Metrol. Meas. Syst., Vol. 31 (2024), No. 2
DOI: 10.24425/mms.2024.149706

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

COMPARISON OF DIFFERENT TYPES OF MAXIMUM POWER POINT TECHNIQUES FOR PHOTOVOLTAIC SYSTEMS

Mariusz Ostrowski, Janusz Mroczka, Kamil Płachta

Wroclaw University of Technology, Faculty of Microsystem Electronics and Photonics, Chair of Electronic and Photonic Metrology, Bolesława Prusa 53/55, 50-317 Wroclaw, Poland (✉ mariusz.ostrowski@pwr.edu.pl)

Abstract

In this paper the comparison between different types of maximum power point search methods for the photovoltaic panels is made. The methods that represents each group of maximum power point techniques will be implemented in the software that allows to test behavior of the photovoltaic panel in different environment conditions including partial shading conditions. In this paper each of implemented methods was compared including time of convergence with the maximum power point, tracking error and differences in the energy obtained from photovoltaic during the simulation time. The algorithms was compared under both uniform lighting and partial shade conditions.

Keywords: maximum power point, partial shading conditions, comparison of MPPT methods, direct MPPT methods, indirect MPPT methods, hybrid MPPT methods.

1. Introduction

Photovoltaic (PV) panels are devices that directly convert solar energy into electrical energy. The amount of energy generated by the panels is mainly dependent on illumination and temperature, as well as the output voltage and current due to the non-linear characteristics of the PV panel. The relationship between voltage and current, including temperature and illumination changes, can be described using a one-diode model of a photovoltaic cell [1, 2], where I_{PH} is the photocurrent, R_S is the series resistor and R_{SH} is the shunt resistor (represents recombination losses mainly), and the diode D represents a semiconductor from which the photovoltaic cell is made.

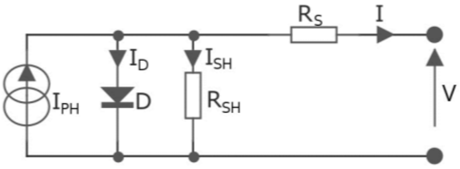

Fig. 1. One-diode equivalent model of a photovoltaic cell.

The one-diode equivalent model can be specified using (1),

$$I = I_{PH} - I_o\left(e^{\frac{V+R_S\,I}{nV_t}} - 1\right) - \left(\frac{V+R_S I}{R_{SH}}\right), \tag{1}$$

where, I_0 is the reverse saturation current, n is the ideality factor of the diode and $V_t = kT/q$ is the thermal voltage. The characteristic curves of the MSX-64 PV solar module, comprising of 36 series-connected PV cells, are presented in Fig. 2.

Article history: received January 16, 2024; revised February 26, 2024; accepted March 15, 2024; available online April 11, 2024.

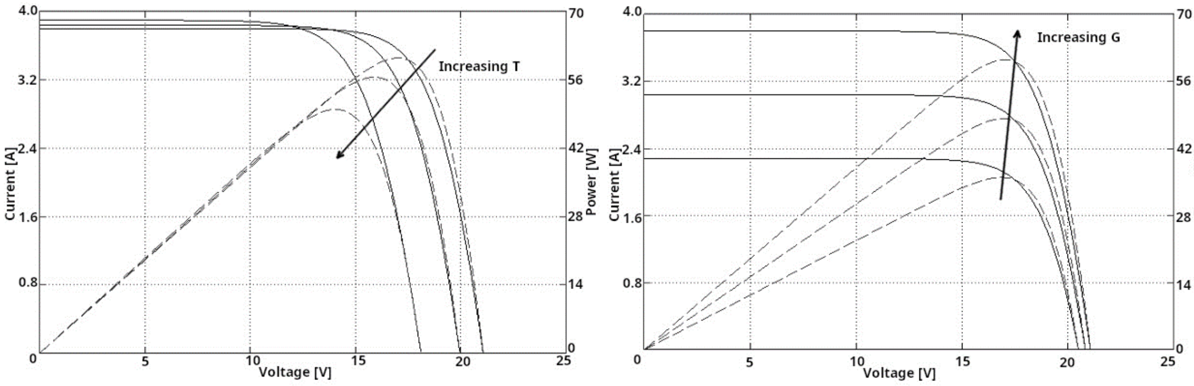

Fig. 2. Characteristics of PV module in different temperature and light conditions.

It can be observed that there is a single point where the output power is maximized, known as the *maximum power point* (MPP). The voltage and current values at the MPP depend on environmental conditions. The output voltage of the PV panel decreases with an increase in temperature, while the output current remains relatively stable. The reduction in voltage decreases the power at the MPP. Conversely, changes in illumination result in a different behavior of the PV panel. An increase in illumination leads to a corresponding increase in the output current of the PV panel, with minimal change in the output voltage. This increase in illumination ultimately boosts the output power of the PV panel at the MPP.

Typically, a solar panel comprises several solar modules connected in series to augment the output voltage of the panel. To mitigate the risk of damage to the panel due to partial shading or irregular illumination, bypass diodes are utilized. Usually, each module incorporates two or three diodes. The presence of bypass diodes allows for alterations in the characteristics of a PV panel under irregular illumination [3, 4], especially with the use of solar tracking systems [5], or module defects [6], as depicted in Fig. 3 for 3 series connected CL005-12 modules.

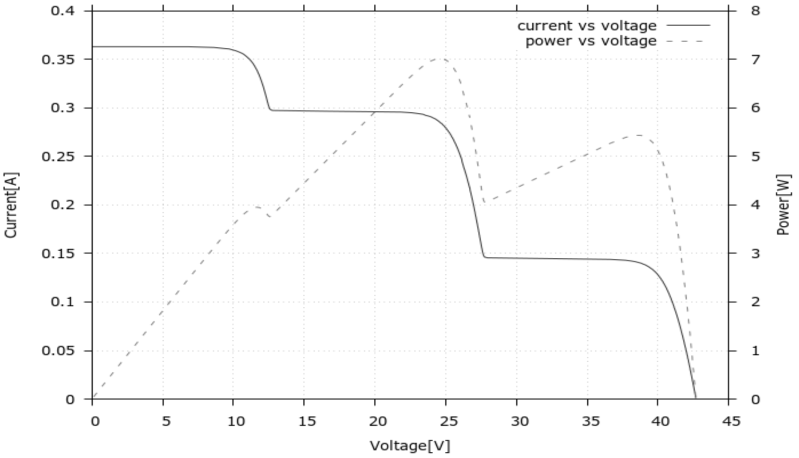

Fig. 3. Example characteristic of the solar panel illuminated irregularly.

