factor of the current-voltage characteristic (FF) (Figure 9) decreases with increasing temperature with temperature coefficient $(\Delta FF)/\Delta T$=0.09%/deg. The efficiency factor (Efficiency) (Figure 10) decreases linearly with increasing temperature with temperature coefficient $(\Delta Eff)/\Delta T$=0.31%/deg. From the presented experimental results it follows that the open-circuit voltage falls with increasing T from 570 mV to ≈ 470 mV. The efficiency of solar cells decreases with increasing T from ≈ 16.8% to ≈ 13%, and FF decreases from ≈ 74% to ≈ 70%.

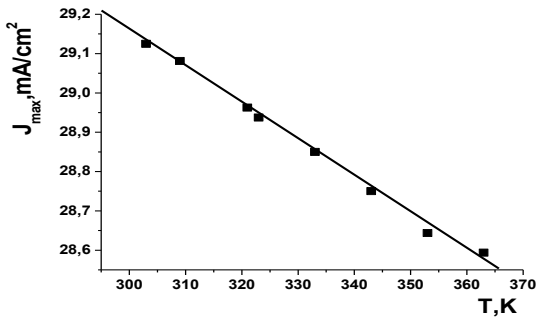


FIGURE 6. Temperature dependence of the photocurrent at the point of maximum power $J_{max}(T)$ pc-Si solar cells

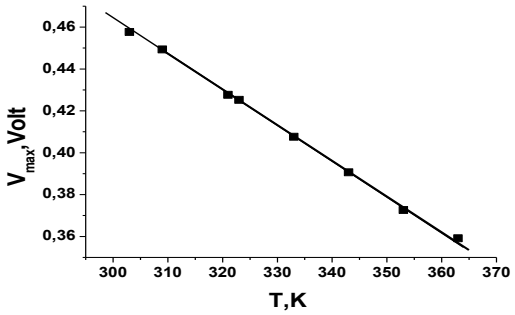


FIGURE 7. Temperature dependence of voltage at the point of maximum power $V_{max}(T)$ pc-Si solar cells

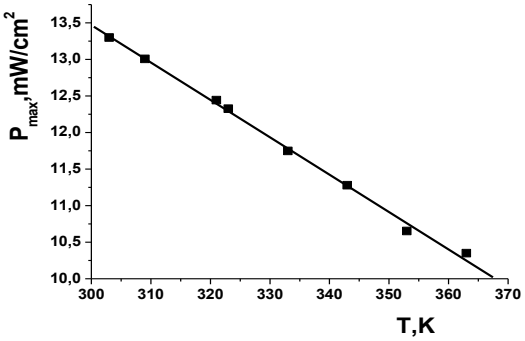


FIGURE 8. Temperature dependence of the maximum output power $P_{max}(T)$ pc-Si solar cells

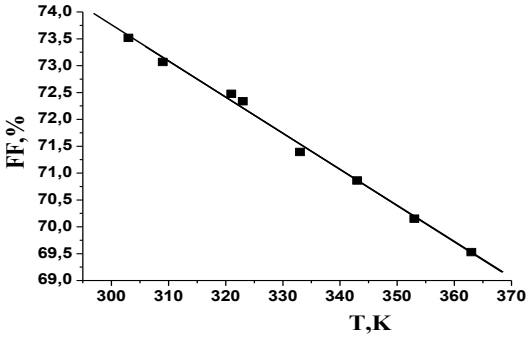


FIGURE 9. Temperature dependence of the filling factor of the current-voltage characteristic FF of pc-Si solar cells

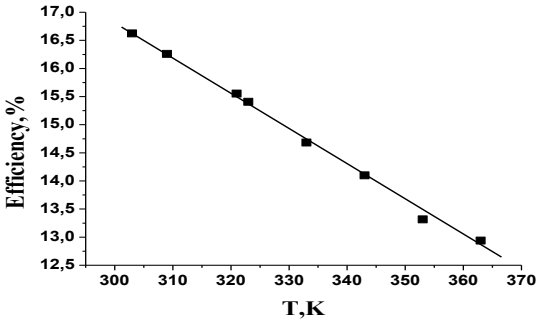


FIGURE 10. Temperature dependence of efficiency of pc-Si solar cells

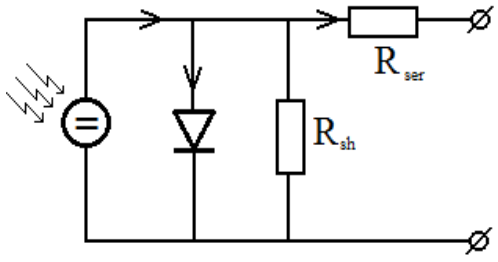


FIGURE 11. Equivalent scheme of a real solar cell.

