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Designing and Prototyping a Microcontroller Device for Measuring the Main Parameters of Solar Panels

This article presents the results of prototyping and designing a device for measuring the basic characteristics of solar panels (photocurrent and voltage) and climatic conditions (temperature and illumination). This device is being developed to identify potential faults in the solar panel-microinverter system, as well as the causes of reduced efficiency in converting light energy into electrical energy. As a result of prototyping, a prototype of the measuring device was assembled using an Arduino Mega 2560 R3 with a W5100 Ethernet module. Current is measured by an ACS712 sensor. Voltage is measured via a voltage divider connected to the microcontroller's analog-to-digital converter input. OPT4003 light and DS18B20 temperature sensors are used. The IoT device is assembled using a RAK3172 sensor module and INA228, OPT4003, and DS18B20 microcircuits. A power module based on two IRFP460 field-effect transistors was developed to measure the solar panel's current-voltage characteristics. Software has been written for the developed prototype and the IoT device.

Keywords: IoT device, Solar panel, failure detection, microcontroller, current-voltage characteristics, operating algorithm

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Introduction

One of the current trends in the development of solar energy is an increase in the proportion of households using renewable energy sources [1-3]. One of the most popular sources is photovoltaic solar panels. With the development of this trend, there is a paradigm shift in the design of mini solar power stations. The use of microinverters to generate maximum solar energy from each individual solar module is increasing, as opposed to the use of an MPPT (maximum power point tracking) controller inverter, which works with several solar modules [4, 5]. Given current trends, further growth in interest in this technology can be expected.

To increase the efficiency of solar energy generation by a solar panel-MPPT controller system, it is necessary to constantly monitor the parameters of electricity generation in real-time. It is necessary to find optimal solutions between collecting a large amount of information and analysing it in real time and the minimum set of data necessary to increase the efficiency of electricity generation by solar modules.

To address this issue, scientific research is being conducted in the field of improving the electrical circuit of the MPPT controller [6], algorithms for finding the maximum power point [7, 8], and algorithms for finding possible malfunctions in solar panels [9–11]. Mathematical modelling of solar panel operation [12, 13] can be used to advance all these stages of improvement. One way to monitor the operation of the solar panel-MPPT controller system is to constantly monitor the efficiency of solar panel electricity generation. Usually, the illumination and temperature of the solar panel are monitored, and the current and voltage at the point of maximum power are determined [9, 14]. By comparing the generated electrical power with the theoretical power value obtained from the module's illumination and temperature data, the efficiency of the solar panel is predicted [14]. In the last decade, numerous studies have appeared on the use of neural networks to calculate possible malfunctions of solar panels or their shading [11, 15]. Another option for monitoring the performance of solar panels is to use the volt-ampere characteristic (VAC) of the solar panel to monitor for errors in the operation of the solar panel [11, 15].

Currently, MPPT controllers with an error diagnosis function are not commercially available. The scientific community is paying more attention to identifying more promising algorithms for finding the maximum power point [16–18]. To find faults and inaccuracies in operation, laboratory equipment [19–21] is used, which allows the characteristics of solar modules to be measured by simulating possible errors and problems. Work is also underway to create a device for monitoring solar panel malfunctions based on microcontroller devices [22] and PLC devices [23].

This paper presents the results of work on a microcontroller device for monitoring the main characteristics of solar panels in order to determine possible causes of malfunctions or reasons for a decrease in the efficiency of electricity generation by solar modules.

Materials and Methods

KZ PV 230 M60 polycrystalline silicon solar modules (from LLP “Astana Solar”, Kazakhstan) were used.

A typical volt-ampere characteristic of a solar panel is shown in Figure 1, curve 1. An inverter or microinverter working with a solar panel maintains the operation of the solar panel at the maximum power point (MPP).

