PLOVDIV UNIVERSITY
"PAISII HILENDARSKI"
FACULTY OF PHYSICS AND TECHNOLOGY
DEPARTMENT OF "ELECTRONICS, COMMUNICATIONS AND INFORMATION TECHNOLOGY"

M.Eng. Snezha Ventsislavova Shotarova

INTERACTIVE LABORATORY FOR INFORMATION PROCESSING WITH REMOTE ACCESS

ABSTRACT

of a dissertation for the acquisition of the educational and scientific degree
"DOCTOR"

Field of higher education:
5. Technical sciences

Professional field:
5.3. "Communication and computer technology"

Doctoral program:
"Automation of areas of the intangible sphere
(medicine, education, science, administrative activities etc.)"

Scientific supervisor:
Assoc. Prof. Dr. Silvia Velkova Stoyanova - Petrova

Plovdiv, 2026

The dissertation is 187 pages long, including 73 figures, 30 tables, arranged in an introduction, 4 chapters, general conclusions, scientific-applied and applied contributions, a list of symbols and abbreviations used, a list of the author's publications. The list of cited literature includes 143 titles.

The designations of formulas, figures and tables in the abstract coincide with those in the dissertation.

The dissertation work was discussed and submitted for defense at a meeting of the department council of the Department of Electronics, Communications and Information Technologies at the "Paisii Hilendarski" University of Plovdiv on 04.02.2026, protocol № 85/04.02.2026.

The defense of the dissertation will be held on April 15, 2026 at 11:00 a.m. in the building of Plovdiv University "Paisiy Hilendarski", 21 "Kostaki Peev" Str., 4th floor, at a meeting of the scientific jury.

The materials for the doctoral defense are available to those interested in the office of the Faculty of Physics and Technology at "Paisii Hilendarski" University of Plovdiv, 24 Tsar Asen St., 2nd floor, room 214.

Scientific jury:	Prof. Dr. Eng. Dimitar Mihaylov Tokmakov
	Prof. Dr. Eng. Todor Stoyanov Jamiikov
	Assoc. Prof. Dr. Eng. Borislav Hristov Milenkov
	Assoc. Prof. Dr. Eng. Nicolay Atanasov Shopov
	Assoc. Prof. Dr. Eng. Vladimira Krasteva Ganchovska

Author: M.Eng. Snezha Ventsislavova Shotarova
Title: **INTERACTIVE LABORATORY FOR INFORMATION PROCESSING WITH REMOTE ACCESS**

Circulation: 30 pcs.

GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

In the contemporary world, technological progress and digitalization are expanding into all aspects of life. In the fields of education, scientific research, and information processing, an increasing need is observed for interactive technologies that allow access to specialized tools and resources without physical presence. This leads to the necessity of developing interactive laboratories for information processing with remote access, enabling the transfer of real laboratory experiments to remote and interactive platforms.

The role of interactive laboratories in modern education is essential. They support the understanding of complex concepts through visualization and practical interaction, develop skills for system management and analysis of experimental data, and provide a safe environment for experimentation. Owing to the possibility of remote access, interactive laboratories expand the scope of education and provide equal learning conditions for students regardless of their location or access to physical resources. Therefore, they become a key instrument in engineering education and form a basis for the development of practical skills in a digitalized educational environment.

One of the main challenges facing contemporary educational institutions is the provision of high-quality practical training under conditions of limited resources, high costs of laboratory equipment, and the impossibility of constant physical presence. These limitations often lead to reduced access to real experiments and restrict the effectiveness of the learning process.

The context and significance of the research arise from the need for education to adapt to a dynamically developing technological environment.

Considering the relevance and importance of the problem, the topic of the present dissertation is directed toward the study and application of technological solutions for the development of an interactive laboratory with real equipment for information processing with remote access, intended to support the educational process and research activity.

Purpose of the dissertation

The aim of the dissertation is to develop an innovative interactive remote laboratory providing an experimental and simulation environment for research, control and analysis of photovoltaic systems. The laboratory is designed to provide a reliable, secure and accessible platform for conducting experiments and processing data in real time, by combining real equipment and virtual simulation models.

Tasks to achieve the goal:

1. Analysis of existing solutions for interactive laboratories and information processing;
2. Architectural and technological solutions for building an interactive laboratory with remote access;
3. Design and implementation of a web-based interactive laboratory for photovoltaic systems;
4. Development and implementation of an interactive laboratory with remote access for researching photovoltaic systems, providing management of laboratory experiments, integration with sensors and computing resources, as well as real-time data collection and processing.

Research methods and tools used:

The research is based on a systematic and comparative analysis of architectures and technologies for interactive photovoltaic laboratories with remote access. Methods for modeling, simulation and experimental verification, implemented through web-based software platforms, communication protocols and embedded hardware tools for real-time data management and processing, were used.

Implementation and practical applicability

An interactive photovoltaic laboratory with remote access, based on a real photovoltaic system with the ability to remotely control, monitor and analyze electrical parameters, has been designed, implemented and implemented. A web-based platform for real-time collection, processing, long-term storage and visualization of experimental data has been implemented.

Publications on the topic

The results of the dissertation work have been published in 4 scientific publications, of which 1 independent article published in Scientific Proceedings of SUB - Smolyan. 1 in the proceedings of the XXXIV International Scientific Conference Electronics (ET) 2025, indexed in Scopus. 1 in the proceedings of the international scientific conference EDULEARN 2023 and 1 in the proceedings of the national scientific conference with international participation "Education, Science, Society" (2022). The three publications are co-authored with the scientific supervisor.

Scope and structure of the dissertation work

The dissertation is 187 pages long, including 73 figures, 30 tables, organized into an introduction, 4 chapters, general conclusions, scientific and applied contributions, a list of symbols and abbreviations used, a list of the author's publications and a list of references.

CONTENT OF THE DISSERTATION

CHAPTER I. ANALYSIS OF EXISTING SOLUTIONS FOR INTERACTIVE LABORATORIES

In the first chapter of the dissertation, the existing methods, technologies, and tools for the development of interactive and remote laboratories used in engineering education in the field of photovoltaic systems are examined and systematized. The analysis covers the architectural models, classification, technological solutions, and educational applications of interactive laboratories.

1.6. Architectural models of interactive laboratories

Interactive laboratories are implemented through a generalized three-layer architecture comprising a laboratory layer, a communication layer, and an application layer, which provides remote access, control, and monitoring of laboratory resources. Each layer performs specific functions and may be implemented through different technological approaches depending on the requirements of the particular laboratory environment.

The laboratory layer encompasses the real experimental equipment, measurement and control devices, integrated into a laboratory module that ensures the execution and monitoring of experiments.

The communication layer provides reliable exchange of data and control commands between the laboratory module and the end user.

The application layer provides user access through web-based interfaces, offering visualization and real-time control of the experiments.

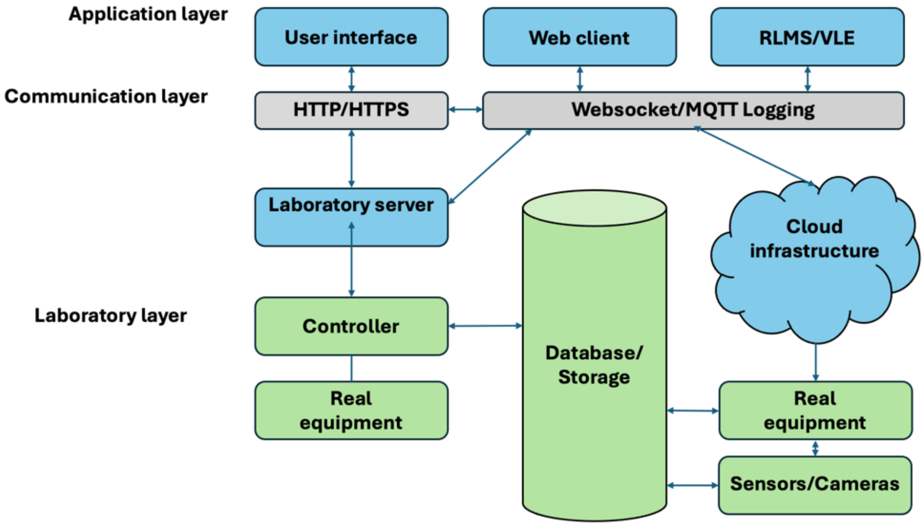


Fig. 1.1. Three-layer architectural model of an interactive laboratory

1.7. Classification of interactive laboratories

In this paragraph, a classification of interactive laboratories is carried out according to the main criteria used in the scientific literature and engineering practice. Depending on the architecture, the method of implementation, and the intended purpose of use, they can be classified according to several principal criteria.

1.7.1. Classification according to the nature of the experiment

According to the nature of the experimental environment, interactive laboratories are divided into:

- laboratories with real equipment and remote access, in which the user controls physical devices via the Internet;
- simulation laboratories, built upon mathematical models and algorithms for the virtual reproduction of real processes;
- hybrid laboratories, which integrate real equipment with simulation models and provide a complete cycle of modeling, experimentation, and verification.

This classification reflects the degree of integration between physical and virtual resources and is widely accepted in contemporary scientific literature.

1.7.2. Classification according to technological implementation

From the perspective of the technologies used, interactive laboratories can be:

- web-based, accessible through a standard internet browser;
- simulator-based laboratories, using specialized engineering environments;
- cloud-based laboratories, which utilize virtualized computational resources and centralized management;
- mixed reality (AR/VR) laboratories, providing enhanced visualization and interactivity.

These approaches enable scalability, flexible access, and integration with electronic learning platforms.

1.7.3. Classification according to functional purpose

According to their intended purpose, interactive laboratories are subdivided into:

educational laboratories, oriented toward training and the development of practical skills;

research laboratories, used for the analysis and development of new technologies.

1.7.4. Classification according to the mode of interaction

Depending on the degree of interactivity, the following are distinguished: static simulation environments; dynamic real-time simulations; and interactive systems with bidirectional communication, enabling active control and adaptive system response.

The presented classifications show that interactive laboratories form a multidimensional and flexible technological environment, integrating real, virtual, and hybrid solutions, various architectural approaches, and a wide range of educational and research applications.

1.8. Educational applications and comparative analysis of traditional and interactive laboratories

Modern engineering education requires the integration of real laboratory experiments and digital tools for analysis and modeling. Traditional laboratories provide practical experience but are limited in time, resources, and accessibility. Interactive laboratories overcome these limitations through simulations and remote access, with the most effective being the integrated model that combines simulation-based preparation and experimental verification within a flexible and scalable learning environment.

Based on these limitations, the main directions for improvement have been formulated, defining the objectives in the development of a modern interactive laboratory for photovoltaic systems.

Table 1.5. Key areas for improvement

Area for improvement	Description
Hardware and software integration	Development of a system that integrates hardware and software components.
Cost reduction	Using open source and low-budget hardware platforms.
Simplifying the interface	Creating an intuitive and easy-to-use interface.
Personalization and flexibility	Providing options for customization and integration with other systems.
Real-time data support	Possibility of monitoring and analyzing data in real time.

CHAPTER II. ARCHITECTURAL AND TECHNOLOGICAL SOLUTIONS FOR CONSTRUCTION OF AN INTERACTIVE LABORATORY FOR PHOTOVOLTAIC SYSTEMS

Within the chapter, the main physical models, formulas, and computational relationships describing the operation of photovoltaic cells are examined, including the relationships between voltage, current, power, irradiance, and temperature. This theoretical knowledge is fundamental for the correct interpretation of the results obtained in the interactive laboratory environment.

