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DEVELOPMENT AND SIMULATION OF A HIGH-PRECISION MPPT CONTROLLER FOR THIN-FILM SOLAR CELLS

The paper presents circuit implementations of a high-precision MPPT (maximum power point tracking) controller adapted to operate with small samples of thin-film solar cells based on cadmium telluride (CdTe). The implemented circuit showed high stability during experimental studies and can operate with currents from 1 μA to 3 A. The effectiveness of the selected maximum power point tracking algorithm was evaluated using a simulation model based on the pvlib library, which operates on the basis of the five-parameter De Soto model and the MPP incremental conductance tracking algorithm with specified parameters. The simulation results show a tracking efficiency of 97.88% over the year and 99.83% over the day, which ensures high efficiency considering the very low output power levels of thin-film photovoltaic cells.

Keywords: MPPT controller, thin-film solar cell, CdTe solar cell, renewable energy, highly sensitive sensors.

Solar photovoltaic energy converters play a leading role among renewable energy sources. The rapid development and improved efficiency of photovoltaic cells have led to the widespread adoption of this technology in various areas of energy supply. The operating principle of a photovoltaic cell is the generation of charge carriers in a semiconductor under illumination, their separation by the internal electric field, and their transport to the contacts. To date, most photovoltaic cells have been fabricated from silicon $p-n$ junctions, which have become widespread due to the high level of manufacturing of silicon technology. However, the production of such panels requires relatively thick silicon wafers and significant energy consumption. In recent years, researchers have focused on second-generation thin-film photovoltaic (**PV**) cells, which can provide efficient absorption of solar radiation while using a significantly thinner absorber layer [1], [2]. An important part of PV system is the maximum power point (**MPP**) tracking controller, which enables the extraction of maximum available power under variable operating conditions, such as changes in irradiance and temperature, soiling of the module surface, or partial shading. The MPP tracking (**MPPT**) is one of the key technologies used to increase the efficiency of photovoltaic systems. The operating principle of an MPPT controller is based on continuously varying the effective load seen by the PV module so that the operating point is shifted toward the condition where the product of voltage and current is maximized. To achieve this, the MPPT controller measures the voltage and current of the PV module, determines the MPP, and adjusts the operating point until maximum power is obtained [3]. A wide variety of MPPT algorithms has been developed [4], [5], including perturb and observe (**P&O**), incremental conductance (**InC**), current sweep (**CS**), fuzzy logic controller (**FLC**), fractional open-circuit voltage, fractional short-circuit current, artificial neural network, and others.

Literature Review

In [6], an improved maximum power point tracking method for photovoltaic systems under partial shading conditions is proposed. A key feature of this approach is the detection of partial shading, achieved by combining the popular P&O tracking method with a dedicated subroutine that searches for the global maximum power point through analysis of individual module voltages. The authors evaluated the effectiveness of the method using simulations in the MATLAB/Simulink environment and experimental tests, and showed that the proposed technique reduces energy losses compared with classical methods operating under partial shading conditions.

The study [7] describes a new adaptive MPPT controller for photovoltaic systems based on the model reference adaptive control method, which enables fast and accurate tracking of the maximum power point by minimizing the error between the PV system output and a reference model, thereby eliminating the oscillations typical of classical P&O and InC controllers. As reported, the proposed controller achieves an average tracking accuracy of 99.77% and 99.69% under different irradiance and temperature levels, as well as an extremely fast MPP search time of about 3.6 ms.

The article [8] describes a combined approach to improving the efficiency of photovoltaic systems by integrating FLC maximum power point tracking with PI control for stabilizing battery charging parameters. In the proposed scheme, a boost converter is driven

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by the FLC-based MPPT controller, which operates without the need for precise system parameters and ensures a fast response to variations in irradiance and temperature. At the second stage, a buck converter with a PI controller is used to maintain a constant charging voltage of approximately 15 V and a current of about 2.93 A, thereby minimizing losses during charging and extending the battery lifetime. Simulation results in MATLAB/Simulink demonstrate a tracking efficiency of 94.8 – 99.4% under different operating conditions (700 – 1000 W/m², 25 – 60°C) and stable output parameters at the load.

