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Autonomous power supply systems

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INTRODUCTION

Global demand and power outages have shown that systems should not rely only on a source of centralized power. Especially when it comes to mobile systems, which in most cases will operate in places without constant power. Generators and batteries have become a way out of this situation, but these systems require additional costs, such as fuel and maintenance, and in the case of batteries, they need to be recharged, which means that during long periods without electricity they quickly lose their usefulness. In such situations, alternative energy sources will be the best option for domestic and industrial users.

Development of renewable energy sources has become especially important in recent years. Reasons for this include the fear of global warming and demand for cheaper and more affordable energy sources. The most suitable option would be solar energy, which is free, accessible to everyone, and allows generating clean electricity without creating environmental pollution and has the smallest carbon footprint per unit of energy generated.

Production capacity of solar panels is not constant and is affected by a variety of factors, such as solar radiation intensity, temperature, angle and orientation of the panel to the sun, load, and others. The efficiency of systems using solar panels can be increased by using maximum power point tracking systems and sun position tracking systems. At the current stage, there are a variety of tools for optimizing the output of systems using solar panels based on different methods and algorithms. However, in most cases, the cost of these tools is too high for residential usage. Therefore, most systems use only charge controllers that automatically track the best points that would increase the efficiency of small solar power plants at minimal cost. An important step in the development process is the use of computer simulation. This approach has a number of advantages, as it requires minimal equipment costs and provides the developer with an expanded arsenal of tools for work. Thus, creating a simulation model to track the optimal operating point of solar panels is an urgent task.

1 ANALYSIS OF KNOWN INDEPENDENT POWER SUPPLY SYSTEMS

1.1 Structure and classification of an autonomous power supply system.

Stand-alone power systems are important components of modern infrastructures and facilities, providing reliable power in the face of grid failures, emergencies, and when uninterruptible power is required for the smooth operation of critical systems. Autonomous power supply systems are structured primarily by their functional components, which allow the system to reliably provide power in the event of power outages or the need for constant power supply to remote facilities.

Essential components of the power supply system structure include:

1. Power sources:

This component plays a key role in the power system design as it determines where the system gets its electricity from. Power sources can include different technologies:

- Solar panels: use solar radiation to generate electricity;
- Generators: use fuel to generate electricity;
- Wind turbines: generate electricity by using wind flow;
- Battery systems: store electricity for later use;

2. Control and monitoring:

This component is responsible for controlling and monitoring. It includes various subsystems:

- energy source management: ensures optimal operation of the energy source, including starting, stopping and adjusting power;
- system health monitoring: monitors the status of the power system components, detects outages and performs diagnostics;
- load management: manages the distribution of energy among consumers and can prioritize different loads in case of limited power supply.

3. Transmission and Distribution:

This component includes the infrastructure for the transmission and distribution of electricity to end users. Important elements are:

- distribution cabinets: they separate and distribute electricity to different groups of consumers;
- cable networks: they transport electricity from the source to the consumers;
- protective devices: they ensure system safety, including short-circuit protection and overload protection.

Together, these components work to provide reliable and stable power in environments where it is especially important, such as critical infrastructure, remote locations, or in emergency situations. The architecture and layout of these components can be varied depending on the specific installation and user needs.

Off-grid power systems are typically classified based on various criteria that consider the type of energy source, scale of application, autonomy time, and other factors. Some of the main criteria for classifying off-grid power systems are discussed below.

1. Type of energy source:

- Diesel generators: These systems use diesel generators as the main source of energy. They are well suited for critical applications as they can provide stable power during long grid outages;
- Battery systems (autonomous battery power systems): these systems use batteries to store electricity that can be used when needed. This allows to smooth out peak loads and provide backup power;
- Ecological, green systems: these systems use wind turbines to generate electricity from wind flow or solar panels to collect solar energy and convert it into electricity. In most cases, they are used simultaneously to maximize performance;
- Mixed: These systems use multiple energy sources and are the most advanced, Figure.

2. Scale of application:

- small scale: small autonomous power supply systems are used for residential buildings, apartments, remote lighting systems and individual devices, individual ships, etc. Usually up to several tens of kilowatts, Figure 1.1;

Figure 1.1 small scale energy source

- medium scale: these systems are designed for commercial facilities, small businesses, agricultural complexes, and small towns. From tens of kilowatts to several hundred kilowatts. In most cases, these are powerful generators figure 1.2 or solar farms;

Figure 1.2 medium scale energy source

- large scale: large autonomous power supply systems are installed for industrial facilities, hospitals, airports, and other critical facilities. Industrial generators, large solar farms, combined systems, these systems must consistently deliver huge amounts of energy over a long period of time.

Figure 1.3 large scale energy source

Great example is the solar power plant Opened at Dublin Airport, opened in 2018. The 9 MW solar power plant will generate 11.8% of the airport's annual electricity demand, providing airfield lighting, as well as the energy needs of the terminal and campus. The project is located on an 11.3-hectare plot.[1]

Figure 1.4 solar power plant at Dublin Airport

3. Autonomy time:

- short autonomy time: some stand-alone power systems are designed for a short period of autonomous operation, for example, a few hours. They can be used to maintain power during temporary outages;
- medium autonomy: these systems can operate autonomously for several hours to several days and are often used in small businesses and individual buildings;

- long autonomy: some autonomous power systems are designed for long autonomy, and can provide power for several weeks or even months. They are used at remote sites where access to the power grid is limited or non-existent.

1.2 Analysis of software tools for modeling the autonomous power supply

The calculation of an autonomous power system allows you to accurately determine the amount of electricity that the system will generate for specific site conditions, provided that all its components are installed and connected properly. Tools for modeling autonomous power supply systems are based on mathematical equations that allow you to calculate the input and output power for the installed elements of the system in order to create an hourly schedule of electricity generation and consumption for the autonomous system based on these data. [5, 6] Tools for calculating and modeling autonomous power supply systems are used to solve various problems:

- development of electrification projects for new facilities;
- optimization of installation and operation of existing autonomous power supply systems
- performing preliminary calculations for concluding contracts or preparing commercial offers;
- calculating the efficiency of the installed system. Coordinating the interaction of the autonomous power supply system with the public power system;
- Performing energy calculations and tests.

There are software tools for modeling and calculating off-grid power systems that take into account various components such as batteries, diesel generators, and solar panels, but most such programs will only take into account a few parameters. Such programs allow engineers and researchers to design and analyze complex off-grid power systems, taking into account different energy sources and operating conditions. Below I will present some popular programs for modeling such systems:

- HOMER (Hybrid Optimization Model for Electric Renewables) figure 1.4: HOMER is one of the most well-known programs for modeling hybrid power systems that take into account solar panels, batteries and other energy sources. It allows for system optimization to achieve the best economic performance;

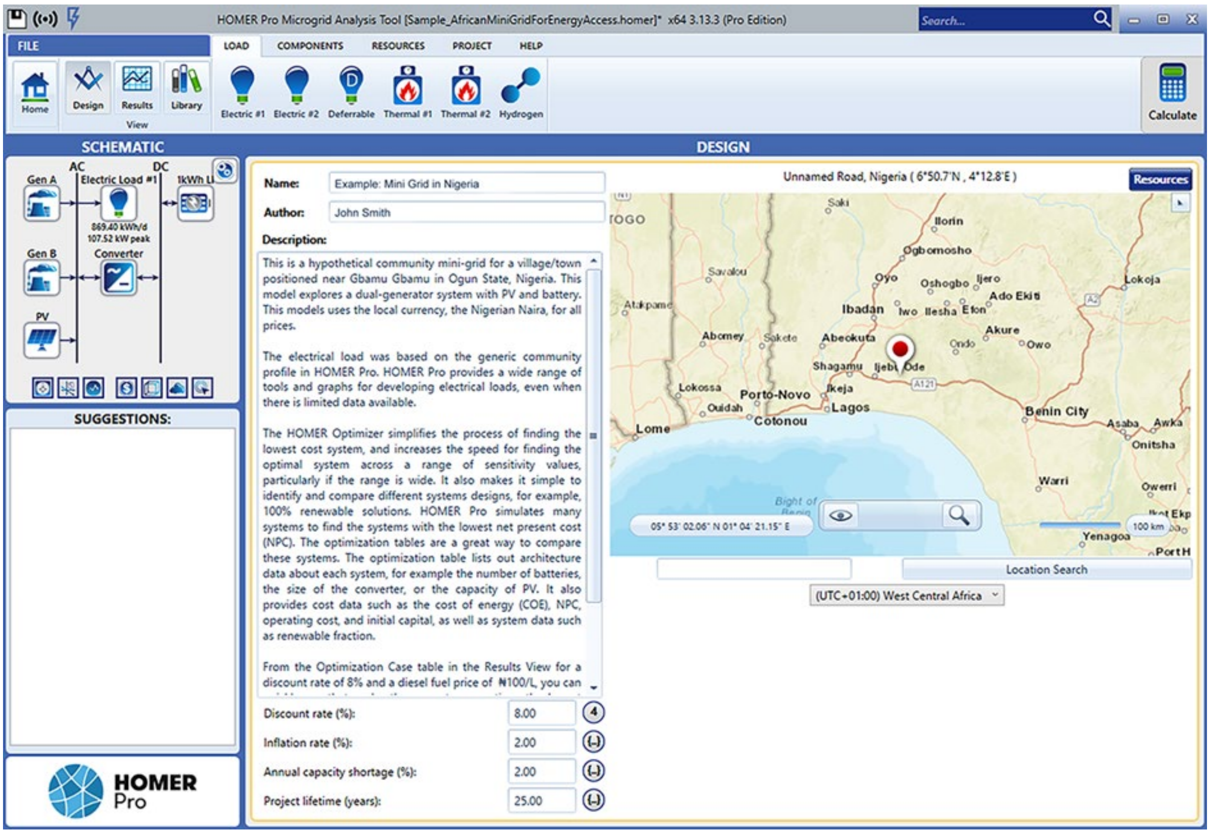


Figure 1.5 HOMER application window

- RETScreen: RETScreen Figure 1.5 is a free program for analyzing renewable energy projects and energy efficiency. It includes the module "Autonomous Electric Power Systems", which allows modeling systems using solar panels, batteries and diesel generators;

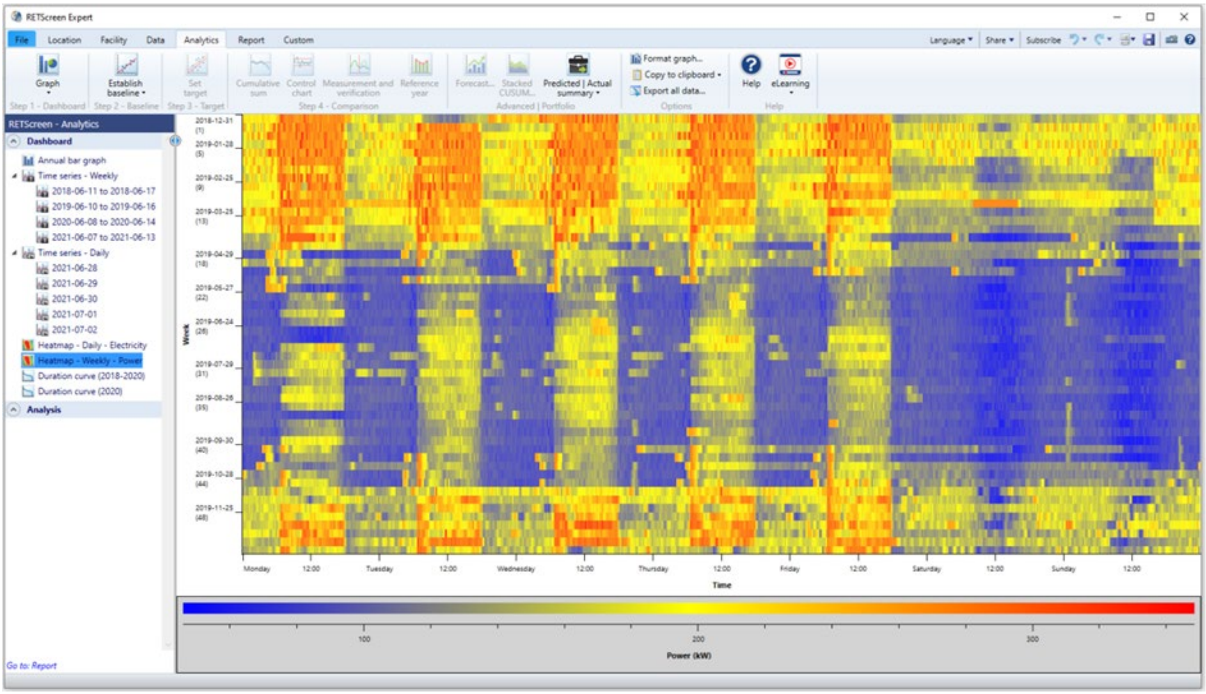


Figure 1.6 RETScreen application window

- PV*SOL: PV*SOL Figure 1.6 is a program for designing and modeling solar power plants. It takes into account solar panels, batteries, and can integrate diesel generators to create autonomous power systems;

Figure 1.7 Example of a project in PV*SOL

- SAM (System Advisor Model): This program was developed by the National Renewable Energy Laboratory (NREL) and takes into account the various components of 15 off-grid power systems, including solar panels, batteries, and generators. SAM allows you to analyze the cost and performance of the system;

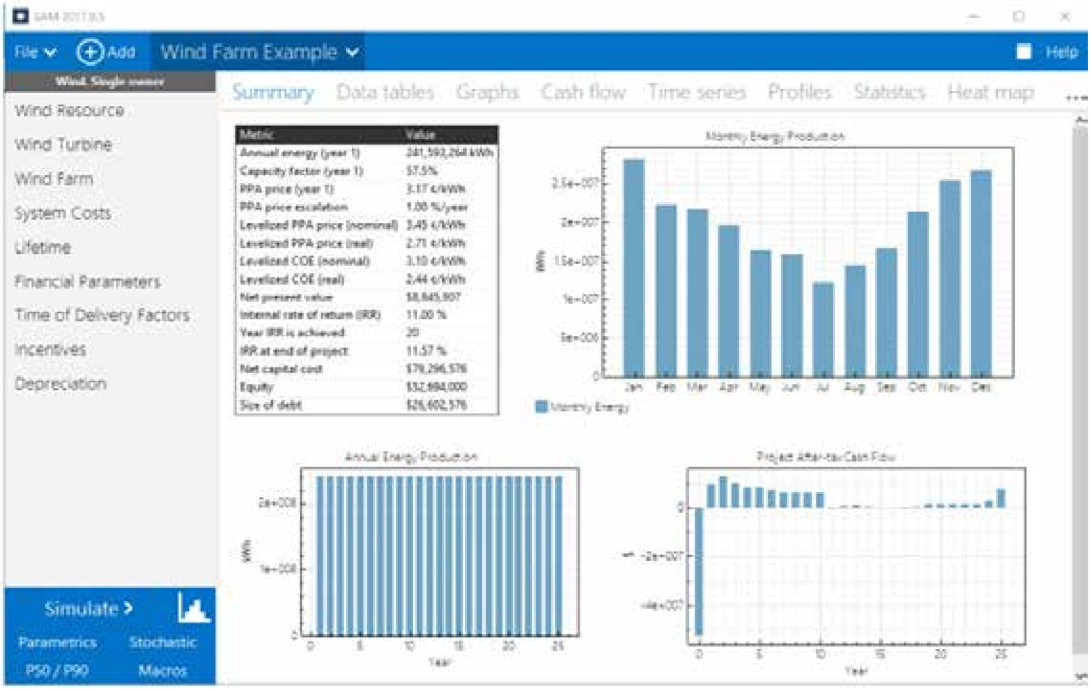


Figure 1.8 System Advisor Model application window

- MATLAB Simulink Figure 1.7 is an integrated modeling and simulation environment included in the MATLAB software package developed by MathWorks. Simulink allows engineers and researchers to model, analyze, and simulate a variety of systems, including off-grid power systems.

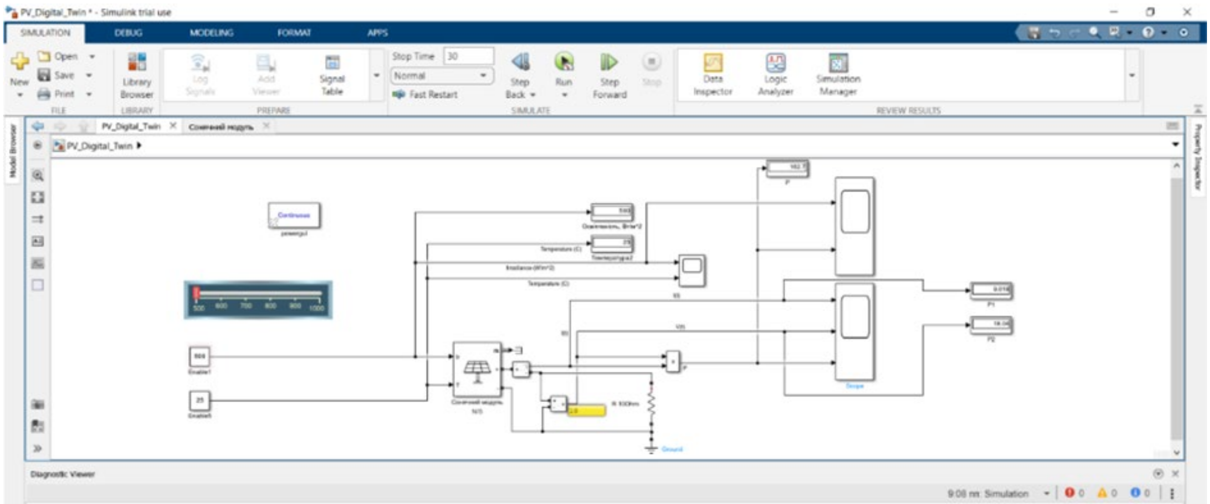


Figure 1.8 MATLAB Simulink application window

Main features and capabilities of MATLAB Simulink for modeling off-grid power systems include the advantages described later in the paper. Solar cell modeling - Simulink can be used to model various characteristics of solar cells, including their efficiency, output parameters, and interaction with other system components. Simulink provides tools for analyzing system dynamics in the time domain, which allows you to study changes in the system over time. Simulation of power systems - Simulink tools allow you to perform simulations of autonomous power systems with different input conditions and different parameters of system components. Analyze and visualize results - Integration with MATLAB allows you to analyze and visualize the results of simulations, including graphs, charts and other tools for understanding system performance. Realistic scenarios - Simulink allows you to take into account realistic scenarios such as changes in weather, electricity costs, and the interaction of external factors.

1.3 Analysis of known methods for optimizing an off-grid power system

As mentioned, there are many types of off-grid power systems with their own parameters, advantages, and installation recommendations, but for all off-grid power systems, there are several basic steps to improve efficiency: - Load Management: One of the key methods is to distribute energy intelligently among the various loads in the system. Load management systems can turn devices on and off depending on the requirements, which can reduce energy consumption. Demand Side Management (DSM) is a strategy for effectively managing and optimizing electricity consumption by users and customers. [7] The main goal of Demand Side Management is to reduce peak loads, use resources efficiently, and reduce energy costs in power systems and power grids;

- Battery Storage: batteries can store energy for use when it is most needed or to store excess energy for future use. This makes it possible to optimize the use of solar panels, wind turbines and other energy sources. The presence of batteries allows you to stabilize energy consumption and use batteries to provide power during peak periods, which in turn will help reduce the load on the grid;

- Hybrid Systems: the use of a combination of several energy sources, such as solar panels, wind turbines and generators, can provide a more stable and efficient power supply. Control systems for hybrid systems can automatically select energy sources depending on the circumstances. For example, inverter with a built-in control system - POW HVM3.2H-24V, in which you can adjust the operating mode and set prioritization of the power source [8];

- Microgrids: Microgrids are small autonomous power supply networks that can operate independently of centralized networks. They can include the distribution of energy sources and efficient consumption management; - Energy-Efficient Technologies: the use of more energy-efficient devices and technologies, such as LED lighting, heat pumps, energy-saving equipment, etc. can help reduce energy consumption;

- Energy Forecasting: the use of forecasting algorithms allows power supply systems to plan in advance the production and use of energy according to needs;

- Automated Control Systems: use of modern management and control systems that can in real time analyze and optimize system performance. Solar panel guidance system, a wind turbine rotation system, or a lighting control system;

- Advanced Materials and Technologies: improving the efficiency of solar panels, wind turbines, and batteries through new materials and technologies. A great example is solar panels, which are rapidly evolving, making old panels unprofitable compared to new ones, panels of the same size can have a difference in maximum power by several times;

- Monitoring and Diagnostics: the use of monitoring and diagnostic systems to detect problems and plan maintenance of power supply systems. Timely detection of damage and losses.