2.2. Architectural and functional requirements for an interactive photovoltaic laboratory

The interactive photovoltaic laboratory should integrate real experiments, simulation models, and remote access within a unified web-based environment, enabling the input of parameters, monitoring, and analysis of the electrical characteristics of the system in real or near-real time. The system must ensure security and scalability, as well as educational functionality through visualization of results, data storage, and accessible learning resources.

2.5.2. Structure of the photovoltaic cell

The photovoltaic cell has a multilayer structure comprising protective glass, an antireflection layer, transparent contacts, a p–n junction, and a rear metal contact. This construction ensures efficient capture of solar radiation, reliable current conduction, and high operational efficiency.

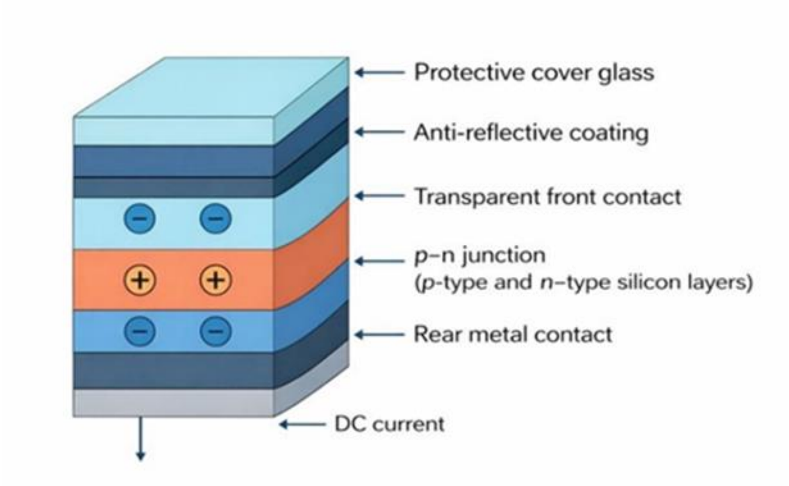


Fig. 2.2. Multilayer structure of a photovoltaic cell

This structure ensures reliable operation, high efficiency, and a long service life of the photovoltaic cells.

2.5.3. Mathematical model of the photovoltaic cell

The operation of the photovoltaic cell is described by an equivalent electrical circuit with a photocurrent source, a diode, and parasitic resistances. The model serves as a basis for simulations and analysis in the interactive laboratory.

Fundamental equation of the PV cell:

$$\boldsymbol{I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S}{nkT}} - 1\right) - \frac{V+IR_S}{R_{sh}}} \qquad (2.1)$$

Photogenerated current:

$$\boldsymbol{I_{ph} = \left[I_{sr,ref} + \alpha(T - T_{ref})\right]\frac{G}{G_{ref}}} \qquad (2.2)$$

Efficiency:

$$\boldsymbol{\eta \ = \frac{Pmax}{G.A}} \qquad (2.3)$$

2.6.1. Parameters of photovoltaic cells

The operation of photovoltaic cells is analyzed through the I–V and P–V characteristics, which determine the key parameters Voc, Isc, MPP, Pmax, Pmax and FF. The maximum power point is fundamental for the control and optimization of PV systems.

Fill factor:

$$\boldsymbol{FF = \frac{P_{MPP}}{V_{OC}.I_{SC}}} \qquad (2.6)$$

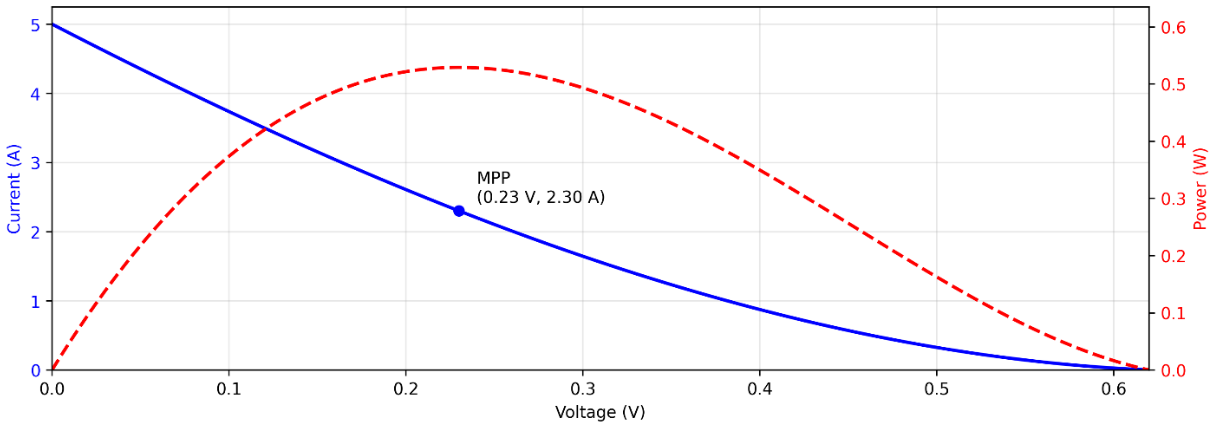


Fig. 2.3. I-V and P-V characteristics of a photovoltaic cell at STC

The I–V curve (current–voltage) shows the relationship between the current (I) and the voltage (V) produced by the photovoltaic cell at a given level of irradiance and temperature.

2.7. 1. Configuration and electrical characteristics of photovoltaic cells

The main technologies (mono-, poly- and thin-film cells) and their influence on efficiency are presented. The configuration of the cells (series and parallel) determines the output electrical parameters of the PV modules and strings.
When N cells are connected in series:

$$\boldsymbol{V_{total} = N.V_{cell}} \tag{2.12}$$

$$\boldsymbol{I_{total} = I_{cell}} \tag{2.13}$$

N– number of parallel connected cells (with equal resistance RRR)

$$\boldsymbol{V_{total} = V_{cell}} \tag{2.16}$$

$$\boldsymbol{I_{total} = N\,.\,I_{cell}} \tag{2.17}$$

The technology and configuration of photovoltaic cells are key factors influencing the efficiency, reliability, and adaptability of PV systems.

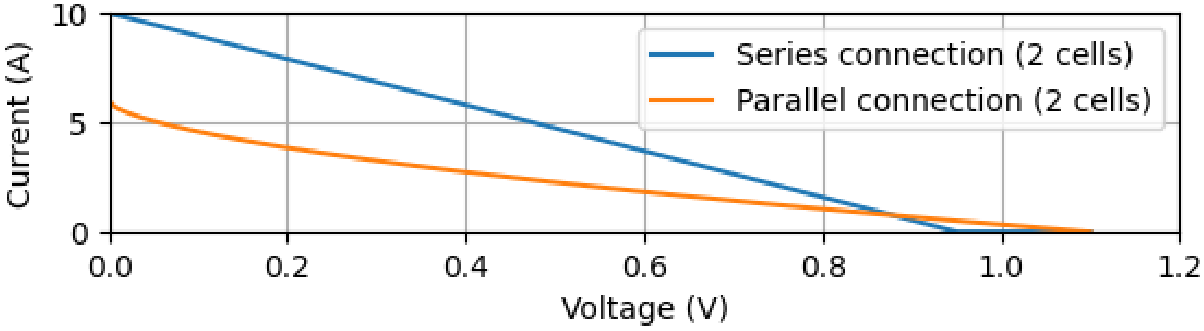


Fig. 2.8. I–V characteristics for series and parallel connection of PV cells

From the presented I–V and P–V characteristics, it can be observed that series connection leads to an increase in the output voltage at a current determined by the characteristics of the individual cell, while parallel connection provides an increase in the output current while maintaining an approximately constant voltage.

2.9. Generalized architecture and main configurations of photovoltaic systems

Photovoltaic systems represent an integrated set of electrical, electronic, and control components whose primary function is the conversion of solar energy into electrical energy, its management, storage, and efficient utilization. Depending on their interaction with the electrical grid and their intended purpose, they are classified into three main configurations: autonomous (off-grid), grid-connected, and hybrid.

In this way, the main architectural solutions in the construction of photovoltaic systems are outlined, serving as a basis for the subsequent analysis of their components, control, and operational characteristics.

2.10. Main hardware elements and control devices in photovoltaic systems

The photovoltaic system includes PV panels, charge controllers, batteries, an inverter, sensors, and protective devices that ensure the conversion and efficient utilization of electrical energy.

PV modules connected in strings are the energy source, while bypass diodes reduce the effect of shading. Charging is controlled by PWM or MPPT controllers, with MPPT maintaining operation at the maximum power point and increasing energy yield. The battery system with a BMS ensures reliable operation, and the inverter converts direct current into alternating current.

Monitoring is implemented through sensors and remote supervision, while fuses, relays, and SPDs ensure safety. MPPT controllers are more efficient than PWM solutions..

Table 2.4. Comparison table - PWM and MPPT controller

Characteristics	PWM controller	MPPT controller
Principle	Connects PV directly to the battery, regulating voltage by switching on/off	Constantly tracks the maximum power point and converts voltage/current
Efficiency	Lower (up to ~75-80%)	Higher (up to ~98%)
Voltage	PV voltage ≈ battery voltage	PV voltage is maintained at MPP
Losses due to temperature and lighting changes	Higher	Minimum

2.11.1. Measurement of irradiance

Measuring solar radiation and temperature is critical for assessing efficiency and correction to standard operating conditions (STC).

Irradiation:

$$\boldsymbol{G = \frac{V_{out}}{S}} \qquad (2.18)$$

Module temperature (NOCT):

$$T_{mool} = T_{air} + ((NOCT - 20) / 800) \times G \qquad (2.19)$$

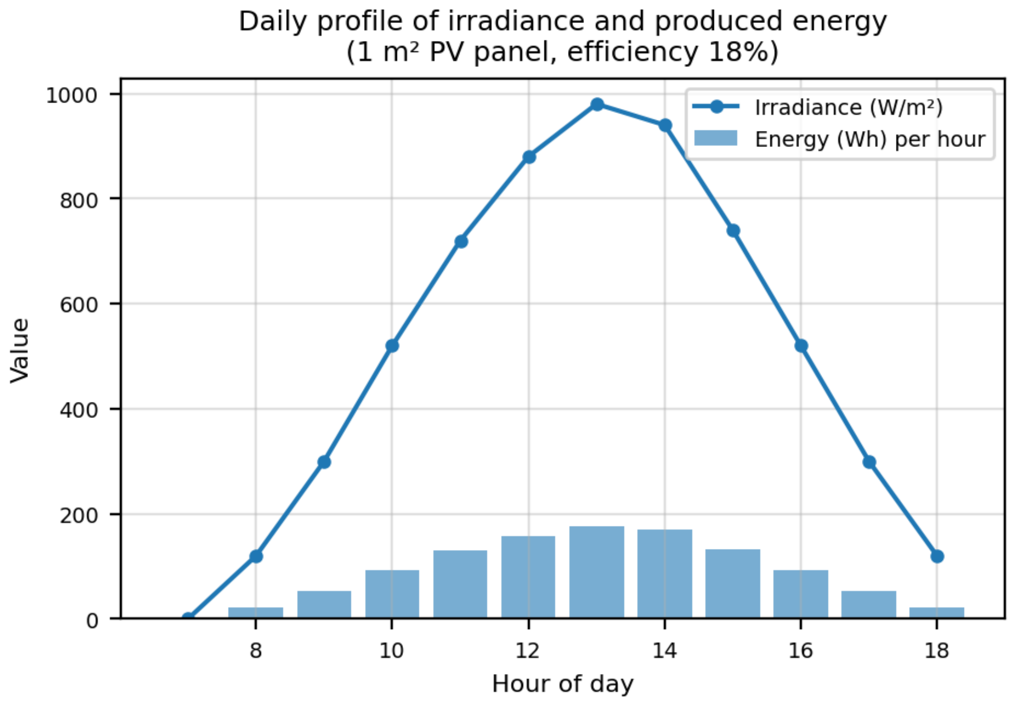


Fig. 2.12. Daily profile of irradiance and generated energy

2.11.2. Measurement of temperature and main relationships in photovoltaic systems

Temperature correction of electrical parameters:

$$V(T) = V + \alpha\_V \times (T - 25) \qquad (2.26)$$

$$I_s(T) = I_s + \alpha\_I \times (T - 25) \qquad (2.27)$$

2.12. Methods for characterizing the efficiency of photovoltaic panels

The efficiency of photovoltaic panels is evaluated through analysis of the current–voltage (I–V) and power–voltage (P–V) characteristics, from which the main parameters are determined: maximum power (Pmax), open-circuit voltage (Voc), short-circuit current (Isc), as well as the voltage and current at maximum power (Vmp, Imp).