In [9], two maximum power point tracking methods for stand-alone photovoltaic systems are investigated: P&O and FLC. The verification is carried out in the Simulink environment using a boost converter, and their performance is evaluated under different irradiance and temperature levels. It is reported that the FLC provides a faster dynamic response and is able to maintain the operating point closer to the MPP, exhibiting smaller output power oscillations and better stability compared to P&O. The authors conclude that although P&O is simple to implement, the use of FLC is a promising approach due to its higher efficiency and more stable control of PV systems.

Despite numerous studies focused on the development and enhancement of modern MPPT controllers, the of adapting MPPT controller circuits with dynamically adjustable loads for laboratory-fabricated thin-film photovoltaic cells with ultra-low output power remain unresolved. In addition, insufficient attention has been paid to the development of circuit design solutions capable of providing maximum power tracking for different types of PV samples, taking into account the diversity of materials and compounds used to fabricate solar cells, as well as the power range from ultra-low-power devices to medium-power samples.

Purpose of the Study

The aim of this study is to develop and check the operation of an MPPT controller circuit capable of operating with experimentally fabricated thin-film solar cells, in particular CdTe-based devices, and to carry out computer simulations of the MPPT controller operating with low-power solar cells.

To achieve this goal, it is necessary to address the following tasks:

— to develop the concept of a high-precision MPPT controller capable of ensuring high operational stability and operating over a wide voltage range of photovoltaic cells, starting from several tens of millivolts;

— to analyze the algorithms used for maximum power point tracking and select an algorithm that will perform well at low voltages;

— based on the Python programming language and available libraries, develop a simulation model that will allow the operation of the system to be simulated over an extended period of time.

Methods

For maximum power point tracking in this work, InC method is used. As shown in **Fig. 1**, it is based on the maximum power condition $\mathrm{d}P/\mathrm{d}V=0$. Compared with the popular P&O method, its advantages include the ability to determine when the MPP has been reached, a fast response to changes in irradiance and temperature, and reduced oscillations around the MPP, resulting in higher efficiency [10]. The main equations of the method can be described in the form of [11]:

$$\frac{\mathrm{d}P}{\mathrm{d}V}\begin{cases} if > 0, \text{ to the left of MPPT;} \\ if = 0, \text{ at MPPT;} \\ if < 0, \text{ to the right of MPPT.} \end{cases} \quad (1)$$

Since the power of a photovoltaic cell depends simultaneously on both voltage and current, the change in power with respect to voltage takes into account both the current itself and the rate of its change, and is computed using the product rule

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}(VI)}{\mathrm{d}V} = I + V\frac{\mathrm{d}I}{\mathrm{d}V}\ . \quad (2)$$

Based on these equations, InC method for determining the maximum power point uses the following relationship when $\Delta V=0$:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}\ . \quad (3)$$

It should be noted that $\Delta I = I_n - I_{n-1}$, $\Delta V = V_n - V_{n-1}$ are the discrete current and voltage values measured by the microcontroller between two consecutive sampling cycles.

The operation of the circuit shown in **Fig. 2** is based on a high-performance STM32G474 microcontroller, which controls the load according to the selected algorithm. The load for the solar cell under test is implemented by transistor Q1, which, together with the MCP617 operational amplifier, forms a software-controlled precision current regulator. Transistors Q2…Q6 and resistors R2…R6 form a switched shunt, the signal from which is fed to the internal operational amplifier and ADC of the microcontroller with a reference voltage of 2.5 V. The operational amplifier is driven by the STM32's integrated 12-bit DAC. Additionally, the circuit provides the option to connect resistor R8 to ground via Q7, thereby creating a controllable voltage divider for adjusting the operating range and improving step resolution (accuracy) within the selected range.

To simulate the operation of the InC method, a custom Python-based model was developed using the pvlib library [12]. The library computes the *I–V* characteristic of the solar cell using the De Soto model, also known as the five-parameter model, as a function of the cell