Let's look at the implementation in practice, taking as an example a project we worked on at the university, and go through all the steps of project analysis and implementation. We have a certain unit that performs a certain action, in our case it is a mobile unit that recycles waste and needs access to the network, since the unit is mobile, we want to get autonomy to perform, so we want to implement additional power systems in case of operation in a remote village or in case of power outages.

First step could be the implementation of batteries. Our system theoretically consumes 3 kilowatts, which in turn will discharge any battery very quickly, for comparison, the standard EcoFlow DELTA 2 charging station has a capacity of 1024 Watt-hours and a rated power of 1800 watts, which means that it is not suitable for power supply, and even if it had sufficient rated power, it would be exhausted in 20 minutes. So, we need to use a powerful inverter and a fairly large number of batteries. Let's analyze this step in more detail:

1) Inverter Selection:

To support a system that theoretically consumes 3 kilowatts (kW), we'll need an inverter that can handle at least that much power. For reliability, it is better to buy a 20-30% more powerful one right away. So, an inverter rated for 3.5 to 4 kW would be suitable.

2) Battery Storage Calculation:

Calculate this point right away: how many hours should you run on batteries? This point is unique to all cases, our system will not work for a long time and will not be left unattended overnight, so we believe that 3 hours of battery life will be enough, but certain systems may require 12 hours or even several days.

Operating Time: 3 hours.

Power Consumption: 3 kW

$$Energy = Power * Time \tag{1.1}$$

$$Energy = 3kW * 3\,hours = 9\,kWh \tag{1.2}$$

Convert energy to battery capacity: Battery capacity is typically measured in ampere-hours (Ah). To convert kilowatt-hours (kWh) to ampere-hours (Ah), you need to know the voltage of the battery system. For example, let's assume standard in our shops a 12V battery system:

$$Capacity\ (Ah) \ = \ Energy(Wh)\ /\ Voltage\ (V) \tag{1.3}$$

$$Energy \ = \ 9kW\ 1000 \ = \ 9000\ Wh \tag{1.4}$$

$$Capacity\ (Ah) \ = \ 9000\ Wh\ /\ 12V \ = \ 750\ Ah \tag{1.5}$$

Other Considerations:

● Battery Efficiency: Batteries are not 100% efficient. Consider a typical efficiency of about 85-95%.

● Depth of Discharge (DoD): To prolong battery life, it's common to only use a certain percentage of the battery's capacity. For example, if you use 80% DoD:

$$Usable\ capacity \ = \ 750\ Ah\ /\ 0.8 \ = \ 937.5\ Ah \tag{1.6}$$

As can be seen from the calculations, our system needs one 12 V battery and 1000 Ah of hours to operate for 3 hours, or other configurations can be used. For example, two 12 V 500 Ah batteries in parallel would give you 1000 Ah. Alternatively, three 12 V 350 Ah batteries in parallel would give you 1050 Ah. This setup ensures you have enough capacity to power your 3kW system for 3 hours.

In conclusion, you can see how to calculate how many batteries you need, their capacity, and understand the number of operation hours. But this method has its drawbacks, the batteries need to be recharged, so there are several options for doing this: the first is to charge when the power is available when the system is not working; the second is to charge when the power is available when the system is working (which will create a large load on the network and in places with old and unreliable power).

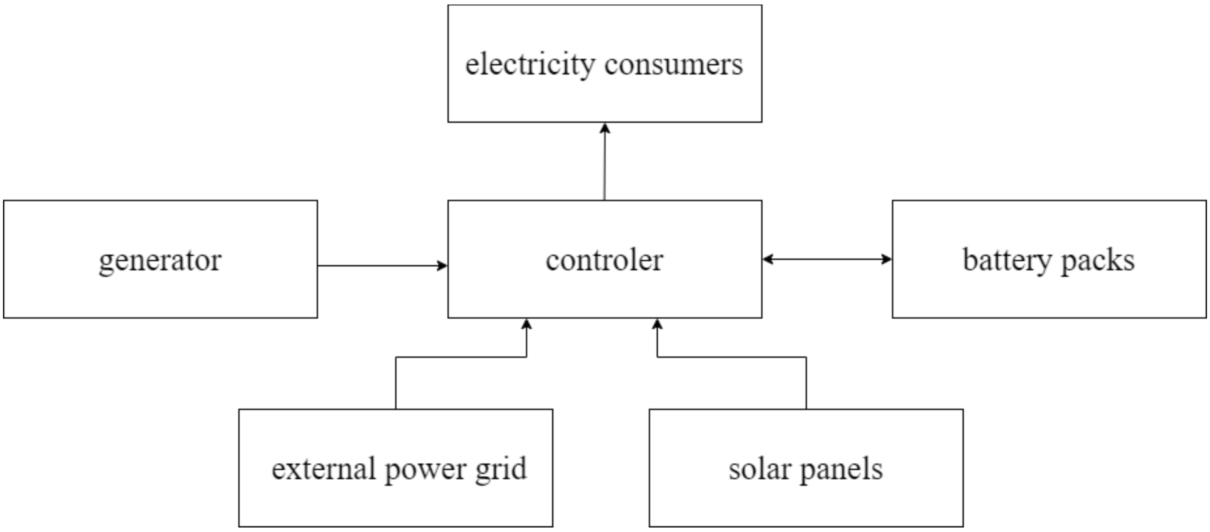
Now the most important part, if you are planning to use solar panels, each panel has its own characteristics, and the panels produce the maximum amount of energy when they are directed ideally to the sun (at an angle of 90 degrees). With the loss of ideal angle, the panels will lose their power. Temperature also greatly affects the power output of the panels, so it is best to run a simulation using appropriate software.

2 MODEL OF AN AUTONOMOUS POWER SUPPLY SYSTEM OF THE SET SYSTEM AND CALCULATION OF ITS PARAMETERS

2.1 Formal model of an autonomous power supply system for a waste recycling unit

Let's consider a generalized diagram of the power supply system of the plant for processing waste into fuel, which includes the following components:

- electricity consumers (waste recycling unit);
- external power grid;
- solar panels;
- battery packs;
- generator.



The total power of node i is determined by the following formula:

Pgeneral= Pgenerated - Pconsumed (2.1)

where P generated is the total power generated at node i, P consumed is the consumed power at node i.

Energy balance at node i: defined by equation (2.2)

Pgeneral,i=j=1nPtransferred,ij (2.2)

Using equation (2.2), we can derive the system of equations for the calculation of

Pgeneral,1=j=1nPtransferred,1j

Pgeneral,2=j=1nPtransferred,2j (2.3)

…

Pgeneral,i=j=1nPtransferred,ij

The problem of the electrical balance of an electric system can be expressed by a system of equations that takes into account the generated and consumed power. In our case, taking into account solar panels, batteries, and a generator, we can formulate the following system of equations:

1. Energy generation by solar panels: equation (2.4)

Psolar=N· Pone panel (2.4)

Where Psolar - is the total power of solar panels, N is the number of solar panels, Pone panel - power of one solar panel;

2. Power from batteries - equation (2.5):

Pbatteries= Qt (2.5)

W here Q is the battery charge, t is the autonomous operation time of the system on batteries;

3. Power consumption by the plant: equation (2.6), where Pplant is the power required by the processing plant:

Pconsumed = Pplant (2.6)

4. Charging of batteries from the installation: equation (2.7), where Pgenerated is the total power generated, Pconsumed is the total power consumed:

Pcharge = Pgenerated - Pconsumed (2.7)

5. Generator power: Pgenerator is the power output of the generator.

The total electrical power of the system is the sum of the power from solar panels, batteries and generators.

$$Ptotal = Psolar + Pbatteries + Pgenerator - Pplant \quad (2.8)$$

So, having formula (2.8), we can derive a system of dependencies for calculating the power of our circuit when taking into account the operating modes. The system should contain several key operating modes:

- operation of the waste cnit from combination of previous;
- battery charging:

$$\{ \; Pgrid \geq Pplant \; Psolar \geq Pplant \; Pgenerator \; Pplant \; Pbatteries \geq Pplant \; Psolar \geq Pplant \quad Pcharge \geq Pplant \quad (2.9)$$

You can manually insert the power values for the calculation in the following calculations, but for now we will take into account that the system is capable of running on only one of the power sources, thus giving to our system four power sources, three of which are not depend on the gonversion unit from the power grid;

- operation of the waste conversion unit from solar panels;
- operation of the waste conversion unit from the generator;
- operation of the waste conversion unit from batteries;
- operation of the waste conversion urid, making our system as autonomous as possible.

2.2 PV conversion in the power supply system of waste conversion unit

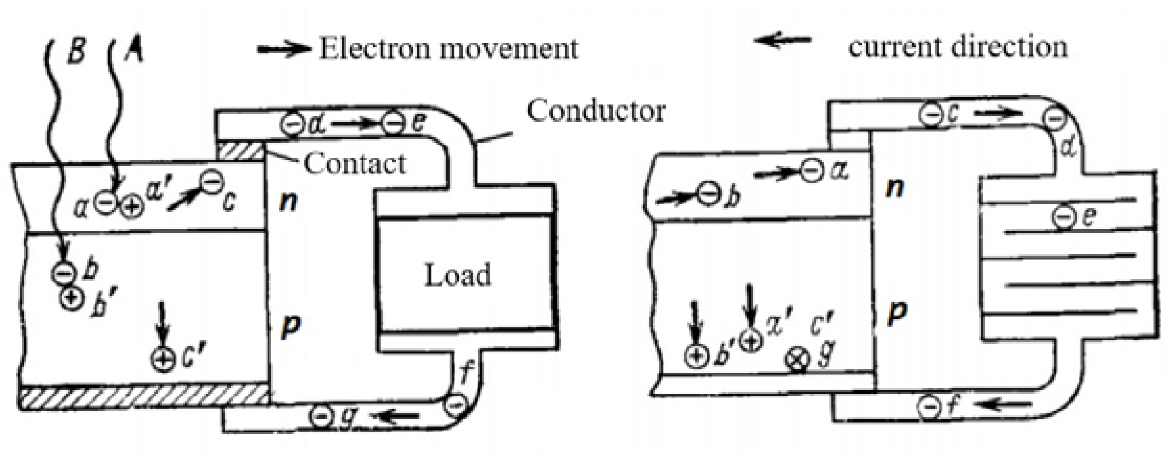
Basic principle of solar cells is the internal photoelectric effect, which allows direct conversion of solar radiation into electricity in semiconductor materials. The essence of this phenomenon is that light photons can eject electrons from the surface of bodies (external photoelectric effect) or only from the crystal lattice inside the semiconductor (internal photoelectric effect). Additionally, an electromotive force occurs at the metal-semiconductor interface, which causes changes in the current in the external circuit (gate photoelectric effect).

This phenomenon was discovered by the German physicist Hertz in 1887 and studied in detail in 1888. The photoelectric effect defines the basic principles of modern solar cells, making it possible to convert solar radiation into useful electricity.

Today, in the field of alternative energy, semiconductor devices with a p-n junction, known as solar cells or photovoltaic cells, are widely used. A real breakthrough in this area is the use of such devices, where under the influence of solar radiation, charges are redistributed, which leads to the emergence of an electromotive force. The vast majority of solar cells are produced using silicon, which emphasizes the importance of this material in production. [10]

These semiconductor devices not only provide reliable conversion of solar radiation into electricity, but are also becoming an important component of modern energy infrastructure, helping to reduce dependence on traditional energy sources. Given their high efficiency and sustainability, solar cells are becoming an essential element of sustainable development and environmental protection strategies.

Solar cell consists of two semiconductor plates, n- and p-type, which in turn form a p-n junction. The design of a solar cell is shown schematically in Figure 2.2.



In the presence of solar radiation, solar cells actively absorb photons x with different energies at different depths. The process of electron emission from the semiconductor atoms by photons A and B occurs, which generates two electron-hole pairs aa′ and bb′. Under the influence of the generated electric fields of the p-n junction, electrons and holes move in the material. For example, an electron c and a hole c′ caused by a photon move towards the n- and p-regions, respectively. The further movement of electrons from the n-region due to an external load to the p-region (denoted as d, e, f, and g) generates an electric current. [11] At the interface with the p-region, the electrons recombine with holes, thereby becoming neutral, until the next photon creates a new electron-hole pair. This process of electric current generation reflects the complex mechanism that underlies the functioning of solar cells, ensuring the efficient conversion of solar radiation into electricity.

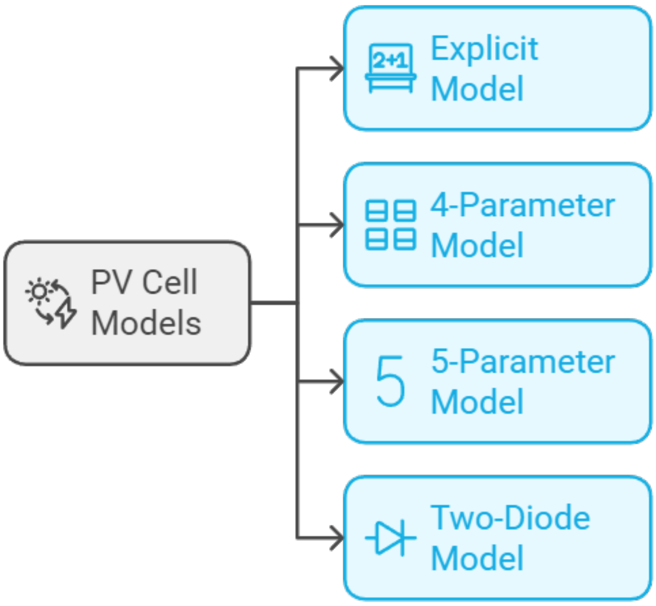
Various mathematical models have been developed to determine the nonlinear characteristics of photovoltaic cells. [12] These models vary in the number of unknown parameters to be determined. Among the most popular mathematical models of photovoltaic cells are the following:

1. Explicit model: This model is defined by expressions that explicitly describe the relationship between the input and output parameters of the PV cell.

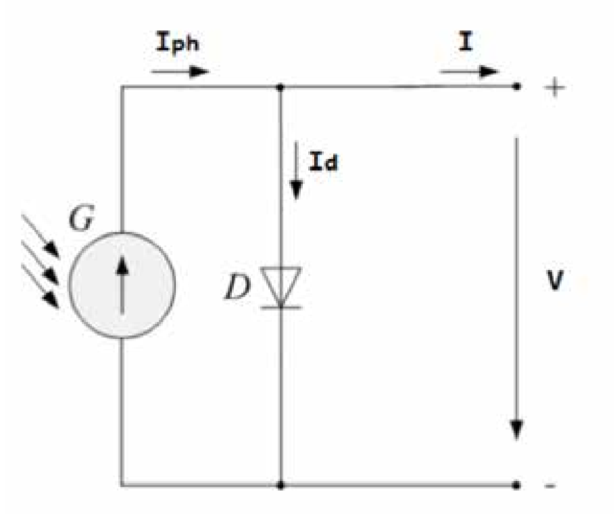
2. Model with 4 parameters: In this model, four parameters are used to describe the characteristics of the PV cell. These can be, for example, short circuit current, open circuit voltage, shape factor, etc.

3. Model with 5 parameters: An extended version of the previous model that includes an additional parameter to more accurately describe the nonlinear properties of the PV cell.

4. Two-diode model: This model uses two diodes to approximate the characteristics of a PV cell. It allows for a more accurate account of the interaction of different diodes in the PV cell structure.



Given the variety of models available, it is important to choose the one that best suits the specific conditions and objectives of the study. Each of these mathematical models has its own advantages and limitations, and the choice of model depends on the specific application and the accuracy to be achieved. An ideal solar cell can be represented by an equivalent circuit consisting of a diode and a current source, Figure 2.4.



Current source of a solar cell is determined by the photocurrent that arises as a result of the creation of non-basic charges by light. In this case, the volt-ampere characteristic (VAC) of a solar cell (SC) depends on the photocurrent and the current flowing through an idealized p-n junction at a given temperature T and output voltage V, and it is defined by the following equation:

$$I = I_{ph} - I_0\left(exp\ exp\ \left(\frac{qV}{nkT}\right) - 1\right) \tag{2.10}$$

I- total current of the solar cell;
I_{ph} - photocurrent;
I_0 - reverse saturation current;
q - $1{,}602 * 10^{-19}$- electron charge;
V - voltage at the output of the solar cell;
n - the perfect sensitivity factor;
k - $1{,}381 * 10^{-23}$Boltzmann's constant;
T - temperature, K;

This equation takes into account the effect of photocurrent and reverse temperature current on the total current of the solar cell. It is key to understanding the electrical characteristics of solar cells and their response to different operating conditions. [13]

2.3 Digital twin of the photovoltaic power supply system for waste conversion unit

Digitalization and the use of digital twins, as virtual replicas of physical assets and processes, represent a distinct advantage for industries looking to optimize and improve their operations. In the solar industry, this technology is a powerful tool to increase the productivity of solar installations, reduce costs and facilitate the transition to a sustainable energy future.

While the concept of digital twins is not new, its application in the solar sector is only just reaching its potential. The growing demand for clean energy and the need to improve solar power production is leading to a growing interest in using digital twins to optimize the process. By creating a virtual representation of a solar power plant, operators can monitor, analyze, and optimize the performance of their assets in real time, resulting in increased efficiency and reduced costs.

One of the key benefits of digital twins in solar power generation is their ability to provide a complete view of the solar plant in real time. This allows operators to identify and resolve issues before they escalate, minimizing downtime and maximizing plant efficiency. For example, digital twins can recognize anomalies in solar panel performance, such as power loss due to dust accumulation or shading, and automatically take action to resolve them.

The use of digital twins is also proving to be important for optimizing the design and layout of solar power plants. By simulating different configurations and evaluating the impact on the amount of energy produced, operators can determine the efficient placement of solar panels, maximizing the plant's performance. This can be particularly useful during the planning stages of a new solar project, as it allows developers to optimize the design from the outset, reducing the need for costly modifications later on.

Another area where digital twins can be very valuable is in maintenance forecasting. By continuously monitoring the performance of solar power plant components, digital twins can identify patterns and trends that may indicate potential problems or failures. This allows operators to plan maintenance in advance, reducing the likelihood of unexpected downtime and ensuring optimal plant efficiency.

In addition, digital twins can play a key role in improving the accuracy of solar energy forecasting. By integrating real-time data on weather conditions, solar radiation, and other factors, digital twins can help operators predict the amount of energy a plant will generate in the coming hours and days. This can be an important element for grid operators who need to balance supply and demand to ensure grid stability.

Besides the above benefits, digital twins can also facilitate knowledge sharing and collaboration between different stakeholders in the solar energy sector. By providing a common platform for data analysis and decision-making, digital twins can help solve problems collaboratively, bridge the gaps between different teams and departments, and create a more efficient and dynamic working environment for cooperation.

To simulate the digital twin of the photovoltaic power supply system for the polymer waste-to- diesel plant, Matlab Simulink was chosen as the modeling environment, an example of which is shown in Figure 2.5.

