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DETERMINING PHOTOVOLTAIC ARRAY CONFIGURATIONS WITH REDUCED IMPACT OF PARTIAL SHADING ON ENERGY PERFORMANCE

Olexandr Shavolkin
Doctor of Technical Sciences, Professor*
ORCID: https://orcid.org/0000-0003-3914-0812
Hennadii Kruhliak
Senior Lecturer
Department of Power Systems Engineering
National University of Life
and Environmental Sciences of Ukraine
Heroiv Oborony str., 15, Kyiv, Ukraine, 03041
ORCID: https://orcid.org/0000-0003-2634-3856
Iryna Shvedchykova
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: shvedchykova.io@knutd.edu.ua
ORCID: https://orcid.org/0000-0003-3005-7385
Tetiana Bila
PhD, Associate Professor*
ORCID: https://orcid.org/0000-0002-5014-9052
Andrii Pisotskyi
PhD, Senior Lecturer*
ORCID: https://orcid.org/0009-0003-3761-2019
*Department of Computer Engineering
and Electromechanics
Kyiv National University of Technologies and Design
Mala Shyianovska str., 2, Kyiv, Ukraine, 01011

This work explores energy processes in the array of photovoltaic panels within an object's power supply system under dynamic modes of the partial-shading strip movement. The study aims to increase the energy productivity of a photovoltaic panel array in the power supply system at a local facility under partial shading conditions.

Based on climatic data, the methodology for modelling the movement of a cloud shading strip, taking wind direction into account, has been substantiated. The array model has been improved by introducing a partial-shading strip that moves in specified directions. That has made it possible to assess the influence of strip direction and speed on dynamic modes for selected panel configurations, based on their location and connection topology.

In accordance with the adopted array power, possible configurations with 16 photovoltaic panels, each of 655 W, have been determined. Modeling confirmed the complication of the trajectory of the global maximum power point under the conditions of shading strip movement. This manifests in the multiplicity of local maxima and in the unpredictable trajectory of the global maximum, which depends on the array configuration and the direction of strip movement.

It was established that the strip speed did not affect the performance. According to the simulation results, recommended configurations with minimal shading impact on energy performance were obtained when the strip moved along the prevailing wind direction. It was shown that the generation power along the prevailing directions of the shading strip relative to the average value in all directions of movement is not less than 96%. The trajectory of the global maximum is monotonic, so no special algorithms are needed to track the maximum power. This makes it possible, at a panel power of 655 W, to form array configurations with a total power in the range of 3.93–15.72 kW

Keywords: photovoltaic array configuration, shading strip movement, global maximum power trajectory

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1. Introduction

In 2023–2025, the use of renewable energy sources to power local facilities, in particular households, became not only technically feasible but also an economically viable solution. This is especially relevant in the context of energy instability, rising tariffs, and threats to centralized infrastructure.

The growing interest in photovoltaic (PV) systems is driven by the desire to reduce electricity costs and the desire to increase energy autonomy. The evolution of energy storage technologies, support for government programs, as well as increasing the efficiency of photovoltaic modules (PVMs) to 22–24%, have made photovoltaic systems (PVSs) attractive even in regions with moderate insolation.

However, the energy efficiency of PVSs remains vulnerable to external factors, the most important of which is the partial shading condition (PSC) because of clouds and surrounding objects (buildings, trees). Thus, partial shading caused by a chimney 2 meters high could lead to annual energy losses in the range of 2–12.5% [1]. In [2], it is stated that shading by clouds and trees could reduce the generation capacity of PVSs by up to 60%. Therefore, the issue of minimizing the impact of partial shading on the operation of photovoltaic arrays is relevant.

The maximum energy efficiency of a PVM array is enabled by the maximum power point tracking (MPPT) algorithms, which are implemented by MPPT controllers for a DC-DC converter at the input of a PVS inverter. With the same illumination of PVM in the array, its overall power characteristic

$P(U)$ has a monotonic character with a pronounced global maximum power point (GMPP). PSC leads to a violation of the monotonicity of the overall power characteristic $P(U)$ with the occurrence of multiple local maximum power points (LMPP) along with the global one. Under these conditions, ensuring maximum energy efficiency of a PVM array becomes more difficult. This predetermines the relevance of research aimed at improving the energy efficiency of a PVM array and minimizing power losses due to partial shading.

