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EFFICIENT CONTROL SOLUTIONS FOR PHOTOVOLTAIC POWER SYSTEMS

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Abstract. *Solar power generation is the fastest-expanding segment of the energy sector in the European Union, with installed capacity expected to reach approximately 600 GW by 2030, compared to 41.4 GW in 2022. To achieve efficient operation under stochastic solar irradiance conditions, advanced automation solutions are proposed. A mathematical model is formulated, incorporating a DC motor for panel positioning and a power transducer for continuous energy output monitoring. Based on this model, a nominal RST control system is designed. Furthermore, the study investigates a control approach aimed at maintaining low operating temperatures of the photovoltaic panels. The theoretical results, validated through simulations and experimental hardware-in-the-loop testing, demonstrate strong potential for practical implementation in real-world photovoltaic energy systems.*

Keywords: Photovoltaics, Energy, Automation, Optimization, Control

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1. Introduction

Conventional electricity generation methods based on fossil fuels have, over time, led to substantial environmental damage, primarily through greenhouse gas emissions and irreversible ecosystem degradation. As a result, renewable energy sources-particularly photovoltaic energy, alongside hydroelectric and wind power-have become fundamental to the transition toward a more sustainable energy future. Given the widespread availability of solar radiation across most regions of the globe, electricity generated from photovoltaic systems represents a significant opportunity for increasing the share of clean energy in the global energy mix [1].

The exploitation of solar energy has made significant progress in recent decades, driven by technological advances in energy conversion and the decreasing

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production costs of photovoltaic panels. Modern panels can achieve conversion rates of up to 37.66%, due to the use of multi-junction photovoltaic cells [2]. Nevertheless, photovoltaic energy production remains highly variable, primarily due to its dependence on environmental conditions.

The expansion of installed photovoltaic capacity in Europe has been fueled by the Paris Climate Agreement's measures, which have resulted in the establishment of organizations such as Solar Power Europe. In 2023, the European Union (EU) reached 269 GW, with a target of 671 GW by 2028 [3]. In the meantime, 447 GW represents the current global capacity.

Using different Maximum Power Point Tracking (MPPT) techniques [4], the problem of optimizing the power generated by photovoltaic panels is technically expressed as determining the Maximum Power Point (MPP). These techniques continuously adjust the operating point to maximize the energy delivered to the load. Under normal operating conditions, traditional MPPT techniques such as Perturb and Observe (PO), Hill Climbing, and Incremental Conductance produce good results. However, they have limitations in variable environmental conditions with oscillations around the MPP, as is presented in [5], [6], [7].

The first part of this paper includes the mathematical modeling of the entire photovoltaic structure, composed of a direct current motor, photovoltaic panel and power transducer. This is followed by the design and validation of control strategies within the Matlab/Simulink simulation environment. Finally, the proposed control solutions are analyzed in terms of performance and robustness.

The second part of the study proposes a control alternative that ensures panel operation at the temperature close to the Standard Test Condition temperature (typically 25°C) during summer, enabling the implementation of active evaporative cooling methods, applied to the panel through atomization. A mathematical model was developed for evaporative cooling, as a function of surface area, solar radiation, and temperature and a control strategy was developed for water atomization, on the operating PV area.

2. Mathematical model for a photovoltaic panel with variable orientation

The photovoltaic system targeted for analysis and optimization integrates a dynamic mechanism for adapting the panel's position according to the point of maximum power. This involves the use of a DC motor to adjust the panel's position and a power transducer for continuous monitoring of the energy produced by the system.