The choice of Matlab Simulink can be due to several factors:

1. Ease of use: Matlab Simulink is a powerful tool for modeling dynamic systems that has an intuitive interface and a large number of ready-made blocks for building complex models. Its graphical interface makes it easy to determine the interaction between different components of the system;

2. Power supply modeling capabilities: Matlab Simulink offers a wide range of tools for modeling electromechanical, thermal, and other systems, which can be important for a detailed study of PV systems and their power supply in the context of a waste-to-energy plant;

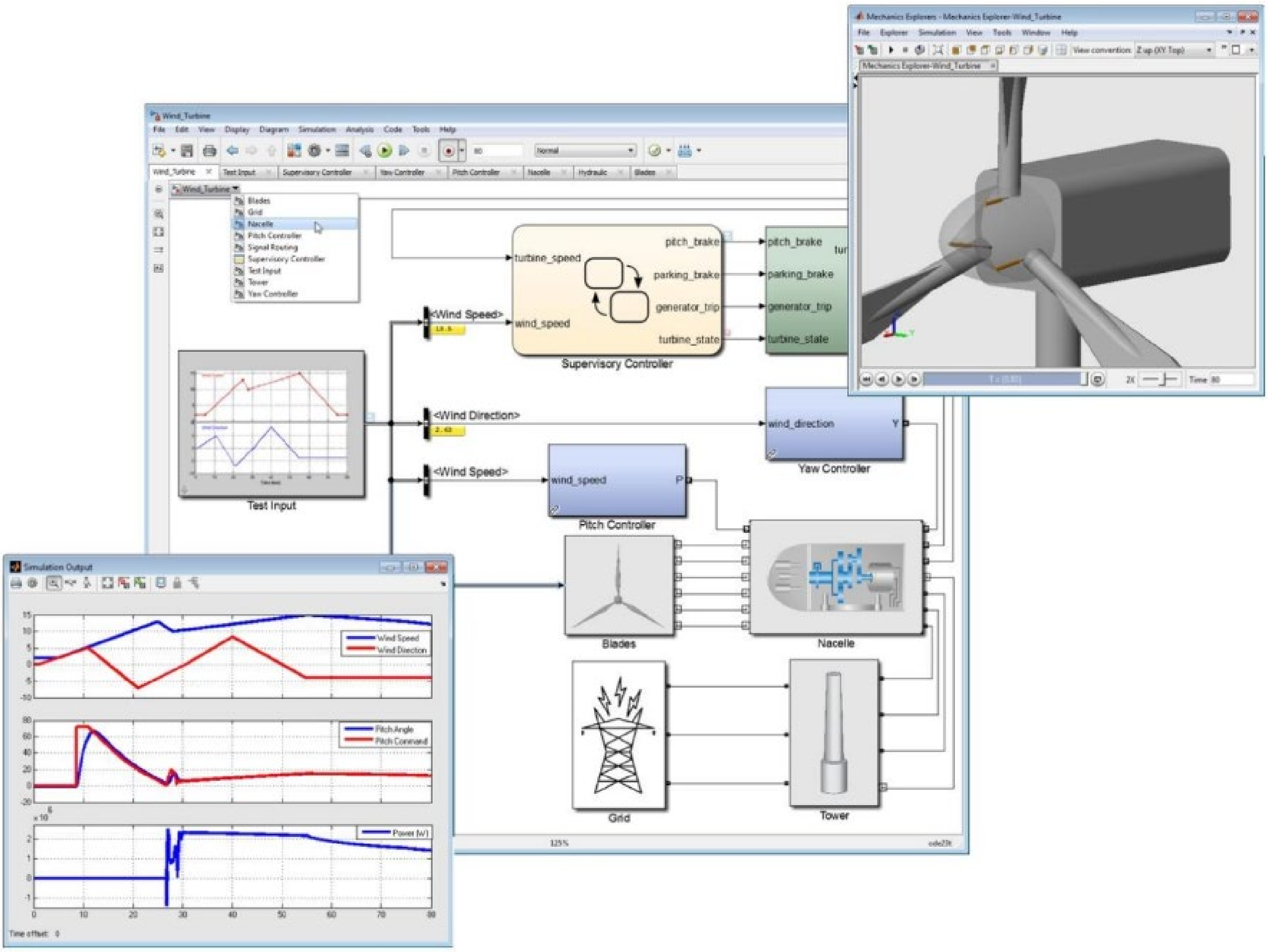
3. Huge community of users and support: Matlab has a large community of users and a wealth of materials, documentation, and online resources to help you solve problems and explore the power of Simulink;

4. Integration with other tools: Matlab can be easily integrated with other tools and programming languages, which can be useful for further development and optimization of the system.

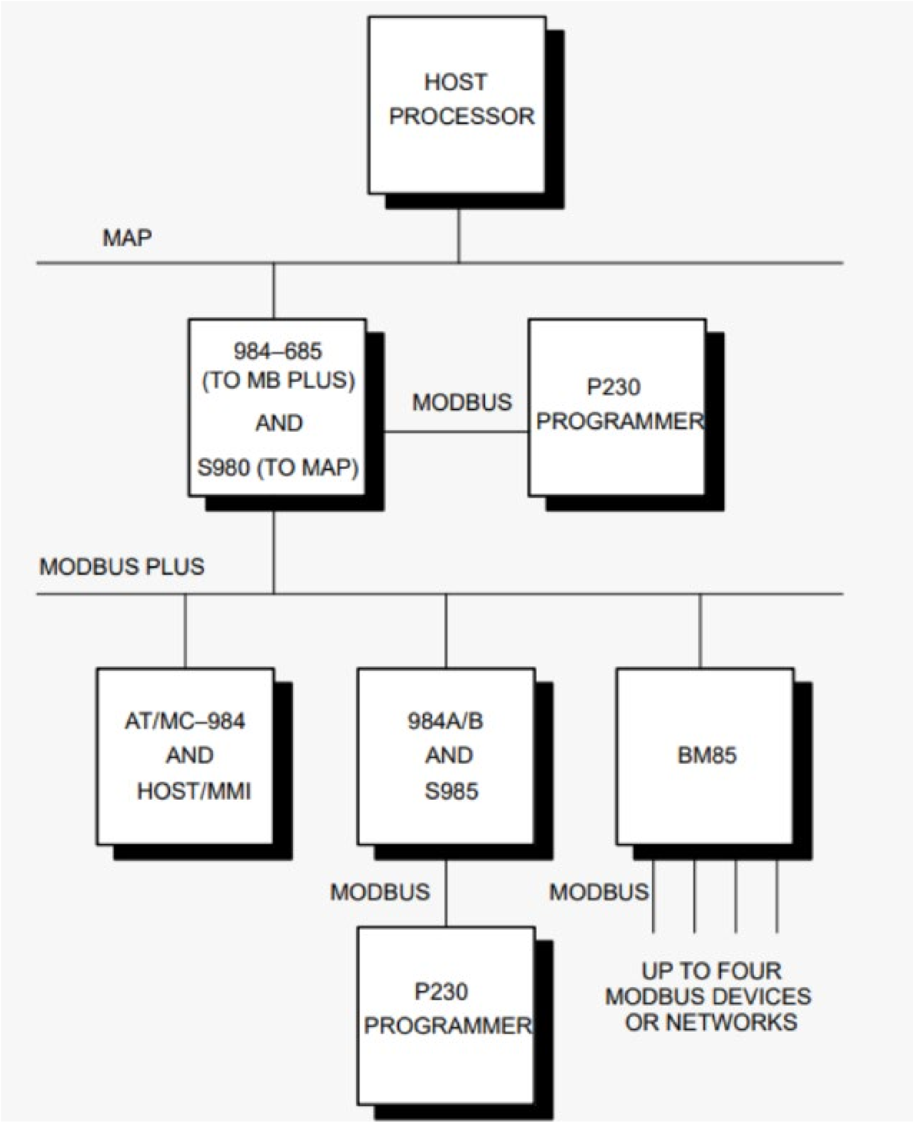
5. Advanced analysis and visualization of results: MatlabSimulink provides extensive analysis and visualization capabilities for simulation results, which can contribute to a better understanding and optimization of PV systems and their power supply.

Modbus communication protocol was chosen to receive data from the sensors. The Modbus protocol provides an internal standard that controllers use to parse messages. When communicating on a Modbus network, the protocol defines how each controller learns the address of its device, recognizes the address addressed to it, determines the type of action to take, and extracts any data or other information contained in the message. If a response is required, the controller will create a response message and send it using the Modbus protocol.

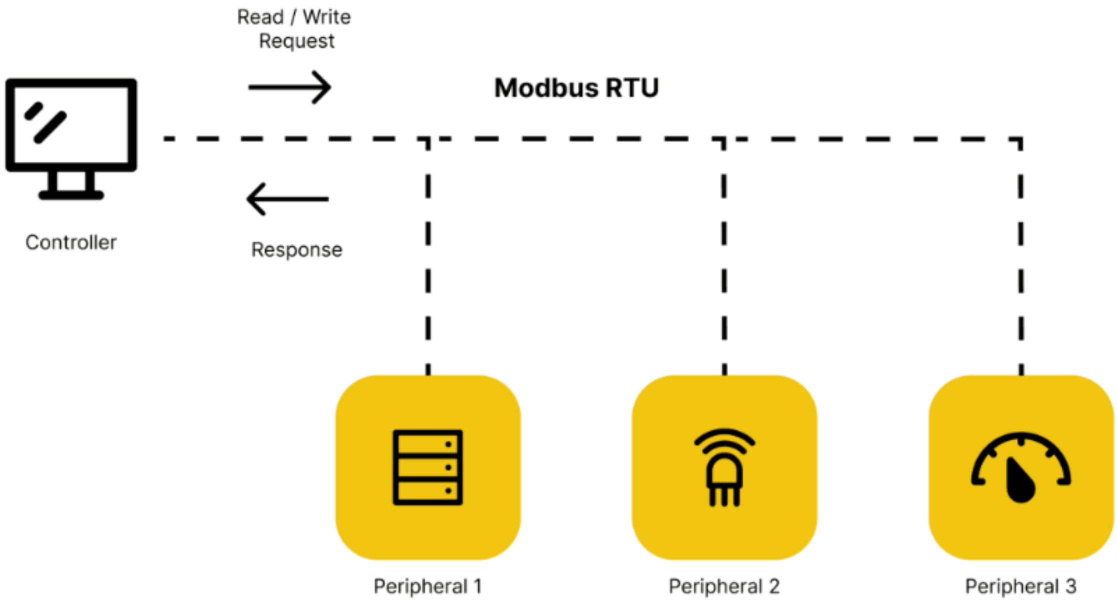
In other networks, messages containing the Modbus protocol are embedded in the frame or packet structure used on the network. For example, Modicon network controllers for Modbus Plus or MAP, with their respective application software libraries and drivers, provide the conversion between the embedded Modbus message and the Modbus protocol and the special framing protocols that these networks use to communicate between node devices.

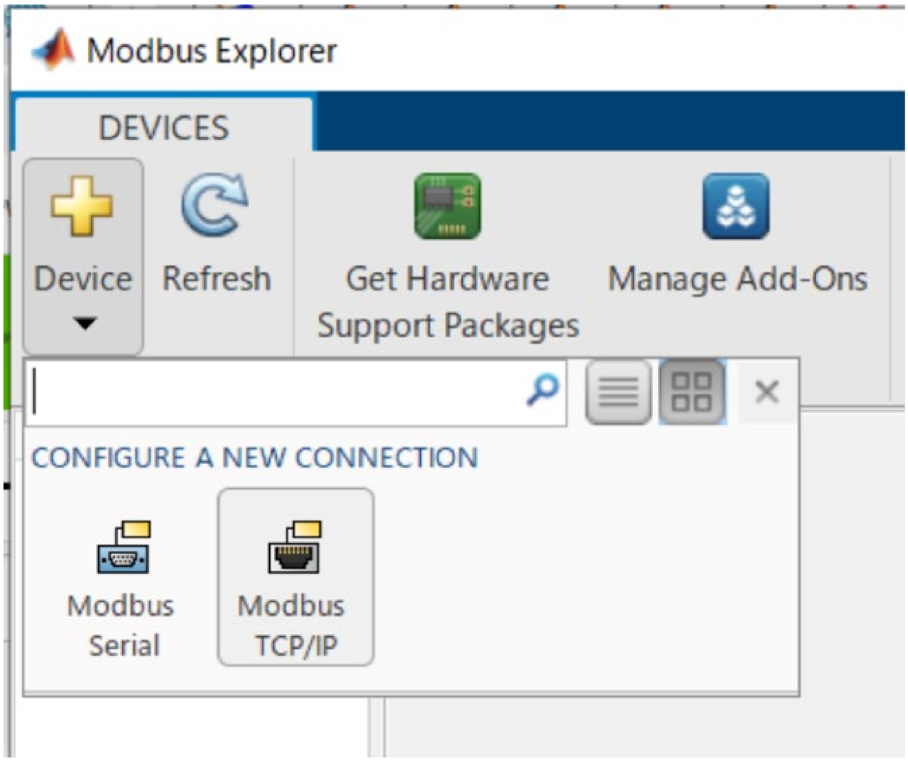


This conversion also extends to the definition of node addresses, routing paths, and error checking methods specific to each network type. For example, Modbus device addresses, Figure 2.6, contained in the Modbus protocol will be converted to node addresses, and device addresses contained in the Modbus protocol will be converted to node addresses before messages are transmitted. Error checking fields will also be applied to the message packets according to the protocol of each network. At the delivery endpoint, such as the controller, the contents of the embedded message recorded using the Modbus protocol determine the actions to be taken.



Matlab Simulink has support for the Modbus protocol, Figure 2.7 and Figure 2.8, and is able to work with it in real time, which is most suitable for modeling processes and controlling the system, and Modbus is also partially used in working with programmable logic controllers, which will allow us to improve the control system in the future to work with programmable logic controllers without changing the data transfer protocol.





Modbus Simulink is a rather unpopular topic for research, since most users and work done in Matlab use pre-made data sets or are obtained from modeling systems in Simulink, so the process of integrating real-time data is a kind of plus for the model. Figures 2.9 and 2.10 show an example of the implementation of data exchange between sensors and the model.

As can be seen in Figure 2.8, the system transmits data from the charge controller to the inverter via an rs-485 connector, which is connected to a computer via a Modbus USB converter. The charge controller inverter allows you to read the data that it calculates and displays on the screen, such data includes the indicators of solar panels, namely voltage, current and power, and if additional modules are connected to the system, in our case it will be a battery system, generator and external power supply, you can get data from all elements. Also, thanks to the smart charge controller inverter, we have the ability to change the operating modes by transmitting a feedback signal, which will allow us to switch from the solar panel and battery power mode to the battery charging mode, and will also allow us to monitor its status.

When you start the model, in the StartFcn* submenu, you enter a code that runs when you start modeling the system, this simple code specifies the parameters for reading or writing information, such as connector, id, server_id, read/write speed if it differs from the standard 9600 bits/s, and also selects what actions to perform with the register.

3 ALGORITHMS AND TECHNOLOGIES FOR MODELING POWER SUPPLY OF A POTENTIAL SYSTEM

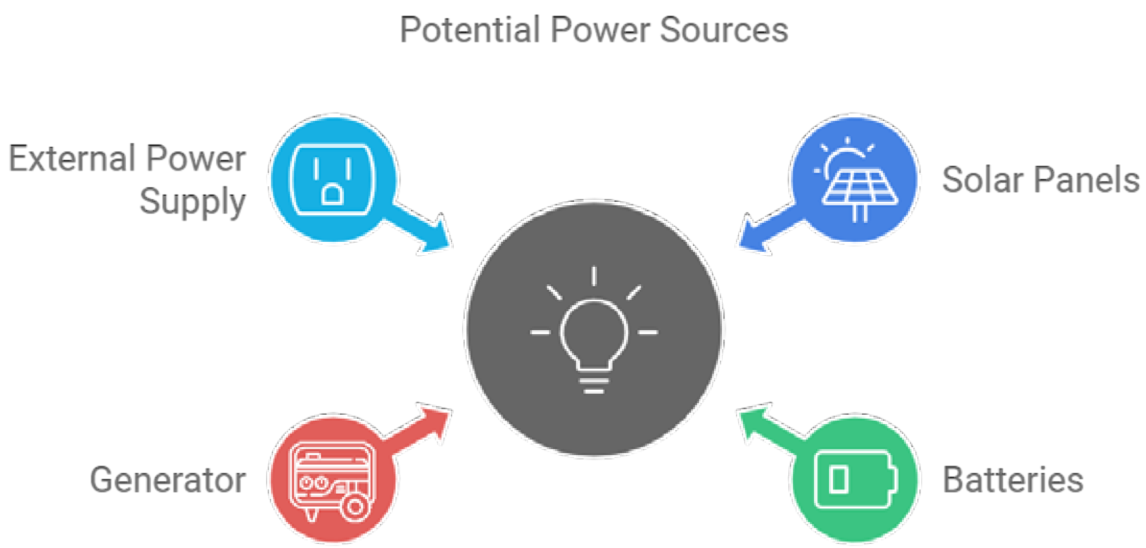
3.1 Algorithm for calculation of the power supply system for the potential system

For the sake of simplicity, we will take as an example a system for processing polymer waste into diesel fuel, which was developed by the university. All we need to know is that it consumes 3000 watts, you can calculate how much your appliances consume in your system yourself, a refrigerator consumes 300 watts, add a TV - 40 watts, and so on. The stages of the algorithm for calculating the power supply system for the potential system will be as follows:

1. Initial data collection: identification of all electrical devices and equipment that will be connected to the system. In our system, five main groups can be distinguished: power consumed by the polymer processing system; power provided by the external network; power provided by the generator; power provided by the solar panel system; batteries;

2. Estimation of power consumption: calculation of the total power required by the system from all connected devices. For a polymer processing system, the maximum power required to maintain operation should be considered closer to 3k Watts, if batteries are used, we can compensate some energy from them or they can charge which will create additional load, system operation should also be considered and if the system allows simultaneous charging of batteries and operation of polymer processing, the power should be added, and the possibility of corrections for peak loads should also be considered;

3. Selection of power source Figure 3.1: The polymer waste disposal plant will be powered by four potential power sources: six solar panels, a group of batteries, a generator, an external power supply system;

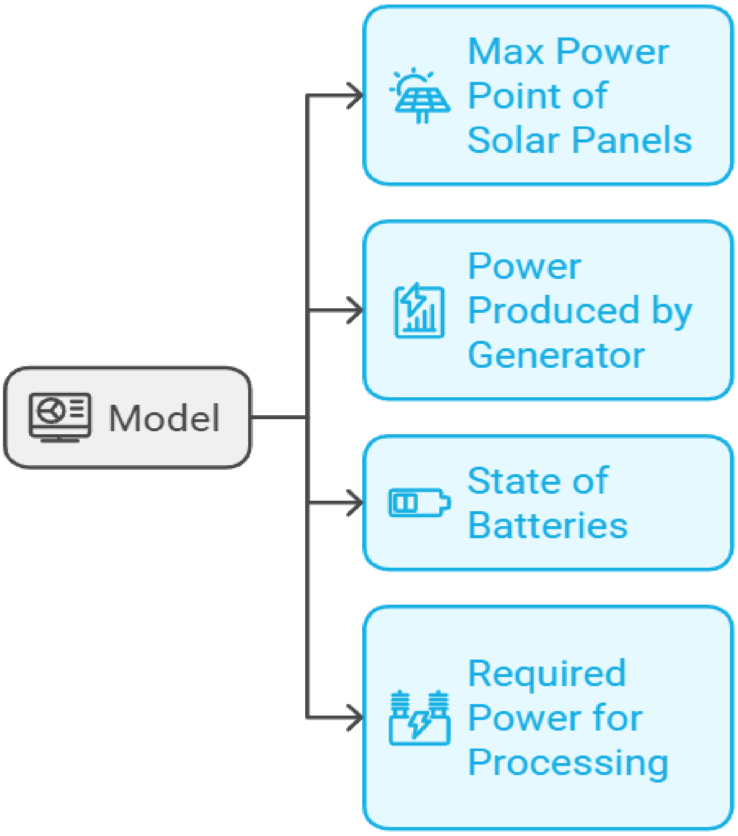


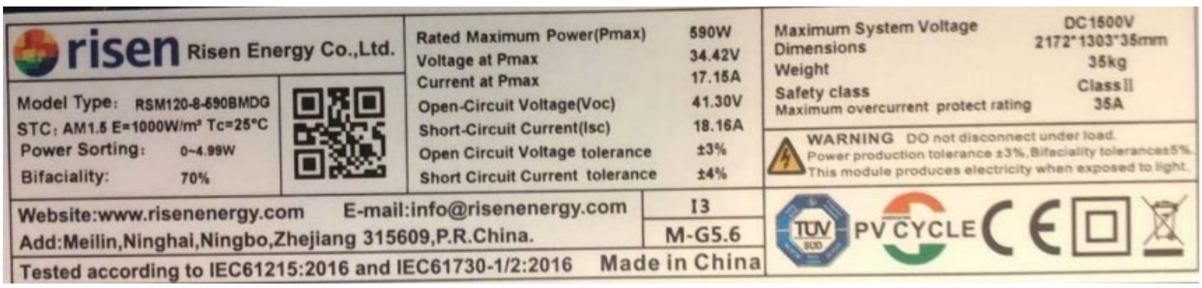
4.Redundancy: for successful and economical operation of the system, power redundancy is provided in the form of different, independent power sources.

Next stages of developing an algorithm for calculating the power supply system for a waste-to-derivative system can be postponed until the beginning of the next stages of project implementation, while at this stage they should not be taken into account, since for modeling, such parameters as wire material, length, grounding schemes and documentation do not play a significant role in the calculations.

The input data for calculating the power of solar panels are:
- solar panel parameters specified by the manufacturer;
- battery parameters specified by the manufacturer;
- generator parameters specified by the manufacturer;
- lighting and temperature indicators;
- charge controller readings.