2. Literature review and problem statement

To date, several approaches to solving a PSC problem have been identified. One of the main ones is the search for an MPPT method that would ensure tracking of the global maximum under any conditions. MPPT controllers are rapidly improving. In this regard, they can be divided into conventional and advanced, based on paper [3]. Conventional ones cannot distinguish between local and global maxima, so their efficiency is relatively low. Metaheuristic optimization methods such as PSO (Particle Swarm Optimization) and CS (Cuckoo Search) [4] are more effective in conditions of partial shading. In the cited work, the assessment was carried out for different partial shading schemes that are static. There is no assessment of the dynamics of shading changes. Reducing the effect of partial shading in the case of sliding mode control, which is configured based on the PSO optimization method algorithm, was proposed in [5]. The study was performed with alternate changes in PVM radiation for 5 PSC scenarios. The authors limited themselves to considering an array with a series connection of 4 PVMs.

The above-mentioned and other methods for improving MPPT are very popular with developers and scientists. But they have not yet been widely implemented in real commercial inverters for PVSs. Most of the verification of these methods has been carried out within the framework of simulation tests.

The most common in commercial low-power inverters are modifications of the P&O (Perturb and Observe) algorithm as they provide high efficiency without a significant increase in the cost of components.

Another approach is associated with the weakening of the influence of partial shading. Thus, in work [6] it is noted that the influence of partial shading depends on the type of shading, shading scheme, and PVM connection configuration. However, the work is of a general nature. Random shading schemes were considered and analyzed only for certain configurations of a PVM array with higher values of the maximum power point.

In [7], a comparative analysis of the performance of SP (Series Parallel) and TCT (Total Cross Tied) PVM arrays under different shading schemes was performed. The results showed that under TCT, the PVM array generates more energy than under SP in most situations. Only static shading scenarios were considered: vertical and horizontal. Under static scenarios, the shadow is stationary, and its orientation changes slowly throughout the day. A similar study comparing series, parallel, and TCT configurations of a six-PVM array under partial shading conditions was conducted in [8]. The parallel configuration was preferred. The recommendation is limited and applies to a specific six-PVM array under static shading. The characteristics for the selected shading scenarios are determined.

An analysis of the impact of partial shading for a 6×6 PVM array is reported in [9]. Series-parallel SP, fully cross-linked TCT, bridge BL (Bridge Linked), and honeycomb HC (Honey Comb) PVM connection schemes were considered. Different shading schemes were explored: long-narrow (LN), short-narrow (SN), long-wide (LW), and short-wide (SW) with variable radiation intensity. It is shown that the least impact of partial shading is achieved for the TCT configuration. However, this applies to a specific PVM array under the limitation of static shading schemes and shading direction.

In [10], the reconfiguration of a 4×4 array was considered with the analysis of 19 variants of static configurations. Their performance was analyzed for 18 different shading schemes. It is argued that static reconfiguration methods are predictable, simple, and economical. They are best suited for cases with static or predictable shading conditions.

The efficiency of 15 static configurations of a 5×5 PVM array is evaluated in [11] under different shading schemes. The results are limited to the characteristics of all configurations to select the optimal configuration under specific static shading conditions. An improved PVM configuration in the array is proposed in [12] to dissipate the shading effect. The power increase compared to conventional configurations is 1.55–28.21%. Although six shading scenarios are considered, only static shading modes are considered.

To reduce the problems associated with shading, a new Noval Grecian Reconfiguration (NGR) for a 4×4 array is proposed in [13]. The NGR scheme increases and stabilizes the power generation in each row of the array. However, the results are limited to the 4×4 configuration. The efficiency is confirmed for four shading schemes in static. In [14], an original scheme of the PV array configuration based on the chessboard moves is described, which pursues the goal of uniform shading distribution between PVMs under partial shading of the array. Such a PVM arrangement forms a square array. However, this mainly concerns the static shading mode.

In [15], a "black widow" reconfiguration method with a reduced number of switches is proposed to mitigate the impact of partial shading of the arrays. Three arrays of 2×4, 5×5 and 9×9 are considered under static and dynamic partial shading conditions. The proposed methodology effectively reduces the difference in currents between rows of the photovoltaic array in a short period of time with a higher calculation speed and provides electrical switching of modules. However, the dimensions of the arrays are specific.

In [16], a hybrid algorithm HWSA (Hybrid Weighted Superposition Attraction) is proposed. The tracking of the maximum power point under conditions of uniform shading, partial shading, and dynamic illumination is considered. The universality of the algorithm is declared while the movement of the partial shading strip in different directions is not considered directly.