It can be observed that there are multiple points on the characteristic curve where the output power is maximized [7]. These points are referred to as *local maximum power points* (LMPPs) [8]. The count of LMPPs depends on the number of bypass diodes and the complexity of the shadow pattern or illumination irregularity. Among these, only one point is the true maximum power point and is termed as the *global maximum power point* (GMPP).

Due to the variability in current and voltage values at the MPP, specialized devices called *maximum power point trackers* (MPPTs) must be employed to minimize energy losses generated by the PV panel. These devices ensure that the PV panel operates as close to the MPP as possible.

2. Maximum power point tracker

The MPPT is the DC/DC converter with control unit that allows tracking the position of voltage or/and current of maximum power point. In standalone systems the battery chargers are used in which the buck or boost converters are used. In grid connected systems microinverters and string inverters used the forward converter and power DC/AC inverter. In solar optimizers SEPIC or buck converter are used. The control unit can be analog or digital. Therefore, there are different types of MPPT methods in literature. They can be divided into four groups: the indirect, direct, genetic and population algorithms [9] and hybrid methods [10].

2.1. Indirect maximum power point tracking methods

Indirect methods, due to their simplicity, are often used in small-scale projects. These methods employ models or relationships between parameters to determine the optimal operating voltage of a photovoltaic panel.

2.1.1. Best constant voltage method

Directly powering devices from a photovoltaic panel is essentially impossible. This is due to the non-linearity of the characteristics of the photovoltaic panel itself, where the voltage value decreases under load. If the load is significant enough that the voltage drop doesn't ensure proper operation of the device connected to the PV panel, it will result in frequent device shutdowns, which in extreme cases could lead to its damage. Therefore, it seems necessary to use certain voltage stabilizing solutions at the device terminals [11]. The simplest solution is to use a battery and/or a DC/DC converter. During the circuit design, all voltage stabilizing system settings are established in such a way that the voltage of the PV panel is not lower than the voltage at the MPP. This can be achieved by using dedicated integrated circuit converters or by modifying standard converters to additionally ensure the operation of the PV panel at its optimal working point. This solution results in the panel operating close to the MPP. However, it is essential to remember that the voltage at the MPP changes with variations in temperature and sunlight intensity. Therefore, it would be necessary to adjust the device settings to respond to changes in these parameters.

The hardware implementation of this method can be achieved using the circuit shown in Fig. 4, by providing the appropriate reference voltage value to the V_{ref} input.

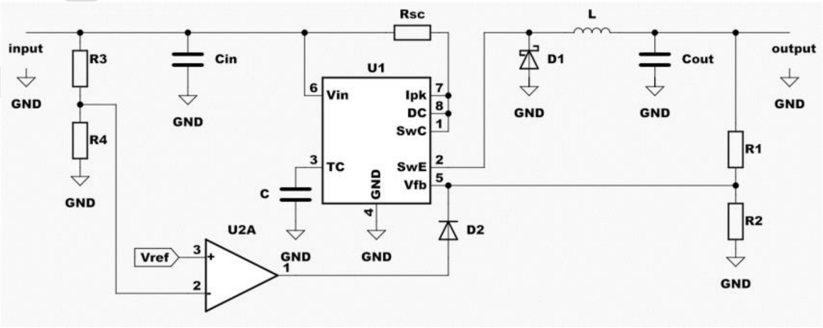

Fig. 4. Example of modifying a regular voltage step-down converter MC34063 (U1) by adding operational amplifier (U2A) enabling the implementation of the maximum power point tracking algorithms.

2.1.2. The open circuit voltage or short-circuit current divide method

The voltage at the MPP is directly proportional to the open-circuit voltage. It is a constant for a specific PV panel [9]. This fact can be utilized to create a simple method that extends the capabilities of the best constant voltage method by providing automatic reference voltage regulation. Usually, a microcontroller is used for this purpose.

The algorithm starts by measuring the open-circuit voltage. Next, the calculation of the voltage value for the MPP is performed based on the equation [9]:

$$V_{MPP} = k_v \cdot V_{OC} \ , \tag{2}$$

where k_v is a proportionality coefficient with a value ranging from 0.7 to 0.9, depending on the panel used [9]. After determining the voltage value at the MPP, the algorithm sets a new reference value for the DC/DC converters. For measuring the open-circuit voltage, it's necessary to disconnect the panel from the converter. This leads to energy losses and requires additional electronic circuits.

There are many modifications to this method. Instead of measuring the open-circuit voltage, one can measure the short-circuit current. The current at the MPP is directly proportional to the short-circuit current. The value of the proportionality coefficient falls within the range of 0.8 to 0.9, depending on used PV panel [9]. Another modification involves using an additional PV cell representing the entire PV panel. This approach eliminates the need to disconnect the panel, resulting in reduced energy losses. It's important to note that the accuracy of this method depends on selecting the proportionality coefficient and the frequency of its updating, as it changes over time.

2.2. Direct maximum power point tracking methods

Direct methods exhibit better parameters than indirect methods. They require measuring both the voltage and current of the PV panel for proper operation, and their regulation usually necessitates the use of a microcontroller. Algorithms in this category do not require prior knowledge about the PV panel.

2.2.1. Perturb and observe method

The perturb and observe method is one of the most commonly used techniques for finding the MPP due to its simplicity and reliability under uniform illumination conditions. The algorithm's principle is based on momentarily changing the voltage and observing the power level at the output of the PV panel. If the voltage change results in an increase in power, the new operating point derived from this change becomes the current operating point. If the disturbance causes a decrease in power, the algorithm returns to the previous operating point, and the disturbance direction is reversed. There are many modifications to this method. When the algorithm approaches the vicinity of the MPP, any further voltage change will result in reduced power. The algorithm operates by oscillating near the MPP of the PV panel [18]. The basic version of the algorithm controls the duty cycle of the voltage converter [12]. The operational principle remains exactly the same. If an increase in the duty cycle leads to an increase in the PV panel's power, the altered coefficient becomes the new coefficient. The algorithm continues to adjust the duty cycle by the same value and in the same direction. However, if the power decreases, the direction of the coefficient change is reversed. The simplest modification to the perturb and observe algorithm involves changing the fixed disturbance step to a variable one. This results in faster convergence and reduced oscillations near the MPP. Another modification of the algorithm involves using a PID controller to regulate the duty cycle for better converter response to rapid changes in irradiance intensity [13].