The dynamic photovoltaic process model shown in Figure 1 includes the DC motor, the photovoltaic panel and the power transducer. The transfer function of the motor was evaluated considering the voltage U(s) as the input to the motor and the tilt angle α(t) as the output. The main objective of modeling the photovoltaic panel is to define the generated power Pgen [W] as a function of the tilt angle α(t) In terms of dynamics, the variation of the power generated by the photovoltaic panel with respect to the tilt angle is significantly faster compared to the response of the electric motor, thus the power dynamics is modeled by a static gain. This fact requires addressing and because the power transducer exhibits faster dynamics compared to the DC motor, this allows it to be modeled as a static gain. [16]

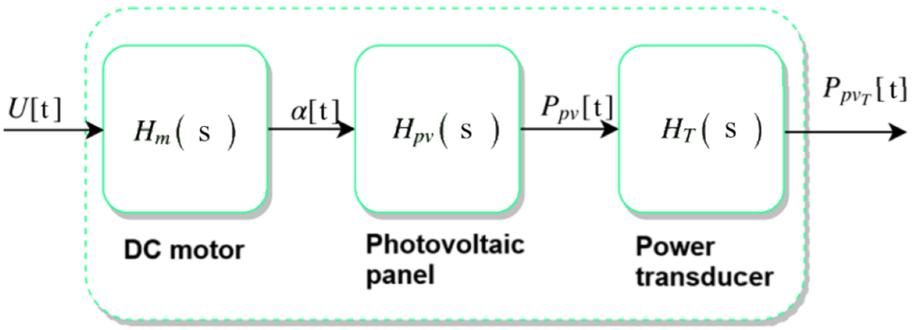

Fig. 1. Model of the photovoltaic process

The global dynamic model is expressed as:

$$H_F(s)=H_m \cdot H_{pv}(s) \cdot HT(s)=\frac{1}{s} \cdot \frac{137.09}{0.117 \cdot 10^{-3} \cdot s^2+0.02509 \cdot s+28.9} \quad (1)$$

For the identified continuous model of the photovoltaic process, a corresponding sampling period was selected, and the equivalent discrete model was estimated (2).

3. Robust control system design for photovoltaic panels with variable orientation

Based on the estimated dynamic model of photovoltaic panels with variable orientation, a robust control solution with the main objective of maximizing the captured solar radiation and implicitly, the generated electrical power, regardless of environmental conditions, is proposed. By continuously adapting the tilt angle, the system aims to achieve an optimal operating regime.

3.1. Design of nominal RST polynomial control

The pole allocation method (PAM) is proposed to compute the RST control algorithm for imposed performances in closed loop. The RST closed-loop system achieves the desired regulation and tracking performances [4].

For this purpose, the continuous-time system model was discretized using the Zero-Order Hold (ZOH) method with a sampling period of Te = 0.5 s, resulting in the following discrete transfer function:

$$H_{Fd}(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{0.4702 \cdot z^{-1} + 4.121 \cdot 10{-}3 \cdot z^{-2} + 2.08 \cdot 10{-}7 \cdot z^{-3}}{1 - z^{-1} - 7{,}247 \cdot 10^{-6} \cdot z^{-2} - 4.864 \cdot 10^{-10} \cdot z^{-3}} \quad (2)$$

The characteristic polynomial that defines the closed-loop system performance is introduced by a polynomial equation:

$$P(z^{-1}) = S(z^{-1}) \cdot A(z^{-1}) + R(z^{-1}) \cdot B(z^{-1}) \quad (3)$$

where A (z^{-1}) and B (z^{-1}) are the two polynomials of the discrete identified model, respectively R(z^{-1}), S(z^{-1}) and T(z^{-1}) are the control unknown polynomials.

The design was done using the pole-allocation method (PAM) by means of the specialized Software (WinReg), and the following control polynomials are obtained:

$$R(z^{-1}) = 2.210848 - 1.606819\, z^{-1} + 1.215\, 10^{-5}\, z^{-2} + 7.892\, 10^{-10}\, z^{-3}$$
$$S(z^{-1}) = 1 - 0.99338 z^{-1} - 0.00662 z^{-2} - 1.137\, 10^{-13}\, z^{-3}$$
$$T(z^{-1}) = 2.108729 - 2.011854\, z^{-1} + 0.507166 z^{-2} \quad (4)$$

The dynamic response of the nominal system is shown in Figure 2, where a disturbance is injected after stabilization.