The model should calculate the following parameters Figure 3.2:





For the calculation, we will use the standard Matlab Simulink PV array element, which uses the standard solar panel data shown on Figure 3.3 [14] to simulate the output parameters. The PV Array block implements an array of photovoltaic (PV) modules. The array is constructed from chains of modules39 connected in parallel, each chain consisting of modules connected in series. This block allows you to model pre-installed PV modules from the National Renewable Energy Laboratory System Advisor model, as well as PV modules that are specified independently. The volt-ampere characteristics of the diode for one module are determined by expressions (3.1) and (3.2). Where:

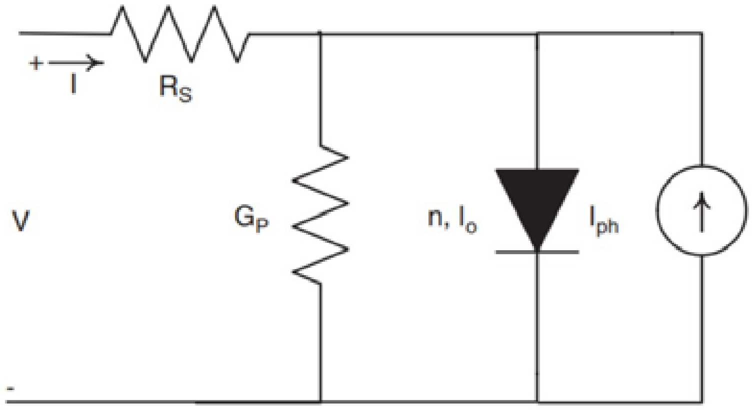
I_d - *diode current*
V_T - diode voltage
I_0- diode saturation current
nI - diode ideality coefficient
k - Boltzmann's constant
q - electronic charge
T - cell temperature
$Ncell$ - number of consecutive cells in the module

$$I_d = I_0 \left[exp \left(\frac{V_d}{V_T} \right) - 1 \right] \tag{3.1}$$

$$V_T = \frac{kT}{q} * nl * \ Ncell \tag{3.2}$$

A standard solar cell is considered to be of this type, the volt-ampere characteristics of which can be described by an equivalent circuit consisting of a single ideal exponential transition, a source of constant photogenerated current, a series parasitic resistance, and a parallel parasitic conductivity. Figure 3.4 shows the equivalent circuit of such a model. The mathematical description of this circuit is given by the following equation:

$$I = I_0 \left[exp \left(\frac{V - IR_S}{mV_t} \right) - 1 \right] + (V - IR_S)\, G_P - I_{ph} \tag{3.3}$$

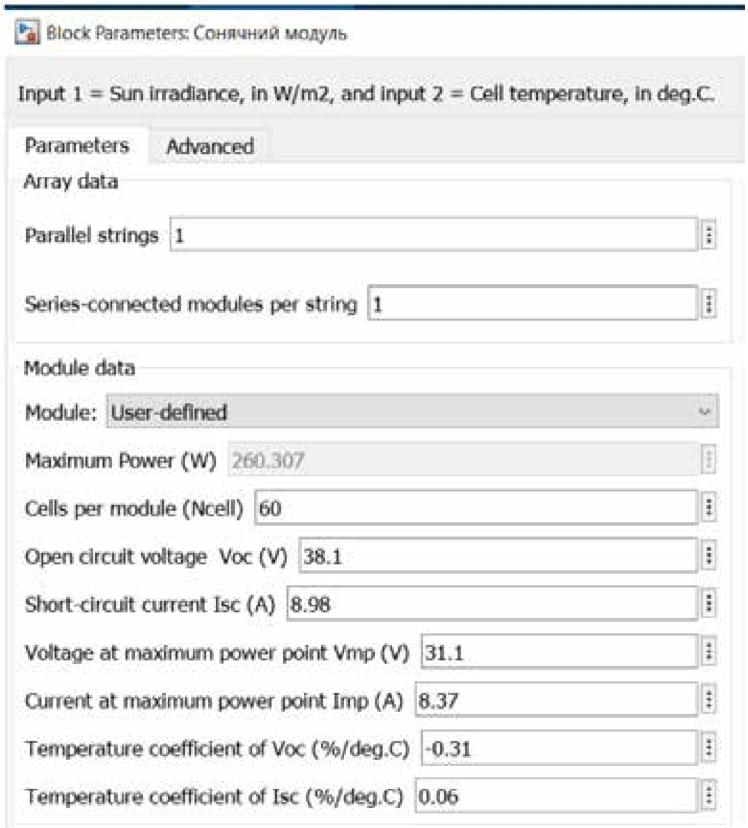


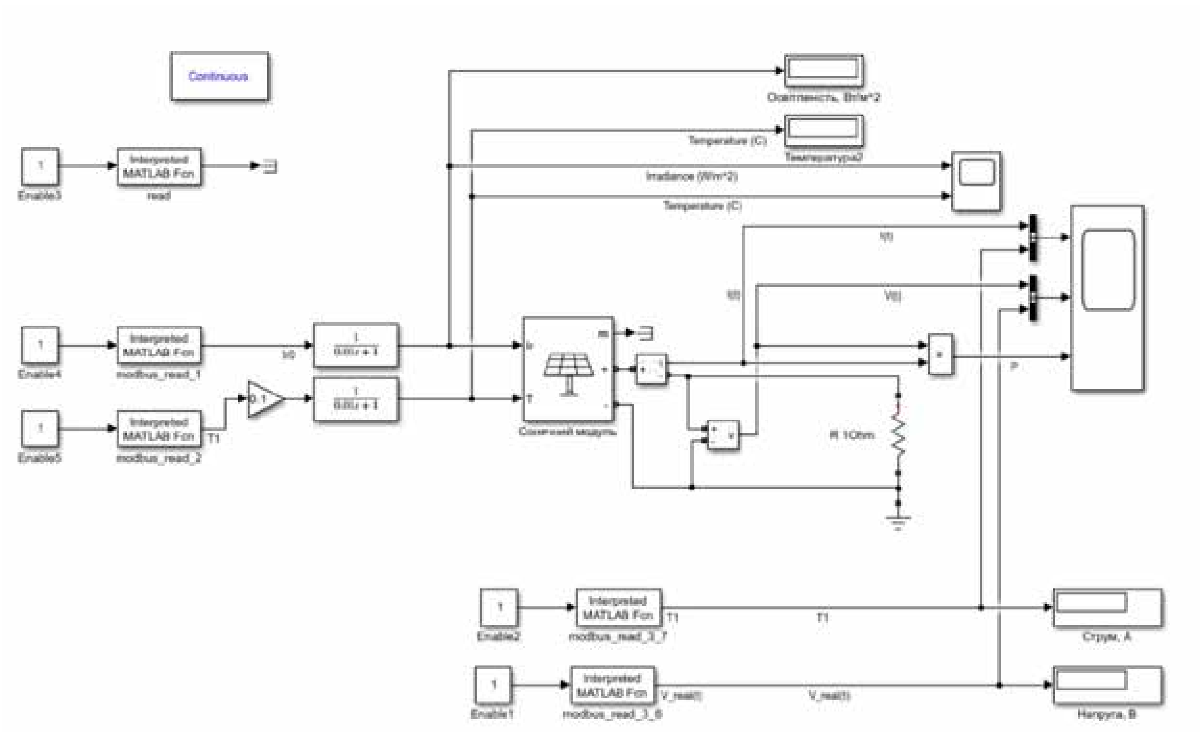
It is well known that the above implicit transcendental equation cannot be solved explicitly in the general case of I or V using ordinary elementary functions. Therefore, it was decided to use explicit approximate solutions for modeling purposes. Several such approximate solutions have been proposed that use only elementary functions. [17]

The generator output will not be calculated, and its output power will be set to the output power according to the generator documentation for modeling under certain system operating conditions. The battery system will be fully controlled by a charge controller inverter, which will be able to cover part of the required power from the external grid if necessary.

3.2 Development of a model of the power supply system in the Simulink environment

Solar panel model was implemented in MATLAB Simulink, a specialized environment for simulation modeling. [18] The parameters of the panel in the PV Array block are set manually in Figure 3.5. Scheme for modeling the volt-ampere and volt-watt characteristics of a solar panel using sensors is shown in Figure 3.4.





Model built for real-time acquisition of the solar panel's volt-ampere characteristic to the given temperature and illumination parameters is shown in Figure 3.6. [The model receives the light and temperature data directly from the sensors, modbus_read_1 and modbus_read_2, both of which have a reading speed of 9600, marked as id1 and id2, respectively. The external resistance is set to 1 ohm, it is advisable to measure the external resistance directly, or having the model's readings, make sure that the model's power and the real panel match, if the power indicators match, then enter the resistance corrections. The rest of the data is received by the model from the hybrid inverter POW-HVM3.2H-24V, the inverter has rs-485 connector that transmits data via MODBUS, namely, real load and voltage readings, for comparison with the model. [20]

$$I = I_{ph} - I_S \left[exp\ exp\ \left(\frac{V-IR_S}{mV_t}\right) - 1\right] + \frac{V-IR_S}{R_{Sh}} \quad (3.4)$$

Structure of the PV Array subsystem, built on the basis of the analytical expression (3.4) for the array volt-ampere characteristic and having the following form, is shown in Figure 3.7. It also includes subsystems for current modeling.

Controlled current source determines the output current for the electrical outputs. The vector m that defines the output consists of the current and voltage values coming from the solar panel. These current values (I_d) and the current values of temperature (T) and insolation (G) are also taken into account in the output vector. [21]

Figure 3.8 shows the internal structure of the subsystem that models the current. The input data for it are the temperature and intensity of solar radiation G, which in certain versions of Matlab Simulink can be denoted as k and have a different structure.

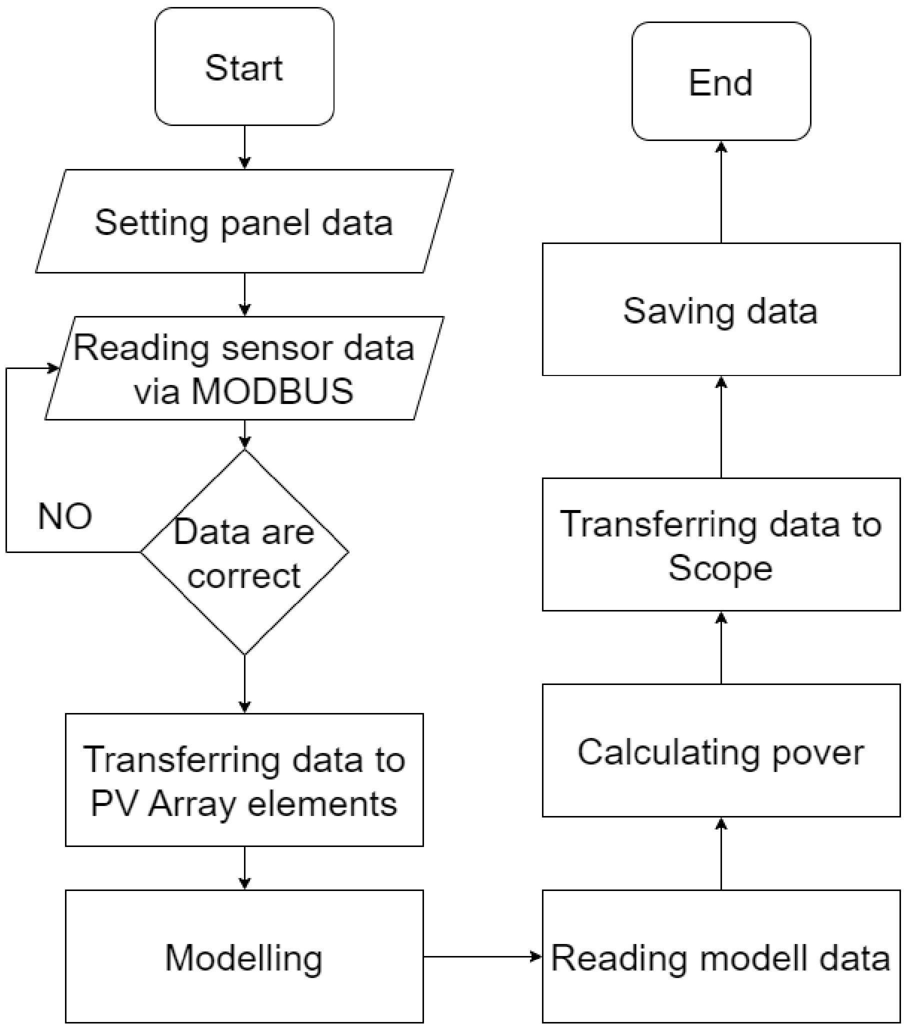
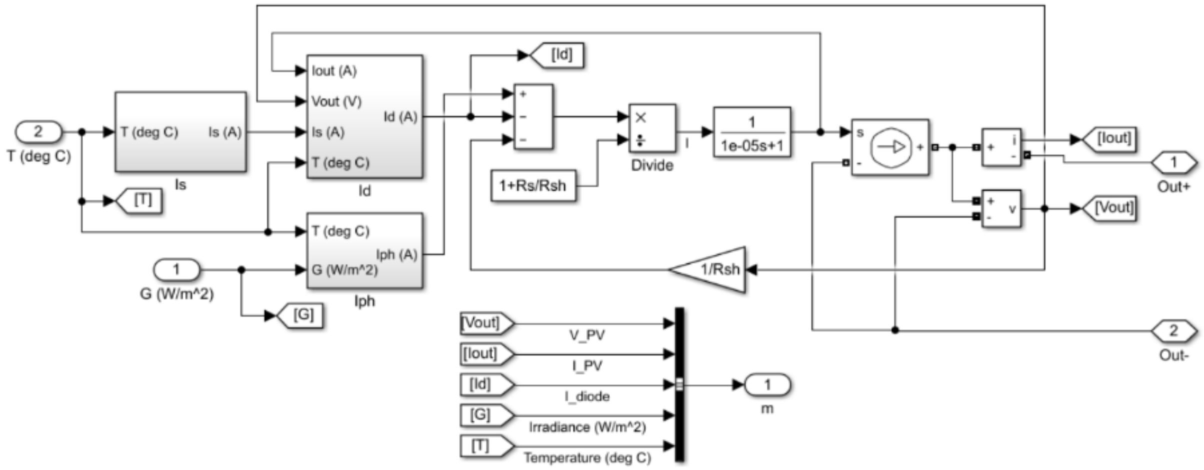


Figure 3.7 - Flowchart of the work algorithm



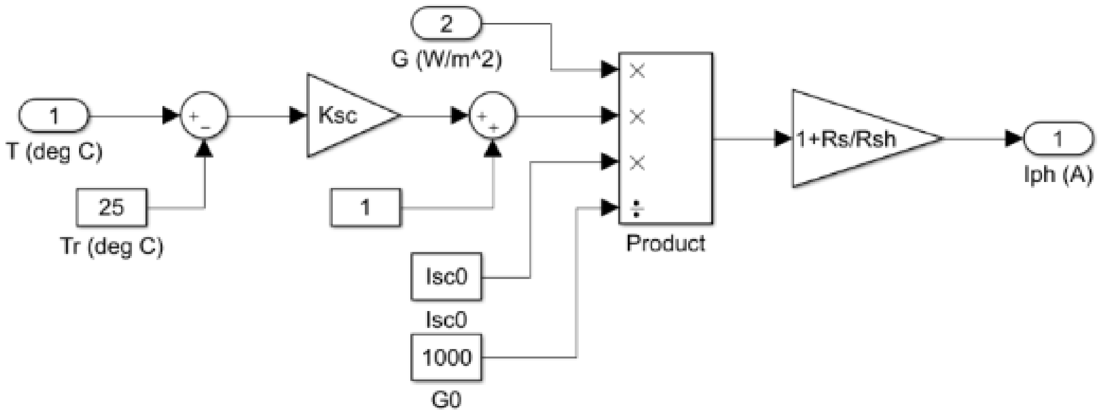


Figure 3.9 - Structure of the Iph subsystem

Figure 3.9 shows the structure of the subsystem that models current saturation. This structure takes into account the temperature dependence of the current using temperature coefficients. The input data for this subsystem is the surface temperature of the solar panel. [22]

Figure 3.10 shows a subsystem that models the diode current. The subsystem receives as input, in addition to temperature and current, the current and voltage values at the output of the solar panel.

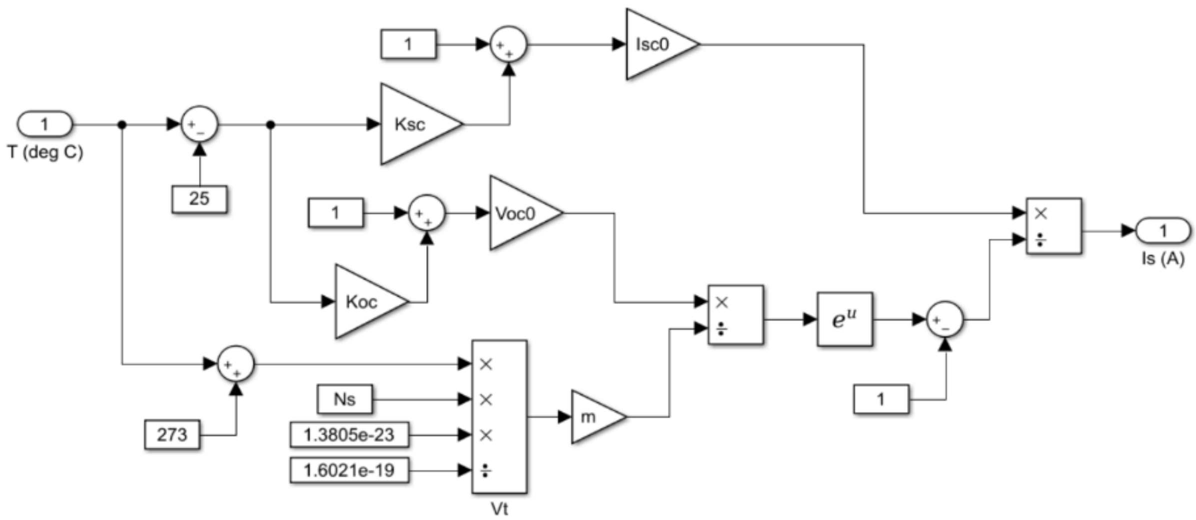


Figure 3.10 - Structure of the Is subsystem

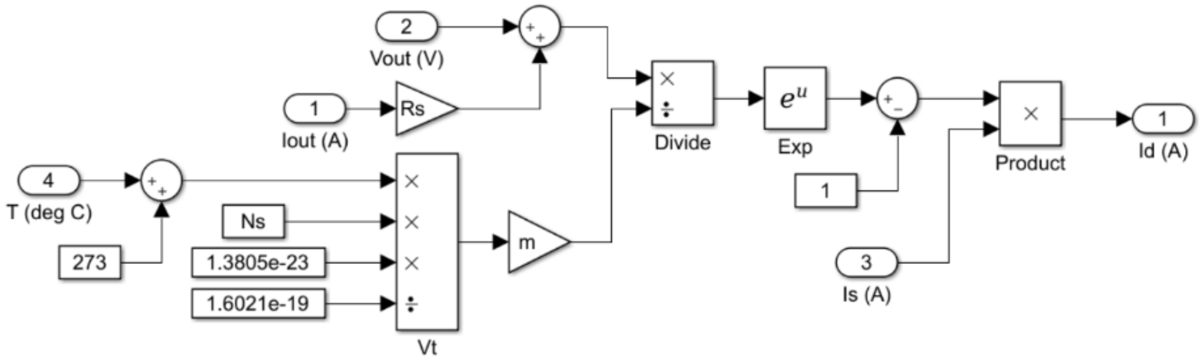


Figure 3.11 - Structure of the Id subsystem

To verify the correctness of the model, we compared the data obtained from the simulation with the experimental data obtained using RSM120-8-590BMDG solar panels. The data were obtained on a sunny day using a light and temperature sensor, a number of changes in the angle of the solar panel were made to change the light index, which resulted in different indicators, which in turn affected the temperature of the panel. In this study, five datasets were obtained for voltage and current. The graphs comparing the simulation results with the experimental data are shown in the figures below, so Figure 3.12 and Figure 3.13 show the comparison at 550 illumination and 35 temperature and 850 illumination and 40 temperatures, respectively, and Figure 3.13 shows the graph for all of the data sets. Orange colored line is for theoretical while the blue one is for real measures

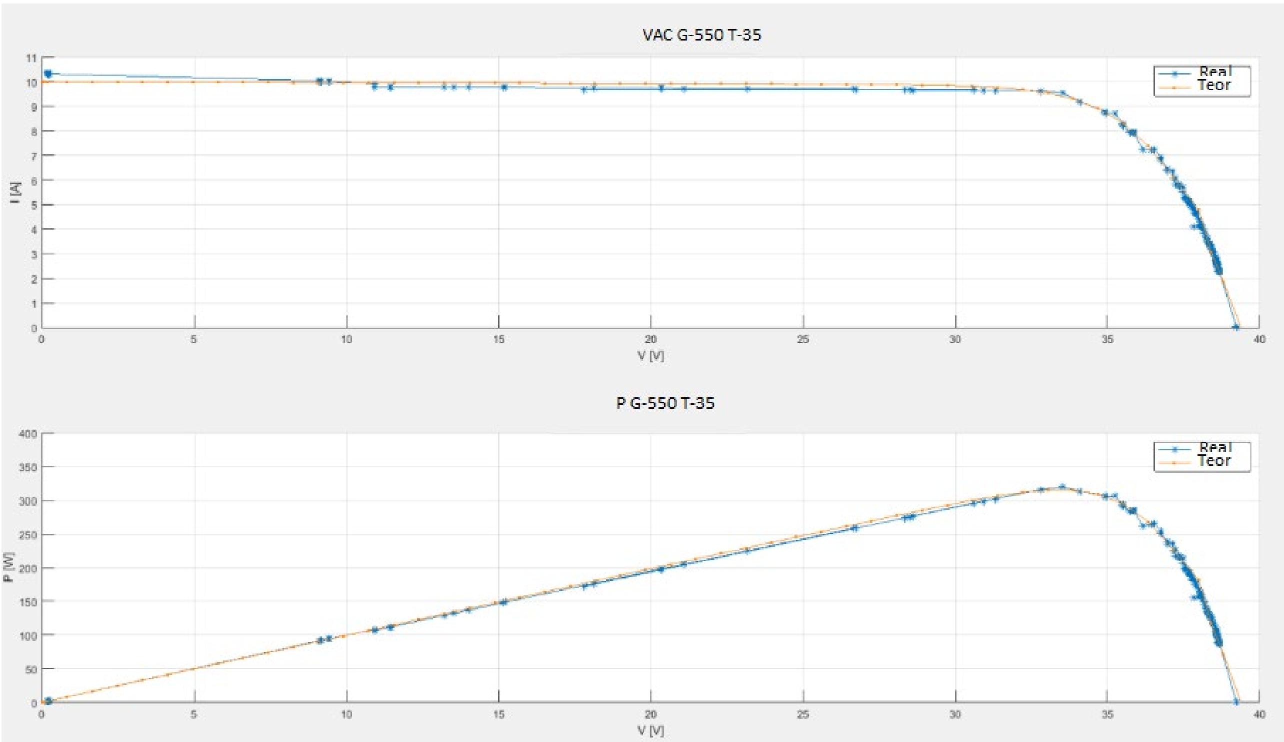


Figure 3.12 - Comparison of solar panel modeling results with real experimental data at G-550 T-35

Developed simulation model allows us to create volt-ampere characteristics of solar panels depending on the level of solar radiation intensity and temperature. Using this model, it is possible to approximate a real photovoltaic module with a certain degree of accuracy within the limits of permissible errors. The model allows us to investigate how the characteristics of solar panels change under different light and temperature conditions, which helps in solving issues related to their efficiency and performance in different scenarios.