There is also an analog version of this algorithm known as force oscillation method. This method involves perturbing the operating point of the PV panel with a low-frequency and low-amplitude signal. If the current operating point is to the left of the MPP, the disturbances caused by the oscillations will be in phase with the modulating signal. If the operating point is to the right of the MPP, the power change is in antiphase with the modulating signal. When the operating point is at the MPP, the power change due to forced oscillations is close to zero, and the frequency of changes is twice that of the forced signal frequency.

The drawback of the perturb and observe method is its slow convergence towards the MPP. Additionally, if there's an increase in irradiance intensity during perturbations, and the perturbation direction was opposite to the MPP, the algorithm might start tracking an incorrect point, leading to prolonged search times. This issue becomes particularly apparent in rapidly changing sunlight conditions. Furthermore, this algorithm is unable to track the global MPP.

2.2.2. Incremental conductance method

Similar in operation to the perturb and observe method is the incremental conductance method. This method utilizes the fact that the instantaneous conductance is equal to the incremental conductance [9, 14]:

$$-\frac{I_{PV}}{V_{PV}} = \frac{dI_{PV}}{dV_{PV}}\,. \tag{3}$$

Additionally by analysing the derivative of the equation, it can be observed that $dI_{PV}/dV_{PV} < 0$ for voltage below the voltage at the MPP, $dI_{PV}/dV_{PV} = 0$ at the MPP, and $dI_{PV}/dV_{PV} > 0$ for voltage above the voltage at the MPP.

An undeniable advantage of this method is its ability to accurately track the MPP even in rapidly changing lighting conditions, unlike the perturb and observe method. Furthermore, it is characterized by lower power disturbances after reaching the MPP. However, this doesn't change the fact that the incremental conductance method is unable to track the global MPP.

2.2.3. Evolutionary and population methods

Another group of direct control methods consists of evolutionary and population-based algorithms [15, 16, 18]. They utilize mechanisms observed in nature to achieve the best possible outcome for a given set of solutions. This group includes genetic algorithms, particle swarm optimization, cuckoo search, and others.

Genetic Algorithms (GAs) are a computational method inspired by the principles of natural selection and genetics [17]. They are used for optimization and problem-solving in various fields. GAs simulate the process of natural selection by evolving a population of potential solutions (represented as individuals or chromosomes) over successive generations [18]. The basic concept involves creating an initial population of potential solutions to a problem. These solutions then undergo operations such as selection, crossover (recombination), and mutation to produce new offspring in subsequent generations. Solutions that better fit the problem's criteria are more likely to be selected and pass their genetic material to the next generation. This iterative process continues until a satisfactory solution or an optimal solution to the problem is found.

Particle Swarm Optimization (PSO) is a computational method inspired by the social behavior of birds flocking or fish schooling [20, 21]. In PSO, a population of candidate solutions, called particles, moves around in the search space to find the optimal solution to a given problem. Each particle adjusts its position based on its own experience (personal best) and the collective experience of the entire group (global best). By iteratively updating their positions and velocities according to these experiences, particles converge towards an optimal solution over successive iterations. PSO is widely used in optimization and problem-solving tasks across various fields due to its simplicity and efficiency in finding solutions within complex search spaces.

Cuckoo Search is a nature-inspired optimization algorithm that draws its principles from the breeding behaviour of cuckoo birds [22, 23]. The basic concept of Cuckoo Search involves the behaviour of cuckoo birds in reproduction, particularly the method of laying eggs in the nests of other bird species. In the optimization algorithm, these birds' behaviour is simulated to solve problems by creating new solutions from existing ones. The process begins with a population of solutions, represented as nests in the algorithm. Cuckoos lay eggs in these nests, representing new potential solutions. Afterward, the algorithm evaluates the quality of these new solutions. Solutions with higher fitness (better solutions) are retained, while the lower-quality ones are discarded. The nests are then modified through a process of random exploration and local searches to enhance their quality. Cuckoo Search with Levy Flight [24] is an modification of optimization algorithm that combines the Cuckoo Search method with Levy Flight behaviour. The Levy Flight pattern involves using probability distributions, specifically the Levy distribution, to determine step sizes or distances during the search for optimal solutions. This distribution pattern enables the algorithm to introduce greater randomness and more extensive exploration in the search space, potentially allowing the algorithm to escape local optima and explore a wider range of solutions.

All evolutionary and population-based methods can be implemented using variable step size perturb and observe method, which makes their implementation less complicated. Undoubtedly, the advantage of these methods is their ability to track the global MPP.

2.3. Hybrid maximum power point tracking methods

Another group of MPP tracking methods are hybrid methods [25]. These methods combine different advantages and strategies from various algorithm groups, aiming to improve the parameters and effectiveness of these methods. By integrating different techniques, hybrid methods can achieve better results by leveraging the strengths of individual algorithms while minimizing their weaknesses. This approach allows for the creation of more efficient and adaptable solutions to optimize the operation of PV systems.

2.3.1. Constant step search method

In this method, the entire voltage range of the PV panel is divided into multiple subsets. The number of subsets is determined based on the knowledge of the PV system designer. An perturb and observe algorithm is activated relative to the center of each subset. As a result of the algorithm's operation, a set of solutions is obtained, and the solution with the highest power becomes the chosen solution. Subsequently, the perturb and observe algorithm operates relative to this point. The entire process is repeated periodically to ensure the algorithm operates at the global MPP [26]. The accuracy of tracking largely depends on the designer's knowledge. Having too many subsets slows down the search for the global MPP. Conversely, having too few subsets may lead to tracking a local point. This approach does not differentiate between working conditions in partial shading and uniform illumination, potentially leading to power losses due to the power curve search algorithm.