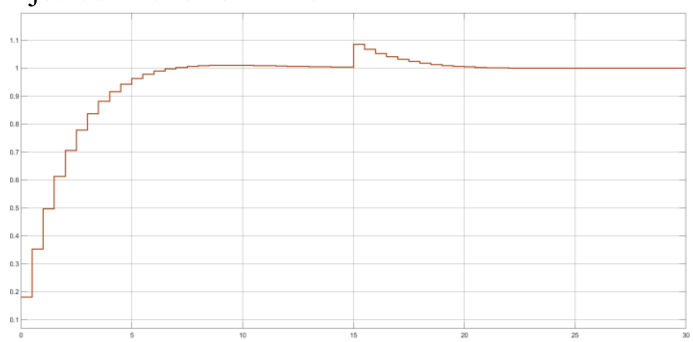

Fig. 2. Nominal photovoltaic control system-dynamic response

3.1. Design of robust RST polynomial control

The robust analysis of the controller was performed by evaluating the disturbance-output sensitivity function of the closed-loop system. In this case, the sensitivity function is considered to quantify and to design the robustness of the system. [18-19]. The sensitivity function for the RST system structure (transfer perturbation-output of the system) is:

$$S_{py}(z^{-1}) = \frac{\hat{A}(z^{-1})S(z^{-1})}{\hat{A}(z^{-1})S(z^{-1}) + \hat{B}(z^{-1})R(z^{-1})} \tag{5}$$

where $\hat{A}(z^{-1})$ and $\hat{B}(z^{-1})$ are the polynomials of the discrete identified model, respectively $S(z^{-1})$ and $R(z^{-1})$ are the computed control polynomials.

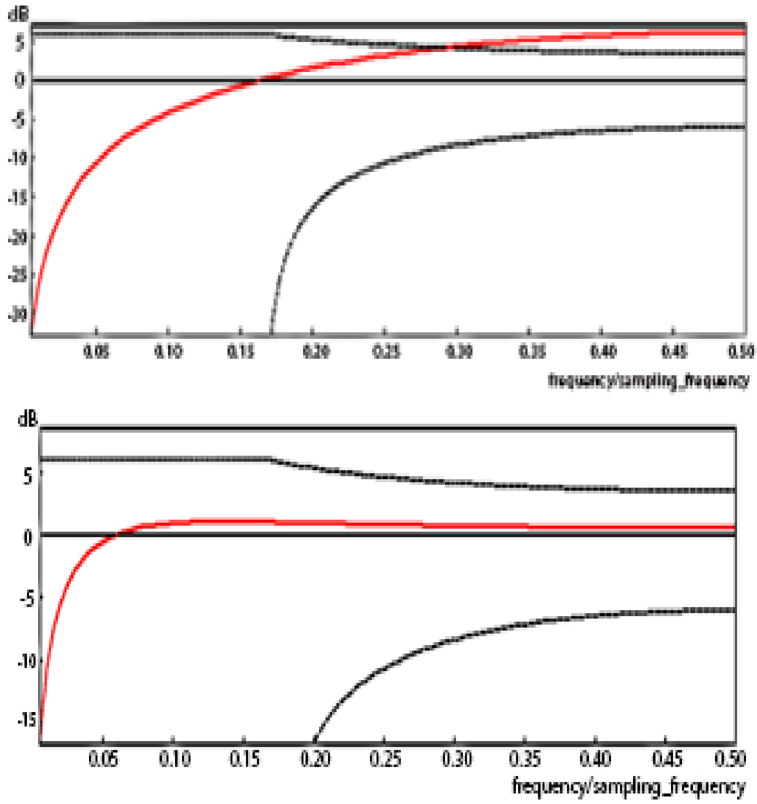

Fig. 3. Sensitivity function of the nominal system compared to the sensitivity function of the robust system

The maximum value of the sensitivity function is 11 dB (see Figure 3), and it is necessary to reduce the maximum value under 6 dB, to decrease the perturbation actions at the output of the system. For improving the robustness of the control system, we have added auxiliary zeros to R and S polynomials. The new robust controller RST respects the imposed 6dB limit after the sensitivity function calibration (see Figure 3).

The tracking and the regulation dynamics of the robust system is given in Figure 4.