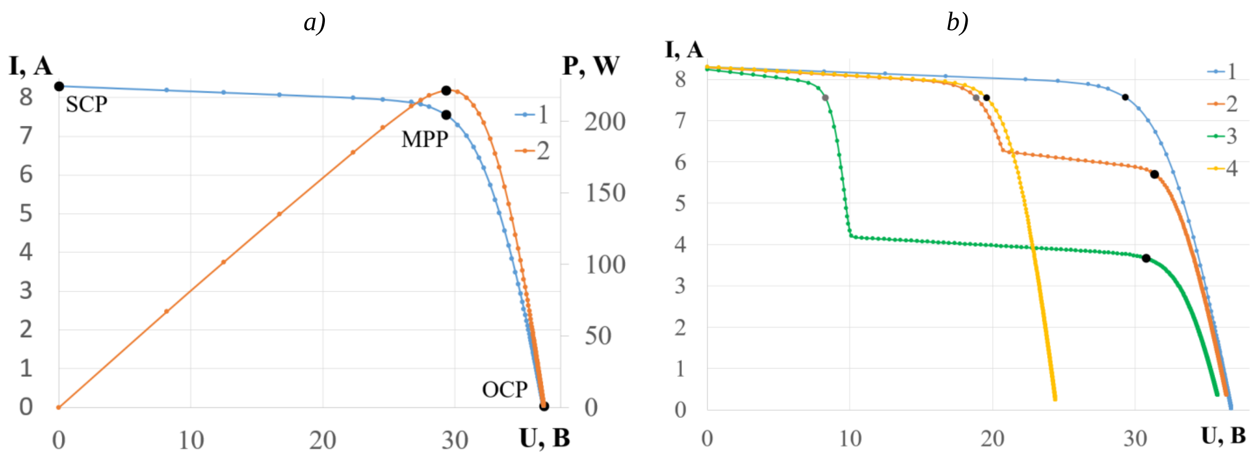

Figure 1. *a)* Standard view of the VAC (1) and volt-power characteristic (2) of the KZ PV 230 M60 solar panel at illumination Eυ = 1000 W/m² and temperature T = 25 °C: MPP — maximum power point, OCP — open-circuit point; SCP — short-circuit point. *b*) Standard view of the VAC (1), VAC of the panel with short circuit of 20 series-connected elements (2), VAC of the panel under conditions when 2 cells from different parts of the module are shaded by 50 % of the standard illumination of 1000 W/m² (3), VAC of the panel under conditions of shading of 1 cell by 25 % of the value of 1000 W/m² (4)

The VAC of a solar panel can be generally described using the formula:

$$I = I_{PV} N_{par} - I_0 N_{par} \left[\exp\left(\frac{V + R_S \left(\frac{N_{SER}}{N_{PAR}} \right) I}{V_T A N_{SER}} \right) - 1 \right] - \frac{V + R_S \left(\frac{N_{SER}}{N_{PAR}} \right) I}{R_{SH} \left(\frac{N_{SER}}{N_{PAR}} \right)}, \quad (1)$$

where I_{PV} — photocurrent (A), I_0 — diode reverse saturation current (A), I — output current of the solar panel (A), V — output voltage of the solar panel (V), V_T — thermal voltage of the solar panel elements (V), A — diode ideality factor, R_S — series resistance of the solar cell (Ω), R_{SH} — shunt resistance (Ω), N_{SER} — number of series-connected cells in the module, N_{PAR} — number of parallel-connected cells in the module.

The thermal voltage of the solar panel components is determined using the formula below:

$$V_T = \frac{k(T + 273.15)}{q} \quad (2)$$

where, T — ambient temperature (°C), q — electron charge (1.106×10^{-19} C), k — Boltzmann constant (0.138×10^{-23} J/K).