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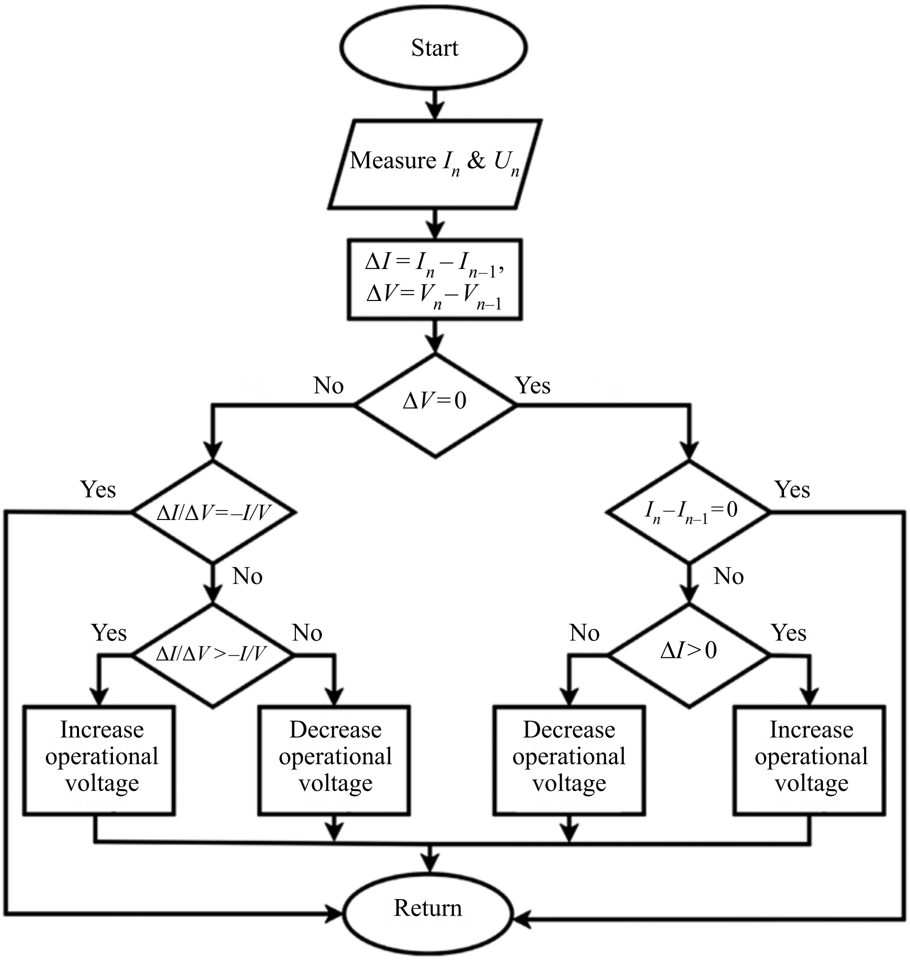