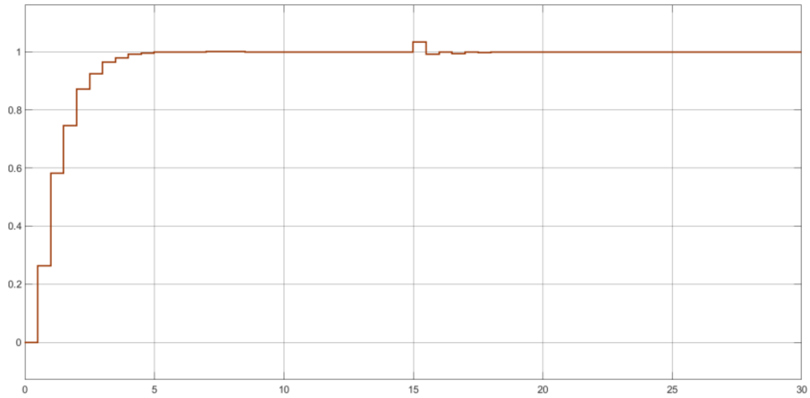

Fig. 4. Robust photovoltaic control system - dynamic response.

4. Temperature control system for photovoltaic panels with variable orientation

This paper proposes an efficient approach for harnessing photovoltaic energy sources using modern automation tools. Advanced control techniques are proposed to estimate the maximum power output of solar panels under real-world conditions, considering seasonal variations in solar radiation and ambient temperature. Since solar radiation and PV operating temperature are inherently stochastic, maximizing energy production requires systems that can dynamically adjust panel orientation to capture as much solar energy as possible. Normally, an object will receive only a fraction of solar irradiance due to the angle of incidence of the sun. Our system, however, will always receive the maximum amount of irradiance because of the positioning system, and as a result, it will have a different temperature compared to the local environment. The first step is to map this behavior. This is done using a solar panel positioned at 0° and a dataset containing the average ground temperature. The assumed panel will provide information about the normal amount of irradiance received, while the ground temperatures can be used as a calculation baseline average.

Fig. 5.a. Temperature test setup

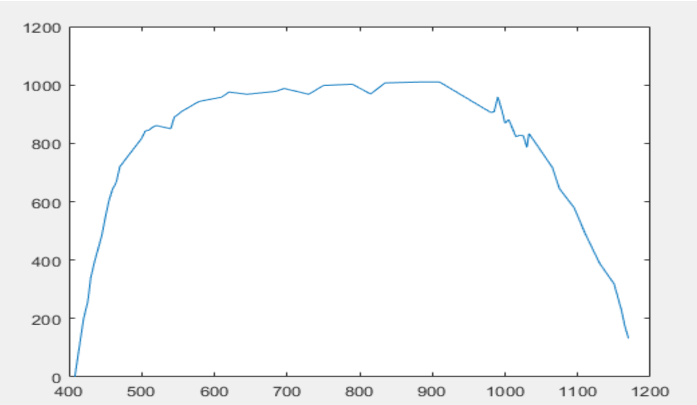

Fig.5.b. Solar irradiation on 12.06.

To counteract these temperature-related losses, the study explores active evaporative cooling using atomized water, with the goal of maintaining the panel temperature near the manufacturer-recommended level—typically around 25°C.

Table 1. Temperature response of a solar panel

Temperature of the control panel (Celsius)	Temperature under the effect of 10ml of atomized water	Temperature under the effect of 20ml of atomized water	Measured Solar Irradiation	Time
39	39	39	1022	12:00
41.3	40.7	39.6	999	12:05
42	40.8	38.6	992	12:10
42.8	41	37.7	999	12:15
43.6	41.2	36.8	999	12:20
44.2	41.2	35.7	998	12:25
44.6	41	34.5	952	12:30
46.1	41.9	34.2	966	12:35
47.8	43	34.2	993	12:40
47.7	42.3	32.4	980	12:45
47.5	41.5	30.8	970	12:50
47.7	41.6	29.4	994	12:55
47.3	39.5	28.9	1000	13:00

While other active cooling methods are available, they are ineffective by comparison, as shown in [21] and [23].

We construct a polynomial equation to correlate these two datasets and obtain the temperature behavior as a function of irradiance. This curve represents a differential relative to the average ambient temperature because, although the system behaves atypically compared to its environment, it is still part of it.