In the case of the KZ PV 230 M60 panel, which contains 60 series elements and no parallel electrical circuits, formula 1 can be rewritten:

$$I = I_{PV} - I_0\left[\exp\left(\frac{V + R_s N_S I}{V_T A N_s}\right) - 1\right] - \frac{V + R_s N_S I}{R_{SH} N_S}. \quad (3)$$

To monitor the efficiency of power generation in a solar panel microinverter system, it is recommended to measure the voltage and current in the circuit. In operating mode, these are the voltage and current at the maximum power point (MPP) U_{max} and I_{max}. These parameters can be compared with the model parameters determined by formula (3). To use this formula, it is necessary to measure the solar panel temperature and its surface irradiance. The main solar panel parameters I_{PV}, I_0, R_S, R_{SH}, and A from formula 3 can be determined using the algorithm described in the article [24] from the parameters given in the solar panel technical specifications: U_{max} — voltage at P_{max}, I_{max} — current at P_{max}, V_{oc} — open-circuit voltage, I_{sc} — short-circuit current, α — temperature coefficient of I_{sc}, β — temperature coefficient of V_{oc}.

Previously, part of this research group implemented a project to design and manufacture a microcontroller device for playing musical melody in the presence of a person [25]. The experience gained during the implementation of this project was used in the work on this microcontroller device.

In the event of significant differences between experimental and theoretical readings, an attempt is made to determine probable faults based on the U_{max} and I_{max} values. Figure 1*a* shows the short-circuit and open-circuit points on the solar panel's VAC. These values are possible due to an electrical open-circuit or short circuit between the solar panel and the microinverter (Fig. 1).

There is a possibility that U_{max} and I_{max} data will be insufficient to identify potential faults and causes of reduced solar panel output. If U_{max} and I_{max} parameters are insufficient to determine potential faults, it is recommended to measure the solar panel's VAC. Using the measured and theoretical I-VAC, it is possible to identify other potential faults and causes of reduced electrical energy generation. Based on the curve's appearance or the difference in the numerical values between the measured VAC and the reference VAC, it is possible to identify potential faults or other causes of reduced solar panel electrical energy generation efficiency (Figure 1*b*, curves 2-4). In Figure 1*b*, the curves show the main (black dots) and additional (gray dots) points of maximum power.

If the observed effects are not included in the list of those entered into the database, a message may be sent to the operator regarding an unspecified error type.

The block diagram of the prototype and device under development is shown in Figure 2. This module contains a microcontroller device, a voltage and current measuring device, and temperature and illuminance meters.

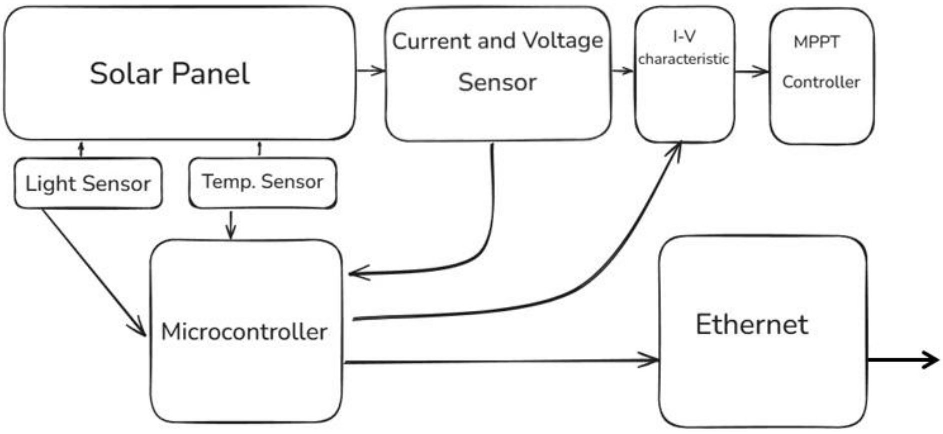

Figure 2. Functional diagram of the electrical device for measuring voltage and current at the maximum power point (U_{max}, I_{max}) and the I–V curve of the solar panel

LTSpice software was used to verify the functionality of the accepted circuit solutions. The printed circuit board was designed on the ECAD platform.

Functional requirements for the device — measurement of voltage, current, temperature and I–V curve of the solar panel.

Power supply — the device must operate independently of power control systems and be charged by a solar panel or wind turbine.