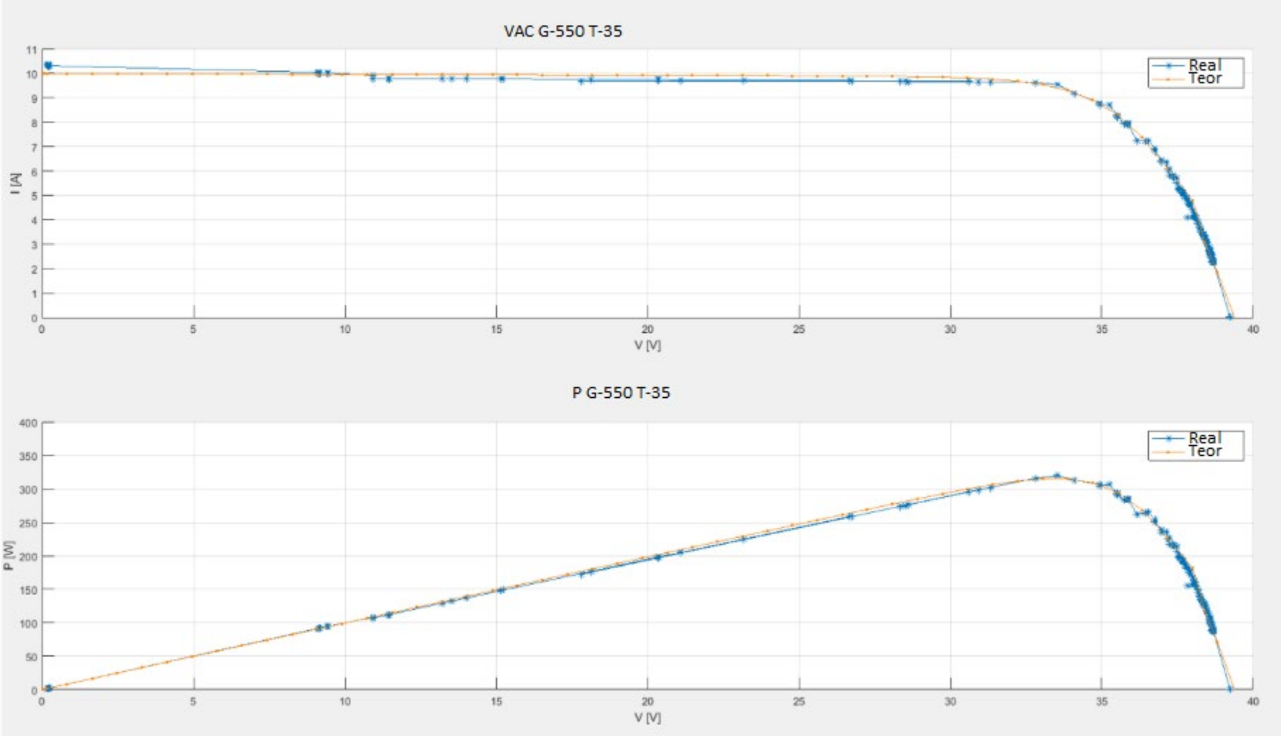
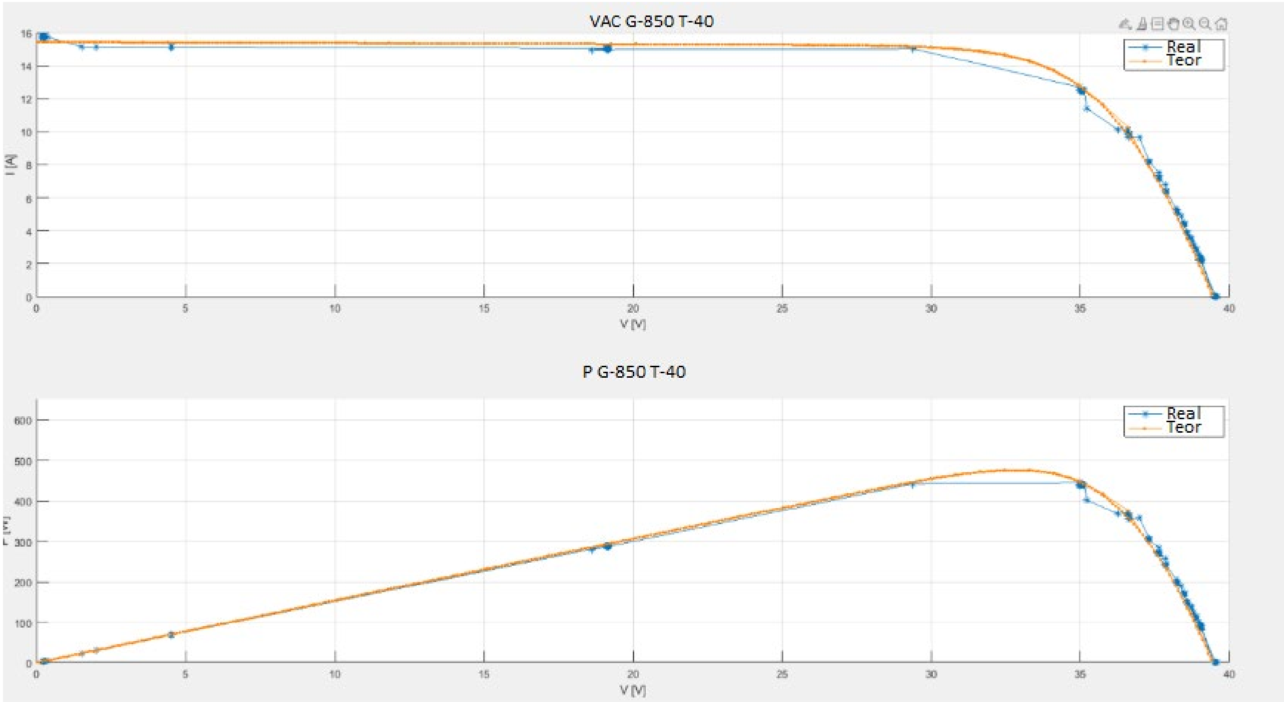


Figure 3.13 - Comparison of solar panel modeling results with real experimental data at G-550 T-35

Developed simulation model allows us to create volt-ampere characteristics of solar panels depending on the level of solar radiation intensity and temperature. Using this model, it is possible to approximate a real photovoltaic module with a certain degree of accuracy within the limits of permissible errors. The model allows us to investigate how the characteristics of solar panels change under different light and temperature conditions, which helps in solving issues related to their efficiency and performance in different scenarios.



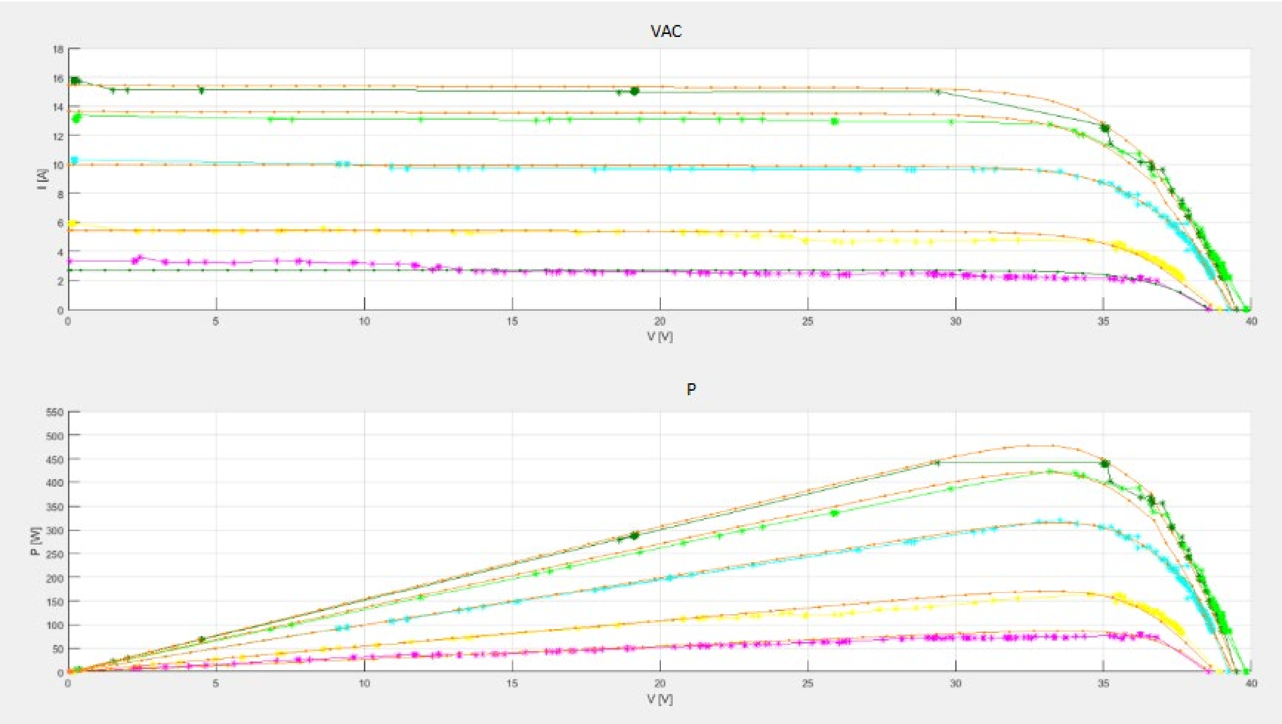


Figure 3.15 - Comparison of solar panel modeling results with real experimental data

Developed solar panel models can be effectively used to solve various problems in the field of photovoltaic systems. Among them are:

- optimization of the solar panel connection scheme: the use of the model allows to analyze and select the optimal way to connect the panels to maximize system efficiency;
- power analysis in the presence of a weather forecast: the model allows to analyze the operation of mobile solar power plants, taking into account the predicted temperature and lighting, which in turn will allow to predict the available green energy for use anywhere in the world;
- modeling the process of tracking the trajectory of the maximum power the model can be used to efficiently calculate and design solar power systems for various applications;
- Analysis and forecasting of solar power plants: the model allows for the analysis of solar power plants, taking into account various parameters and operating conditions, which contributes to the effective forecasting of their operation.

3.3 Modeling the process of tracking the maximum power point

Simulation of the process of tracking the maximum power point in Simulink can be performed using various blocks and tools provided by this software. For most cases, the PV Array block is enough for the user, which, after processing, provides data such as current, voltage, power and input parameters, but the problem with this block is the lack of the ability to adjust external resistances, which we have corrected in our model. [23]

In Matlab Simulink, which was used in our work, the maximum power point tracking (MPPT) is performed using the PV Array block. This block allows to model the photovoltaic effect and provides the possibility to choose different MPPT algorithms, such as P&O (Perturb and Observe), Incremental Conductance, or Constant Voltage. [24]

This algorithm makes small changes to the output voltage of the solar panel and monitors how these changes affect the power output. If the power is increasing, the algorithm continues to make changes of the same nature, increasing or decreasing the voltage until it reaches what is considered the maximum power point. [25] If the power is decreasing, the algorithm will start making opposite voltage changes to find the maximum power point. The step and start parameters can be set manually.

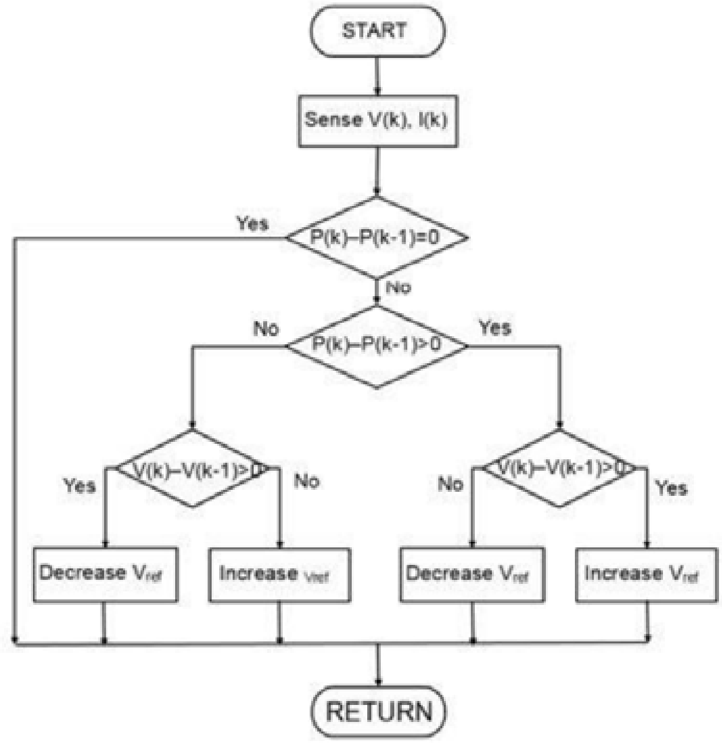


Figure 3.16 - Block diagram of the basic Disrupt and Observe algorithm

Incremental Conductance. The algorithm determines the point of maximum power by observing the ratio of current change to voltage change. The algorithm changes the voltage so that the ratio of voltage to current equals I/V. That is, when δ (P)/ δ V =δ (IV)/ δ V =I+V*(δ I/δ V) =0;

The incremental conductivity algorithm works as follows:

- It starts by setting the initial value of the voltage and current of the solar panel.
- Current I and voltage V on the solar panel are measured;
- Differential coefficient δI/δV or, equivalently, I/V is calculated;
- Resulting differential coefficient is compared to zero;
- Voltage is adjusted so that the differential coefficient is equal to zero or as close to zero as possible;

The process is repeated until the differential coefficient is not close to zero. This process allows the MPPT system to efficiently determine the MPP point, maximizing the power output of the solar panel under different operating conditions, such as changes in light and temperature.

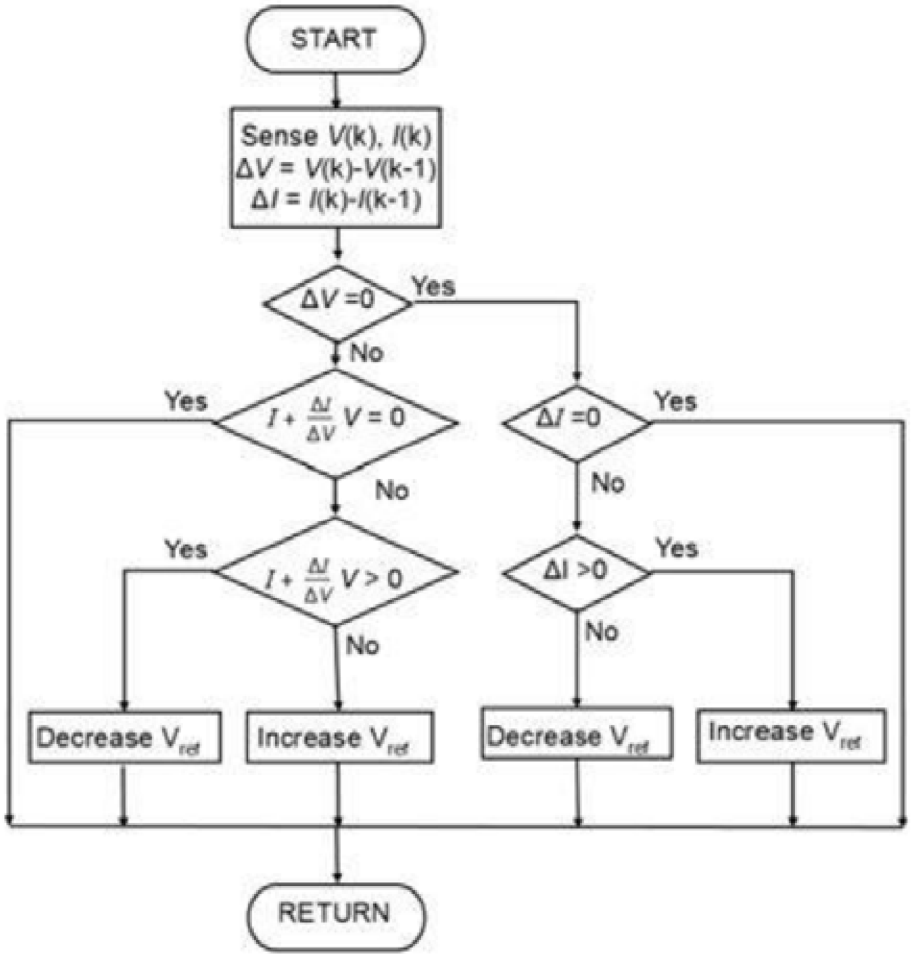


Figure 3.17 - Block diagram of the incremental conductivity algorithm.

Constant Voltage. This algorithm uses a fixed voltage value to provide the highest power. It measures the current and increases or decreases the voltage until the current reaches the maximum value, then adjusts the voltage to maximize the power.[26] There is no specific formula because the voltage remains constant. Rarely used, the Constant Voltage algorithm is one of the Maximum Power Point Tracking methods in solar power systems. The main advantage of this method is its simplicity and high efficiency under certain conditions. Easy to implement: The Constant Voltage algorithm is characterized by its ease of implementation. This is especially important for industrial applications and systems where reliability and ease of maintenance are important. Stable operation: The Constant Voltage method ensures stable operation of the system in conditions of changes in light and temperature. It keeps the voltage across the solar panel at a stable level, which can be important for some types of loads. High efficiency in certain conditions: Constant Voltage can be effective in cases where the light is relatively stable and there are no sudden fluctuations.[27] In such conditions, it can provide a stable power output. No frequency fluctuations: Since the Constant Voltage method works on the principle of holding a constant voltage, it can avoid frequency fluctuations, which can be important in some applications where voltage stability is important. Ability to work with different types of batteries: The Constant Voltage method can be easily integrated with different types of batteries because its main function - holding a stable voltage - is independent of the specific type of battery. This is the algorithm we will use in our model.

Here is a step-by-step guide on how to use the PV Array unit to track the maximum power point:

1. Adding the PV Array block: Open Simulink and open your model. - Find the PV Array block in the library. Select “Library Browser” and then locate the PV Array under “Simscape” or “Simscape > Foundation Library > Electrical > Specialized Power Systems > Machines” -Drag the PV Array onto your model.

2. Configure the PV Array: Double-click on the PV Array to open its options. - Under “MPPT Algorithm”, select the MPPT algorithm you want to use (P&O, Incremental Conductance, etc.). Configure the MPPT algorithm parameters as needed, such as steps, thresholds, etc.

3. Simulation: - Run a simulation of your model.

4. Analyze the results: - Use measurement blocks (e.g., Scope) to visualize the input signal (solar panel voltage and current) and the output signal (power).