Most studies are based on the construction and improvement of mathematical models using MATLAB/Simulink (MathWorks, Inc., USA). A PVS under shading conditions is considered in [17]. The dynamic mode of radiation change for the PVM is investigated when the cloud quickly moves along the array. However, the radiation level (1000, 800, 600, 400 W/m^2) for all PVMs of the matrix changes simultaneously. Radiation gradations between PVMs in the matrix are not considered. Three scenarios with different PVM radiation (1000, 800, 600 W/m^2) in the array are also considered. In fact, these are three static shading modes. Only 4 PVMs are used in the matrix, connected in series-parallel, which does not allow the results to be extended to a different number of PVMs.

In [18], the results of testing MPPT algorithms in MATLAB/Simulink for dynamic mode with a jump-like transition from partial shading to uniform (maximum) illumination of the array are reported. 3 schemes of uniform radiation and one with uneven radiation at variations of 400, 200, 1000 and 200 W/m^2 are considered. This is a certain simplification of the shading process.

In [19], modeling using MATLAB/Simulink was used to verify the effectiveness of the proposed MPPT method under shading conditions. An array of 8 PVMs was composed into two branches of 4 PVMs. Four shading schemes (patterns) with radiation from 200 W/m^2 to 1000 W/m^2 were used. The study was performed in statics for each of the shading schemes, and then additionally, in the case of changing the shading pattern, with an interval of 0.4–1.2 seconds. The modeling methodology is somewhat extreme for assessing the tracking speed, accuracy, and stability of the MRRT. There is no justification for the shading schemes and radiation gradations for PVM.

Thus, in the case of using commercial hybrid inverter solutions in PVSs, the capabilities of MPPT are limited by the algorithms laid down by the manufacturer. The same applies to the possibilities of changing the array configuration (PV connection scheme) during operation, which requires additional switching devices with an appropriate control scheme. At the same time, it seems appropriate to determine the array configuration that minimizes the impact of partial shading on its power and MPPT operation, taking into account the PVS power and climatic conditions for the location of a local object (LO). In the case of the array being located on the roof of a building, the main factor of shading is the shadow strip from clouds that moves in accordance with the wind direction. However, the issues of the influence of the dynamics of the shading process on the array operation mode and MPPT operation are currently insufficiently studied and require additional research.

This necessitates the need to solve the task of determining photovoltaic array configurations with minimal impact from partial shading on the energy efficiency of LO PVS. The complexity in evaluating the solutions relates to the need to improve the mathematical model of an array of panels at their different configurations, taking into account the movement of the shading strip. Such a model, together with the methodology for determining the recommended configuration of a PVM array, could lay foundation for designing LO PVM under specific conditions.

3. The aim and objectives of the study

The purpose of our study is to determine configurations of a photovoltaic array with minimal impact of partial shading on the energy efficiency of a local facility's PVS. The proposed recommendations and solutions for the array model under shading conditions provide the opportunity to choose the configuration of a PVM array when designing PVSs for local facilities.

To achieve the goal, the following tasks were set:

– to compile possible array configurations with the number of PVMs according to the adopted PVS power;

– to substantiate the methodology for modeling the movement of the shading strip, taking into account a wind direction;

– to build a mathematical model of the array and assess the influence of the direction and speed of the strip movement for the selected configurations while determining configurations with maximum energy efficiency under partial shading conditions;

– to define, according to the recommendations received, array configurations for different numbers of PVMs and carry out modeling with an assessment of indicators, to compile general recommendations for array configurations for different PVSs.

4. The study materials and methods

The object of our study is the energy processes in a PVM array of a facility's power supply system under dynamic movement modes of a partial shading strip. The subject of the study is to determine the configuration of a panel array that minimizes the impact of partial shading under specific conditions.

The principal hypothesis assumes that under conditions of partial shading by clouds, the shading strip's direction of movement is decisive. A decrease in the PVM array productivity could be minimized by choosing the configuration of the array in accordance with the prevailing wind direction for the PVS location. In this case, static shading can be considered as a special case of movement at low speed.

Generally accepted methods of analysis of electrical circuits were used. An approach based on the analysis of specific configurations was adopted with further generalization of the results to compile recommendations. Possible PVM array configurations for connection to a specific commercial inverter were considered, which were compiled according to the adopted PVS power with specific PVMs. The possibilities of their location along the slope of the roof of the house were also taken into account.