Technical requirements for the measuring device:

Measurable value ranges — voltage measurement range from 0 to 38 volts, current range from 0 to 10 amps, temperature range from –40 to +55 °C, illuminance range from 0 to 130,000 lux. The device must measure the I–V curve of a solar panel with a capacity of up to 240 watts.

Supported battery type (Li_2TiO_3) for independent power supply. Battery voltage not less than 5 volts.

Operating conditions: operating temperature from –40 to +60 °C. Dust and moisture protection class IP 65, complete protection against dust and jets from all sides under low pressure. No protection against overvoltage and overheating.

Supported communication interfaces: I2C, SPI, UART, OneWire, LoRawan 868 Mhz (license-free frequency permitted in Kazakhstan). Device control via LoRawan communication protocol. There are no buttons or screens.

Software and hardware requirements: STM32 platform microcontroller, support for firmware updates via UART and SWD interfaces. All collected data is transmitted to cloud storage via the LoRa wireless communication protocol, first to the gateway and then to the cloud.

Results and discussion

A prototype of a solar panel performance meter was assembled based on Arduino Mega 2560 R3 (Fig. 3, *a*). A Wiznet W5100 Ethernet module supporting TCP/UDP protocols was used to connect the Arduino Mega board to a local network or the Internet. The board is based on the W5100 chip and supports up to 4 connections at speeds of 10 and 100 Mbit/s. The board contains a micro-SD memory card slot. The data exchange protocol is SPI.

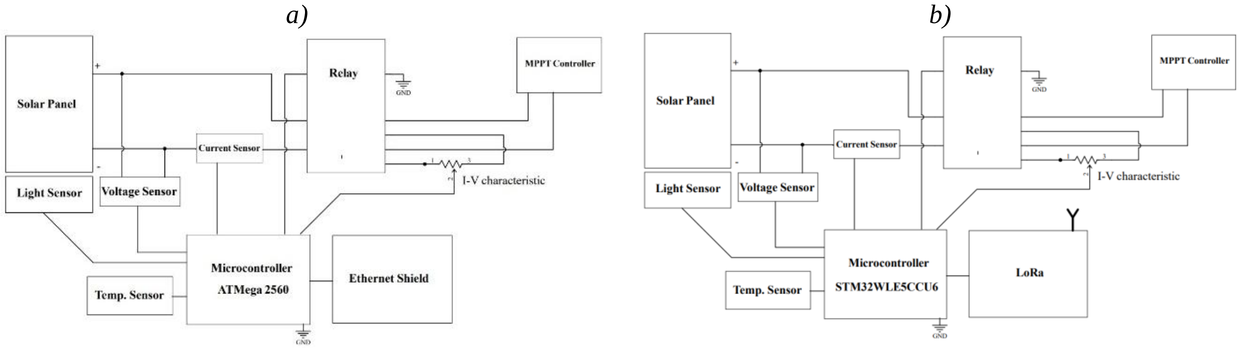

Figure 3. Block diagrams of the prototype (*a*) and measuring device (*b*)

The current is measured by an ACS712-20A Hall-effect sensor (maximum 20 A), and the panel voltage is measured via a divider connected to the microcontroller's ADC input. The Hall-effect sensor with a nominal sensitivity of 100 mV/A. The sensor output was digitized by a 16-bit ADS1115 ADC. The total current measurement uncertainty is dominated by the sensor sensitivity tolerance and offset voltage, resulting in an estimated accuracy of ±0.25 A (±2.5 % at 10 A).

The DC voltage was measured via a resistive divider (75 kΩ/10 kΩ, 2 % tolerance) followed by the same ADS1115 ADC. The resulting voltage measurement accuracy is approximately ±1.1 V, corresponding to ±2.8 % at 40 V. The ADC quantization error is negligible compared to the passive component tolerances.

A high-precision OPT4003-Q1 sensor is used to measure the illumination of the solar panel. It has high sensitivity and is designed for automotive use (class Q1), which guarantees its performance at low temperatures and under external influences. The device provides factory-calibrated illuminance data with a typical absolute accuracy of ±5 % and a maximum error of ±10 % over the specified operating conditions. Since the sensing element and ADC are integrated within the device, the quantization error is negligible compared to the sensor's specified accuracy.