These steps are general and may vary depending on the specific version of Simulink and your model. For example, consider the RSM120-8-590BMDG PV module. Table 3.1 shows the parameters for this solar panel. Our solar panel is characterized by a maximum power value of 590 W at an illumination of 1000 W/m2, but the power can be higher due to the back side of the panel that works as an additional solar panel, in the simulation we will take into account that the panel receives insufficient illumination on the back side.

Table 3.1 - Parameters of the CL-P72300 photo module

I_{SC}	V_{OC}	I_{mp}	V_{mp}	P_{mp}	K_I	K_V	N_S	R_S	R_{sh}
18,16	41,3	17,15	34,42	590	0,004	-0,25	120	0,022	2

Figure 3.18 shows a Simulink model to simulate the operation of the RSM120-8-590BMDG when the intensity of solar radiation changes. This scheme provides for the measurement of current, voltage and power values directly at the output of the SP and at the external load. [29] The parameters of the PV Array module are filled in according to the values in Table 3.1. The maximum power point tracker (MPPT), represented by the “MPPT” element, receives the output current and voltage parameters of the solar panel. After that, it returns the optimal value of the fill factor. This value is used to generate the PWM signal g using the PWM-Generator block. The resulting PWM signal g, in turn, serves as a control signal for the switching voltage converter. The latter is responsible for correcting the output voltage of the solar panel. This is done by setting the output voltage to a level that corresponds to the voltage at the maximum power point. Thanks to this correction mechanism, the system provides effective MPP tracking, optimizing the output parameters of the solar panel for maximum power. [Figure 3.19 shows the graph of solar irradiation intensity change during the simulation and the effect of the change on the power. Figure 3.20 shows the graphs of current, voltage and power obtained from the simulation. As can be seen from Figure 3.18, the power at the start of the model exceeds the maximum power of 590, but after a short time the model finds the acceptable points and shows the real result. You can also see the process of calculating the model's power when the lighting indicator changes.

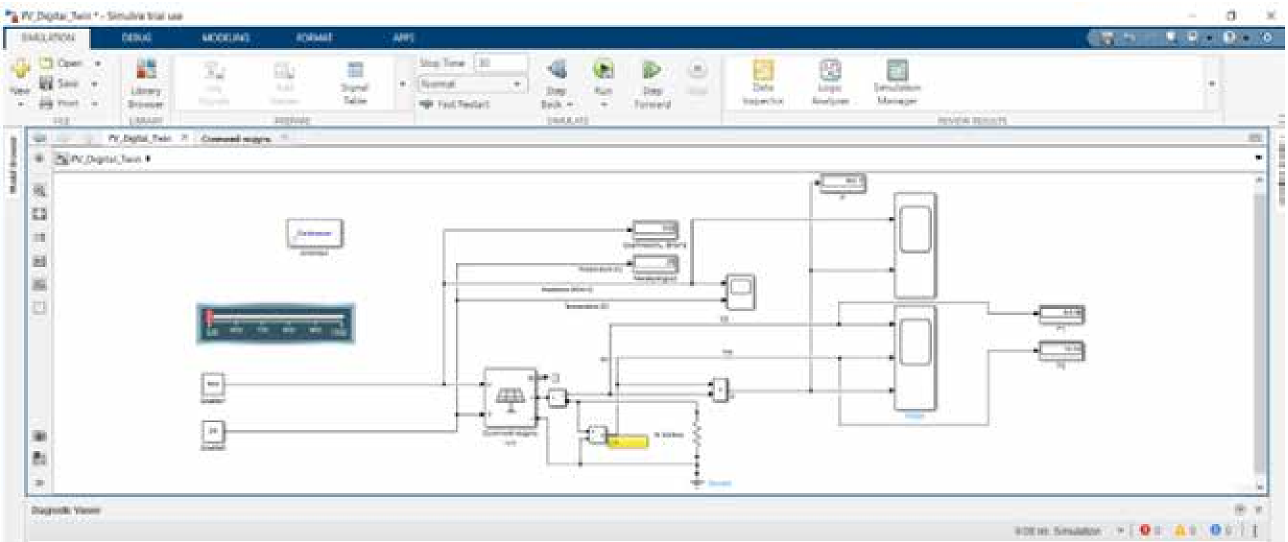


Figure 3.18 - Scheme for modeling the process of tracking the TMP when changing of solar radiation intensity

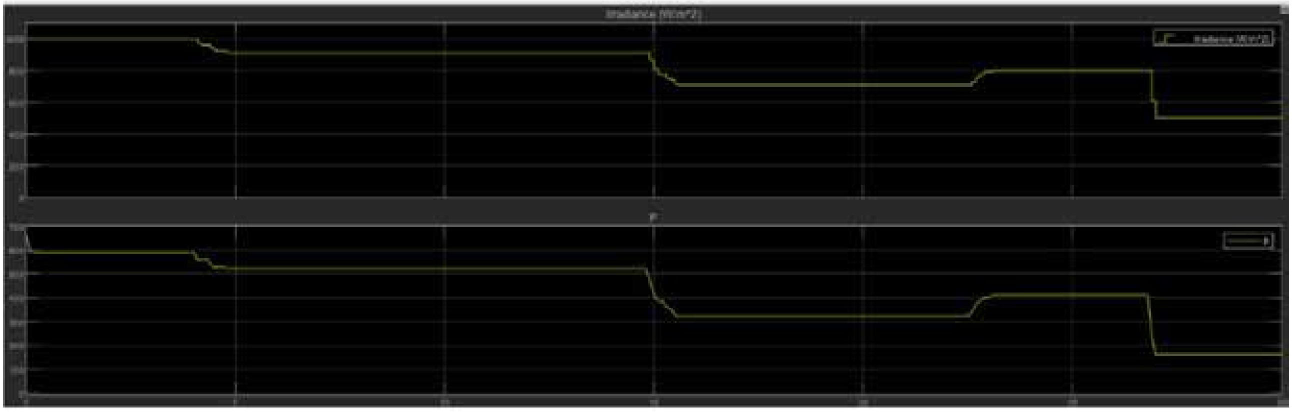


Figure 3.19 - Graph of changes in solar radiation intensity and power

Figure 4.21 shows the final version for modeling a solar panel using modbus, a Simulink model, to simulate the operation of the RSM120-8-590BMDG, when the intensity of solar radiation changes. This scheme involves measuring the values of light and temperature by sensors and transmitting them to the solar panel; the subsequent processes coincide with the previous stage.

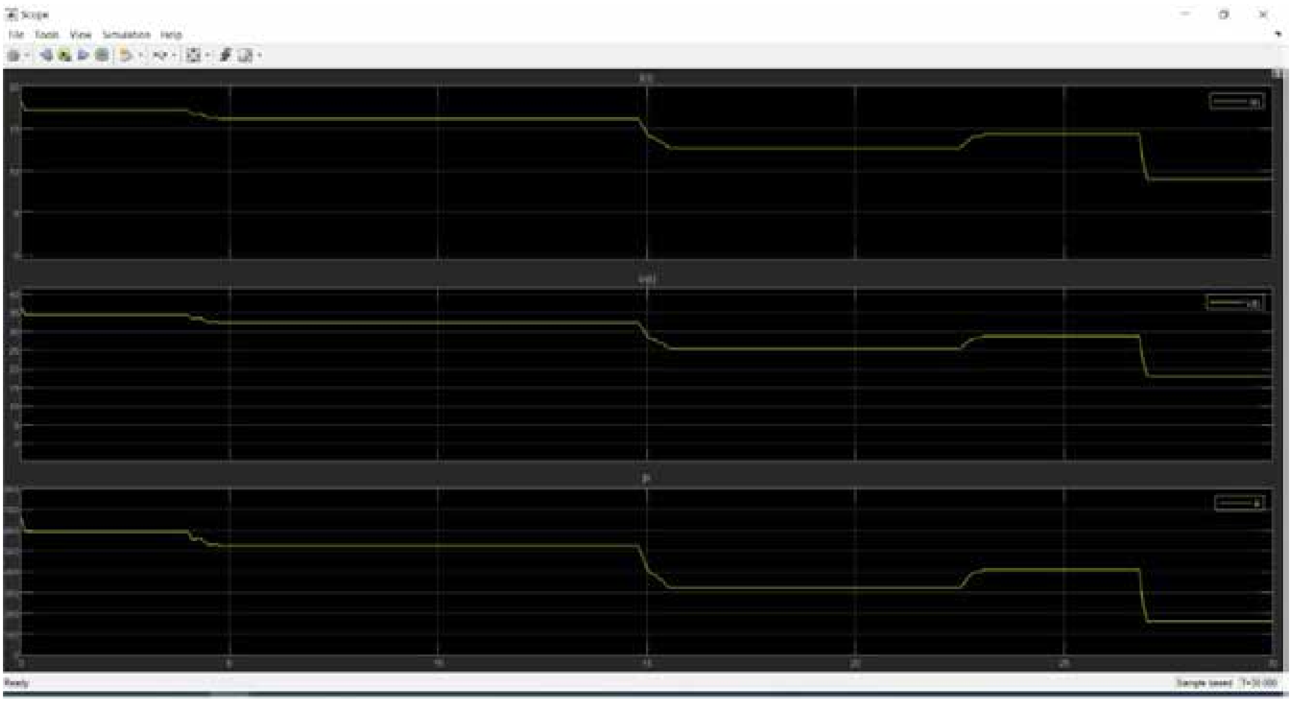


Figure 3.20 - Graphs of changes in current, voltage and power with changes in solar radiation intensity

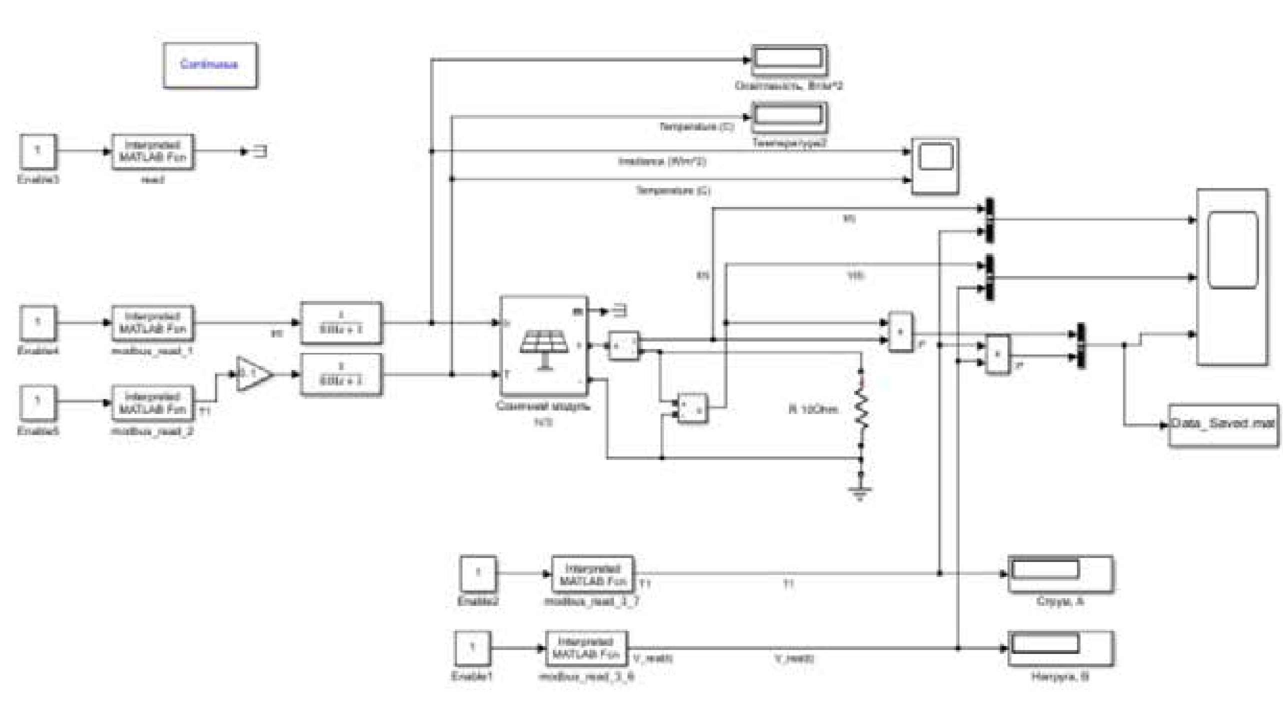


Figure 3.21 - the final Simulink model for modeling a solar panel with using sensors

4 IMPLEMENTATION OF AN AUTONOMOUS POWER SUPPLY SYSTEM FOR THE WASTE DISPOSAL UNIT AND CALCULATION OF ITS PARAMETERS

4.1 Choosing a development environment and programming language

MATLAB Simulink environment and MATLAB programming language were chosen as development tools.

MATLAB uses a proprietary programming language, also known as MATLAB. Developed by MathWorks, this tool is designed to solve problems of numerical calculations and matrix processing. It is widely used in scientific, engineering, and technical fields, including signal processing, data analysis, modeling, and control system development.

MATLAB is a high-level programming language that simplifies mathematical operations, data processing, and complex calculations. In addition, MATLAB has a significant number of built-in functions and tools that facilitate work with numerical data and solving various problems. [33]

MATLAB is used to organize, clean, and analyze complex data sets from a variety of fields, such as climatology, forecasting, medical research, and finance. MATLAB provides:

- data types and preprocessing capabilities designed for engineering and scientific data;
- interactive and highly customizable data visualizations;
- applications and tasks in the Live Editor that help you interactively clean, prepare, and generate data code;
- thousands of built-in functions for statistical analysis, machine learning, and signal processing;
- extensive and professionally written documentation;
- accelerated productivity through simple code changes and additional hardware;
- extend analysis to big data without significant code changes;
- automatically package analysis results into freely distributable software components or embedded source code without manually recording algorithms;
- sharable reports automatically generated from your analysis.

Simulink is an interactive tool for modeling, designing, and analyzing data. Integration of virtual systems can help reduce dependence on hardware prototypes and give everyone access to the system at almost any stage of the product development cycle. [34] Users can use Simulink to model, simulate, and analyze complex virtual systems consisting of physical hardware, firmware, algorithms, and the environment in which the system operates. Simulink allows you to:

- describe system architecture using intuitive architectural models;
- model systems spanning multiple domains using domain-specific tools and off-the-shelf blocks;
- develop maintainable large-scale models with reusable and runtime-ready components;
- easily and reliably integrate components from different teams and tools into a single system-level simulation;
- model and analyze to understand and validate system behavior;
- be able to run massive simulations

4.2 Description of the simulation model software components

List of blocks used for simulation modeling: Powergui - The powergui block allows you to choose one of these methods to solve the circuit: Continuous, which uses a variable time-step solver from Simulink; Discretization of the electrical system for a fixed time-step solution; Continuous or discrete solution of the phase diagram. [35] The Powergui also provides tools for steady-state analysis of simulation results and advanced parameter design.

Interpreted MATLAB Function Figure 4.1- A MATLAB Interpreted Function applies a specified MATLAB function or expression to an input. The output of the function must match the original dimensions of the block;

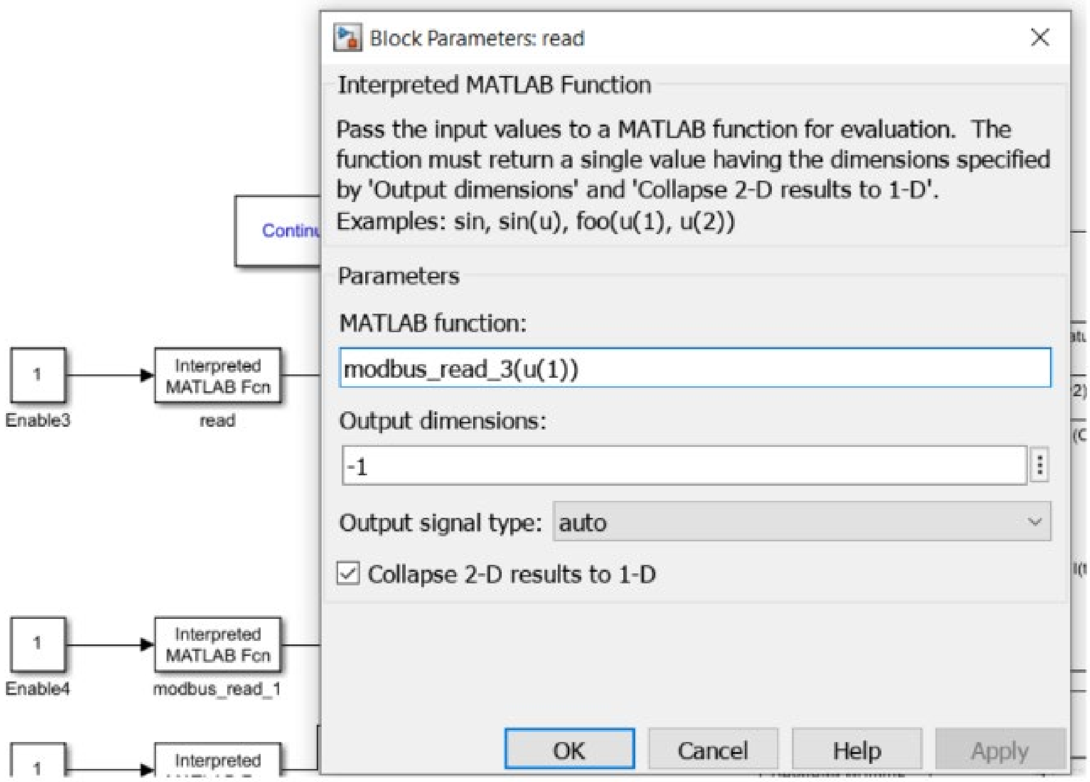


Figure 4.1 - Interpreted MATLAB Function and function implementation

To File. The To File block writes the input signal data to the MAT file. The block writes to the output file incrementally, with minimal memory usage during the simulation. If the output file already exists when the simulation starts, the block overwrites it. The file is automatically closed when the simulation is paused or when the simulation is terminated. If the simulation terminates with an error, the To File block saves the data that was recorded up to the time of the crash. The block is saved in the folder with the model file.

Scope. Displays the signals generated during the simulation. The scope element contains only input elements, from one to the number specified by the user. A separate graph is plotted for each input, and in the settings, you can limit the graphs and completely adjust them. [36, 37] Toggle Switch.

The Toggle Switch block switches the parameter value of the connected block between two values during the simulation, the block is not directly connected to the element, the user must open the element and configure the connections. For example, the user can connect a Toggle Switch block to a Switch block in the model and change its state during the simulation.

From File Figure 4.2. Loading data from a MAT file into a Simulink model. The From File block reads data into the model from a .mat file and provides the data as a signal or a virtual bus at the block's output. A model can contain several From File blocks that load data from a single .mat file.

Figure 4.2 - the From File element that reads data from the Data_Saved_PV.mat file

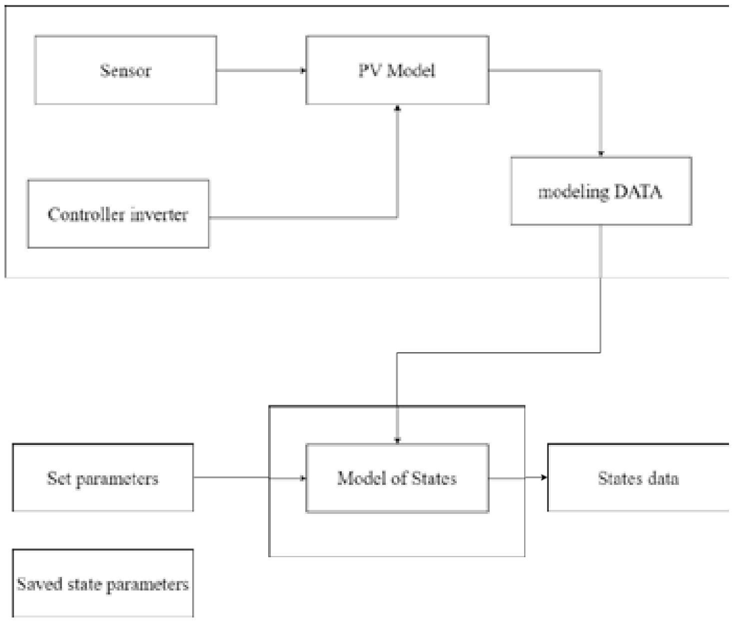


Figure 4.3 Structure of the power supply system of the polymer waste to diesel plant

4.3 Description of the user interface and instructions for use

A high-performance model of the power supply system for the polymer waste-to-diesel plant was implemented in the Matlab Simulink modeling application. Matlab was used as a programming language. Standard elements and additional coding in Simulink were used to build the user interface. The architecture of the model is described in Section 4.2. Figure 4.4 shows State.slx, which acts as the main window of the model of the power supply system of the polymer waste to diesel fuel processing plant. You can improve this window, make changes and implement it in another application, connect sensors or other ways of reading and controlling it. But for theoretical work, this is enough.