Fig. 1. Block diagram of the Incremental Conductance method

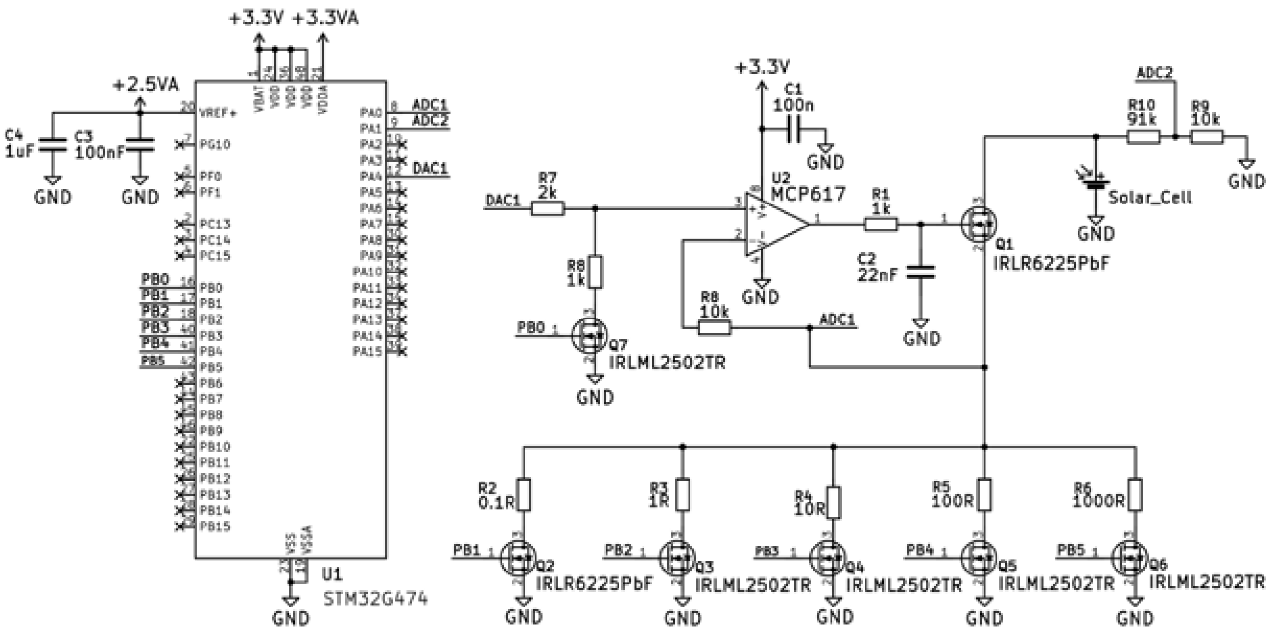

Fig. 2. Schematic diagram of the MPPT controller

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temperature T_c and the total absorbed irradiance S, and includes [13] the photocurrent equation

$$I_L = \frac{S}{S_{\text{ref}}}\frac{M}{M_{\text{ref}}}\left[I_{L,\text{ref}} + a_{I\text{sc}}(T_c - T_{c,\text{ref}})\right], \quad (4)$$

where M/M_{ref}=1 in the absence of spectral;
S_{ref} is the irradiance of the solar cell under STC;
aI_{sc} is the temperature coefficient of the short-circuit current;
$T_{c,\text{ref}}$ is the solar cell temperature under STC.

The diode saturation current for a CdTe-based photovoltaic cell is determined in accordance with [14]

$$I_0 = I_{0,\text{ref}}\left(\frac{T_c}{T_{c,\text{ref}}}\right)^3 \exp\left[\left(\frac{E_{g,\text{ref}}}{k_{eV}T_{c,\text{ref}}} - \frac{E_g(T_c)}{k_{eV}T_c}\right)\right], \quad (5)$$

where $I_{0,\text{ref}}$ is the saturation current at $T_{c,\text{ref}}$;
T_c is the cell temperature;
$T_{c,\text{ref}}$ is the reference cell temperature;
$E_{g,\text{ref}}$ is the CdTe bandgap energy at $T_{c,\text{ref}}$;
$E_g(T_c)$ is the CdTe bandgap energy at the temperature T_c;
k_{eV} = 8.617333262·10^{-5} eV/K.

Series resistance R_s, parallel shunt $R_{sh}(S)$ and bandgap energy $E_g(T_c)$ are determined in accordance with

$$R_s=\text{const}; \quad (6)$$

$$R_{sh}(S)=R_{sh,\text{ref}}\cdot S_{\text{ref}}/S; \quad (7)$$

$$E_g(T_c)=E_g(T_{\text{ref}})[1-0.0002677(T_c-T_{\text{ref}})]. \quad (8)$$

It is also assumed that the diode ideality factor n is constant. Short-circuit current $I_{sc,\text{ref}}$ as a function of the sample area A:

$$I_{sc,\text{ref}}=J_{sc,\text{ref}}\cdot A, \quad (9)$$

where $J_{sc,\text{ref}}$ is the short-circuit current density under STC.

The value of $I_{L,\text{ref}}$ represents the light-generated current under STC and is assumed to be approximately equal to $I_{L,\text{ref}} \approx I_{sc,\text{ref}}$.

The thermal voltage is given by [15]:

$$V_T=k_{ev}\,T_c \quad (10)$$

Complete equation of the single-diode model [16]:

$$I = I_L - I_0\left[\exp\left(\frac{V+IR_s}{nN_sV_T}\right)-1\right] - \frac{V+IR_s}{R_{sh}}, \quad (11)$$

where N_s is the number of series-connected cells.

Exponential parameter:

$$a(T)=nN_sV_T. \quad (12)$$

Limits of the curve:

$$V_{oc} \approx a\cdot\ln\left(\frac{I_L}{I_0}+1\right); \quad (13)$$

$$I_{sc}\approx I_L. \quad (14)$$

Power and $P-V$ characteristic:

$$P(V)=V\cdot I(V). \quad (15)$$

Analytical determination of V_{mpp}, I_{mpp}:

$$\frac{dP}{dV}=0 \Leftrightarrow \frac{dI}{dV}=-\frac{I}{V}. \quad (16)$$

Calculation of the I–V curve fill factor:

$$FF=\frac{V_{mpp}I_{mpp}}{V_{oc}I_{sc}}. \quad (17)$$

To obtain data on the variation of solar irradiance and temperature throughout the day, the model uses data from the open National Solar Radiation Database (**NSRDB**) provided by NREL (USA) [16]. The NSRDB dataset Prime Meridian: Africa and Europe, derived from images of the Meteosat geostationary satellites, provides irradiance and temperature data with a 15-minute temporal resolution and includes records for the year 2022.