2.3.2. Multiple division of open circuit voltage

In this method, similar to the previous one, the entire voltage range is divided into multiple subsets, with the difference being that the segmentation of the curve is not into subintervals of constant width. According to the method's assumptions, dividing the open-circuit voltage using (2) enables the calculation of the MPP. If this point becomes the starting point of the perturb and observe algorithm after several disturbance cycles, the correct MPP will be reached. If we repeat the segmentation according to (2) multiple times and, for each resulting point, initiate the perturb and observe algorithm, a set of solutions will be obtained. From this set, one point with the highest power becomes the starting point for the perturb and observe method, ensuring the PV panel operates at the MPP [27]. The entire procedure must be repeated periodically to respond to changes in shading distribution. Similar to the previous method, this approach does not differentiate between working conditions in partial shading and uniform illumination, potentially leading to power losses due to the power curve search algorithm.

2.3.3. Adaptive computational method based on module temperature

In this innovative method developed by Mariusz Ostrowski, the relationship from the open-circuit voltage division method of the PV panel, (2), is utilized. The position of each local MPP can be calculated using the equation:

$$V_{LMPPn} = \sum_{n=1}^{N} k_v \, V_{OCn} \,, \tag{4}$$

where V_{LMPPn} is the nth local MPP, and N represents the number of PV modules. If we also take into account the relationship between temperature and the open-circuit voltage value, as depicted in Fig. 2, and create a correlation curve, the value at each of the local points can be determined using the equation:

$$V_{LMPPn} = \sum_{n=1}^{N} k_T \;\; T_{amb} - T_{PV} \;\;, \tag{5}$$

where $k_T$is the adaptive correlation function updated based on the actual MPP and the module temperature [28]. After determining all possible MPPs, the algorithm checks each of them. For the point with the highest power, the perturb and observe algorithm is activated. There exists a modification to this method by incorporating an additional solar radiation sensor [29]. This addition allows for verification of whether the panel operates under partial shading or uniform illumination conditions. In this modification, a relationship derived from Fig. 2 is utilized. If the product of the current calculated based on the measured illumination and the adaptive correlation coefficient of illumination, and the voltage calculated based on the temperature and the adaptive correlation coefficient of temperature at the MPP, differs from the measured value at this point, the PV panel is operating under partial shading. Consequently, the curve searching algorithm described at the beginning is initiated. If not, the panel is operating under uniform illumination, and the perturb and observe algorithm is initiated based on the calculated point. The key advantage of this method is its speed, as it determines potential MPPs through calculations without altering the operating point of the PV panels. Additionally, the utilization of adaptive coefficients enables the connection of various PV modules. The sole responsibility of the system designer lies in inputting the quantity of PV modules in series into the algorithm.

2.4. Summary of maximum power point tracking methods

Various methods of tracking the MPP of PV panel are characterized by various properties applicable in specific technological solutions. The above methods have been divided based on different characteristics, such as dependency on the used PV panel or the ability to track the global MPP. The comparison of methods and their parameters is presented in Tab. 1.

Tab. 1. Comparison of maximum power point techniques.

MPP method	Panel dependence?	Real MPPT?	Measured values	Is it possible to track GMPP?
Best constant voltage method	Yes	No	none	No
The open circuit voltage or short-circuit current divide method	Yes	No	voltage or current	No

Perturb and observe method	No	Yes	voltage and current	No
Incremental conductance method	No	Yes	voltage and current	No
Cuckoo search method	No	Yes	voltage and current	Yes
Particle swarm optimization	No	Yes	voltage and current	Yes
Constant step search method	No	Yes	voltage and current	Yes
Multiple division of open circuit voltage	No	Yes	voltage and current	Yes
Adaptive computational method based on module temperature	No	Yes	voltage, current and temperature	Yes

Summing up, the application of specific methods has its consequences. The simplest indirect methods cannot ensure the operation of the PV panel at the MPP. Direct methods, albeit more complex, are capable of operating at this point; however, they may not guarantee tracking the global maximum during partial shading. Evolutionary or population-based algorithms as well as hybrid ones solve this issue, but due to their complexity, they are slower.

3. Problem of overloading electrical grids due to photovoltaic installations

The increasing number of PV installations is beneficial for the natural environment. The amount of emitted greenhouse gases decreases because electricity is generated by PV installations. However, this solution also has its negative impact, especially for small prosumer installations. During the afternoon on sunny days from spring to autumn, the high power generated by the installations leads to power grid overloads. This manifests in the voltage exceeding the permissible standards for a given country. The impact of PV installations on voltage levels in Poland - TN-C-S power supply system - can be observed in Fig. 5 and 6.

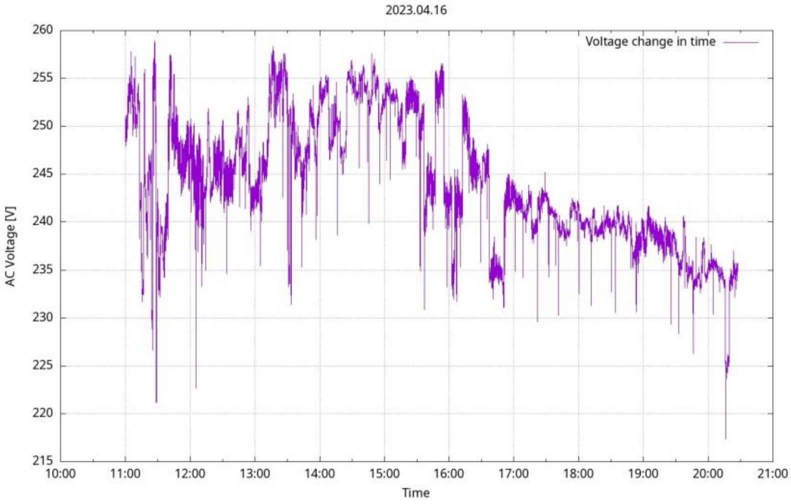

Fig. 5. Voltage waveform measured on one of the three phases made on April 16,2023 using the Agilent 34461A multimeter.

In Fig. 5, the voltage profile in the power grid is depicted for one of the phases. The measurement was taken using an Agilent 34461A multimeter on April 16, 2023. The graph shows that during the measurement, the voltage value exceeded the maximum value specified in the standards multiple times. This resulted in a decrease in the efficiency of the PV installation due to frequent inverter shutdowns. Hence, from the perspective of a PV installation, it is crucial to resume full electricity production as quickly as possible after inverter shutdown. This provides an opportunity to increase energy production.