The starting point is that in the case of location on the roof and the absence of shadow from other objects, the main factor determining the shading of PVM is the movement of clouds. The hypothesis of the independence of PVM performance indicators from the wind speed and, accordingly, the speed of movement of the shading strip was accepted. In this case, the direction of movement of the shading strip is decisive for PV indicators. According to reference data, in the summer months (June, July, August) for the Kyiv region, mainly northern and western wind directions occur. In July, the repeatability for the western direction is 20%, for the northern – 18%, and north-western – 18%.

The justification of the methodology for modeling the movement of the shading strip taking into account the wind direction is based on the generally accepted assumption that within a separate PVM the value of solar radiation corresponds to the average value and is constant. The basic gradation of solar radiation for individual PVMs during the movement of the shading strip is taken to be 12.5% of the maximum on a clear summer day. Depending on the speed, the gradation can decrease almost to 0. The initial data on the level of cloudiness, the range of changes in solar radiation and wind speed values are taken on the basis of reference statistical data for the location of LO (Kyiv). In this case, the average number of clear days in summer is from 2.8 to 4.9, and cloudy days – from 5.8 to 6.3. Comparison of the values of energy generated by PVM W_{PVM} on a clear summer day for the Kyiv region with the average monthly value (0.7–0.75) W_{PVM} shows that a characteristic phenomenon is slight cloudiness. According to [20], the average cloudiness in summer is 25–35%. That is, the shading is not constant but changes with the passage of clouds. This creates conditions for partial shading of a PVM array when the strip moves in accordance with the wind direction.

According to the adopted maximum PVS power, 12 possible configurations of arrays with 16 PVMs and the arrangement of panels in 1–4 rows according to the corresponding connection schemes were compiled. The configurations were determined for the limiting characteristics of the inverter and the panel array in terms of current and voltage. The use of modern monocrystalline PVMs of the Longi LR7-72HVH-655M type [21] and a hybrid high-voltage inverter of medium power SUN-8K-SG01HP3-EU-AM [22] was considered.

The simulation was performed using MATLAB/Simulink. A simplification was adopted regarding the same temperature of PVMs in the array. The simulation of the passage of a partial shading strip through a PVM array is given by a shading template that determines the radiation for each PVM with a given gradation of values. For the simulation, each of the templates is linearly interpolated to 48 frames. The simulation is performed by shifting the frame by one line with the calculation of the power at the point of the global maximum GMPP. To check the influence of the speed of the shading strip passing through a PVM array on the total generation, the template arrays were scaled (compressed) to 1 (normal speed 1x), 1/2 (speed 2x), 1/3 (speed 3x), 1/4 (speed 4x). As a result of the simulations, GMPP motion trajectories were constructed along *P*(*U*) curves with averaging of total energy generation for different directions and speeds of the shading strip movement through the PVM array.

All configurations in the array of 16 PVMs were considered under the same conditions for different wind directions, which ensures the objectivity of the comparison of the results. In this case, the angle of the direction of movement was set by a range of values from 0° (north-south direction of movement) to ± 76°.

According to the simulation results, the generation power of a PVM array and the impact on the operation of MPPT according to the GMPP trajectory were estimated. Based on this, recommendations were compiled to limit the number of series-connected PVMs in a row to four and to limit the number of rows.

According to the recommendations, the implementation of two-row and three-row arrays with the number of PVMs from 6 to 24 and the corresponding value of the maximum power of the array was considered. This to some extent provides an opportunity to generalize the proposed approach with the determination of PVM array configurations to minimize the impact of partial shading under the dynamics of strip movement.

5. Results of research on increasing the energy efficiency of an array for a photovoltaic system at a local facility

5. 1. Determining possible panel configurations for a photovoltaic system of accepted power

The climatic conditions in the Kyiv oblast (Ukraine) in summer are characterized by temperature and radiation parameters that are close to the standard NOCT (Nominal Operating Cell Temperature) mode [20]. This allows the use of typical models of PVM performance without significant corrections for local climatic deviations. To obtain the maximum possible generation power P_{PVM} = 10400 W, 12 possible configurations of PV arrays with 16 PVMs were compiled, taking into account the output currents and voltages of PVMs and the inverter (Fig. 1): five serial configurations in 1, 2, and 4 rows; seven serial-parallel configurations in 2 and 4 rows.

The structure of the MATLAB/Simulink model of the 16S-1P_3 (4 × 4) PV array series configuration is shown in Fig. 2.

All PVMs are connected in series in one line (string). The current of the photovoltaic array is equal to the module current, and the voltage of the array is the sum of the voltages of individual PVMs. The common outputs of the array are connected to the data calculation and processing module.