The panel efficiency is calculated as the ratio between the generated electrical power and the solar energy incident on the surface, measured under standard test conditions (STC: 25°C, 1000 W/m², AM1.5).

For real operational assessment, the performance ratio (PR) is used, which accounts for losses due to temperature, contamination, shading, and electrical imperfections, while the temperature coefficient describes the reduction of power with temperature increase above 25°C.

2.13. Degradation modes of photovoltaic panels

The main degradation modes are examined—hot spots, shading, damaged diodes, and PID, which lead to deformation of the I–V and P–V curves and loss of power.

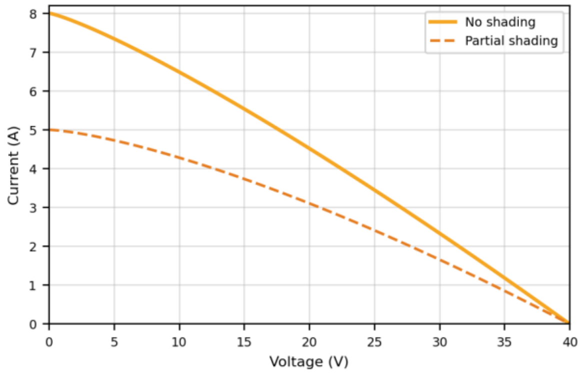


Fig. 2.14. I-V curve in partial shade

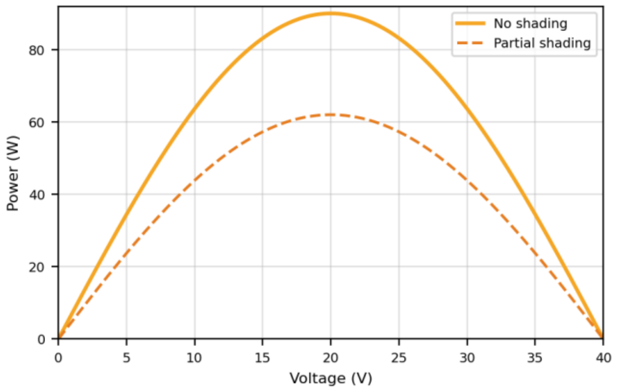


Fig. 2.15. P-V curve in partial shade

The presented physical principles, mathematical models, electrical characteristics, and measurement methods form the theoretical and technological basis for the development of an interactive laboratory for photovoltaic systems. They ensure the correct interpretation of experimental and simulation results and support the architectural implementation of the laboratory presented in the following chapters.

2.14. Solar Trackers – Types, Principle of Operation, and Components

Solar trackers are intelligent mechanical systems that increase the efficiency of photovoltaic installations by automatically orienting the PV panels according to the position of the sun, increasing the energy yield by approximately 20–40% compared to stationary systems.

Single-axis trackers provide rotation about one axis (usually east–west) and are widely used in large PV power plants due to lower cost and simpler construction. Dual-axis trackers allow movement along two axes (east–west and north–south), providing more precise solar tracking and higher yield, but requiring greater investment and maintenance.

CHAPTER III. DESIGN AND IMPLEMENTATION OF A WEB-BASED INTERACTIVE LABORATORY FOR PHOTOVOLTAIC SYSTEMS

The third chapter presents the design and implementation of a web-based interactive laboratory for photovoltaic systems, including simulation modules, visual tools, administrative functionalities and training components, implemented in an integrated platform for engineering training and analysis.

3.1 Functional and non-functional requirements

The functional and non-functional requirements for the web-based laboratory have been formulated. The functional requirements cover the implementation of interactive simulations of photovoltaic modules and systems under different operating conditions, visualization of key parameters such as I–V and P–V characteristics, maximum power, efficiency and temperature dependences, support for multi-user mode with profiles, roles and simulation history, as well as export of results in CSV, PNG and PDF formats.

The non-functional requirements include web access via a standard browser without the need for local installation, modular and extensible architecture, ensuring security and validation of input data, as well as traceability through archiving and subsequent analysis of results.

3.2. Architecture and functional structure

The web-based photovoltaic systems laboratory is implemented on a multi-tier client-server architecture, which ensures modularity, reliability and high performance of the platform.

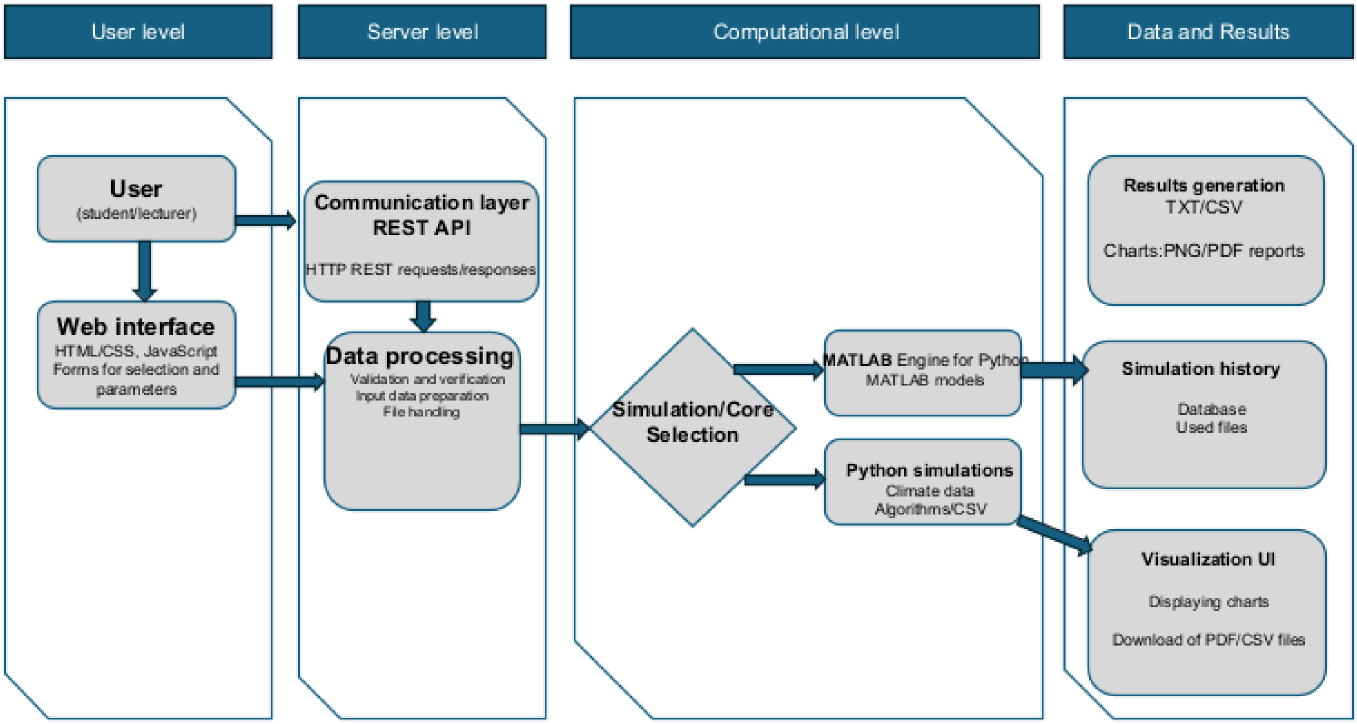


Fig. 3.1. A generalized block diagram of the software architecture of the web-based simulation platform for photovoltaic systems

The system structure is organized to provide a clear separation between the user interface, business logic, and data. It is based on the Flask web framework, which allows for modular organization and rapid deployment.

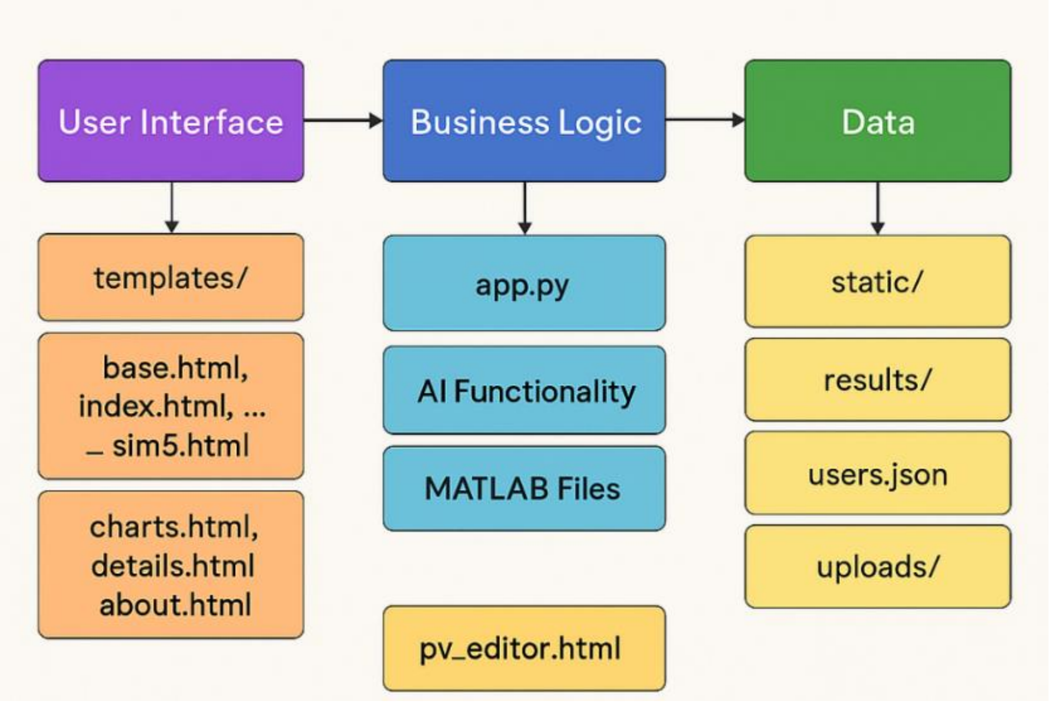


Fig. 3.2. Logical structure of the web-based laboratory and organization of directories