The next step is to establish the correlation between temperature and efficiency, based on the manufacturer's data presented earlier.

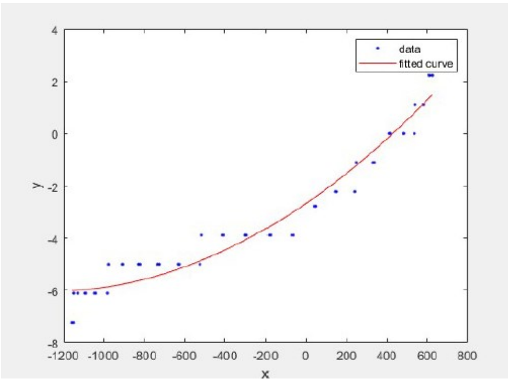

Fig.6.a Irradiation-temperature dependence

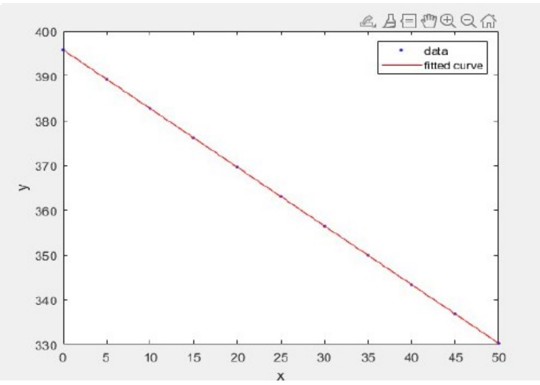

Fig.6.b Temperature-efficiency dependence

This relationship is linear and easy to implement. These functions will be used both for temperature control and for identifying external factors by comparing actual data with predicted values and identifying discrepancies.

The study in [21] evaluates several nozzle types—flat fan, hollow cone, and full cone—along with two different nozzle diameters (2 mm and 3 mm). The results indicate that full cone nozzles offer superior cooling due to their complete circular spray pattern, which provides more even water distribution over the panel surface. In contrast, hollow cone nozzles concentrate the spray along the perimeter, and flat fan nozzles tend to cover only the upper portion of the panel, allowing water to run downward with limited coverage.

Furthermore, nozzle diameter significantly affects cooling efficiency. Smaller nozzles (2 mm) produced finer droplets that enhanced evaporative cooling, resulting in lower panel temperatures compared to larger nozzles (3 mm). For example, at 11:00 AM under solar radiation of 1000 W/m², Full cone nozzles cooled panels to 36.27°C (2 mm) and 37.07°C (3 mm), Hollow cone nozzles to 37.78°C (2 mm) and 38.84°C (3 mm), Flat fan nozzles to 41.42°C (2 mm) and 42.07°C (3 mm).

Based on this known data and the heat transfer rate equation where Q is the heat transfer rate, M is the mass of the water, C is the specific heat capacity of water, and ΔT is the temperature difference between the water and the surface it contacts a controller will be designed.

For testing under normal operating conditions, we will create a new Simulink simulation(Fig. 7) representing day 200 of the year (July 19), which has an average temperature of 27.3°C and is located at latitude 44°.

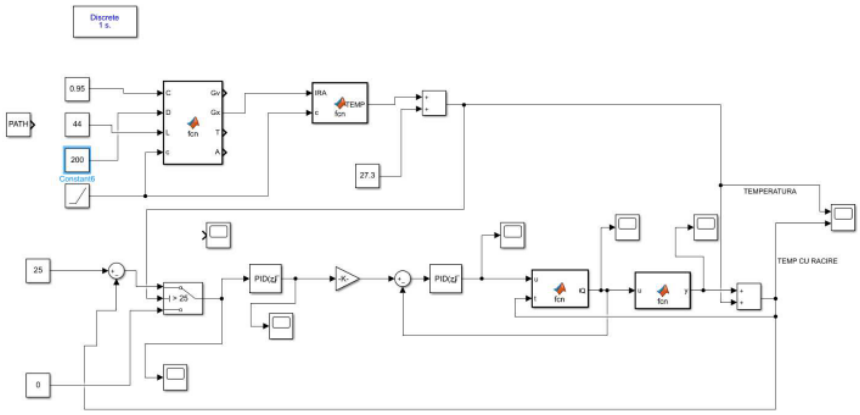

Fig. 7. MATLAB SIMULINK model including the PV panel model, position controller and temperature controller

In the case of evaporative cooling, we can equate the complexities of the process to a larger ΔT, given that the effect and behavior are identical between evaporative cooling and contact cooling. The simulation will include three idealized cases of temperature variation will run for 20 minutes and will show the temperature drop achieved by a 2mm flat nozzle.