DS18B20 digital temperature sensor was chosen as a reliable and widely used component with a digital interface, making it ideal for use in cold climates. The sensor provides factory-calibrated temperature readings with a guaranteed accuracy of ±0.5 °C in the –10 to +85 °C range and a resolution of 0.0625 °C. Since the sensing element and ADC are integrated within the device, the quantization error is negligible compared to the sensor's specified accuracy.

The Arduino board collects readings from all sensors and publishes them to the MQTT broker (Mosquitto). Telegraf subscribes to the relevant topics, receives the data and stores it in InfluxDB and PostgreSQL. Grafana connects to these databases and displays the data in the form of graphs and dashboards. More detailed information on the operation of the prototype and the experimental data obtained is given in [26].

The Arduino board control programme includes the following main modules:

1. Initialisation and interaction with sensors;
2. Collection, averaging, and storage of measurement data.
3. The programme measures the following physical quantities:

– panel electric current;
– panel electrical voltage;
– illuminance level;
– solar module surface temperature.

4. Data transmission via MQTT protocol;
5. Receiving control commands from the server;
6. In case of a request from the server, an algorithm for step-by-step change of electrical load is played to measure current and voltage from the solar panel in order to build the I–V curve of the solar panel.

One of the key functions of the device is the ability to automatically measure the I–V curve of the solar panel. Upon receiving a command from the server, the device performs the following sequence of actions:

– A relay is activated, which connects an electronic load to the panel;
– The load was adjusted step by step, which made it possible to obtain 50 discrete current values and 50 voltage values;
– The experimental points obtained form the panel's I–V curve;
– After the measurements are completed, all data is automatically sent to cloud storage via the MQTT protocol.

The software can be found at [27].

An example of measured I–V characteristics for the KZ PV 230 M60 solar panel is shown in Figure 4. The I–V curves of the cells are measured under current operating conditions, short-circuit conditions for 20–40 module cells, and open-circuit conditions for 20–40 module cells. The measurements showed results that correlated with model representations (Figure 1, *b*). However, analysis and comparison of theoretical and experimental data is not the primary goal of this work and will be conducted in future work.

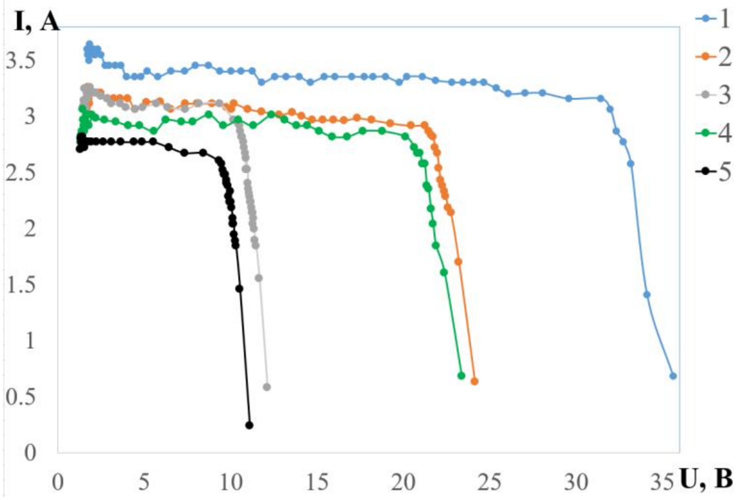

Figure 4. Measured I–V curves of the solar panel under different conditions:
1) I–V curve of the module at illumination level and temperature (Eυ = 430 W/m^2 and temperature T = 25 °C);
2) with a short circuit of 20 module cells (Eυ = 395 W/m^2, T = 25 °C);
3) with a short circuit of 40 module cells (Eυ = 395 W/m^2, T = 25 °C);
4) with a break in electrical connection with 20 module cells (Eυ = 370 W/m^2, T = 25 °C);
5) with a break in electrical connection with 40 module cells (Eυ = 370 W/m^2, T = 20 °C)

When designing an embedded IoT system for measuring the electrophysical parameters of a solar panel (Fig. 3, *b*), special attention was paid to the selection of components capable of functioning at low temperatures and ensuring stable operation of the device in field conditions. All electronic components used were selected taking into account climatic and operational requirements, as well as their functional compliance with the tasks solved within the system.