Results and Discussion

To evaluate the stability of the circuit operation and the dynamic response of the current regulator, the regulator's response to a triangle-wave input signal (**Fig. 3**) and to a square-wave input signal (**Fig. 4**) at different frequencies was investigated.

At frequencies above 10 kHz, slight signal distortion is observed, but this does not effect of the operation MPPT controller, since the operating frequency of the algorithm is significantly lower. The oscillograms obtained indicate an increase in delay between the generator control signal and the shunt current signal as the shunt resistance is reduced, amounting to 28 μs for a 1000 Ω shunt; 40 μs for a 100 Ω shunt and 48 μs for a 1 Ω shunt.

Since a few hertz are sufficient for the MPPT algorithm to operate due to the smooth change in illumination, the obtained result confirms the high stability of the circuit and ensures the fast operation of the MPPT controller.

The parameters of the CdS/CdTe/Cu/Au (see the **Table**) thin films were determined based on the results reported by the authors of [17] for a CdTe absorber thickness of 3 μm.

For the simulations, irradiance and temperature data from Ivano-Frankivsk were used, which made it possible to evaluate the effectiveness of the algorithm under operating conditions typical of the western region of Ukraine. The model settings were chosen for operation with very small-area photovoltaic converter samples and the correspondingly low open-circuit voltage V_{oc}. The voltage perturbation step ΔV is defined as a relative fraction of V_{oc} equal to 0.2% with a hard lower bound of 0.002 V, which ensures correct algorithm operation at very low V_{oc} values, since a smaller step would be inappropriate and uninformative. The deadband is set to 0.3% of the actual power change. In addition, the operating voltage range is limited to V_{low} = 0.05V_{oc} and V_{high} = 0.98V_{oc}, and the operating point is initialized

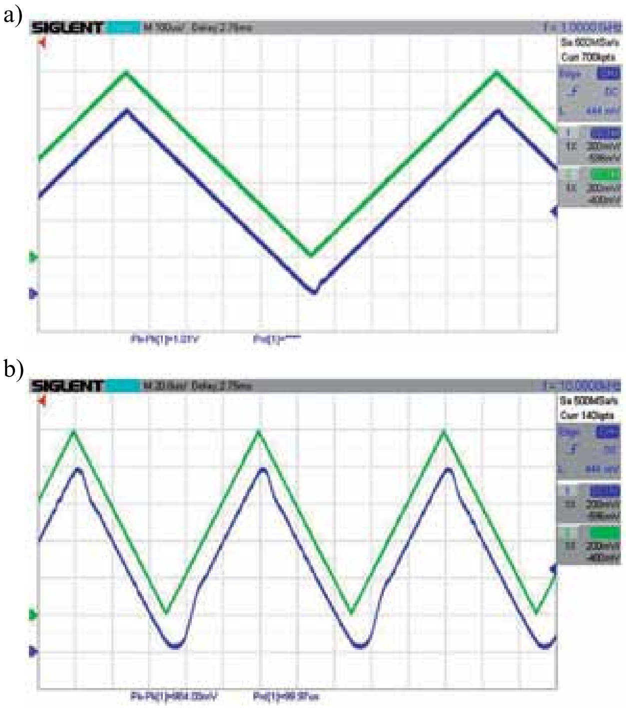

Fig. 3. Current oscillogram (*shunt signal — upper curve*) during variation of the triangular reference signal (*lower curve*) at a frequency of 1 kHz (*a*) and 10 kHz (*b*) for the shunt resistance is 100 Ω