The results are showcased in Fig. 8. The temperature of both the water and the panel are marked by the orange and yellow line respectively. The first case features a variation of +1°C, the second +2°C, and the third +0.8°C.

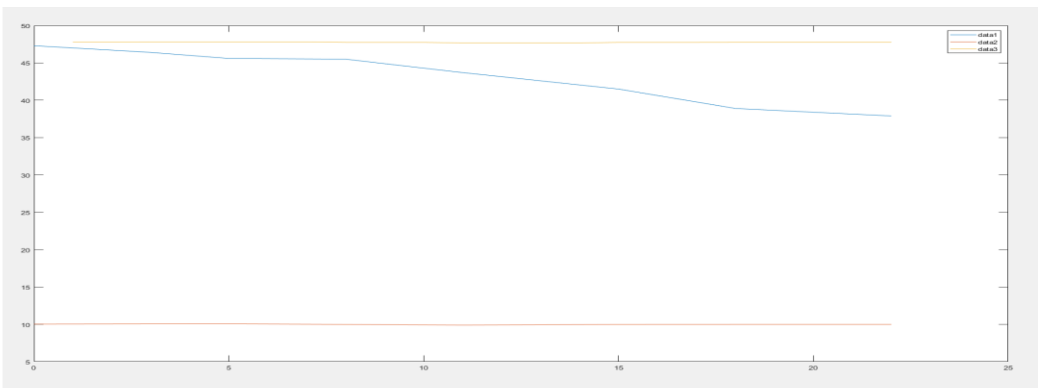

Fig. 8. Cooling results compared to a normal panel obtained during maximum irradiation conditions

Conclusions

The paper proposes an efficient solution for the generation and delivery of the maximum power for a photovoltaic system, by integrating new advanced control strategies that transform solar radiation, available across the Earth's surface, into electrical energy.

The dynamic model of the photovoltaic process with variable orientation, including the photovoltaic panel itself, an electric motor to adjust the panel's position and a power transducer for continuous monitoring the energy produced by the system is estimated, and a robust control technique using a polynomial RST algorithm for panel oriented on the sun's movement is computed.

Based on experimental data acquired from a photovoltaic platform, a mathematical model was developed for evaporative cooling, as a function of surface area, solar radiation, and temperature and a control strategy was computed for water atomization in PV operating temperature.

The long-term benefits are significant, consisting in increased green electricity production, reduced maintenance costs, and extended system lifespan. The theoretical results validated through simulation and on an experimental hardware-in-the-loop platform can be transferred to practical applications in photovoltaic energy systems of different sizes.

R E F E R E N C E S

[1] L Kruitwagen *et al.* "*A global inventory of photovoltaic solar energy generating units*". In: *Nature* 598.7882 pp. 604–610, 2021.

[2] George G Njema, Joshua K Kibet, and Silas M Ngari, "*Performance optimization of a novel perovskite solar cell with power conversion efficiency exceeding 37% based on methylammonium tin iodide*". In: *Next Energy* 6, 2025.

[3] *Global Market Outlook for Solar Power 2024-2028*. https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028/detail, accesat: 2025-03-12. 2025.

[4] Jalal Dadkhah and Mehdi Niroomand, "*Optimization methods of MPPT parameters for PV systems: review, classification, and comparison*", *Journal of Modern Power Systems and Clean Energy* 9.2, pp. 225–236, 2021.

[5] S Sheik Mohammed, D Devaraj, and TP Imthias Ahamed. "*A novel hybrid maximum power point tracking technique using perturb & observe algorithm and learning automata for solar PV system*", *Energy* 112 pp. 1096–1106, 2016.