The RAK3172, an energy-efficient STM32-based module supporting the LoRaWAN protocol, was selected as the central control module. It provides reliable data transmission and has low power consumption, which is especially important for autonomous power plants. OPT4003 light sensors and DS18B20 temperature sensors are used. Current and voltage are measured using the INA228, a precision digital measurement amplifier capable of operating in an extended temperature range and providing high measurement accuracy. Electrical circuit diagrams are shown in the Figures S1–S4 in the Supplementary materials with a brief description of their functional purpose.

The device is powered by an LM2596T-5.0 DC-DC (Buck converter, step-down) stabilizer, which provides a stable output voltage of 5 V even when the input voltage fluctuates. ME6206A33PG linear stabilizer is used to power peripheral circuits, demonstrating high conversion efficiency and resistance to temperature fluctuations.

The design of the VAC removal unit is based on two powerful IRFP460 field-effect transistors, which made it possible to work with the required currents and voltages. To increase reliability and electrical safety, the system was designed with galvanic isolation from the microcontroller, which eliminated the impact of high currents on the control electronics. For analog control of the transistor gate voltage, an HA17358B operational amplifier is used, which is designed for precise regulation and is characterized by stable operation when the temperature changes.

The design uses X7R SMD capacitors, which are characterized by stable electrical parameters over a wide temperature range. This dielectric class ensures reliable operation of the devices in low temperatures typical for outdoor use. X7R capacitors maintain their capacitance with minimal deviations during temperature fluctuations, which is especially important for the operation of analog and power circuits.

The circuit also uses electrolytic capacitors specially selected for operation at sub-zero temperatures. Components with an extended temperature range are used, ensuring stable operation down to –40 °C and below, which prevents capacitance degradation and reduces the risk of failure during prolonged exposure to cold. This selection of passive components increases the reliability of the device and guarantees its resistance to external climatic influences.

A 3D view of the printed circuit board is shown in Figure 5.

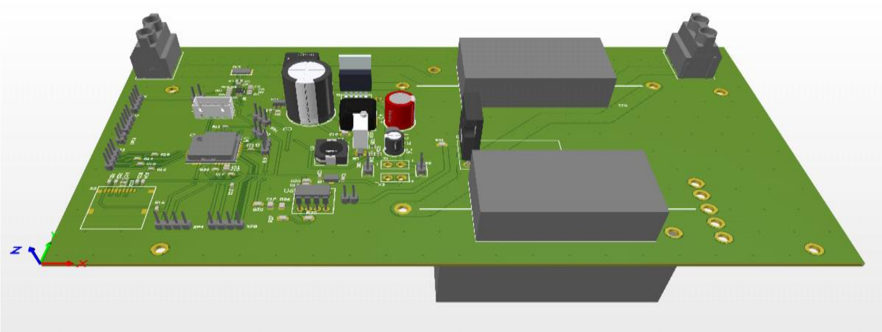

Figure 5. 3D view of the finished printed circuit board

The software for the device was developed in the Arduino IDE environment. This environment was chosen as the primary one for a number of practical reasons. First, it provides a convenient interface and access to a wide range of libraries, which simplifies interaction with microcontrollers. Secondly, and critically, the firmware pre-installed in the RAK3172 module is officially supported in Arduino IDE. The module is based on the STM32 architecture and works using the LoRaWAN protocol, so the choice of environment was actually predetermined [28].

The C language was chosen for writing the programme because it allows you to work effectively with systems where precise resource management is important. It provides direct access to hardware capabilities and is considered the primary language for working with microcontrollers.