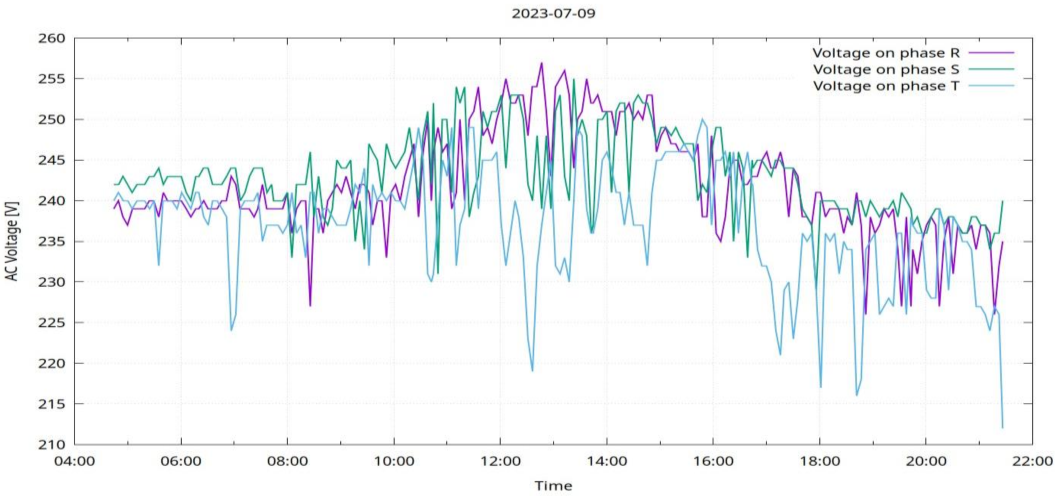

Fig. 6. Voltage waveform on each of tree phase reported by Sofar SF4ES005 inverter on July 9, 2023.

In Fig. 6, the voltage profiles on various phases recorded by the Sofar SF4ES005 inverter equipped with 5kW-peak PV installation on July 9, 2023, are presented. The graph illustrates that the issue of excessively high values is not limited to a single phase but extends to the other phases as well. Furthermore, a correct voltage value on one phase does not necessarily dictate the voltage value on the other phases.

To prevent power grid overload, inverters shut down the PV installation. In extreme cases, if power grid overload is detected, there can be a cascading shutdown of inverters, resulting in a sudden drop in power grid voltage. Such cascading shutdown can be observed in Fig. 5 at 11:30 and 16:50. After the inverters are shut down, there is a several-minute interruption in the production of electrical energy (depending on the inverter, the time may vary, but it is typically 5 minutes), after which the inverters test the state of the power grid. If the voltage on any phase exceeds 253V, another interruption occurs. If the voltage is correct, the inverter starts and transfers power from the PV panels to the power grid. Observing the voltage profiles on both graphs, it appears necessary to implement systems that enhance self-consumption of energy for PV installations in a prosumer system. This will lead to a reduction in voltage fluctuations and an equalization of interphase voltages.

To maximize production from PV installations and additionally reduce voltage fluctuations it is necessary to rapidly activate the PV installation once the voltage stabilizes below the permissible level. Therefore, an essential parameter for the inverter's operation is the speed and accuracy in tracking the MPP.

4. Simulation results

There are many solutions that allow testing MPP algorithms under specified lighting conditions [30]. The simulations were proved in the software created by Mariusz Ostrowski [31]. It allows to run MPP tracking algorithms for the PV panel with the parameters and test conditions defined in the simulation. It is important that each algorithm is tested in exactly the same conditions so that the results reflect the behavior of each tested algorithm as closely as possible. The software allows to read any shadow pattern from graphic file, for example from photo, and uses a photovoltaic panel model described in the Matlab script, therefore any type of photovoltaic panels can be simulated. All simulation were provided for computer model of PV panel consists of six series connected MSX60PV modules with one bypass diode for module. The basic value of irradiance was 1000W/m2 during all simulations. Ambient temperature was set to 25℃. Simulations were conducted for four different lighting scenarios: sudden decrease in irradiance from 1000W/m^2 to 500W/m^2, gradual shading progressively covering the panel, shading caused by a tree and shading caused by a building.

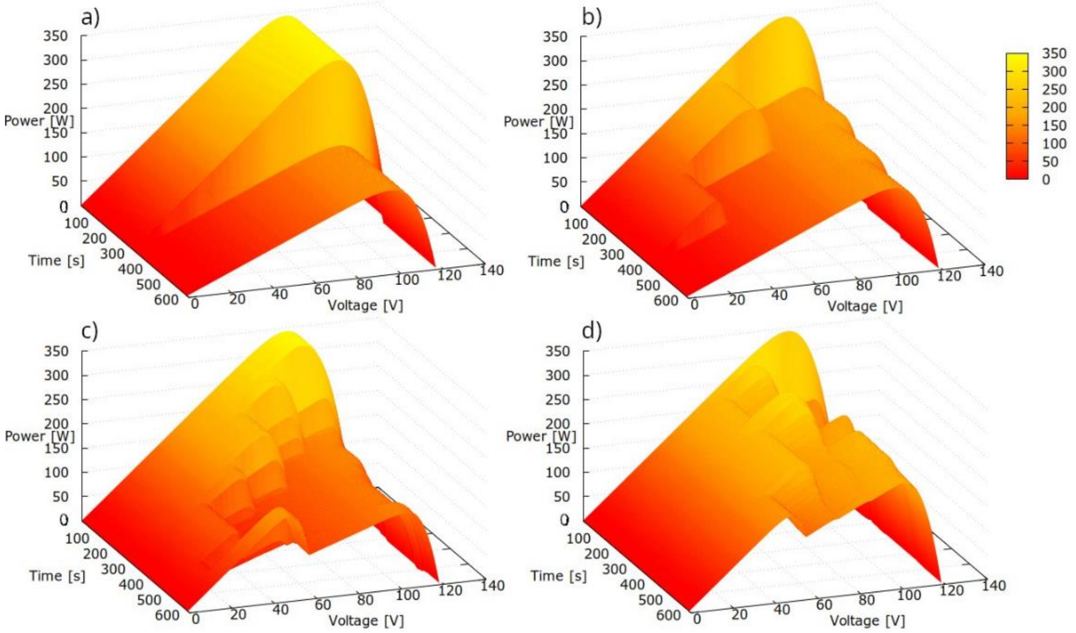

Fig. 7. The characteristics of the photovoltaic panel model used in simulations: a) sudden decrease in irradiance, b) gradual shading covering the panel, c) shading caused by a tree, d) shading caused by a building.