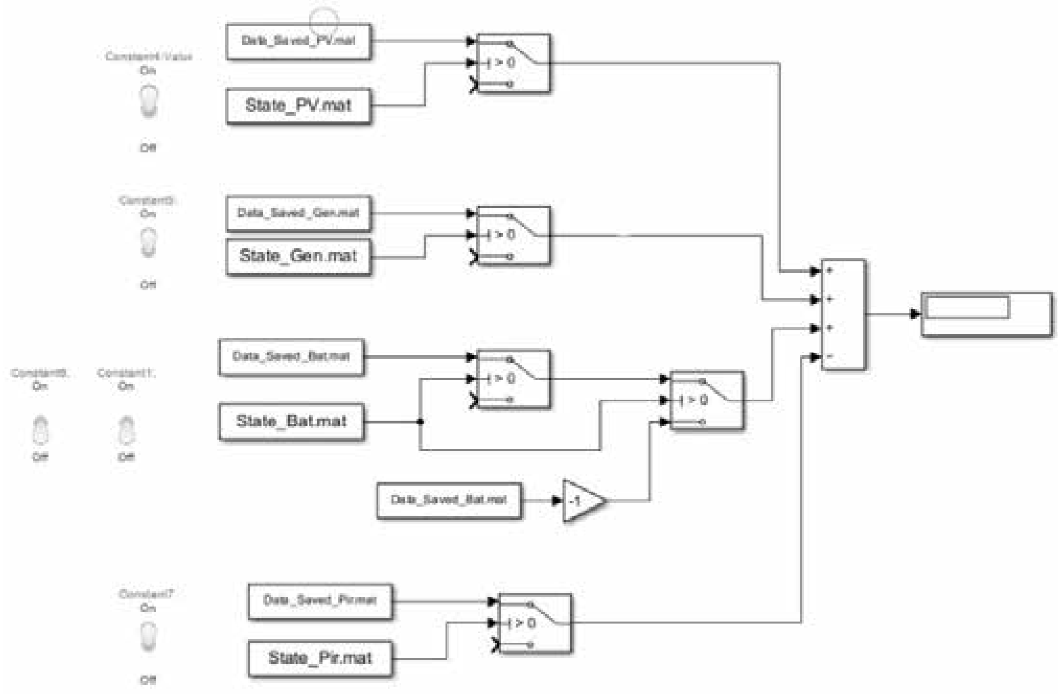


Figure 4.4 - The main window of the Stat.slr file

The main window of the application consists of the following groups of elements: - state switches, responsible for the state of the system, each of the states is loaded from a personal saved .mat file; -

saved sensor readings in .mat format, the readings are stored inside an additional model file;

- switch, a standard switch that is responsible for the passage of the indicator signal;
- add element, which receives the readings after passing the switches;

- Gain block, which converts the signal to negative.

Figure 4.5 shows one of the system operations states where the system is powered by a group of solar panels, the power received from them is 3200W, the generator and battery group are offline, the polymer waste to diesel plant is operating and consuming 3000W, which was measured and is indicated by a constant. If the user needs to change the plant consumption, when using a different plant or additional consumers, the changes can be easily recorded in the Data_Saved_Pir.mat file. [38, 39] The number shown on the rightmost display corresponds to the energy remaining after the system passes through, if the number is positive, we have an excess of energy, which in the example is 200W, if the number is negative, it indicates a lack of energy to power the system. If necessary, you can change the operating mode by enabling battery charging with the excess energy in the system or discharging the batteries to cover the shortage. The charge and discharge of the batteries is the responsibility of the charge controller inverter.

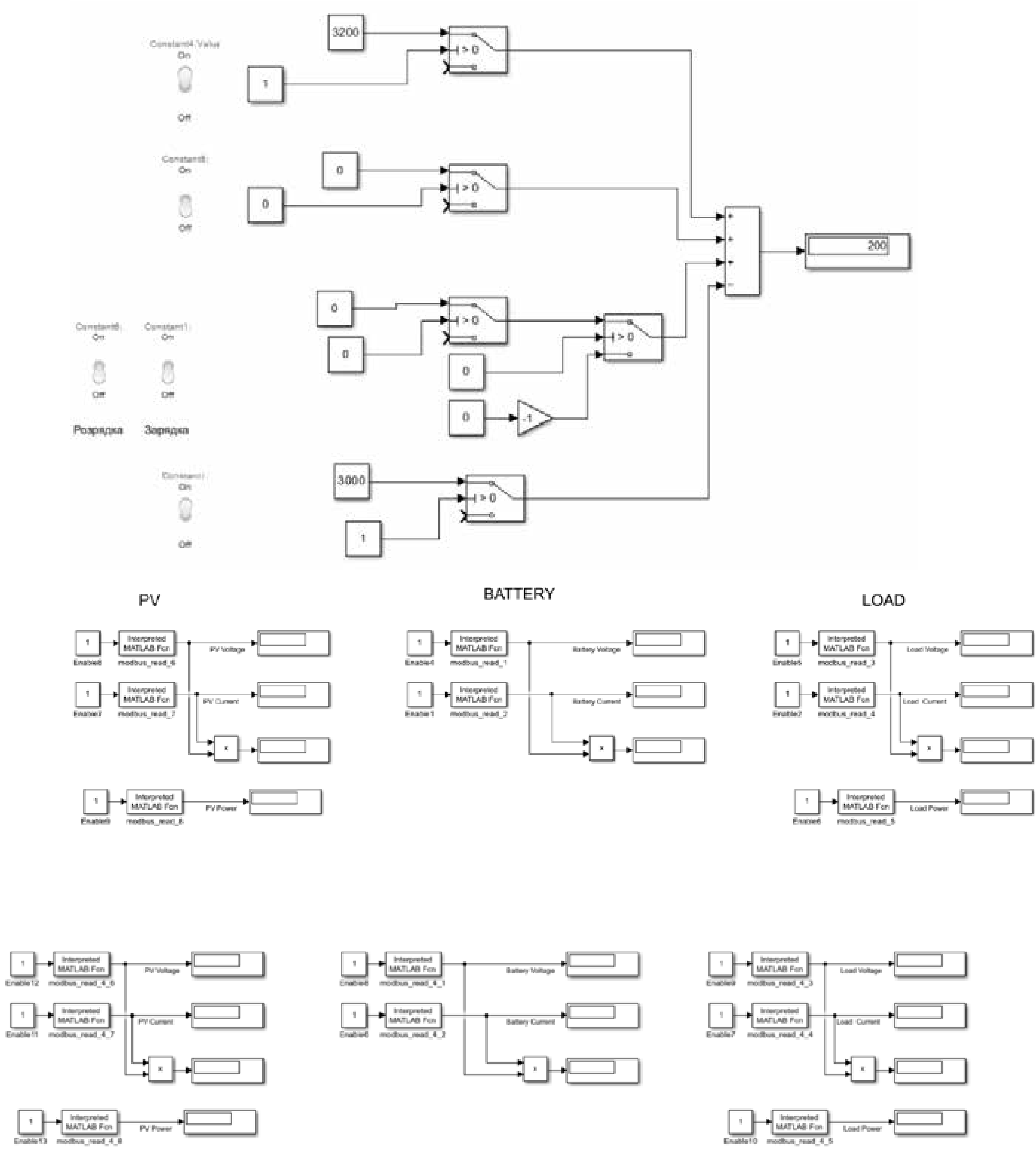


Figure 4.6 - Part of the window of the file PV_Digital_Twin.slr

As you can see from Figure 4.6, the model receives the following parameters:
- solar panel current;
- solar panel voltage;
- solar panel power;
- battery discharge current;
- battery discharge voltage;
- load current;
- load voltage;
- load power.

These are only a few basic parameters, the system can output many more parameters, but these parameters will depend on the version and type of charge controller, in our example we used pow-hvm3.2h-24v, which can transmit the parameters listed in Table 4.1.

Table 4.1 - part of the parameters that can be transmitted by pow-hvm3.2h-24v

The voltage of the solar panel	V
Solar panel current	A
Solar panel power	W
Battery current	A
Battery voltage	V
Charging power	W
Charging current	A
Charging voltage	V
Input frequency	Hz
Output frequency	Hz
load acceptable for for a particular inverter	%
Load	VA
Load	W
Battery charge	%
Inverter operating mode	number
Error signal	number
Battery type	word
Output voltage	V
Output current	A
Output power	W
Input voltage	V
Input current	A
Input power	W
Battery charge limit	%
First operation priorities	SBU priority/Solar First
Charging priorities	Cut/Cso/Snu/OSO
signal control	On/Off
Battery charge equalizer	En/Ds

This table shows some of the data that the user will have access to via Modbus, but when using different types of charge controllers, make sure that the readout speed of the device matches and check the documentation (if available) for the registers assigned to the specific information. One of the reading problems can be the replacement of the low and high byte, which will cause the data to be displayed incorrectly, but this will only be displayed when reading directly from the device.

4.4 Simulation modeling of a solar power plant

To calculate the output power of the solar panels, an additional model, PV_Digital_Twin.slr, was developed, which stores the initial parameters and overwrites them into the main model, and the final model of the solar power plant is shown in Figure 4.7.

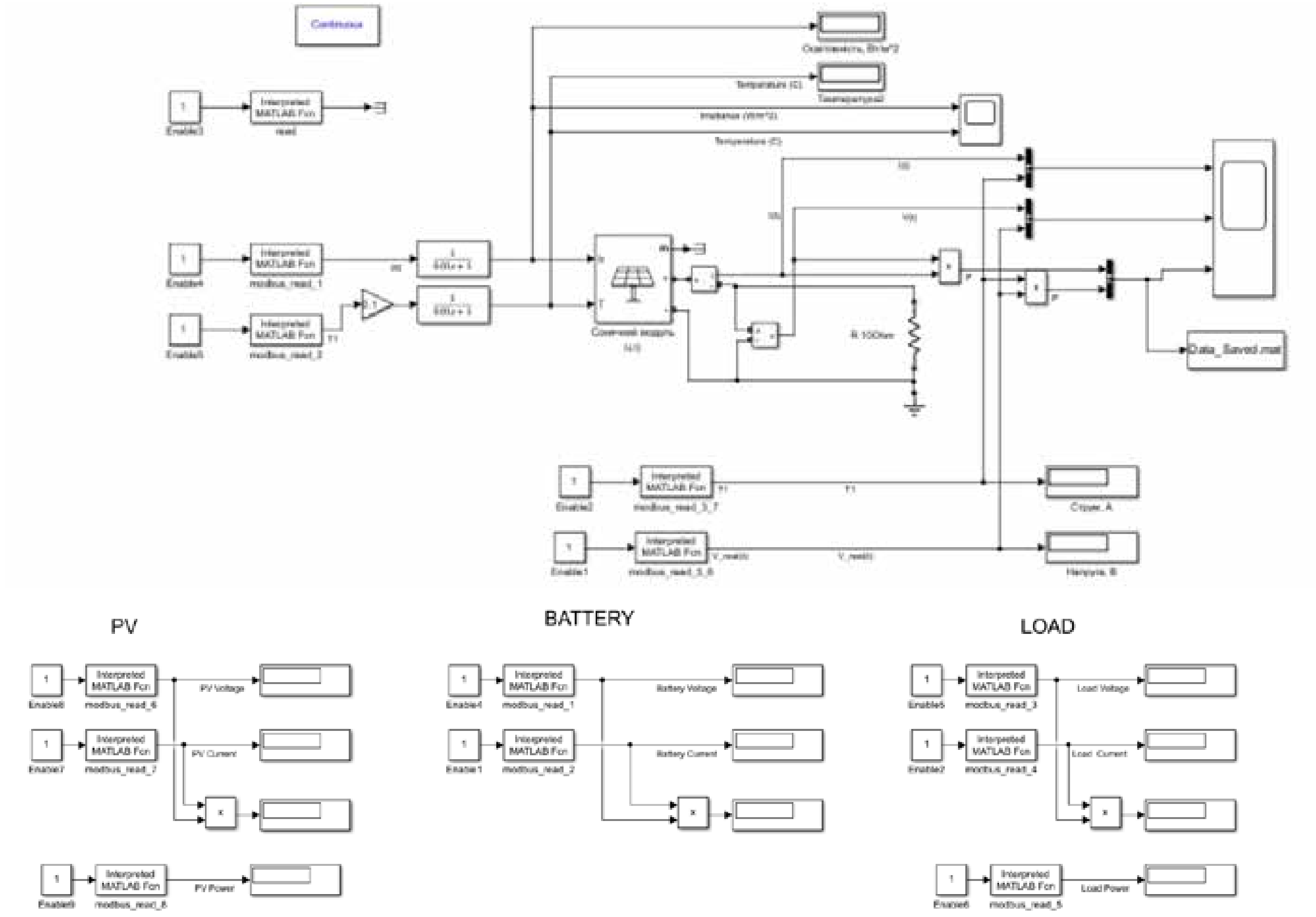


Figure 4.7 Model of solar panel PV_Digital_Twin.slr

The input data for the simulation model, PV_Digital_Twin.slr, are the parameters of the solar panel and the number of solar panels connected in series [41, 42]. As an example, let's again consider the model used in the laboratory studies, RSM-8-590 BMDB.

In Table 4.2, the parameters of this solar panel are presented, provided by the manufacturer, and correspond to standard test conditions.

Table 4.2 - RSM-8-590 BMDB parameters under standard test conditions

Parameter	Value
Maximum power	590
Cell technology	12
Voltage at maximum power	34.32
Current at maximum power	17.2
No-load voltage	41.2
Short circuit current	18.21
Maximum system voltage	1500
Maximum current	30
Number of cells	120 [6*10+6*10]
Operating temperature	°C -40 < t < +85
Efficiency not less than	% 20.8

Using the developed software tool, we will conduct a detailed modeling of the characteristics of the photovoltaic module. During this simulation, voltage and power curves will be considered at different equal values of solar radiation intensity and temperature.

Figures 4.8, 4.9 show the graphs of VAC (volt-ampere characteristic) and VWC (volt-watt characteristic) of the RSM-8-590BMDB PV module at a temperature of 25 degrees Celsius and illumination of 1000 W/m2, 600 W/m2, 300 W/m2, and 0 25 45 degrees Celsius and illumination of 1000 W/m2, respectively. These graphs allow you to determine how the module reacts to changes in solar radiation intensity.

Modeling such characteristics is important for understanding and optimizing the performance of photovoltaic systems in different operating conditions. The results obtained can be useful for selecting optimal system parameters and improving its efficiency in real-world operating conditions.

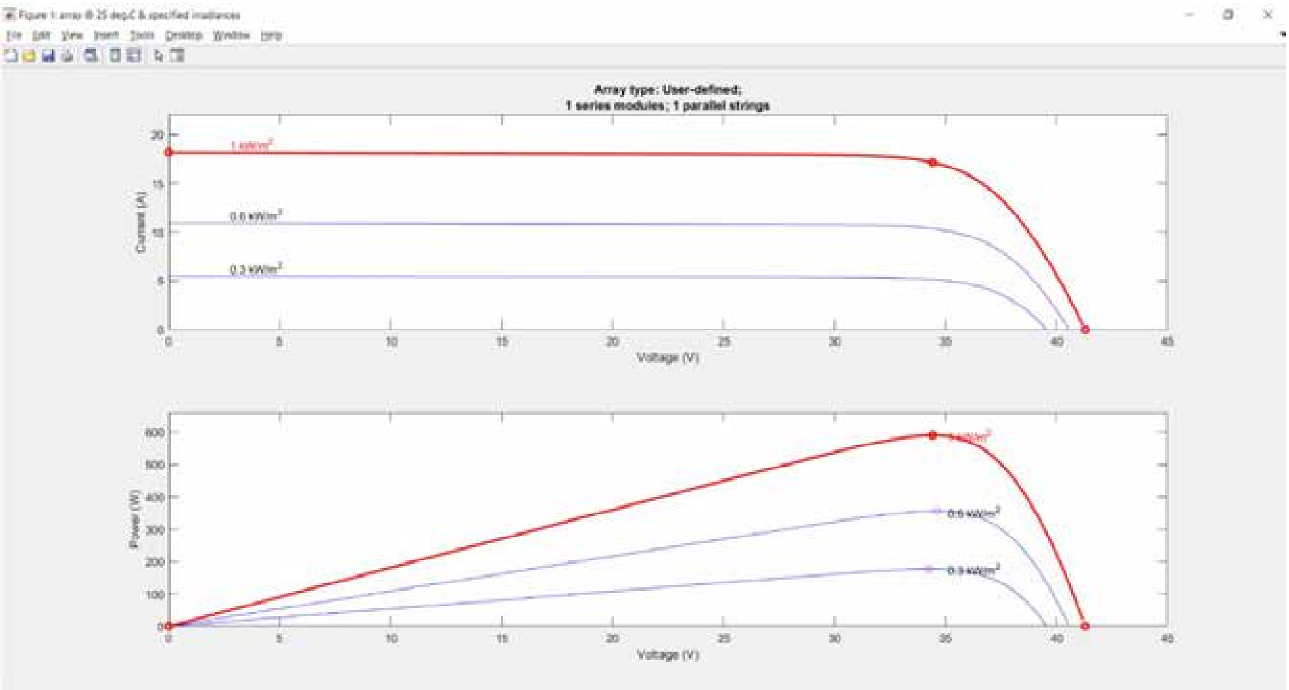


Figure 4.8 - VCF and VCF plots at 25°C and 300, 600, 1000 W/m2

From the analysis of the graphs in Figures 4.8 and 4.9, it is obvious that the maximum power output of a solar panel directly depends on the intensity of solar radiation and is inversely proportional to the surface temperature of the panel. The use of temperature coefficients for short circuit and open circuit in the model allows us to conduct detailed simulations of the volt-ampere and volt-watt characteristics of a solar panel at different values of its surface temperature.

It is clear that as the intensity of solar radiation increases, the maximum power of solar panels increases. Figure 4.9 shows the dependence of the maximum power point on the solar radiation intensity, as well as the corresponding current and voltage values on the solar radiation level, obtained using MODBUS [44]. This allows for a deeper understanding of how different operating conditions affect the efficiency and performance of a PV module.

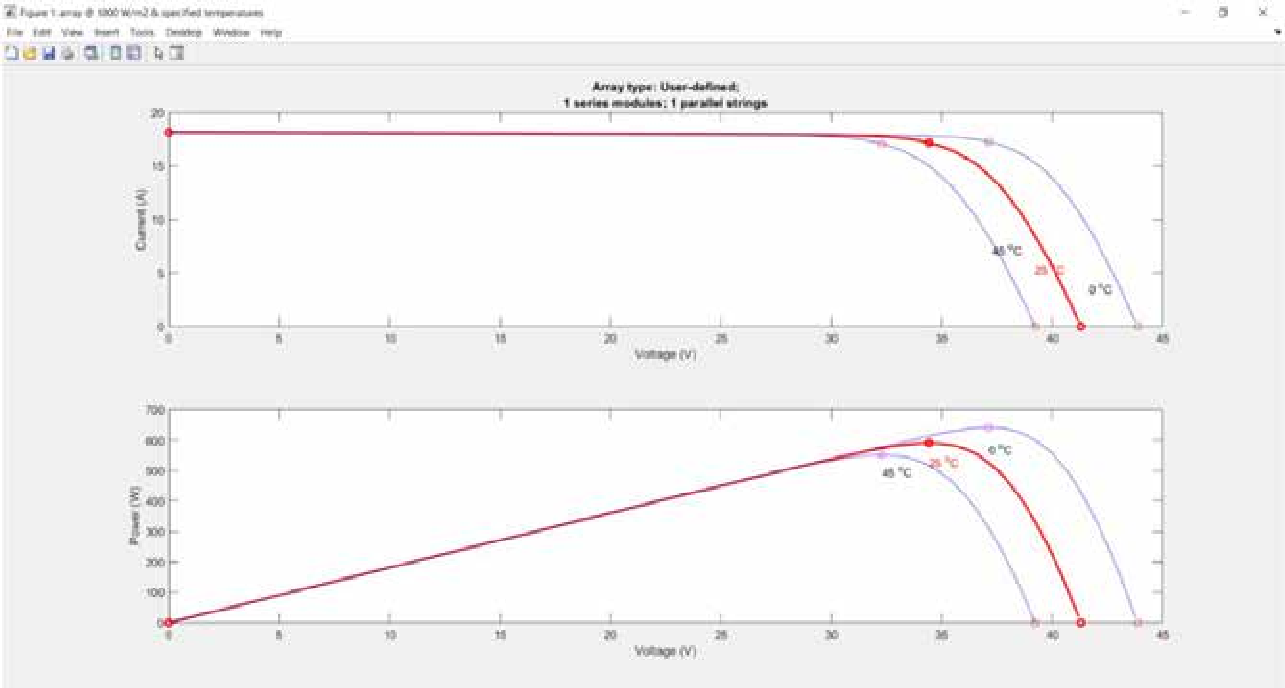


Figure 4.9 - Graphs of VAC and VVC at temperatures 0 °C 25 °C 45 °C at illumination of 1000 W/m2

Figure 4.10 shows the dependence of the maximum power of the solar panel and the corresponding current and voltage values on the temperature of the panel surface. As can be seen from the graph in Figure 4.11, the maximum power of the solar panel decreases with increasing temperature. Next, we will conduct simulations in our model and compare the values obtained during laboratory measurements of the panel, Figure 4.13. The readings were taken on a sunny day, specially designed sensors were used to measure the light and temperature, and to change the light, the solar panel was adjusted. The result of comparing all the measured and modeled data is shown in Figure 4.14.