A real solar cell is characterized by the attendance of series R_{ser} and shunt R_{sh} resistance. R_{ser} consists of the series-connected resistances of the contact layers, the resistances of each of the p- and n-regions of the solar cell, and the metal-semiconductor transition resistances. R_{sh}-represents presumable surface and volumetric current outflow through the resistance parallel to the p-n junction of the SC [3]. In the Figure 11 the equivalent scheme of a real

solar cell is presented, taking into account (R_{ser}) and shunt (R_{sh}). Figures 12 and 13 show the experimental temperature dependences of the series (R_{ser}) and shunt (R_{sh}) resistance of the pc-Si SC.

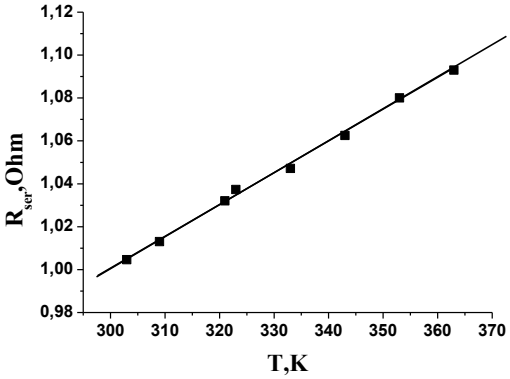


FIGURE 12. Temperature dependence of series R_{ser} resistance of pc-Si solar cells

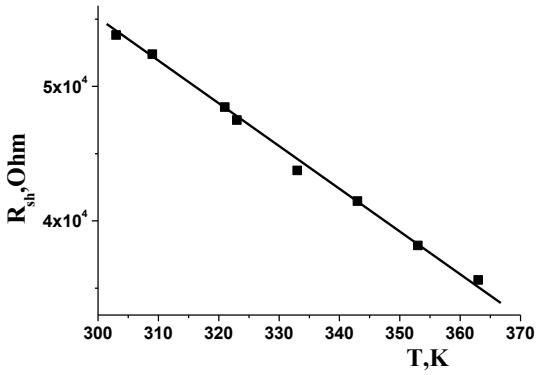


FIGURE 13. Temperature dependence of shunt R_{sh} resistance of pc-Si solar cells

From Figure 12 and Figure 13 it follows that R_{ser} increases and R_{sh} decreases with increasing temperature. The decrease in the filling factor of the current-voltage characteristic (FF) and efficiency (Efficiency) of pc-Si SCs with temperature can be explained from the temperature dependence of R_{ser} and R_{sh}. An increase in R_{ser} and a decrease in R_{sh} with temperature leads to undesirable losses of photogenerated charge carriers on R_{ser} and R_{sh} of a real solar cell based on pc-Si SC.

CONCLUSIONS

A study of the light photovoltaic characteristics of PC-Si SCs at different temperatures showed that the output load parameters deteriorate with temperature. These changes are associated with an increase in the series resistance of the solar cell with increasing temperature, due to an increase in the resistance of metal contacts. Also, the decrease in the shunt resistance of the solar cell is explained by the semiconductor properties of the shunt channels of the p-n junction, which also reduce the conversion efficiency of the solar cell.

REFERENCES

1. K. Yoshikawa, H. Kawasaki, W. Yoshida, et al, “Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%”, Nature energy, vol. 2, no. 17032, pp. 1-8, 2017. https://doi.org/10.1038/nenergy.2017.32

2. R. R. Kabulov, L. O‘. Shuhratova, K. T. Suyarov, F. A. Akbarov, D. B. Istamov. Structural, Compositional, and Photoluminescence Properties of $CsPbBr_3$ Thin Films Grown by Single-source Thermal Vacuum Chemical Vapor Deposition. e-Journal of Surface Science and Nanotechnology 23. 364–367 (2025). https://doi.org/10.1380/ejssnt.2025-051

3. Farrukh Akbarov; Rustam Kabulov; Anvar Alimov; Erkin Abduraimov; Dildora Nasirova. Dependence of output parameters of photovoltaic module based on CIGS solar cells on external temperatures. *AIP Conf. Proc.* 3331, 040046 (2025). https://doi.org/10.1063/5.0305885