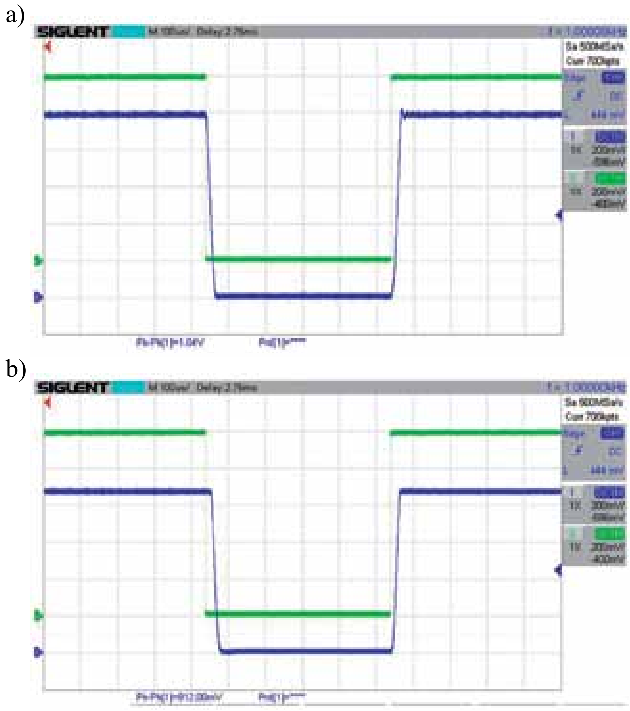

Fig. 4. Current oscillogram (*shunt signal — upper curve*) during variation of the square-wave reference signal (*lower curve*) at a frequency of 1 kHz for the shunt resistance is 1000 Ω (*a*) and 100 Ω (*b*)

Parameters of CdS/CdTe/Cu/Au films according to data [17]

V_{oc}, mV	J_{sc}, mA/cm^2	R_s, Ohm·cm^2	R_{sh}, Ohm·cm^2	J_0, A/cm^2	J_{ph}, mA/cm^2	*n*
682	20.8	7.4	127	$1.6 \cdot 10^{-6}$	21.0	2.7

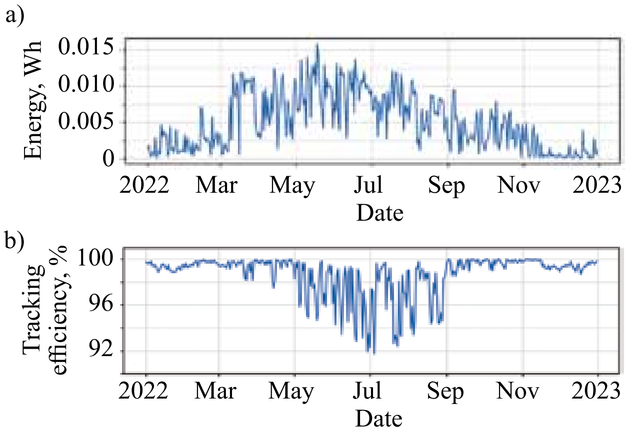

Fig. 5. Simulation results of the MPPT algorithm for one year: *a* — ideal calculated daily energy at the MPP; *b* — daily MPP-tracking efficiency of the InC algorithm

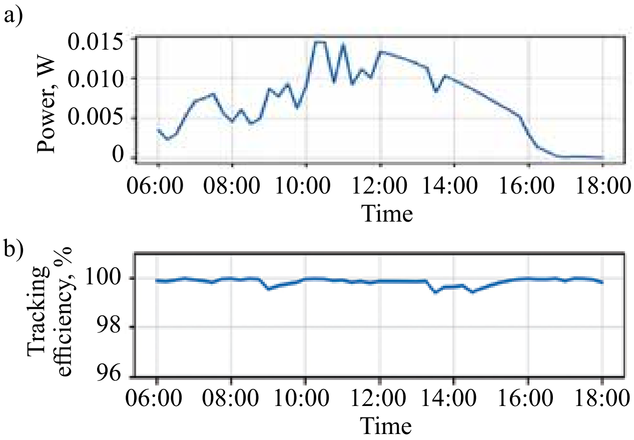

Fig. 6. Simulation results of the MPPT algorithm for one day: *a* — ideal calculated instantaneous power at the MPP; *b* — instantaneous MPP-tracking efficiency of the InC algorithm

after night-time or data errors at $V_{op} = 0.7V_{oc}$, to improve model stability. The results of the year-long algorithm simulation are presented in **Fig 5**.

The year-long simulation plots are presented with power integrated over each day, on the basis of which the annual energy yield and the annual maximum power point tracking efficiency were obtained.

To evaluate the performance of the model over a short time interval, a one-day simulation was carried out; as an example, irradiance and temperature data for May 30, 2022 from the NSRDB were used. In the daily plot in **Fig. 6**, the time dependences of the calculated power at the ideal maximum power point and the operating efficiency of the InC algorithm are shown.