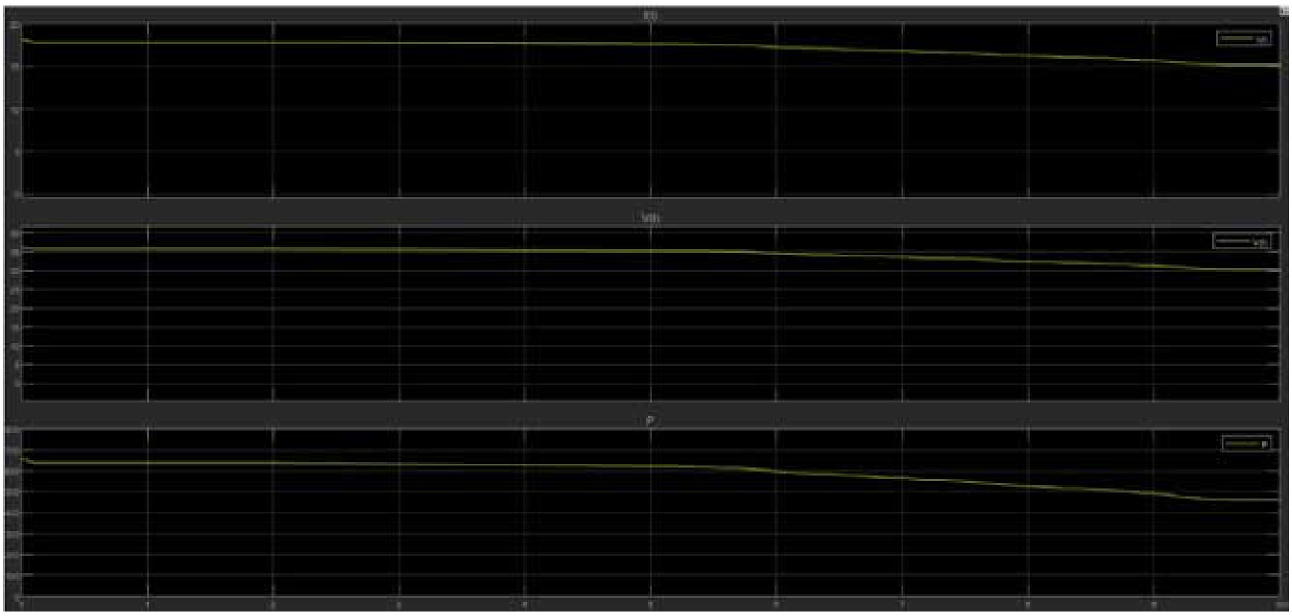


Figure 4.10 - oscilloscope readings with increasing temperature

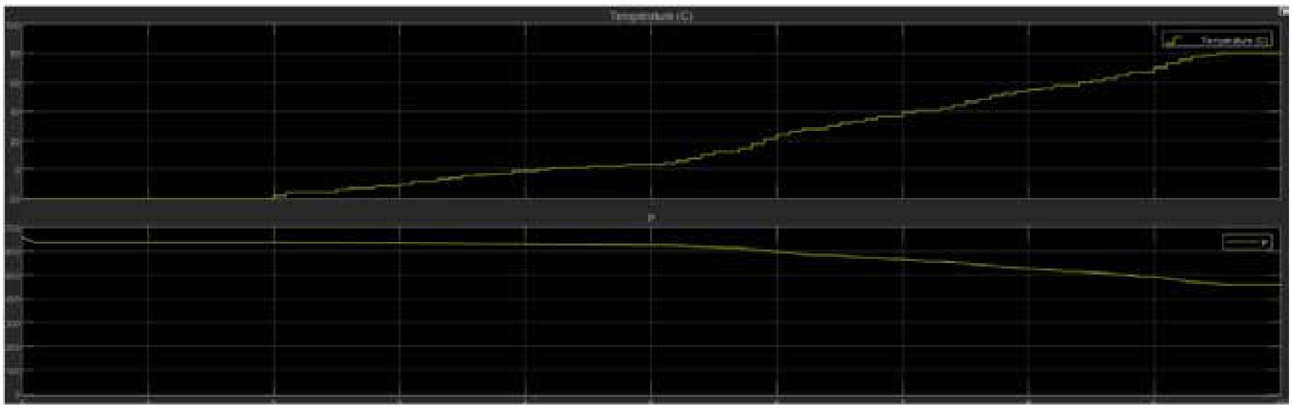


Figure 4.11 - oscilloscope readings with increasing temperature

Figure 4.12 - the process of measuring the performance of the solar panel

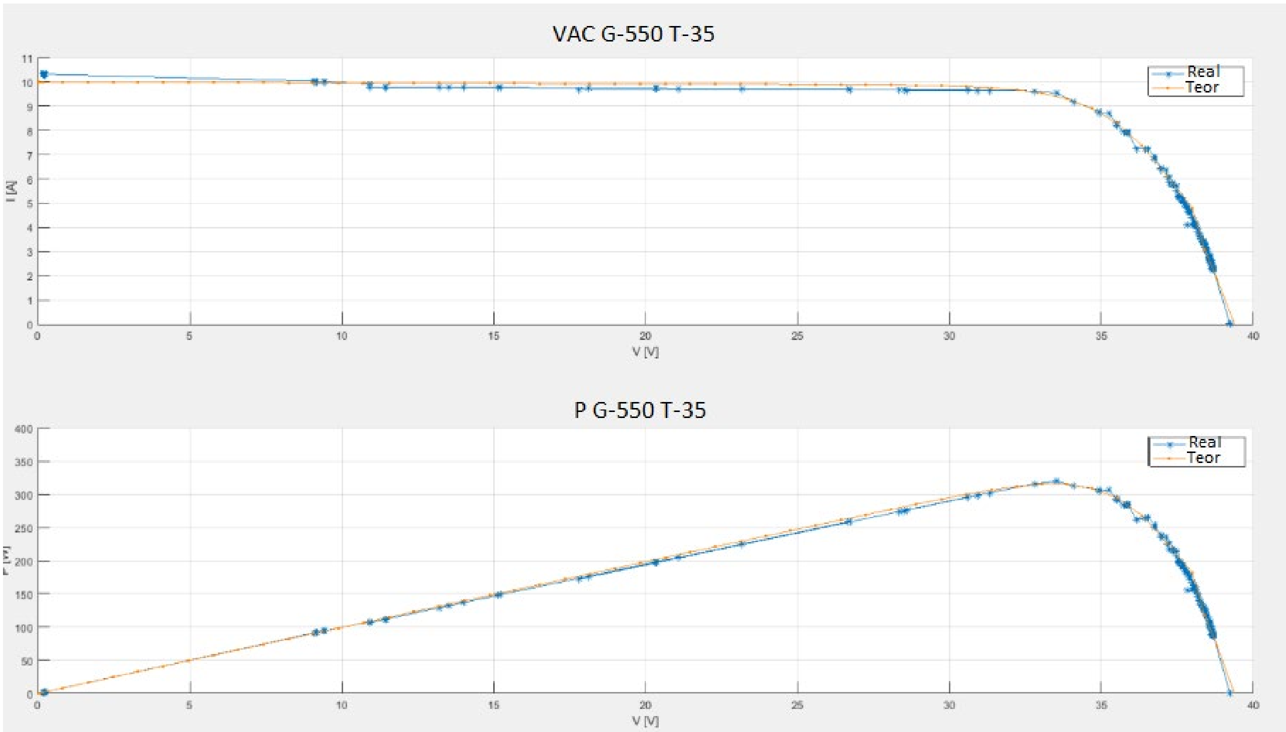


Figure 4.13- Comparison of real parameters and simulated parameters for the G-550 T-35

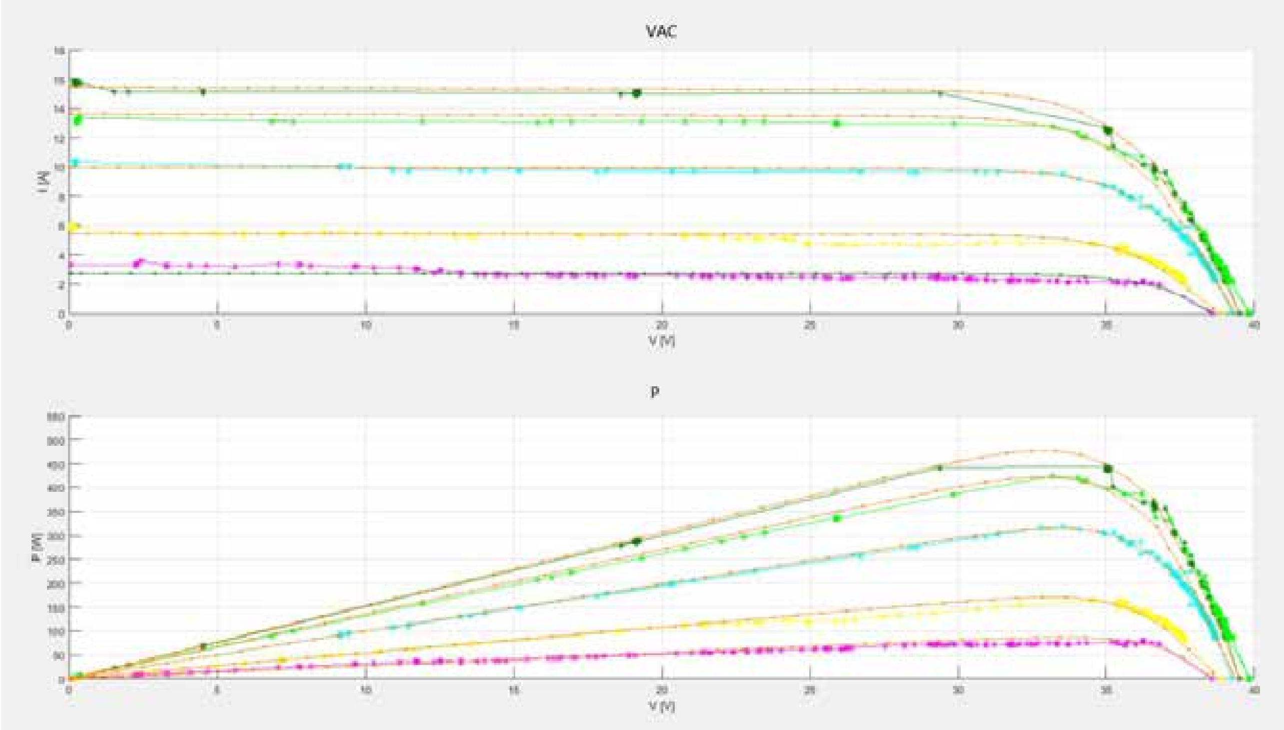


Figure 4.14 - Comparison of real and simulated parameters at different lighting and temperature parameters

CONCLUSIONS

In this master's thesis, a simulation model of a highly efficient power supply system for a polymer waste-to- diesel fuel processing plant was developed. In the first chapter, “Analysis of known autonomous power supply systems,” we analyzed autonomous power supply systems, analyzed the main ways to improve their performance, and analyzed the feasibility of implementing autonomous power supply systems in systems, which resulted in the task of developing a model. In the second chapter, “Model of an autonomous power supply system for a polymer waste-to-derivative plant and calculation of its parameters,” a formal model of the power supply system was developed, which consists of solar panels, a battery system, a generator, and an external power source. The method of data transfer from the sensors to the model was also described and worked out. In the third chapter, “Algorithms and technologies for modeling the power supply system of a polymer waste-to- diesel fuel plant.”, models of the solar panel were developed in the Matlab/Simulink simulation environment, as well as a state system. In developing the model, the method of tracking the maximum power point based on the incremental conductivity algorithm was analyzed. In the fourth chapter, “Implementation of an autonomous power supply system for a polymer waste to diesel plant and calculation of its parameters.” Developed software tools for simulation of a highly efficient power supply system for a polymer waste to diesel plant is a significant step towards modeling an environmentally friendly, additional power source, solar panels. This tool opens up the possibility of intensive modeling, enhanced by innovative methods of tracking the maximum power point, which has revealed the importance of using simulation tools in developing optimization solutions for solar panel systems. Software tool allows you to efficiently model the volt-ampere and volt-watt characteristics of solar panels, and also reproduces their operation under various operating conditions, including different values of solar radiation intensity and temperature. This provides a deeper understanding of how environmental factors affect the efficiency of solar panels. The use of simulation modeling tools is a crucial step in the development and improvement of alternative energy systems. These tools play a key role in identifying optimization opportunities and understanding real-world power performance, contributing to the sustainable and efficient use of solar energy. The results obtained during the simulation confirm that the values of the maximum power point correspond to the nominal operating conditions specified in the passport data of the photovoltaic module under consideration.

Values of the maximum power point obtained during the simulation confirm that the photovoltaic module exhibits excellent compliance with the production characteristics under standard operating conditions. This indicates the high reliability and effectiveness of the developed simulation software, which can serve as a reliable basis for further research and training. The methodology presented in this paper for calculating the parameters and modeling the characteristics of solar panels can be used in the development and testing of algorithms for tracking the maximum power point.

REFERENCES

[1] Maka AOM, Alabid JM. Solar energy technology and its roles in sustainable development. Clean Energy 2022;6. https://doi.org/10.1093/ce/zkac023.

[2] Dileep G. A survey on smart grid technologies and applications. Renew Energy 2020;146:2589–625. https://doi.org/10.1016/J.RENENE.2019.08.092.

[3] Deihimi MH, Naghizadeh RA, Meyabadi AF. Systematic derivation of parameters of one exponential model for photovoltaic modules using numerical information of data sheet. Renew Energy 2016;87. https://doi.org/10.1016/j.renene.2015.10.066.

[4] Murtaza AF, Munir U, Chiaberge M, Di Leo P, Spertino F. Variable parameters for a single exponential model of photovoltaic modules in crystalline-silicon. Energies (Basel) 2018;11. https://doi.org/10.3390/en11082138.

[5] Patra B, Nema P, Khan MZ, Khan O. Optimization of solar energy using MPPT techniques and industry 4.0 modeling. Sustainable Operations and Computers 2023;4. https://doi.org/10.1016/j.susoc.2022.10.001.

[6] Mastrocinque E, Ramírez FJ, Honrubia-Escribano A, Pham DT. Industry 4.0 enabling sustainable supply chain development in the renewable energy sector: A multi-criteria intelligent approach. Technol Forecast Soc Change 2022;182. https://doi.org/10.1016/j.techfore.2022.121813.

[7] De Falco P, Di Noia LP, Rizzo R. Exponential Smoothing Model for Photovoltaic Power Forecasting. Proceedings of 2021 9th International Conference on Modern Power Systems, MPS 2021, 2021. https://doi.org/10.1109/MPS52805.2021.9492538.

[8] Martynyuk V, Fedula M, Petrus R, Makaryshkin D, Kovtun L. Solar Cell data acquisition system. Proceedings of the 2019 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and

Applications, IDAACS 2019 2019;1:140–5. https://doi.org/10.1109/IDAACS.2019.8924386.

[9] Xu HY, Zhang Q. Photovoltaic Power Generation Prediction Technology based on Digital Twin and Improved LSTM. Reneng Dongli Gongcheng/Journal of Engineering for Thermal Energy and Power 2023;38. https://doi.org/10.16146/j.cnki.rndlgc.2023.02.012.

[10] Fernández EF, Ferrer-Rodríguez JP, Almonacid F, Pérez-Higueras P. Current-voltage dynamics of multi-junction CPV modules under different irradiance levels. Solar Energy 2017;155. https://doi.org/10.1016/j.solener.2017.06.012.

[11] Dev S, Alskaif T, Hossari M, Godina R, Louwen A, Van Sark W. Solar irradiance forecasting using triple exponential smoothing. 2018 International Conference on Smart Energy Systems and Technologies, SEST 2018 - Proceedings, 2018. https://doi.org/10.1109/SEST.2018.8495816.

[12] Lindig S, Kaaya I, Weis KA, Moser D, Topic M. Review of statistical and analytical degradation models for photovoltaic modules and systems as well as related improvements. IEEE J Photovolt 2018;8. https://doi.org/10.1109/JPHOTOV.2018.2870532.

[13] Monteiro C, Fernandez-Jimenez LA, Ramirez-Rosado IJ, Muñoz-Jimenez A, Lara-Santillan PM. Short-term forecasting models for photovoltaic plants: Analytical versus soft-computing techniques. Math Probl Eng 2013;2013. https://doi.org/10.1155/2013/767284.

[14] dos Santos LLC, Canha LN, Bernardon DP. Projection of the diffusion of photovoltaic systems in residential low voltage consumers. Renew Energy 2018;116. https://doi.org/10.1016/j.renene.2017.09.088.

[15] Alhousni FK, Alnaimi FBI, Okonkwo PC, Ben Belgacem I, Mohamed H, Barhoumi EM. Photovoltaic Power Prediction Using Analytical Models and Homer-Pro: Investigation of Results Reliability. Sustainability (Switzerland) 2023;15.https://doi.org/10.3390/su15118904.

[16] Pérez Archila LM, Bastidas Rodríguez JD, Correa R. Implicit modeling of series-parallel photovoltaic arrays using double- diode model and its solution. Solar Energy 2021;214. https://doi.org/10.1016/j.solener.2020.11.036.

[17] Archila LMP, Bastidas-Rodríguez JD, Correa R, Grisales LAT, Gonzalez-Montoya D. A solution of implicit model of series- parallel photovoltaic arrays by using deterministic and metaheuristic global optimization algorithms. Energies (Basel) 2020;13. https://doi.org/10.3390/en13040801.

[18] Auzinger W, Pukach P, Stolyarchuk R, Vovk M. Adaptive Numerics for Linear ODE Systems with Time-Dependent Data; Application in Photovoltaics. International Conference on Perspective Technologies and Methods in MEMS Design, 2020. https://doi.org/10.1109/MEMSTECH49584.2020.9109442.

[19] Boulfaf N, Ait Laasri EH, Hamid N, Elyaqouti M, Ghafiri A, Chaoufi J. Modelling and simulation of a photovoltaic module using finite element method: transient analysis. International Journal of Ambient Energy 2023;44.

https://doi.org/10.1080/01430750.2023.2173650.

[20] Chouchen B, Gazzah MH, Bajahzar A, Belmabrouk H. Numerical modeling of the electronic and electrical characteristics of InGaN/GaN-MQW solar cells. Materials 2019;12. https://doi.org/10.3390/ma12081241.

[21] Springer M, Bosco N. On Residual Stresses and Reference Temperatures in Thermomechanical Simulations of Photovoltaic Modules Using the Finite Element Method. IEEE J Photovolt 2022;12. https://doi.org/10.1109/JPHOTOV.2022.3143458.

[22] Wang Y, Qi Y, Li J, Huan L, Li Y, Xie B, et al. The Wind and Photovoltaic Power Forecasting Method Based on Digital Twins. Applied Sciences (Switzerland) 2023;13. https://doi.org/10.3390/app13148374.

[23] Liang J, Qiao K, Yuan M, Yu K, Qu B, Ge S, et al. Evolutionary multi-task optimization for parameters extraction of photovoltaic models. Energy Convers Manag 2020;207. https://doi.org/10.1016/j.enconman.2020.112509.

[24] Campana PE, Landelius T, Andersson S, Lundström L, Nordlander E, He T, et al. A gridded optimization model for photovoltaic applications. Solar Energy 2020;202. https://doi.org/10.1016/j.solener.2020.03.076.

[25] Zhang G, Wang X. Digital twin modeling for photovoltaic panels based on hybrid neural network. Proceedings 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence, DTPI 2021, 2021. https://doi.org/10.1109/DTPI52967.2021.9540210.

[26] Cervera-Gascó J, Montero J, Del Castillo A, Tarjuelo JM, Moreno MA. EVASOR, an integrated model to manage complex irrigation systems energized by photovoltaic generators. Agronomy 2020;10. https://doi.org/10.3390/agronomy10030331.

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