[6] Maissa Farhat, Oscar Barambones, and Lassaâd Sbita. "*Efficiency optimization of a DSPbased standalone PV system using a stable single input fuzzy logic controller*". In: *Renewable and Sustainable Energy Reviews* 49, pp. 907–920, 2015.

[7] Mummadi Veerachary, Tomonobu Senjyu, and Katsumi Uezato. "*Neural-network-based maximum-power-point tracking of coupled-inductor interleaved-boost-converter-supplied PV system using fuzzy controller*". In: *IEEE Transactions on Industrial Electronics* 50.4, pp. 749–758, 2003.

[8] M Nabipour et al. "*A new MPPT scheme based on a novel fuzzy approach*". In: *Renewable and Sustainable Energy Reviews* 74, pp. 1147–1169, 2017.

[9] Jie Shi *et al*. "*Forecasting power output of photovoltaic systems based on weather classification and support vector machines*". In: *IEEE Transactions on Industry Applications* 48.3, pp. 1064–1069, 2012.

[10] Wenhui Hou *et al.* "*A novel maximum power point tracking algorithm based on glowworm swarm optimization for photovoltaic systems*". In: *International Journal of Photoenergy,* 2016.

[11] Hamed Taheri *et al*. "*A novel maximum power point tracking control of photovoltaic system under partial and rapidly fluctuating shadow conditions using differential evolution*". *IEEE Symposium on Industrial Electronics and Applications (ISIEA)*, pp. 82–87. 2010.

[12] P Madhu and V Viswanadha. "*Design of real time embedded solar tracking system*", *International Journal of Emerging Trends in Engineering Research (IJETER)* 3.6, pp. 180–185, 2015.

[13] Tiezheng Lv *et al*. "*Bio-inspired hydrogel with all-weather adhesion, cooling and reusability functions for photovoltaic panels*", *Solar Energy* 216, pp. 358–364, 2021.

[14] Gan Huang, Jingyuan Xu, and Christos N Markides. "*High-efficiency bio-inspired hybrid multi-generation photovoltaic leaf*". In: *Nature Communications* 14.1 p. 3344, 2023.

[15] S. Mentors, "Solar panel tilt angle calculator" https://solarmentors.com/solar-paneltilt- angle-calculator/, online accessed: 2025-03-15, 2025.

[16] Daniel-Marian Băncilă *et al*. "*Optimal control for solar tracking systems*", *International Conference on Control System,Theory and Computing and Communications, ICSTCC. IEEE,* pp. 509–514, 2022.

[17] D Popescu *et al*. "*Industrial Automatics"* Editura AGIR, Bucuresti, 2006.

[18] Daniel Quezada *et al.* "*Linear Quadratic Control design for a Buck-Boost Power Converter supplied by a Solar array", IEEE International Conference on Automation/XXIV Congress of the Chilean Association of Automatic Control (ICA-ACCA) IEEE*, pp. 1–6, 2021.

[19] Mustafa Ergin Şahin, Halil İbrahim Okumuş. "*Comparison of different controllers and stability analysis for photovoltaic powered buck-boost DC-DC converter*". *Electric Power Components and Systems 46.2* pp. 149–161, 2018.

[20] Lucian MIHAI, Severus Constantin OLTEANU, Dumitru POPESCU, "*Trajectory Optimization for Photovoltaic Panels with 2 Degrees of Freedom*", *Studies in Informatics and Control*, ISSN 1220-1766, vol. 33(4), pp. 25-35, 2024.

[21] Wibowo, S. *et al*,. "*Optimization of photovoltaic performance using a water spray cooling system with different nozzle types. International Journal of Computational Methods and Experimental Measurements*", Vol. 12, No. 1, pp. 9-19, 2024.

[22] Soomar Arsalan Muhammad *et al*., "Solar Photovoltaic Energy Optimization and Challenges",Frontiers in Energy Research,Volume 10 – 2022

[23] Haidar, Zeyad. "*Cooling of Solar Pv Panels Using Evaporative Cooling. Journal of Thermal Engineering*". 2. 10.18186/jte.72554, 2016.