The software structure of the device is based on a modular approach. Each block is responsible for a strictly defined function: interaction with peripheral devices, data collection and pre-processing, information transfer via the LoRaWAN network, working with an SD card, receiving commands from the server, etc. This solution simplifies scaling, maintenance, and future functionality expansion.

Initialisation begins with the configuration of all connected sensors. For example, current and voltage are measured using the INA228 microcircuit, which operates via the I²C interface. During initialisation, configuration parameters are written to its registers. The OPT4003-Q1 light sensor, which also uses the I²C interface, is configured using the same principle. The DS18B20 temperature sensor is connected via the OneWire bus using the DallasTemperature library.

After initialisation is complete, the system begins to periodically poll the sensors. The values obtained undergo primary processing: conversion to physical units, filtering, and checking of acceptable value limits. The data is then packaged into a formatted packet containing timestamps and parameters and transmitted via the RAK3172 module to the LoRaWAN network. The information is sent to the server via a gateway and then visualised or stored in a database.

A distinctive feature of the system is its support for feedback. The device not only transmits data, but can also receive commands from the server. This makes it possible, for example, to start the VAC measurement procedure for a solar panel when necessary. In VAC measurement mode, the device switches to a special mode: the output load is regulated by a PWM signal, which is converted into a linear voltage and fed to the gate of IRFP460 transistors, and the parameters—voltage and current—are measured dynamically. On the device itself, the VCC measurement command works as follows: the microcontroller switches the relay to the internal load from the transistors; the microcontroller outputs a PWM signal with a minimum duty cycle of 1 % from the required contact; the integrating chain receives it, and the output is a constant voltage with a minimum amplitude which is fed to the operational amplifier, and from there to the power transistor; it opens to the minimum value, loading the panel; the current and voltage are measured; the data is packaged and sent to the server via the gateway. The process of increasing the opening and recording continues until the PWM signal is completely filled, which means that we have opened the transistor completely and measured the VAC graph.

After each measurement, a packet is formed to be sent to the server and sent via LoRa to the gateway and then to the server.

In the event of a temporary loss of connection to the cloud system, the device switches to local storage mode. In this case, all data is recorded on a memory card, and as soon as the connection is restored, it is automatically transferred in sequence. This prevents information loss and maintains the integrity of the data set.

The program code is structured based on functions, macros, and user data types. Each logical block of the system is implemented separately, which improves readability and ease of maintenance. Working with sensors, LoRa connection logic, writing to an SD card, processing incoming commands — all of this is separated into separate sections of code, which makes it possible to develop the project without affecting its basic structure.

Thus, the software implemented as part of the work performs a full cycle — from collecting and analysing readings to transmitting them and responding to control signals. The architecture remains flexible, allowing the device to be adapted to new tasks, sensors to be added, and additional algorithms to be implemented in the future.

Conclusion

Thus, the proposed hardware and software solution provides comprehensive monitoring of key solar panel parameters — current, voltage, illuminance, and temperature — with data transmission over the network for further storage, processing, and visualisation.

To test the model, a system was assembled on an Arduino Mega 2560 R3 with an Ethernet Shield W5100, including ACS712 (20 A), a voltage divider, OPT4003 and DS18B20; VACs were measured using a controlled electronic load. The data was published in Mosquitto, aggregated by Telegraf, and stored in InfluxDB/PostgreSQL, followed by visualisation in Grafana. The sensors were calibrated against reference current and voltage sources.

An example of the I–V curves of the KZ PV 230 M60 solar panel is given in the text of the article.

During the course of the work, a full-fledged prototype of an embedded IoT system for monitoring solar panel parameters was developed, including both hardware and software components. Based on the prototype, a new device was created that meets all the functional and technical requirements.