In Fig. 7, characteristics of the PV panel are presented for 4 operating scenarios of the PV panel. It can be observed that numerous local maximum power points appear on them. Real shadows, such as those caused by tree or building (Fig. 7c and 7d), lead to greater complexity in the characteristics compared to simple block shading (Fig. 7b). In Fig. 7a, no local maxima of power points are observed because the irradiance remains uniform throughout the simulation. At any given moment, only one point represents the global maximum power.

In Fig. 8, selected voltage curves for various types of Maximum Power Point (MPP) tracking algorithms for shading caused by trees are presented. As observed, the incremental and perturb & observe methods do not track the Global Maximum Power Point (GMPP). The exception is seen with population-based methods. Hybrid methods perform adequately, but in rapidly changing conditions, due to the drawback of disturbance and observation methods, they may start tracking the Local Maximum Power Point (LMPP). The computational method exhibited the best parameters.

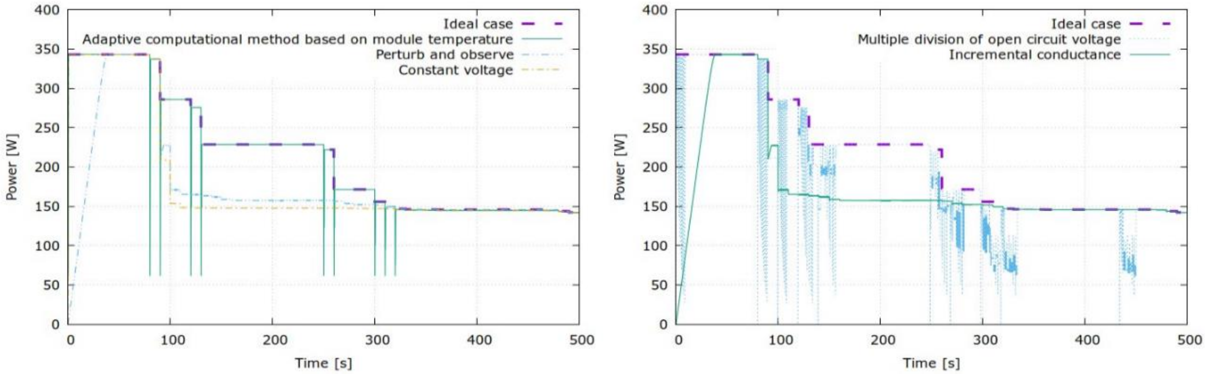

Fig. 8. Simulation results for the 3rd simulation scenario for various types of MPP search algorithms.

To more accurately assess the parameters of each method, a summary has been prepared in Table 2. The table presents the amount of energy obtained from the operation of each algorithm during the simulation period, as well as the time required to find the second MPP.

Tab. 2. Comparison of parameters of selected methods for maximum power point tracking for five different scenarios.

MPP method	1st scenario		2nd scenario		3rd scenario		4th scenario	
	Time [s]	Energy [Wh]	Time [s]	Energy [Wh]	Time [s]	Energy [Wh]	Time [s]	Energy [Wh]
Best constant voltage method	0[1.]	42.26	0[1.]	30.11	0[1.]	20.03	0[1.]	28.48
The open circuit voltage divide	0.1[1.]	40.63	0.1[1.]	28.78	0.1[1.]	27.62	0.1[1.]	28.14
Perturb and observe method	0.1	40.59	14.5	31.29	0.2[2.]	28.18	6.8[2.]	36.44
Incremental conductance method	0.1	41.44	7.1	31.73	0.2[2.]	29.04	6.1[2.]	36.63
Cuckoo search method	20	40.48	17.6[2.]	26.86	11.8[2.]	26.58	19.8[2.]	31.93
Particle swarm optimization	13.7	41.01	18.2	30.37	17.1	30.82	14.7	34.55
Constant step search method	6.9	41.54	7.1	30.94	7.7[2.]	29.56	7.6	35.25
Multiple division of open circuit voltage	7.8	41.08	6.3	30.7	10.1	31.06	10.8	35.93
Adaptive computational method based on module temperature	5.6	42.22	2.2	32.35	0.9	33.56	2.5	38.29

[1.] The algorithm did not track the MPP. [2.] The algorithm, under certain conditions, tracked a LMPP.

The achievable energy in 1st scenario is 42.3Wh, in 2nd scenario is 32.5Wh, in 3rd scenario is 34.09Wh, in 4th scenario is 38.67Wh. The table indicates that the computational method exhibits the best search parameters. Under uniform lighting conditions (1st scenario), indirect control methods, due to their operating principle, are the fastest and can lead to the highest energy gains, what can be evidenced by the Best Constant Voltage method achieving 99% of available energy. The condition is the properly chosen reference voltage value for a specific temperature. However, in non-uniform lighting conditions, these algorithms do not track the GMPP. Direct control algorithms such as P&O or IC retain good properties under uniform lighting conditions (respectively, 96% and 98% of the available energy), but do not track the GMPP under partial shading conditions. Population-based and hybrid algorithms, due to the higher number of comparisons, provided less energy than the other algorithms under uniform lighting conditions. An exception was the computational algorithm utilizing temperature measurement. Due to the preliminary calculation of LMPP, it performs significantly fewer comparison operations and provides 99% efficiency in obtaining available energy regardless of sunlight conditions. The measurement of the MPP tracking time also confirms that indirect methods exhibit the shortest tracking time. Simple indirect algorithms yield good results, but like previous, they do not track the Global Maximum Power Point (GMPP). Population-based algorithms, due to their high number of comparisons, have a longer tracking time compared to hybrid methods.

For a more precise analysis of the accuracy of tracking the MPP, a root mean square error (RMSE) analysis of the PV panel voltage was conducted. The data is presented in Tab. 3. The conducted analysis indicates that indirect control methods and simple direct control methods, such as perturb and observe or incremental conductance methods, exhibit the smallest root mean square error rate for uniform illumination (scenario 1). Evolutionary and population methods, as well as hybrid methods, show a higher tracking error due to the need to search the panel's characteristic after each illumination and temperature changes. Worth noting is the computational method utilizing the temperature measurement of the PV panel, which demonstrates a similar error rate to direct control methods.