4. Anvar Alimov; Kudrat Abidov; Erkin Abduraimov; Farrukh Akbarov; Humoyun Muminov. Generalized model of nonlinear inductance and its parameters. *AIP Conf. Proc.* 3331, 040035 (2025). https://doi.org/10.1063/5.0305883

5. Komilov, A.G., Kabulov, R., Egamberdiev, B.E., Nasrullayev, Y.Z., Akbarov, F.A. The Result of Successive Exposure to Reverse and Forward Bias on the Electrophysical Characteristics of ZnO:Al/i-ZnO/CdS/$CuIn_{1-x}Ga_x(S, Se)_2$/Mo Structure Solar Cells // Applied Solar Energy. 2022, Vol. 58 No4. pp.476-481. https://doi.org/10.3103/S0003701X22040090

6. Anvar Alimov, Erkin Abduraimov; Farrukh Akbarov; Dildora Nosirova. Analysis of the Basic Circuit of Ferroresonant Transistor Parametric Dc Voltage Stabilizers with Built - in Functional Converter. *AIP Conf. Proc.* 3152, 050016 (2024). pp. 1-9. https://doi.org/10.1063/5.0218823
7. R. R. Kabulova, S. Yu. Gerasimenko, and F. A. Akbarov. Effect of Solar Radiation of Different Power on the Internal Amplification of the Primary Photocurrent in Heterostructures Based on Cadmium Telluride. Applied Solar Energy, 2023, Vol.59, No.2, pp.118–124. https://doi.org/10.3103/S0003701X22601065
8. R.R.Kabulov, F.A.Akbarov, A.A.Alimov. Time of transition processes in a CdS-CIGS structural solar cells in the short-wave part of the absorption spectrum at different loading resistances. Nanosystems: Physics, Chemistry, Mathematics, 14(1), pp. 127–131, 2023. https://doi.org/10.17586/2220-8054-2023-14-1-127-131
9. Komilov, A.G., Egamberdiev, B.E., Kabulov, R., Nasrullayev, Y.Z., Akbarov, F.A. The Result of Successive Exposure to Reverse and Forward Bias on the Electrophysical Characteristics of ZnO:Al/i-ZnO/CdS/$CuIn_{1-x}Ga_x(S, Se)_2$/Mo Structure Solar Cells. Applied Solar Energy, 2022, Vol.58, No.4, pp.476–481. https://doi.org/10.3103/S0003701X22040090
10. Muminov, R.A., Tursunov, M.N., and Tukfatullin, O.F., Temperature effect on the current-voltage characteristics of single-crystalline Si photovoltaic arrays, Appl. Solar Energy, 2007, vol.43, No.4, pp.211–213. https://doi.org/10.3103/S0003701X07040044
11. Schwingshackl, C., Petitta, M., Wagner, J.E., et al., Wind effect on PV module temperature: analysis of different techniques for an accurate estimation, Energy Proc., 2013, vol.40, pp.77–86. https://doi.org/10.1016/j.egypro.2013.08.010
12. Grundmann, M., The Physics of Semiconductors. An Introduction Including Nanophysics and Applications, 2nd ed., Berlin, Heidelberg: Springer, 2010, pp. 637–651. https://doi.org/10.1007/978-3-642-13884-3
13. Sze, S.M. and Kwok, K.Ng., Physics of Semiconductor Devices, 3rd ed., Hoboken, NJ: Wiley, 2007, p.793. https://doi.org/10.1002/0470068329
14. Handbook of Photovoltaic Science and Engineering, 2nd ed., Luque, A. and Hegedus, S., Eds., Chichester: Wiley, 2011, p. 1106. https://doi.org/10.1002/9780470974704
15. Meyer, E.L., Extraction of saturation current and ideality factor from measuring V_{oc} and I_{sc} of photovoltaic modules, Int. J. Photo Energy, 2017, vol.7, pp.1–9. https://doi.org/10.1155/2017/8479487
16. Koltun, M.M., The Optics and Metrology of Solar Cells, Moscow: Nauka, 1985, pp.33–53. https://doi.org/10.1080/00908318908945383
17. Carlson, D.E., Lin, G., and Ganguly, G., Temperature dependence of amorphous silicon solar cell PV parameters, in Proceedings of the Conference record of the 28th IEEE Photovoltaic Specialists Conference, Anchorage, USA, Sept. 15-22, 2000, pp.2–7. https://doi.org/10.1109/PVSC.2000.915967
18. Bouzidi, K., Chegaar, M., and Bouhemadou, A., Solar cells parameters evaluation considering the series and shunt resistance, Sol. Energy Mater. Sol. Cells, 2007, vol.91, pp.1647–1651. https://doi.org/10.1016/j.solmat.2007.05.019.
19. Bashahu, M. and Habyarimana, A., Review and test of methods for determination of the solar cell series resistance, Renewable Energy, 1995, vol.2, pp.129–138. https://doi.org/10.1016/0960-1481(94)E0021-V
20. E.X.Abduraimov, A.A.Alimov, A.M.Adxamov, S.A.Dusmukhamedova. Application of Semiconductor Contactless Devices to Improve the Quality and Reliability of Power Supply Systems. AIP Conference Proceedings, 3152(1), 040023, (2024), https://doi.org/10.1063/5.0218898
21. Shukhrat Umarov, Murot Tulyaganov. Peculiarities of simulation of steady modes of valve converters with periodic power circuit structure. III International Scientific and Technical Conference "Actual Issues of Power Supply Systems" (ICAIPSS2023). AIP Conf. Proc. 3152, 050004-1–050004-7; https://doi.org/10.1063/5.0218869
22. Shukhrat Umarov, Murat Tulyaganov, Saidamir Oripov, Ubaydulla Boqijonov. Using a modified laplace transform to simulate valve converters with periodic topology. AIP Conf. Proc. 3331, 030104 (2025); https://doi.org/10.1063/5.0305792
23. Murat Tulyaganov, Shukhrat Umarov, Islambek Abdullabekov, Shakhnoza Sobirova. Optimization of modes of an asynchronous electric drive. AIP Conf. Proc. 3331, 030084 (2025); https://doi.org/10.1063/5.0305786
24. Islombek Abdullabekov, Murakam Mirsaidov, Shukhrat Umarov, Murot Tulyaganov, Saidamirkhon Oripov. Optimizing energy efficiency in water pumping stations: A case study of the Chilonzor water distribution facility; AIP Conf. Proc. 3331, 030107 (2025); https://doi.org/10.1063/5.0305780
25. Islombek Abdullabekov, Murakam Mirsaidov, Furkat Tuychiev, Ravshan Dusmatov. Frequency converter – asynchronous motor – pump pressure piping system mechanical specifications. AIP Conf. Proc. 3152, 040007 (2024) https://doi.org/10.1063/5.0218880