During the development process:

– functional and technical requirements for the system were formed, operating conditions and supported interfaces were defined;

– a selection and justification of components capable of operating in a wide temperature range and ensuring high measurement accuracy was made;

– the schematic diagram and printed circuit board of the device were designed in the ECAD environment, component libraries and mounting locations were created in accordance with the technical documentation;

– individual circuit nodes were simulated in LTspice, which allowed the correctness of the selected circuit solutions to be confirmed prior to the hardware implementation stage;

– Software was developed in Arduino IDE using the **C** language, providing data collection from sensors, their pre-processing, transmission via the LoRaWAN protocol, as well as support for local storage of information and execution of control commands from the server.

– Algorithms were implemented to measure the volt-ampere characteristics of the solar panel with subsequent data transmission to the cloud.

– A functional block diagram has been created that reflects the operation of key system nodes.

Thus, the developed device meets the requirements: it operates autonomously from renewable energy sources, measures the necessary electrical and climatic parameters, is resistant to climatic conditions, and supports modern communication interfaces and the LoRaWAN protocol, which ensures integration into the IoT infrastructure.

The practical significance of the work lies in the creation of a universal platform for monitoring the condition of solar panels and wind turbines, which may be in demand in distributed energy systems, scientific research, and educational purposes. The result can be considered as a basis for further modernisation, adding new sensors and expanding the capabilities of the system depending on the specifics of operation.

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Күн панельдерінің негізгі параметрлерін өлшеуге арналған микроконтроллер құрылғысын жобалау және прототиптеу

Мақалада күн панельдерінің (фототок және кернеу) және климаттық жағдайлардың (температура мен жарық) негізгі сипаттамаларын өлшеу құрылғысын прототиптеу және жобалау нәтижелері келтірілген. Бұл құрылғы күн панелі-микроинвертор жүйесіндегі мүмкін ақауларды, сондай-ақ жарық энергиясын электр энергиясына түрлендіру тиімділігінің төмендеуіне әкелетін себептерді анықтау мақсатында әзірленуде. Прототиптеу нәтижесінде W5100 Ethernet модулі бар Arduino Mega 2560 R3 негізіндегі өлшеу құрылғысының макеті жиналды. Ток ACS712 сенсорымен өлшенеді. Кернеу микроконтроллердің ADC кірісіне қосылған кернеу бөлгіш арқылы өлшенді. Opt4003 жарық және DS18B20 температура сенсорлары қолданылады. Интернет тарату құрылғысы INA228, OPT4003, DS18B20 сенсорлары мен чиптерінің rak3172 модулі негізінде құрастырылған. Күн панелінің Вольт-Ампер сипаттамаларын өлшеу үшін екі irfp460 өріс транзисторларына негізделген қуат модулі жасалды. Бағдарламалық жасақтама әзірленген прототип пен Интернет тарату құрылғысына жазылған.

Кілт сөздер: Интернет тарату құрылғысы, күн панелі, ақауларды анықтау, микроконтроллер, Вольт-Ампер сипаттамалары, жұмыс алгоритмі

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Проектирование и прототипирование микроконтроллерного устройства для измерения основных параметров солнечных панелей

В статье представлены результаты прототипирования и проектирования устройства измерения основных характеристик солнечных панелей (фототок и напряжение) и климатических условий (температура и освещенность). Данное устройство разрабатывается с целью определения возможных неисправностей в системе «солнечная панель — микроинвертор», а также причин, приводящих к снижению эффективности трансформации световой энергии в электрическую энергию. В результате прототипирования был собран макет измерительного устройства на базе Arduino Mega 2560 R3 с Ethernet-модулем W5100. Ток измеряется датчиком ACS712. Напряжение измерялось через делитель напряжения, подключённый к входу АЦП микроконтроллера. Использованы датчики освещенности OPT4003 и температуры DS18B20. IoT-устройство собрано на базе модуля RAK3172, датчиков и микросхем INA228, OPT4003, DS18B20. Для измерения вольт-амперных характеристик солнечной панели разработан силовой модуль на базе двух полевых транзисторов IRFP460. К разработанному прототипу и IoT-устройству написано программное обеспечение.

Ключевые слова: Устройство интернета вещей, солнечная панель, обнаружение неисправностей, микроконтроллер, вольт-амперные характеристики, алгоритм работы

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