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To calculate the maximum power point tracking efficiency, equation (18) is applied:

$$\eta = \frac{\sum P_{\text{op},k} \Delta t_k}{\sum P_{\text{true,mp},k} \Delta t_k} 100\% , \quad (18)$$

where $P_{\text{op},k}$ is the power delivered by the system at the operating voltage set by the algorithm at time step k;
$P_{\text{true,mp},k}$ is the "true" power at the MPP at time step k;
Δt_k is the duration of the time interval between measurements.

The obtained results with the specified settings show a maximum power point tracking efficiency of 97.88% over a one-year period and 99.83% over a single day, which is a good result given the low output power of the CdTe-based photovoltaic samples.

Conclusion

The implemented MPPT controller circuit based on a modern STM32G474 microcontroller made it possible to design a setup adapted to the fabricated laboratory samples of photovoltaic cells, with a voltage measurement resolution of approximately 5 mV and the capability to investigate samples with power levels ranging from tens of milliwatts to several watts. The maximum voltage and current ranges are 0 – 20 V and 1 μA – 3A, which is limited by the maximum power that can be dissipated by the transistor. Experimental studies have demonstrated high stability and measurement accuracy under varying conditions. The mathematical model developed in Python using the pvlib library and the incremental conductance MPPT algorithm made it possible to simulate the algorithm's performance under the conditions of the western region of Ukraine. The results indicate high tracking efficiency, reaching 97.88% over a one-year period and 99.83% over a single day, which is a very good result for small thin-film photovoltaic samples.

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РОЗРОБКА ТА МОДЕЛЮВАННЯ ВИСОКОТОЧНОГО MPPT-КОНТРОЛЕРА ДЛЯ ТОНКОПЛІВКОВИХ СОНЯЧНИХ ЕЛЕМЕНТІВ

Фотоелектричні перетворювачі сонячної енергії є провідним напрямом у сфері відновлюваних джерел енергії. Традиційні кремнієві фотоелементи забезпечили широке поширення технології, проте їх виробництво потребує значних енергетичних витрат та товстих пластин. Натомість тонкоплівкові перетворювачі другого покоління здатні ефективно поглинати сонячне випромінювання при значно меншій товщині поглинального шару, що робить їх перспективними для подальшого розвитку. Важливим елементом таких систем є контролер відстеження точки максимальної потужності (MPPT), який дозволяє забезпечити максимальну електрогенерацію в умовах змінного освітлення, температури чи часткового затінення.

У роботі представлено комплексне дослідження схемотехнічних та програмних рішень високоточного контролера відстеження точки MPPT, створеного на базі сучасного мікроконтролера STM32F407. Основною метою розробки було забезпечення можливості дослідження малопотужних тонкоплівкових фотоелектричних перетворювачів, зокрема на основі телуриду кадмію (CdTe), які характеризуються малими значеннями вихідних параметрів та потребують високої точності вимірювань. Реалізована установка дозволяє працювати з діапазоном напруги від 0 до ~20 В та струмів від 1 мкА до 3 А, що охоплює широкий спектр лабораторних зразків потужністю від десятків міліват до кількох ват. Точність вимірювання близько 5 мВ забезпечує коректне відстеження навіть за умов значних коливань зовнішніх факторів.

Експериментальні дослідження підтвердили високу стабільність роботи контролера та його здатність підтримувати точність вимірювань у змінних умовах навколишнього середовища. Для оцінки ефективності алгоритму Incremental Conductance було створено математичну модель на основі бібліотеки pvlib, яка реалізує п’ятипараметричну модель De Soto. Моделювання проводилося для умов західного регіону України, що дозволило врахувати реальні кліматичні та інсоляційні параметри.

Результати моделювання показали ефективність відстеження точки максимальної потужності на рівні 97,88% протягом року та 99,83% протягом одного дня. Такі показники засвідчують високу ефективність розробленої системи для дослідження та оптимізації роботи тонкоплівкових фотоперетворювачів малої потужності, а також підтверджують перспективність застосування запропонованого підходу для створення лабораторних стендів і навчальних установок.Отримані результати мають практичне значення для подальшого розвитку технологій тонкоплівкової фотовольтаїки та впровадження високоточних методів контролю в умовах змінної сонячної інсоляції.

Ключові слова: MPPT-контролер, тонкоплівковий сонячний елемент, CdTe, відновлювана енергія, високочутливі сенсори.

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