26. Islombek Abdullabekov, Sapaev Khushnud. An Energy Efficient Control System for Water Lifting Units of the Ramadan Pumping Station Based on Frequency Controlled Electric Drives. AIP Conference Proceedings 2552, 040023, (2023), https://doi.org/10.1063/5.0130676
27. Islombek A. Abdullabekov, Murakam M. Mirsaidov, Odiljon O. Zaripov, Samad J. Nimatov, and Yulduz M. Eralieva. Reducing reactive energy consumption bu optimizing operating modes of irrigation pumping stations. E3S Web of Conferences 486, 06017 (2024) AGRITECH-IX 2023. https://doi.org/10.1051/e3sconf/202448606017
28. Shukhrat Umarov, Khushnud Sapaev, Islambek Abdullabekov. The Implicit Formulas of Numerical Integration Digital Models of Nonlinear Transformers. AIP Conf. Proc. 3331, 030105 (2025); https://doi.org/10.1063/5.0305793
29. Makhsud Bobojanov, Furkat Tuychiev, Nuralibek Rashidov, Alim Haqberdiyev, Islombek Abdullabekov. Dynamic simulation of a three-phase induction motor using Matlab Simulink. AIP Conf. Proc. 3331, 040012 (2025) https://doi.org/10.1063/5.0305750
30. Alexandr D. Petrushin, Murot Tulyaganov. Optimal Control of the Switched Reluctance Motor of High-Speed Rail Transport with an On-Board Energy Source. 2024 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM). -2024, https://doi:10.1109/icieam60818.2024.10553741
31. Murot Tulyaganov, Shukhrat Umarov. Improving the energy and operational efficiency of an asynchronous electric drive. III International Scientific and Technical Conference “Actual Issues of Power Supply Systems” (ICAIPSS2023); https://doi.org/10.1063/5.0218876