3.3. Technologies used and integration

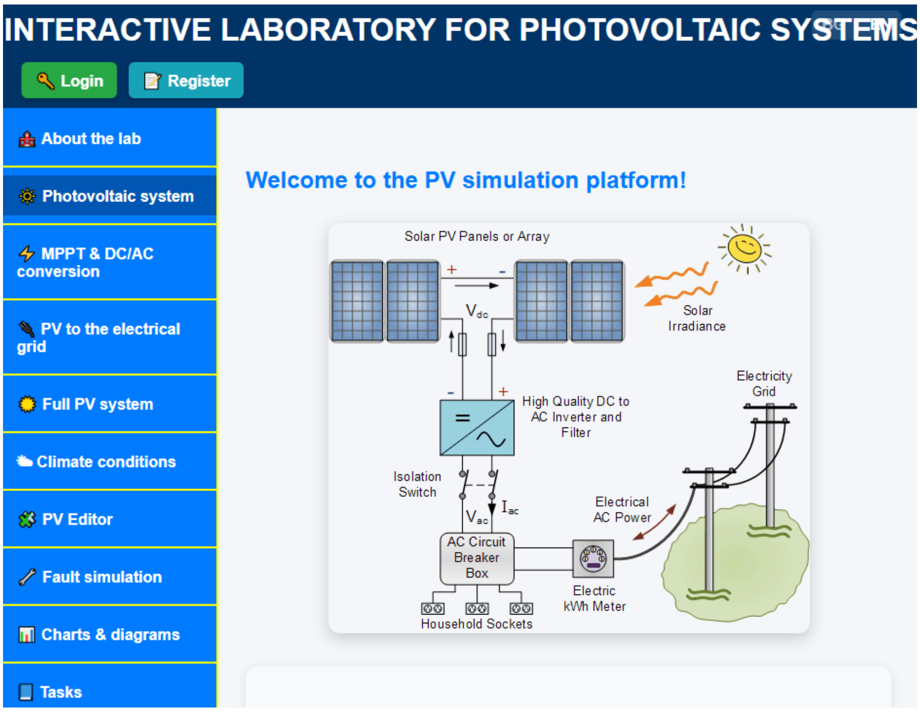
The system is implemented through the integration of modern software technologies, with Python 3 and Flask used to implement server logic, session management, user roles and routes. MATLAB, through API and Python interface, is used to execute simulation models and scripts. Numerical data processing, working with CSV files and generating graphs are performed using the NumPy, Pandas and Matplotlib libraries, and the creation of PDF reports – using ReportLab. The user interface and visualizations are implemented with HTML5, CSS3 and JavaScript, with Chart.js and Canvas/SVG technologies used for the graphical presentation and visual editor.

3.4. Functional modules and user interface

The The functional modules of the platform follow a unified workflow, including input parameter entry, simulation model execution (MATLAB/Python), results visualization through graphs and automatic AI analysis, subsequent storage in the "History" module and export of results in CSV, PNG and PDF formats.

The home screen of the web-based platform provides a centralized access point to all main functionalities through a side navigation menu.

The interface serves as a practical implementation of the described architecture and functional modules, providing an effective connection between the user and the simulation logic of the system.



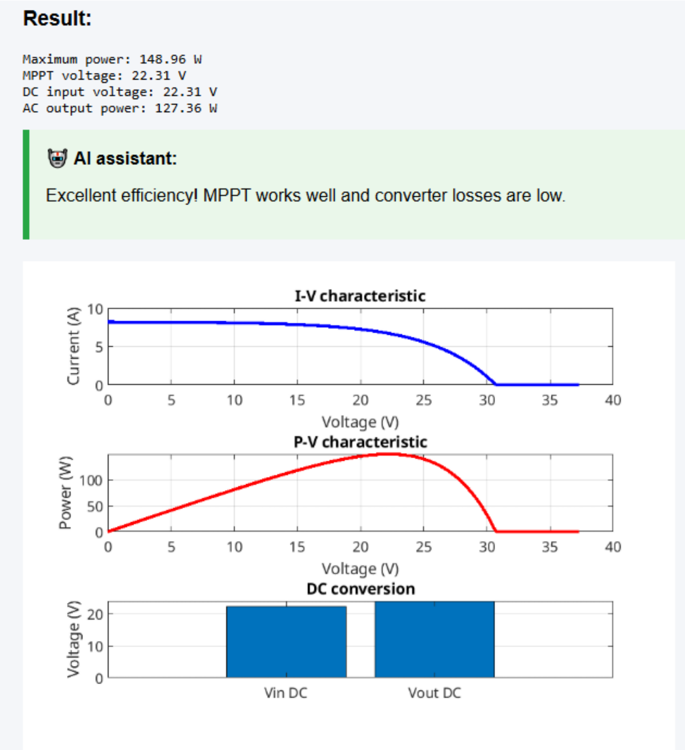
Welcome to the PV simulation platform!

Fig. 3.3. Home screen of the web-based platform for photovoltaic systems

3.4.1. Basic simulations

Simulation 1: I–V and P–V characteristics of a PV module

- calculation of I–V/P–V curves, Pmax, efficiency, MPP; AI analysis included



Result:

```
Maximum power: 148.96 W
MPPT voltage: 22.31 V
DC input voltage: 22.31 V
AC output power: 127.36 W
```

AI assistant:

Excellent efficiency! MPPT works well and converter losses are low.

Fig. 3.6. Real result of Simulation 1 with I–V/P–V graphs and AI analysis

Simulation 2: Temperature dependence

Study the influence of T on voltage/power.

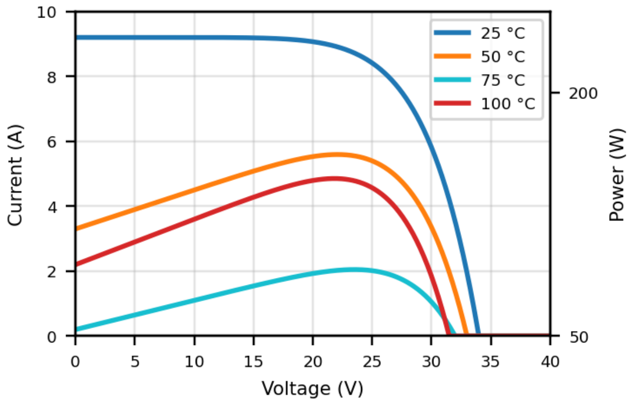


Fig. 3.7. Temperature dependence of voltage and power at different P-V cell temperature values

Simulation 3: MPPT dynamics

Dynamics under changing conditions; comparison with fixed operation/PWM.

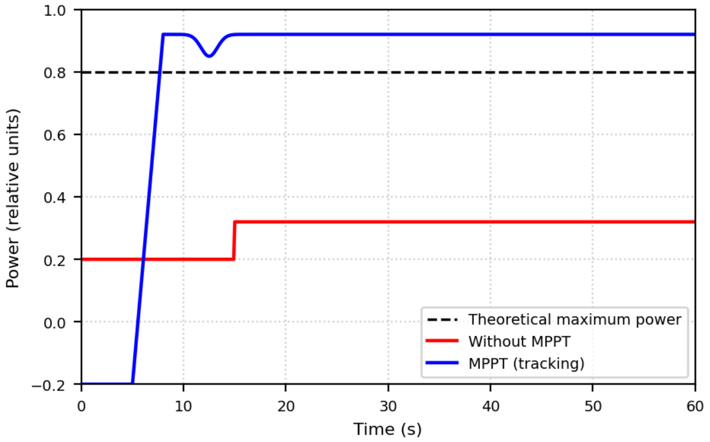


Fig. 3.8. Dynamics of MPPT algorithm – power stabilization around MPPT

Simulation 4: MPPT and PWM comparison

Positioning of operating points on P–V; profit estimation.

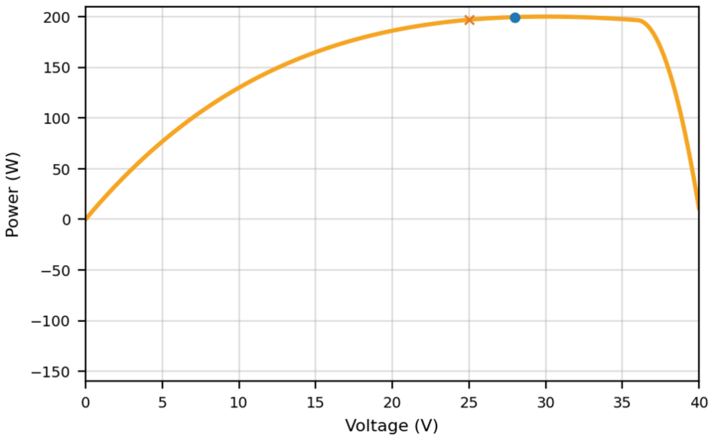


Fig. 3.9. Comparison of PWM and MPPT on the P–V characteristic of a PV module

Simulation 5: Real climate data (CSV)

Hourly profiles of G, T and Pmax; table of results.

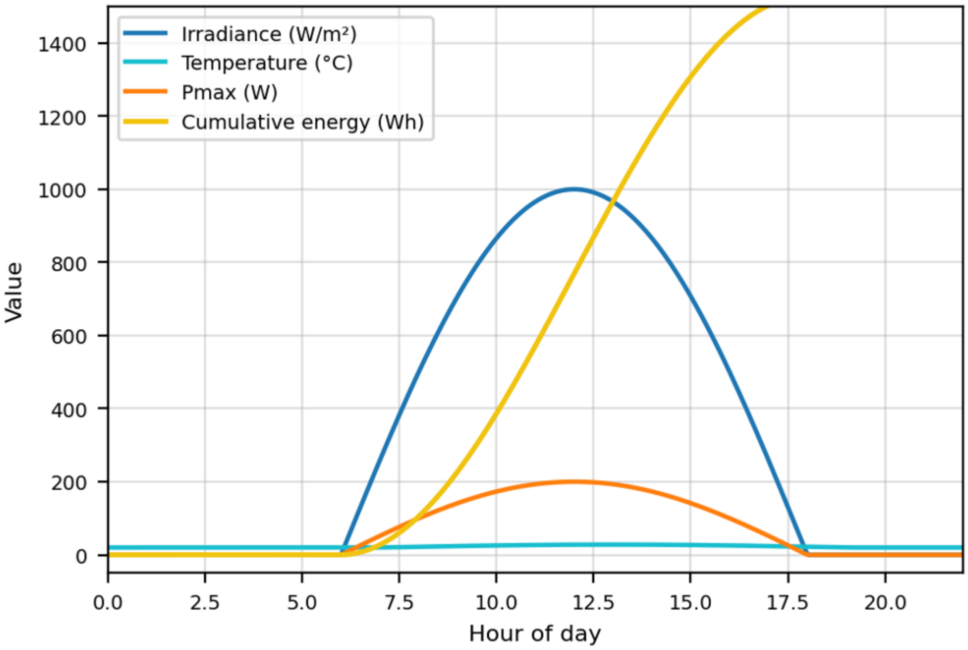
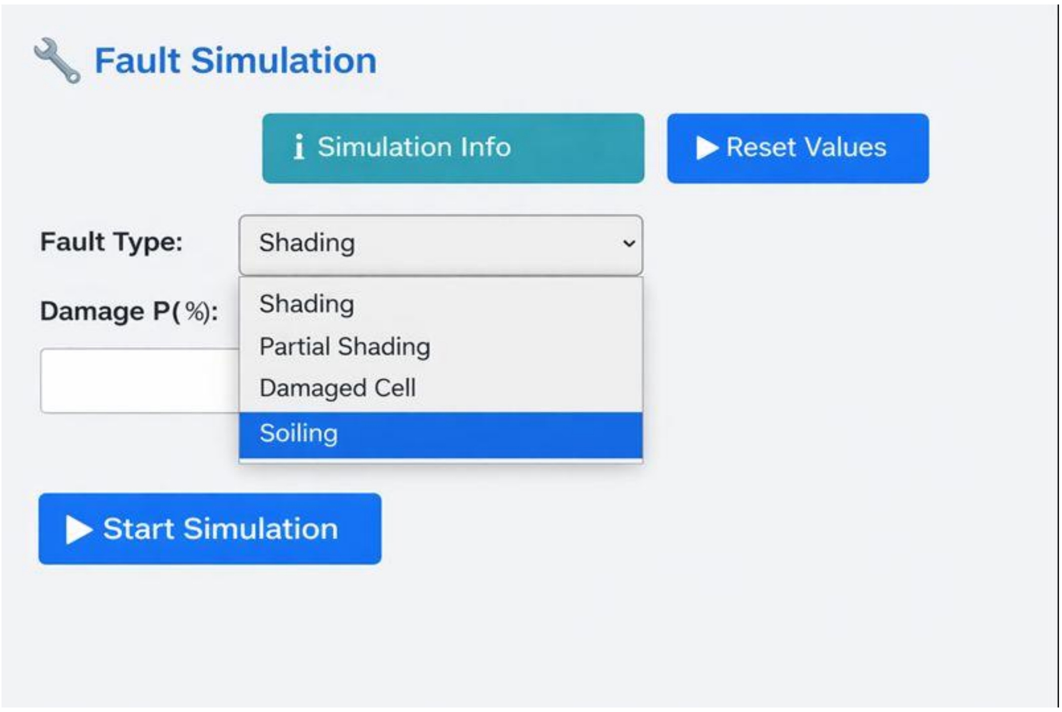