Tab. 3. Comparison of root mean square error rate for global maximum power point voltage tracking for five different scenarios

MPP method	Root Mean Square Error rate of GMPP voltage [V]			
	1st scenario	2nd scenario	3rd scenario	4th scenario
Best constant voltage method	0.58	18.49	21.85	24.83
The open circuit voltage divide	2.72	18.64	21.35	24.57
Perturb and observe method	4.60	12.03	31.21	23.03
Incremental conductance method	3.24	9.82	29.34	23.70
Cuckoo search method	13.89	29.66	31.54	22.20
Particle swarm optimization	11.54	20.53	23.30	19.31
Constant step search method	8.59	17.86	28.03	18.04
Multiple division of open circuit voltage	11.67	17.5	21.45	16.72
Adaptive computational method based on module temperature	4.14	3.7	11.44	7.90

In scenarios 2 and 3, both indirect and direct control methods also exhibited smaller RMSE compared to hybrid, evolutionary, and population methods. This is due to the necessity of searching through a solution space, resulting in significant discrepancies between the voltage of the PV panel and the actual position of the MPP.

However, when comparing the obtained results from Tab. 2 and Tab. 3, it can be noticed that despite the higher RMSE, the energy obtained for hybrid and population methods is higher. The computational method stands out with the best parameters, as the search time through the solution space is minimal, requiring only one measurement of current and voltage for each potential LMPP, thanks to the utilization of temperature measurement of the PV modules.

5. Conclusions

Simulations unequivocally confirm that the adaptive computational method based on module temperature exhibited the best parameters for seeking the maximum power point. Thanks to the applied solutions, it demonstrated the highest speed and effectively tracked the global maximum power point. Other hybrid algorithms, similar to population-based algorithms, although seeking the global maximum power point, converged at a slower rate, resulting in lower energy generated by the PV panel. Direct control algorithms works correctly, allowing for the tracking of the maximum power point under uniform illumination. However, even with minor shading, they caused losses in generated power. Indirect control algorithms did not ensure the tracking of the maximum power point. Nonetheless, in simple setups such as portable PV systems primarily operating in summer at similar ambient temperatures, they might suffice, *e.g.* in simple power banks, the best constant voltage method can be used.

If the search time for the maximum power point is not important and we want to correctly search for the maximum power point, any of the hybrid algorithms, but also genetic and population algorithms, can be used. The cuckoo search algorithm is not a good solution in rapidly changing sunlight conditions, especially when shade is caused by plants.

To ensure maximum energy production and prevent grid overload in the event of sudden inverter shutdowns due to overproduction, it is necessary to employ algorithms that ensure the fastest convergence to the maximum power point. Computational methods supported by the P&O algorithm seem to be the most suitable in such scenarios. This method also exhibits the best tracking parameters for GMPP, considering the root mean square error analysis. It provides the highest speed in searching for the MPP, allowing the inverter to rapidly compensate for changes in grid voltage values. This is particularly important in rapidly changing sunlight conditions and when we want to resume production as quickly as possible when the inverter is disconnected due to too high or too low a grid voltage.

References

[1] Mesbahi, O., Tlemçani, M., Janeiro, F. M., Hajjaji, A., & Kandoussi, K. (2021). Sensitivity analysis of a new approach to photovoltaic parameters extraction based on the total least squares method. *Metrology and Measurement Systems*, 28(4), 751–765. https://doi.org/10.24425/mms.2021.137707

[2] Kamarzaman, N. A., & Tan, C. W. (2014). A comprehensive review of maximum power point tracking algorithms for photovoltaic systems. *Renewable and Sustainable Energy Reviews*, *37*, 585–598. https://doi.org/10.1016/j.rser.2014.05.045

[3] Ram, J. P., Babu, T. S., & Rajasekar, N. (2017). A comprehensive review on solar PV maximum power point tracking techniques. *Renewable and Sustainable Energy Reviews*, *67*, 826–847. https://doi.org/10.1016/j.rser.2016.09.076

[4] Goud, J. S., Kalpana, R., Singh, B., & Kumar, S. (2019). A Global Maximum Power Point Tracking Technique of Partially Shaded Photovoltaic Systems for Constant Voltage Applications. *IEEE Transactions on Sustainable Energy*, *10*(4), 1950–1959. https://doi.org/10.1109/tste.2018.2876756

[5] Lan, J. (2023). Development and performance test of a novel solar tracking sensor. *Metrology and Measurement Systems*, *30*(2), 289–303. https://doi.org/10.24425/mms.2023.144870

[6] Maziuk, M., Jasińska, L., Domaradzki, J., & Chodasewicz, P. (2023). Imaging methods of detecting defects in photovoltaic solar cells and modules: a survey. *Metrology and Measurement Systems*, *30*(3), 381–401. https://doi.org/10.24425/mms.2023.146426

[7] Chalh, A., El Hammoumi, A., Motahhir, S., El Ghzizal, A., Derouich, A., Masud, M., & AlZain, M. A. (2021). Investigation of Partial Shading Scenarios on a Photovoltaic Array's Characteristics. *Electronics*, *11*(1), 96. https://doi.org/10.3390/electronics11010096

[8] Bartczak, M. (2017). Partial Shading Detection in Solar System Using Single Short Pulse of Load. *Metrology and Measurement Systems*, *24*(1), 193–199. https://doi.org/10.1515/mms-2017-0016

[9] Salas, V., Olías, E., Barrado, A., & Lázaro, A. (2006). Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems. *Solar Energy Materials and Solar Cells*, *90*(11), 1555–1578. https://doi.org/10.1016/j.solmat.2005.10.023

[10] Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2023). A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. *Energies*, *16*(5), 2206. https://doi.org/10.3390/en16052206

[11] de Brito, M. A. G., Galotto, L., Sampaio, L. P., e Melo, G. de A., & Canesin, C. A. (2013). Evaluation of the Main MPPT Techniques for Photovoltaic Applications. *IEEE Transactions on Industrial Electronics*, *60*(3), 1156–1167. https://doi.org/10.1109/tie.2012.2198036

[12] Tajuddin, M. F. N., Arif, M. S., Ayob, S. M., & Salam, Z. (2015). Perturbative methods for maximum power point tracking (MPPT) of photovoltaic (PV) systems: a review. *International Journal of Energy Research*, *39*(9), 1153–1178. https://doi.org/10.1002/er.3289

[13] Pathak, D., Sagar, G., & Gaur, P. (2020). An Application of Intelligent Non-linear Discrete-PID Controller for MPPT of PV System. *Procedia Computer Science*, *167*, 1574–1583. https://doi.org/10.1016/j.procs.2020.03.368

[14] Motahhir, S., El Hammoumi, A., & El Ghzizal, A. (2020). The most used MPPT algorithms: Review and the suitable low-cost embedded board for each algorithm. *Journal of Cleaner Production*, *246*, 118983. https://doi.org/10.1016/j.jclepro.2019.118983

[15] Sreedhar, S., & Jagadeesh, D. (2016). *A review on optimization algorithms for MPPT in solar PV system under partially shaded conditions*. *IOSR Journal of Electrical and Electronics Engineering*, 23-32.