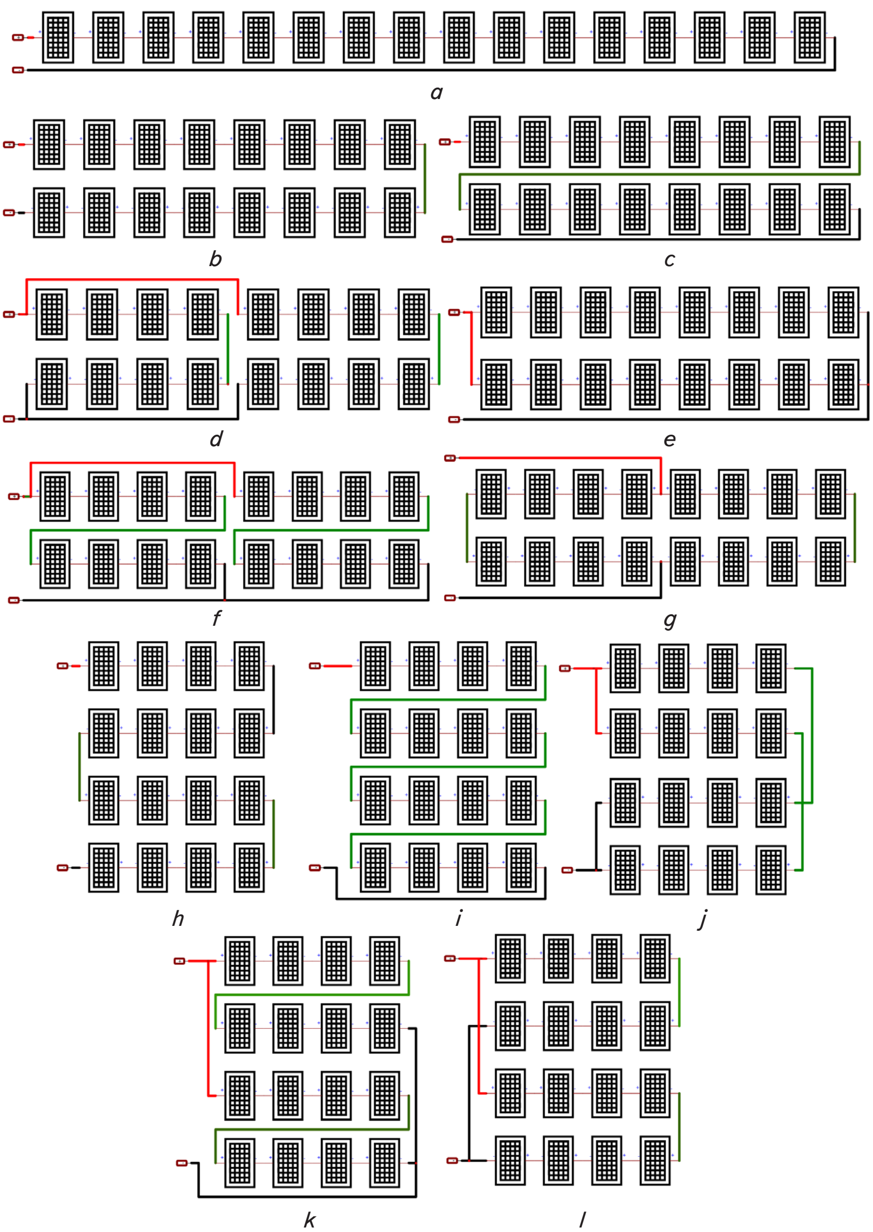

Fig. 1. Array configurations of 16 photovoltaic panels: *a* – 16S-1P_1; *b* – 16S-1P_2; *c* – 16S-1P_3; *d* – 8S-2P_3; *e* – 8S-2P_1; *f* – 8S-2P_2; *g* – 8S-2P_4; *h* – 16S-1P_3; *i* – 16S-1P_4; *j* – 16S-1P_5; *k* – 16S-1P_6; *l* – 16S-1P_7