Fig. 3.10. Real climate data and results from Simulation 5

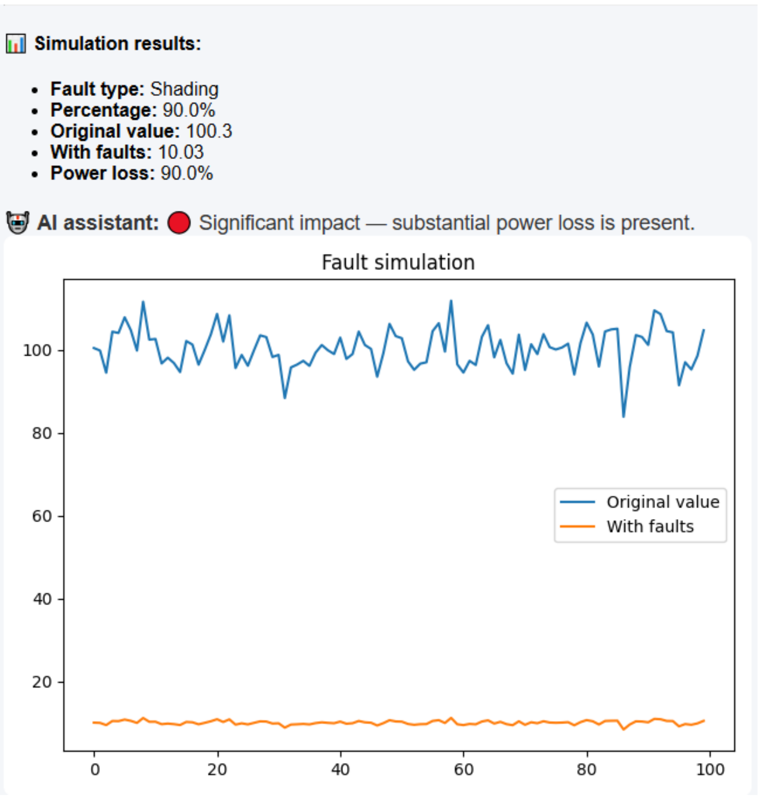
Simulation 6: Failure Analysis
Modeling of shading/damaged cells/contamination and influence on curves.


Fault Simulation

Fault Type: Shading

Damage P(%):

Fig. 3.11. Module interface for simulating faults in a photovoltaic system



Simulation results:

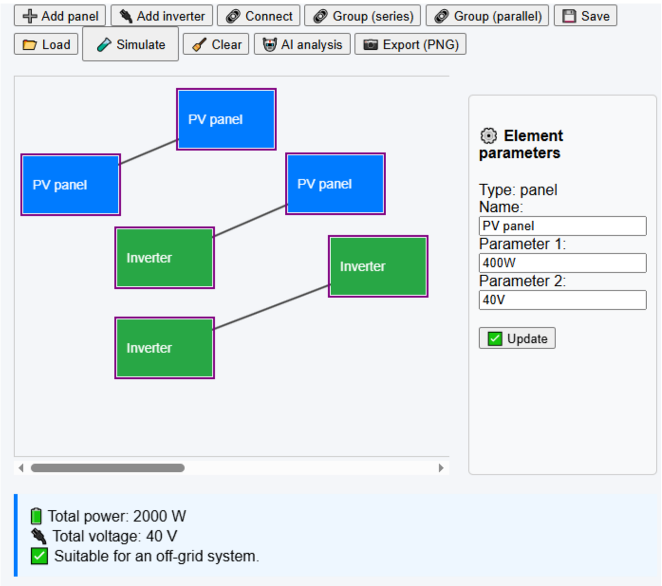
- **Fault type:** Shading
- **Percentage:** 90.0%
- **Original value:** 100.3
- **With faults:** 10.03
- **Power loss:** 90.0%

AI assistant: 🔴 Significant impact — substantial power loss is present.

Fig. 3.12. Result of fault simulation

3.4.2. Visual PV configuration editor

The visual PV configuration editor allows interactive design via drag-and-drop, graphical connection of elements in a Canvas/SVG environment, as well as automatic calculation of total power and generation of AI-based recommendations.



Type: panel
Name: PV panel
Parameter 1: 400W
Parameter 2: 40V

Total power: 2000 W
Total voltage: 40 V
✅ Suitable for an off-grid system.

Fig. 3.13. Visual PV system editor – sample configuration

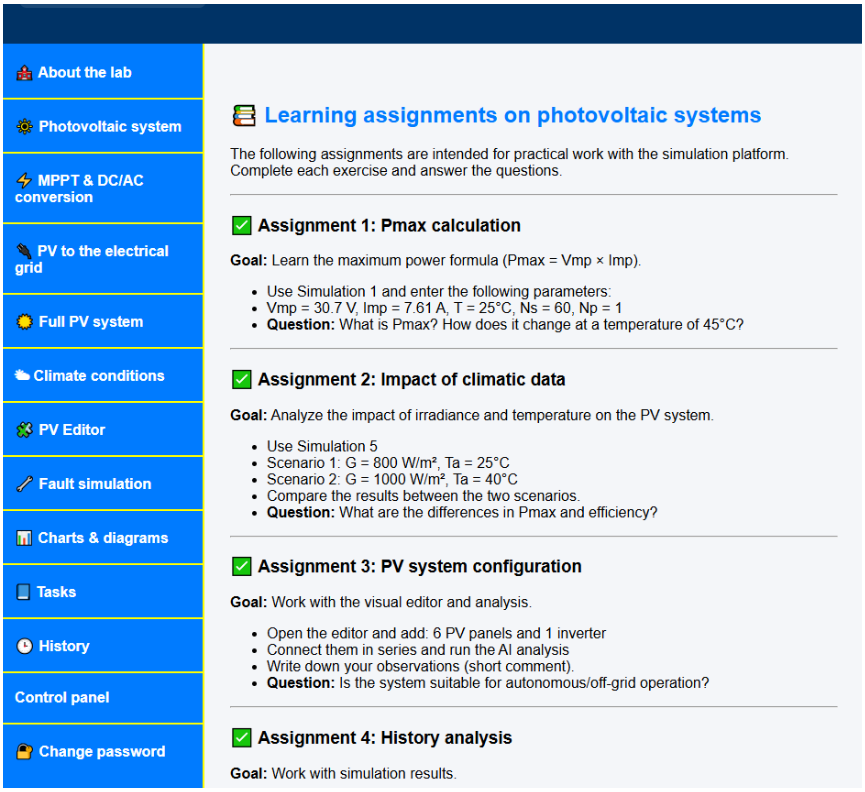
3.4.3. "History and Analysis" Module

The "History and Analysis" module provides storage of results by user, visualization of indicators such as maximum power and efficiency over time, as well as the ability to export data in CSV and PDF formats.

Fig. 3.14. Interface for viewing and analyzing simulation history

3.4.4. Control panel and role access - roles: administrator / teacher student; user and activity management; list export.

3.4.5. Menu with trainings and exercises - assignments, scenarios and exercises related to simulations; supports independent work and structured learning.



Learning assignments on photovoltaic systems

The following assignments are intended for practical work with the simulation platform. Complete each exercise and answer the questions.

☑ **Assignment 1: Pmax calculation**

Goal: Learn the maximum power formula (Pmax = Vmp × Imp).

- Use Simulation 1 and enter the following parameters:
- Vmp = 30.7 V, Imp = 7.61 A, T = 25°C, Ns = 60, Np = 1
- **Question:** What is Pmax? How does it change at a temperature of 45°C?

☑ **Assignment 2: Impact of climatic data**

Goal: Analyze the impact of irradiance and temperature on the PV system.

- Use Simulation 5
- Scenario 1: G = 800 W/m², Ta = 25°C
- Scenario 2: G = 1000 W/m², Ta = 40°C
- Compare the results between the two scenarios.
- **Question:** What are the differences in Pmax and efficiency?

☑ **Assignment 3: PV system configuration**

Goal: Work with the visual editor and analysis.

- Open the editor and add: 6 PV panels and 1 inverter
- Connect them in series and run the AI analysis
- Write down your observations (short comment).
- **Question:** Is the system suitable for autonomous/off-grid operation?

☑ **Assignment 4: History analysis**

Goal: Work with simulation results.

Fig. 3.15. Interface of the photovoltaic systems learning assignment page

3.5. Administrative functionalities, security and validation

Administrative security and validation functionalities have been implemented, including authentication with username and hashed passwords, role-based access control, client-side and server-side validation of input data, as well as session protection and control of user requests.

3.6. Graphic visualizations and educational role

Graphical visualizations are a key element of the developed web-based simulation laboratory, as they provide an intuitive representation of electrical and energy dependencies. The platform implements I–V and P–V characteristics, temperature profiles, dynamic power graphs and interactive visual components in the visual editor of PV systems.

Table 3.2. Visualization technologies used in the platform

Technology	Use
matplotlib(Python)	Plotting PV graphs in simulation 5
Chart.js(JS library)	Graphs in simulation history
HTML5 canvas + JS	Visual editor for connecting components
SVG lines	Graphical representation of cables between elements

3.7. Learning tasks and feedback

The platform implements learning tasks on topics related to Pmax, climate data, PV configurations and analysis of historical results, supplemented with automatic AI analysis and the ability to export the obtained results.

The chapter summarizes the implemented web platform as a modular three-layer system with simulations, visualizations, history and administration, intended for engineering training and as a basis for expansion to real equipment.

CHAPTER IV. DEVELOPMENT AND IMPLEMENTATION OF AN INTERACTIVE LABORATORY WITH REMOTE ACCESS FOR RESEARCHING PHOTOVOLTAIC SYSTEMS

Chapter 4 presents the implementation of an interactive remote access laboratory designed to conduct real-world experiments with photovoltaic systems. The chapter covers the architectural model, hardware and software implementation, IoT communication layer, real-time web visualization, and experimental results.