[16] Kermadi, M., Salam, Z., Eltamaly, A. M., Ahmed, J., Mekhilef, S., Larbes, C., & Berkouk, E. M. (2020). Recent developments of MPPT techniques for PV systems under partial shading conditions: a critical review and performance evaluation. *IET Renewable Power Generation*, *14*(17), 3401–3417. https://doi.org/10.1049/iet-rpg.2020.0454

[17] Harrag, A., & Messalti, S. (2015). Variable step size modified P&O MPPT algorithm using GA-based hybrid offline/online PID controller. *Renewable and Sustainable Energy Reviews*, *49*, 1247–1260. https://doi.org/10.1016/j.rser.2015.05.003

[18] Karami, N., Moubayed, N., & Outbib, R. (2017). General review and classification of different MPPT Techniques. *Renewable and Sustainable Energy Reviews*, *68*, 1–18. https://doi.org/10.1016/j.rser.2016.09.132

[19] Daraban, S., Petreus, D., & Morel, C. (2013, November). A novel global MPPT based on genetic algorithms for photovoltaic systems under the influence of partial shading. *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*. IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society. https://doi.org/10.1109/iecon.2013.6699353

[20] Ishaque, K., Salam, Z., Amjad, M., & Mekhilef, S. (2012). An Improved Particle Swarm Optimization (PSO)–Based MPPT for PV With Reduced Steady-State Oscillation. *IEEE Transactions on Power Electronics*, *27*(8), 3627–3638. https://doi.org/10.1109/tpel.2012.2185713

[21] Bollipo, R. B., Mikkili, S., & Bonthagorla, P. K. (2020). Critical Review on PV MPPT Techniques: Classical, Intelligent and Optimisation. *IET Renewable Power Generation*, *14*(9), 1433–1452. https://doi.org/10.1049/iet-rpg.2019.1163

[22] Ahmed, J., & Salam, Z. (2014). A Maximum Power Point Tracking (MPPT) for PV system using Cuckoo Search with partial shading capability. *Applied Energy*, *119*, 118–130. https://doi.org/10.1016/j.apenergy.2013.12.062

[23] Sarvi, M., & Azadian, A. (2021). A comprehensive review and classified comparison of MPPT algorithms in PV systems. *Energy Systems*, *13*(2), 281–320. https://doi.org/10.1007/s12667-021-00427-x

[24] Charin, C., Ishak, D., Mohd Zainuri, M. A. A., & Ismail, B. (2021). Modified Levy Flight Optimization for a Maximum Power Point Tracking Algorithm under Partial Shading. *Applied Sciences*, *11*(3), 992. https://doi.org/10.3390/app11030992

[25] Mohapatra, A., Nayak, B., Das, P., & Mohanty, K. B. (2017). A review on MPPT techniques of PV system under partial shading condition. *Renewable and Sustainable Energy Reviews*, *80*, 854–867. https://doi.org/10.1016/j.rser.2017.05.083

[26] Koutroulis, E., & Blaabjerg, F. (2012). A New Technique for Tracking the Global Maximum Power Point of PV Arrays Operating Under Partial-Shading Conditions. *IEEE Journal of Photovoltaics*, *2*(2), 184–190. https://doi.org/10.1109/jphotov.2012.2183578

[27] Patel, H., & Agarwal, V. (2008). Maximum Power Point Tracking Scheme for PV Systems Operating Under Partially Shaded Conditions. *IEEE Transactions on Industrial Electronics*, *55*(4), 1689–1698. https://doi.org/10.1109/tie.2008.917118

[28] Mroczka, J., & Ostrowski, M. (2014). A Hybrid Maximum Power Point Search Method Using Temperature Measurements in Partial Shading Conditions. *Metrology and Measurement Systems*, *21*(4), 733–740. https://doi.org/10.2478/mms-2014-0056

[29] Ostrowski, M. (2018, June). An Adaptative OCV and SCC-Based Maximum Power Point Tracking Method for Photovoltaic Panels in the Partial Shading Conditions. *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*. https://doi.org/10.1109/eeeic.2018.8493918

[30] Walczak, M., Bychto, L., Kraśniewski, J., & Duer, S. (2022). Design and evaluation of a low-cost solar simulator and measurement system for low-power photovoltaic panels. *Metrology and Measurement Systems*, *29*(4), 685–700. https://doi.org/10.24425/mms.2022.143067

[31] Mroczka, J., & Ostrowski, M. (2014). Photovoltaic array simulation technique for non-uniform insolation conditions. *Renewable Energy & Power Quality Journal*, (12), 1-5. https://www.icrepq.com/icrepq'14/296.14-Mroczka.pdf

Mariusz Ostrowski, received Ph.D. degree at the Wroclaw University of Science and Technology, Poland**.** Since 2012, he has been a lecturer at the Department of Electronic and Photonic Metrology at the Faculty of Electronics, Photonics and Microsystems of the Wroclaw University of Science and Technology. Currently, he conducts research related to maximizing energy production from photovoltaic panels and the quality of energy in the power grid where renewable energy sources operate.

Kamil Płachta received Ph.D. degree at the Wroclaw University of Science and Technology, Poland. He has been a member of the teaching and research staff at the Department of Electronic and Photonic Metrology since 2013. His current research interests include renewable energy sources, mainly on systems that tracks the apparent position of the Sun on the celestial sphere.

Janusz Mroczka is a Professor at the Wroclaw University of Science and Technology, Poland. Funder of the Polish school of electronic and photonic metrology, member of the Polish Academy of Sciences. He is director of the Department of Electronic and Photonic Metrology at the Wroclaw University of Science and Technology. His research interests include methodology of the cognitive process, algorithmization of the inverse problem, indirect measurements badly conditioned numerically, methodology of combining measurement data with different spatial resolution using deterministic and stochastic processing method