4.1. Concept and design stages of the interactive remote access laboratory

The development of the interactive laboratory was implemented in stages, encompassing the definition of functional and non-functional requirements, the design of an architecture for remote access, the selection and integration of real laboratory equipment, the construction of a communication and software layer, as well as experimental validation of the overall system.

4.2.1. Common architectural model

The architectural model of the interactive laboratory is built as an integration of four main subsystems, united in a single data flow and control. The physical laboratory environment includes a photovoltaic panel, a solar tracker and measuring sensors for voltage, current, temperature, radiation and position. The IoT communication subsystem, based on ESP32, provides collection, pre-processing and two-way data exchange via Wi-Fi or LoRa. The cloud and server environment implements an API layer, data storage in InfluxDB, analysis and command management to the hardware. The web-based information subsystem provides real-time visualization and historical analysis, remote control of the tracker and secure access with a role model for users.

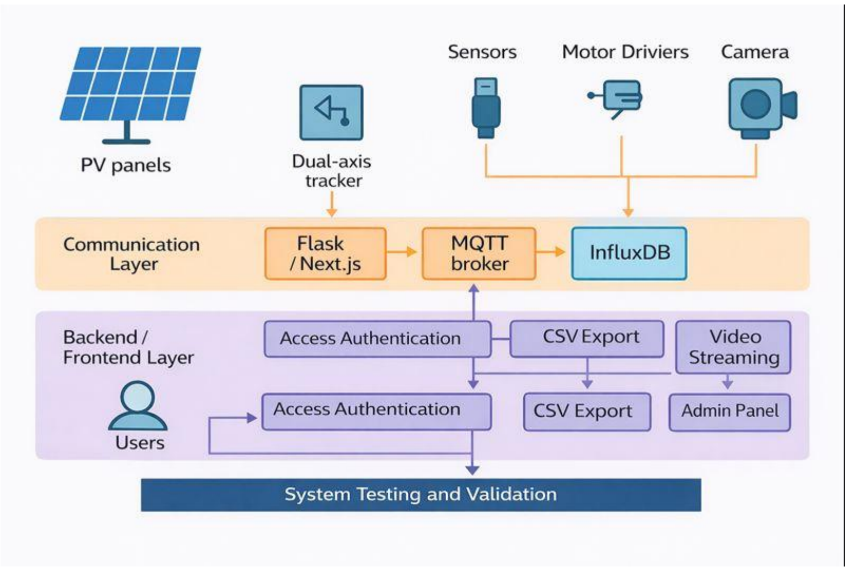


Fig. 4.2. Architectural model of the interactive laboratory for photovoltaic systems with remote access

The architecture provides two-way communication, modularity, and scalability.

4.2.2. Software and network architecture

The system uses the MQTT protocol for transmitting telemetry data with low latency and minimal network load, while the WebSocket channel provides bidirectional control and synchronization in real time with an update rate of about 1 Hz. The REST API interface is implemented for transactional operations such as control management, logs, data export and access to recent measurements. Measurement data is stored in the InfluxDB time series database and visualized analytically using Grafana. Communication security is guaranteed by TLS/SSL encryption, a secure Wi-Fi network, firewall mechanisms and role-based authentication.

4.3. Hardware implementation and subsystems of the interactive laboratory

The hardware configuration of the laboratory is described, including: photovoltaic panels; DC–DC converters; measuring sensors for voltage, current, temperature and irradiation; control microcontroller.

The control of the actuators in azimuth and elevation is implemented through separate driver circuits, electrically isolated by means of optocoupler modules. The power supply unit provides the necessary voltages for the logic and power parts, and the communication lines allow integration with the software and IoT infrastructure.

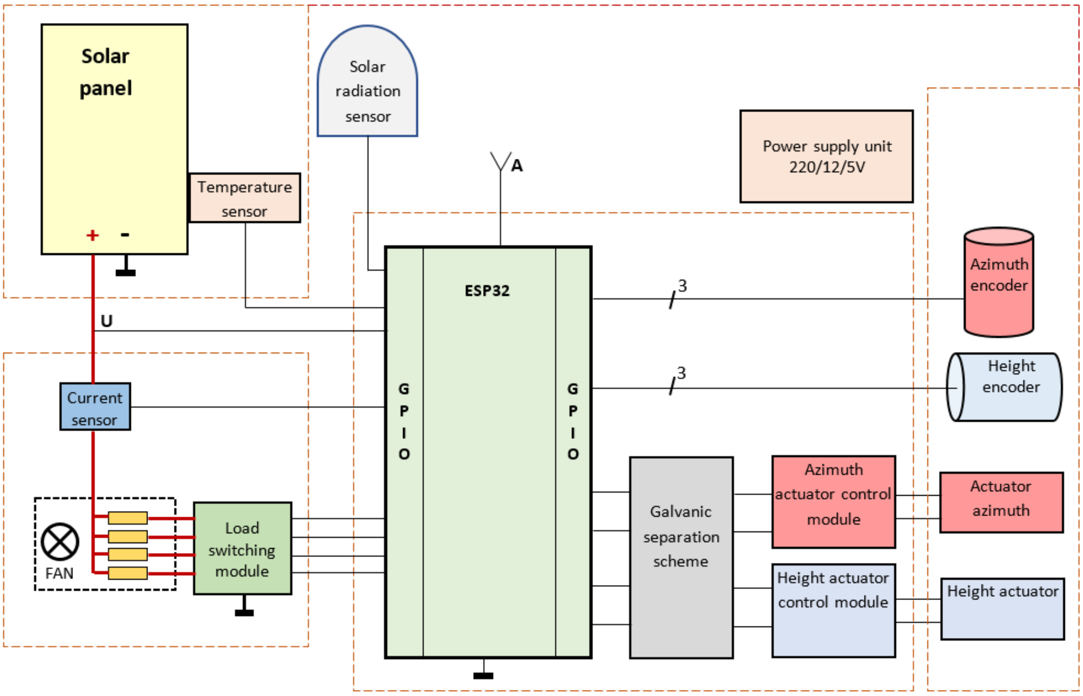


Fig. 4.4. Functional schematic diagram of the hardware architecture of the photovoltaic laboratory

4.3.1 Central control module

The core of the laboratory setup is a microcontroller module based on ESP32.

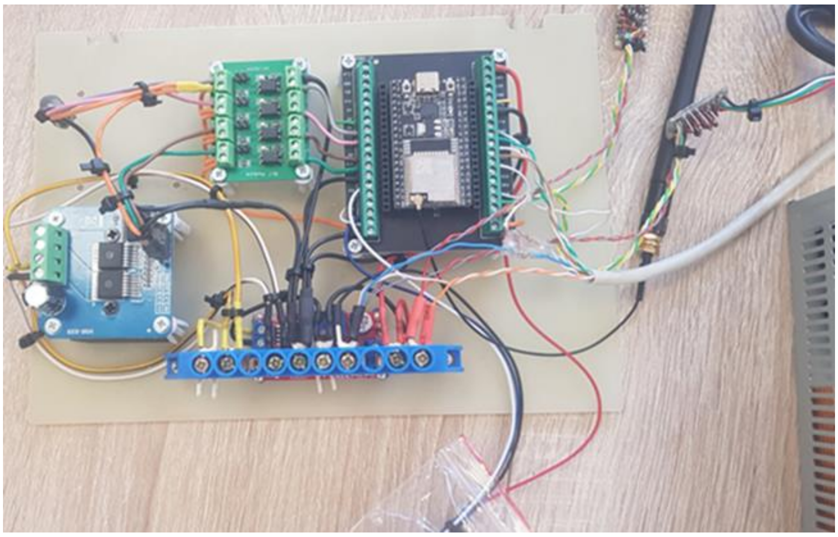


Fig. 4.6. Main control board with ESP32 and peripheral modules

The main functions of the control module include: collecting measurement data from sensors; controlling motor drivers; controlling the load block; sending telemetry information to the server; receiving control commands. The processes of controlling the panel, the load and receiving data from the sensors are controlled by a microprocessor module with ESP32.

The position of the panel is determined by high-resolution industrial ABZ encoders.

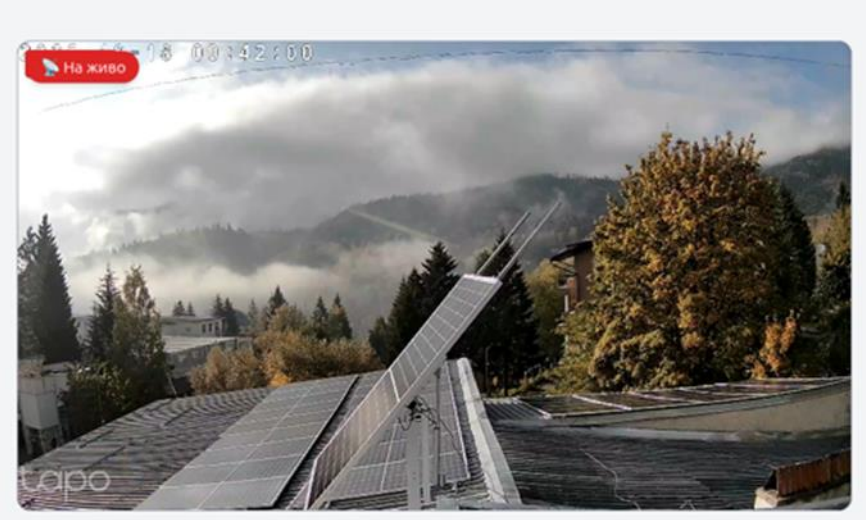


Fig. 4.10. Mounted dual-axis solar tracker

The rotation angle and direction of movement are determined by processing the pulses from channels A and B, and the index channel Z is used for the reference position.

4.4. Communication architecture and IoT layer

The communication architecture of the interactive laboratory is implemented as a multi-layer IoT model based on MQTT, WebSocket and REST API. MQTT is used for reliable transmission of telemetry data from ESP32 devices, WebSocket provides two-way real-time communication for visualization and management, and REST API implements transactional operations, access to historical data and export of results.

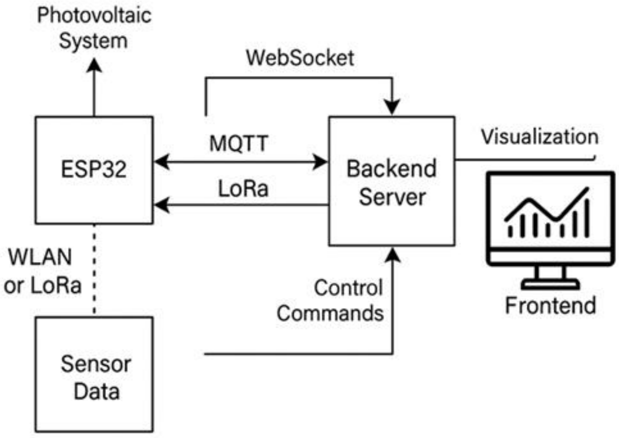


Fig. 4.16. Block diagram of the communication architecture

The web interface receives data in real time via a WebSocket channel, which provides synchronous visualization, graphics, and control over the system.

4.4.1. MQTT topics and telemetry formats

The laboratory system uses the MQTT protocol as the main mechanism for transmitting telemetry data from the ESP32 microcontroller to the server infrastructure, where the information is processed and stored in InfluxDB. A hierarchical structure of topics is implemented, which provides both centralized collection of complete measurements (voltage, current, power, temperature, radiation and tracker position) and optimized telemetry on devices with reduced network traffic and real-time operation.

The system allows simultaneous visualization of data in a web interface and remote control of the PV tracker through MQTT control topics, which provides a low-latency and scalable IoT communication architecture for an interactive remote laboratory.

4.4.2. Real-time WebSocket communication

WebSocket communication is implemented as the main mechanism for two-way control in the interactive laboratory, providing a permanent connection between the web interface and the ESP32 without periodic HTTP requests. Through it, control commands from the user are converted into MQTT downlink messages to the controller, and the current parameters are synchronized and visualized in real time (≈1 Hz) with a latency below 200–300 ms.

4.4.3. REST API – control, management and data access

The REST API interface provides structured access to the transactional and administrative functions of the system, such as managing user sessions, requesting and releasing control over the solar tracker, retrieving archive data and exporting measurements from InfluxDB. Authentication, authorization and logging of user actions are implemented through a secure Bearer Token mechanism.

In this way, the REST API complements MQTT and WebSocket by handling requests that do not require real-time communication and serves as an intermediary between the web interface, the database and the system control modules.

4.4.4. InfluxDB layer and time series management

The InfluxDB time series database, configured with the grafika_org organization and the solar_tracker bucket, is used to store and process the measurement data. The data is structured into measurements such as solar_data and temps, using device, student, and sensor tags for efficient identification and filtering. Flux queries are used to extract the latest values, average, and aggregate data into time windows, which provides preparation of the time series for visualization, analysis, and export.

Fig. 4.19. Dashboard in Grafana for visualization of telemetry data from the photovoltaic system stored in InfluxDB

The multi-layered visualization architecture provides efficient interpretation of photovoltaic system data by combining real-time monitoring, historical analysis, and the ability to externalize.

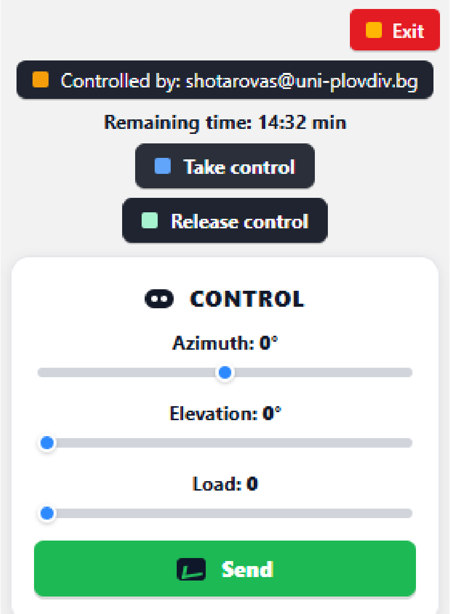
4.4.5. Security mechanisms in the communication layer

In the communication layer of the developed interactive laboratory, multilayer security mechanisms are implemented. MQTT communication is protected by disabling anonymous access, user and password authentication, ACL policies, and IP address restrictions. The backend layer uses Bearer-based authentication, CORS protection, and request rate limiting. The WebSocket channel includes validation of JSON messages, a limited control-time mechanism (15 minutes), and protection against misuse. Access to Grafana and InfluxDB is implemented through role-based models, and at the hardware level, filtering of faulty measurements and automatic restart of critical services are introduced.

4.5.1. Live Telemetry Panel

The current measurement panel provides a real-time visualization of the main parameters, including voltage, current and power, as well as values for solar radiation, temperature, tracker angles and system status. The data is updated at a frequency of about 1 Hz via WebSocket communication, which provides smooth and interactive monitoring of the processes.

The solar tracker control module provides full remote control over the positioning and loading of the laboratory setup. Through the web interface, users can control the movement along the azimuth axis (X±) and the tilt axis (Y±), set specific angular values using sliders, as well as change the electrical load of the system.

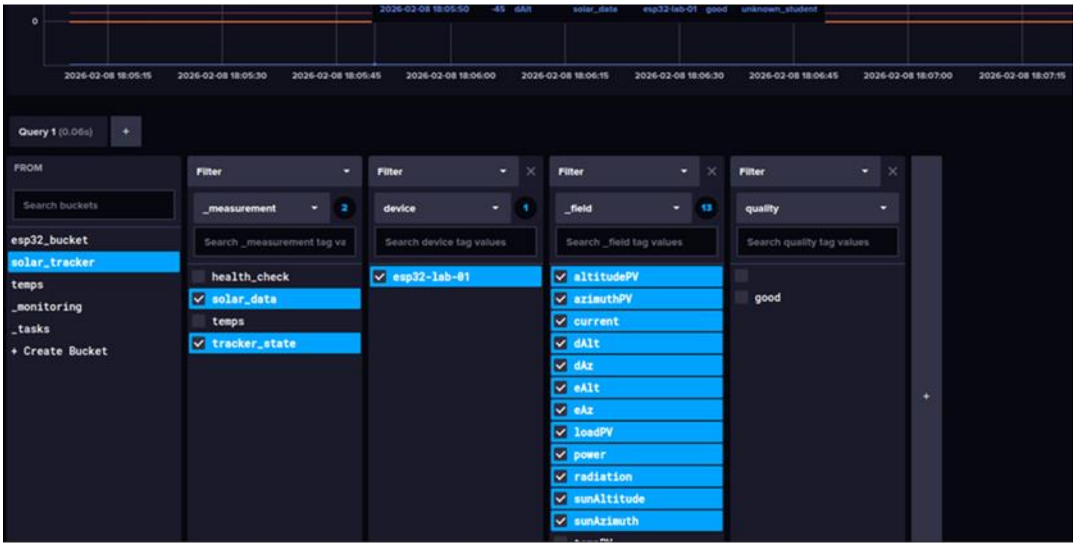


Controlled by: shotarovas@uni-plovdiv.bg
Remaining time: 14:32 min
Azimuth: 0°
Elevation: 0°
Load: 0

Fig. 4.20. Interface for access control in a multi-user environment

The presented visualization demonstrates the real-world environment in which students interact with the system.

The InfluxDB Data Explorer tool accesses the stored telemetry data from the ESP32 controller.



2026-02-08 18:05:50 -45 dAlt solar_data esp32-lab-01 good unknown_student

FROM: esp32_bucket, **solar_tracker**, temps, _monitoring, _tasks

Filter _measurement (2):
☐ health_check
☑ solar_data
☐ temps
☑ tracker_state

Filter device (1):
☑ esp32-lab-01

Filter _field (13):
☑ altitudePV
☑ azimuthPV
☑ current
☑ dAlt
☑ dAz
☑ eAlt
☑ eAz
☑ loadPV
☑ power
☑ radiation
☑ sunAltitude
☑ sunAzimuth

Filter quality:
☐
☐ good

Fig. 4.21. Creating a Flux query in InfluxDB to access historical measurements from the PV system

Flux queries filter by device, measurement type, and data quality, allowing analysis of the historical parameters of the photovoltaic system and their subsequent visualization in Grafana.

4.5.2. Access control and user management

Access control and user management are implemented through a role model that differentiates rights for students, teachers, and administrators. To prevent conflicting actions, an "active controller" mechanism has been introduced, where only one user manages the system at a time, while the others have observer access.

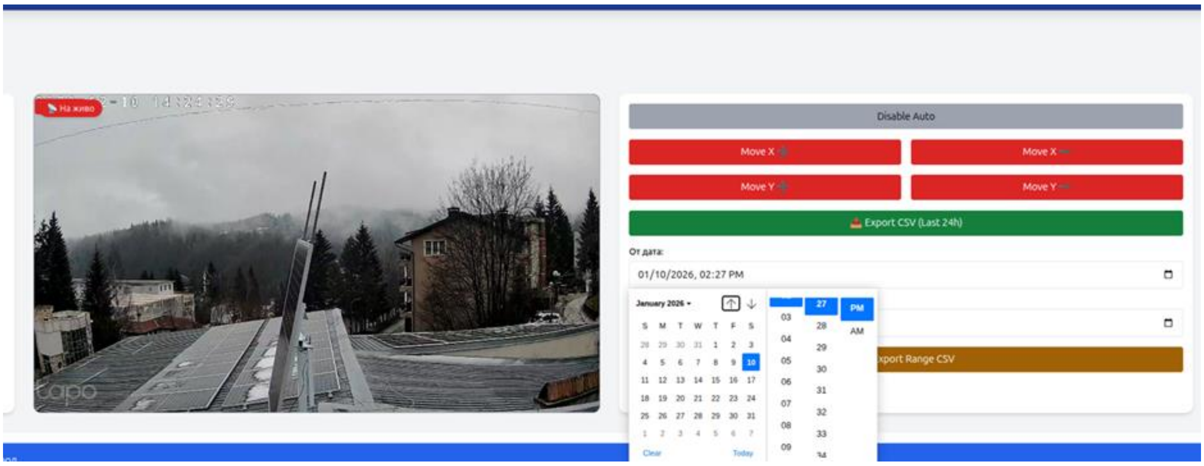


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Fig.4.22. Solar-Dashboard web interface for management

All actions are recorded in logs, which provides traceability and the ability to analyze user activity.

4.5.3. Technological implementation of the interface

The technological implementation of the interface is built using modern web technologies, including React/Next.js for client logic, WebSocket API for real-time data exchange and Chart.js for visualization of measurements. Video monitoring is implemented using HLS.js, and access to archive data and administrative functions is provided using a REST API interface. Secure access is provided using token-based authentication, with client logic and styles implemented in the dashboard.html, dashboard.js and dashboard.css files.

4.6. Data processing and Flux queries in InfluxDB

For storage and processing of telemetry data in the laboratory system, a time-series database InfluxDB, optimized for IoT applications and operation with high measurement frequency, is used. The data received from ESP32 via MQTT is validated by the backend server and written to the database, including the main parameters of the PV system - voltage, current, power, temperature, radiation and tracker position.

4.6.2. Flux requests for processing and analysis

The Flux language was used to analyze the measurements stored in InfluxDB, allowing filtering of data by time, parameters, and devices, as well as calculating statistical indicators (average, minimum, and maximum values). It allows grouping by time intervals, smoothing of measurements, and comparison of different experimental regimes.

4.6.3. Data processing

The time series stored in InfluxDB allow for the implementation of analytical and training tasks, including the calculation of energy yield, efficiency and indicators such as Performance Ratio, as well as comparison between real measurements and simulations (MATLAB, PVsyst, PVGIS). The data can also be used for anomaly detection, forecasting of generated power and machine learning analyses.

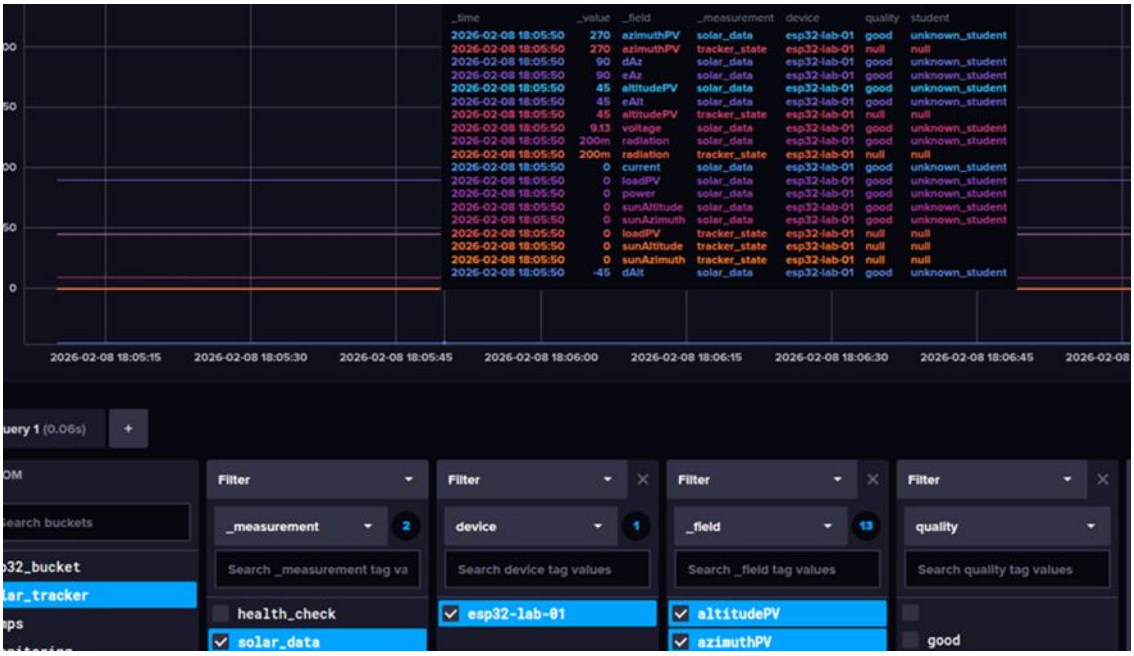
The implemented IoT architecture covers the full cycle - telemetry collection from ESP32, storage in InfluxDB, processing via Flux and visualization in Solar-Dashboard and Grafana, with the possibility of export (CSV, JSON, PDF) for scientific and educational processing.

4.7. Experimental results and visualization

The experimental results were obtained during real operation of the photovoltaic system and include instantaneous measurements, time series of the main electrical parameters and analysis of the dynamics of the processes. The data are visualized through the web interface and the Grafana platform, which allows both real-time monitoring and long-term analytical analysis.

4.7.2. Time series and dynamics of PV processes

The operation of the photovoltaic system is analyzed through time series recorded at a frequency of approximately 1 Hz, which allows detailed tracking of the dynamics of the electrical parameters. By visualizing the power, voltage and current over time, the relationship between the instantaneous PV characteristics, external conditions and the position of the two-axis solar tracker is investigated. The presented graphs and tabular data provide a basis for analyzing transient processes, measurement stability and panel orientation efficiency.



_time	_value	_field	_measurement	device	quality	student
2026-02-08 18:05:50	270	azimuthPV	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	270	azimuthPV	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	90	dAz	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	90	eAz	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	45	altitudePV	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	45	eAlt	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	45	altitudePV	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	9.13	voltage	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	200m	radiation	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	200m	radiation	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	0	current	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	0	loadPV	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	0	power	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	0	sunAltitude	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	0	sunAzimuth	solar_data	esp32-lab-01	good	unknown_student
2026-02-08 18:05:50	0	loadPV	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	0	sunAltitude	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	0	sunAzimuth	tracker_state	esp32-lab-01	null	null
2026-02-08 18:05:50	-45	dAlt	solar_data	esp32-lab-01	good	unknown_student

Fig. 4.26. InfluxDB interface for monitoring and visualization of measurements from the photovoltaic system

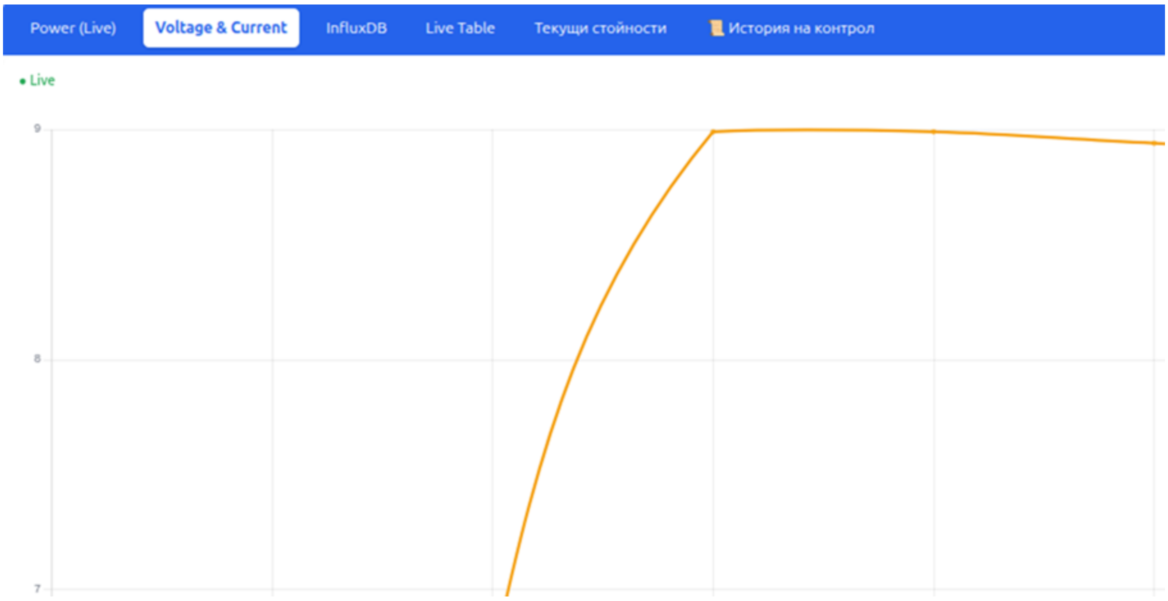


Fig. 4.27. Voltage graph with live update

4.7.3. Average values and trend analysis

The averaged values of voltage, current and power allow analysis of long-term trends and assessment of the influence of solar radiation, temperature and orientation of the tracker on the performance of the photovoltaic system.

4.7.4. Visualization in Solar-Dashboard and Grafana

Data visualization is implemented through two complementary layers – Solar-Dashboard and Grafana. Solar-Dashboard provides real-time operational monitoring of the main parameters of the photovoltaic system, while Grafana provides analytical dashboards for long-term analysis, comparison of experiments, heatmap visualizations and export of results.

4.8. Methodology for validation and tests

A methodology for validation and testing of the system has been developed, which includes verification of the correctness of measurements, assessment of communication stability, remote control tests, as well as reliability and safety analysis. The results obtained confirm the functionality and practical applicability of the developed interactive laboratory.

4.8.1. Validation results and load tests

The results obtained show that the system works stably under different load conditions and in the presence of communication interruptions. The functions for automatic connection restoration (reconnect), validation of telemetry values, timeout mechanisms and authorization mechanisms for access control guarantee reliable and safe operation in a multi-user environment. The system successfully passes all critical tests related to command response, real-time visualization, access control and writing to InfluxDB.

CONCLUSION

This dissertation presents a comprehensive concept and practical implementation of an interactive laboratory with remote access for training and research of photovoltaic systems. The developed laboratory combines simulation tools, a real IoT-based measurement system and a web interface for real-time monitoring, control and analysis in a single platform.

In the first chapter, a literature review of interactive laboratories, their architectural models, technological principles, advantages and limitations is carried out. The analysis emphasizes the need for laboratory platforms that combine simulation environments and real equipment and provide safe remote access, which justifies the chosen direction of the research.

In the second chapter, the concept of an interactive laboratory combining simulation modules, IoT communication and real measurements is formulated. The principles of operation of photovoltaic systems and the factors affecting their efficiency – illumination, temperature, orientation and load are analyzed. A modular and flexible architectural approach is presented, including a simulation module, a web interface, an IoT infrastructure and a time series database, which provides a connection between theory, simulations and real experimental data.

The third chapter presents the developed web-based simulation laboratory as a digital environment for modeling, analysis and visualization of photovoltaic systems. A software module based on MATLAB and Python (Flask) has been implemented, which allows simulations of I–V and P–V characteristics, analysis under real climatic conditions and automatic generation of results. An administrative control panel, mechanisms for storing and analyzing the history of simulations, as well as a visual editor for PV configurations with drag-and-drop capabilities, parameterization, AI analysis and export, which prepares students for working with the real laboratory, are implemented.

The fourth chapter describes the implementation of a fully functional interactive laboratory with remote access, integrating real photovoltaic equipment, web technologies and cloud infrastructure. A hardware architecture based on ESP32, measuring sensors for electrical and climatic parameters, control modules and an intelligent PV tracker has been built, which allows experimental study of the influence of orientation and inclination on the efficiency of the system.

A two-way IoT communication via MQTT, HTTP and WebSocket has been implemented, providing reliable data exchange and real-time visualization. The data is stored and analyzed in InfluxDB, which allows time series processing and comparison between simulated and real measurements. The developed platform provides interactive visualization, remote control, multi-user access and security mechanisms, which makes it suitable for training, laboratory exercises and research..

CONTRIBUTIONS OF THE DISSERTATION

Scientific and applied contributions:

1. An integrated architectural model for remote control and monitoring of photovoltaic systems has been developed, based on IoT technologies, which unites hardware level, communication infrastructure and web-based platform in a single functional environment.
2. A model for two-way real-time communication between a web interface and a physical photovoltaic system is proposed, implemented using WebSocket technology, ensuring low latency and reliable control of experimental modes.
3. A methodology has been developed for validation and experimental evaluation of the photovoltaic system under different control and load modes, allowing analysis of its behavior and efficiency in real operating conditions.
4. An approach has been developed for the integration of simulation models and real measurement data in a web-based laboratory environment, which allows for comparison between theoretical and experimental results in training and research.

Applied contributions:

1. A functioning laboratory platform with remote access has been built, designed for training and practical research in the field of renewable energy sources, applicable to students and engineers.
2. A web-based management and visualization interface has been developed that unites educational, research and engineering functionalities in a single and accessible environment that is characterized by adaptability and scalability, making it suitable for real integration in university laboratories and research centers..
3. An applied tool has been created for conducting simulations and real experiments via remote access without the need for physical presence in the laboratory..
4. A system for monitoring, analysis and long-term storage of experimental data has been implemented, including web visualization, export of results in CSV format and an InfluxDB database.

LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

1. **Snezha Shotarova,**Silvia Stoyanova – Petrova, Aspects of engineering education, through the use of an interactive laboratory. (2022) Participation in a national scientific conference with international participation “Education, Science, Society”, November 3 – 4, 2022, pp. 962-974, ISBN 978-619-7663-43-3.

2. **S. Shotarova**, S. Stoyanova-Petrova, S. Lyubomirov, ENHANCING ENGINEERING LEARNING THROUGH THE USE OF AN INTERACTIVE LABORATORY, EDULEARN23, (2023) 15th Annual International Conference on Education and new Learning Technologies Palma de Mallorca (Spain). 3rd - 5th of July, 2023, pp. 1716-1724, ISBN: 978-84-09-52151-7, ISSN: 2340-1117, doi:10.21125/edulearn.2023.0523.

3. **Snezha Shotarova,**USING LABVIEW AND MULTISIM TO BUILD A VIRTUAL LABORATORY, Union of Scientists in Bulgaria – Smolyan, Scientific Proceedings, Volume 4, 2024, ISSN 1314-9490 (online), p.183.

4. **S. Shotarova,**S. Stoyanova-Petrova, S. Asenov, S. Lyubomirov, S. Staicov, DEVELOPMENT OF AN EDUCATIONAL WEB-BASED PLATFORM FORPHOTOVOLTAIC SYSTEMS, 2025 XXXIV International Scientific Conference Electronics (ET), September 2025:1-4., doi: 10.1109/ET66806.2025.11204051, https://ieeexplore.ieee.org/document/11204051 (Scopus)