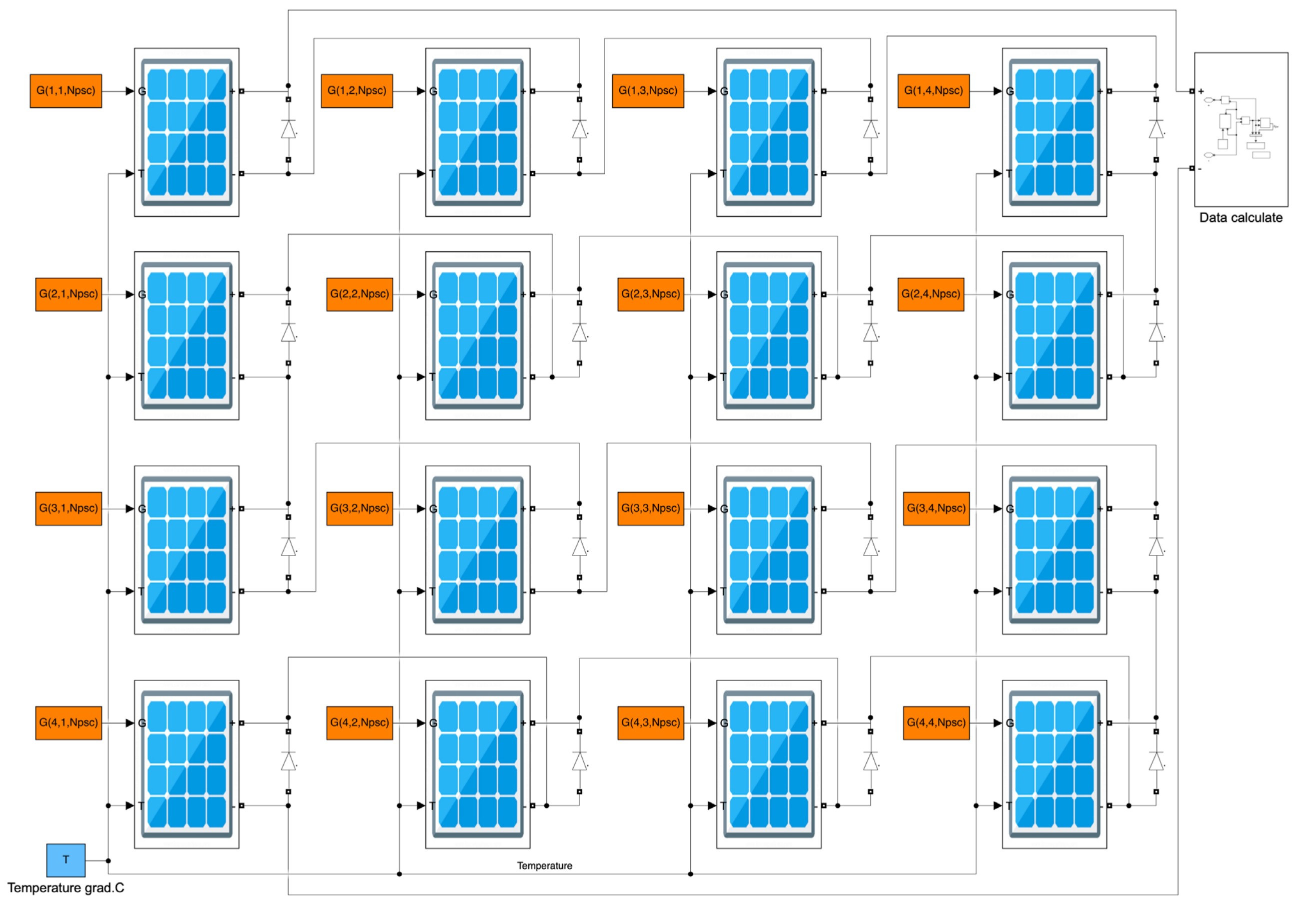

Fig. 2. Structure of the PV array series configuration model 16S-1P_3

The input parameters of PVM are the operating temperature of the module (the same for all modules with the possibility of change) and solar radiation *G*. Their values are fed to the corresponding inputs of PVM. Our studies were performed at the same temperature of PVM.

5. 2. Justification of the methodology for modeling the movement of a shading strip

The solar radiation *G* of each PVM in the array (Fig. 2) is set separately, which makes it possible to simulate the dynamics of changes in illumination. Under clear sky conditions, the maximum total (direct + diffuse) solar radiation for a horizontal surface in July is 691 W/m^2 (direct) + + 171 W/m^2 (diffuse) = 862 W/m^2. Under 10-point cloudiness conditions – 327 W/m^2. Accordingly, the range of radiation changes in the shading strip is assumed to be from 400 W/m^2 to 800 W/m^2.

The shading pattern for simulating the passage of a partial shading strip through a PV array with an 8S-2P configuration (2 × 8 – 2 rows of 8 panels) in the direction from north to south (angle 0°) is shown in Fig. 3, *a*; for the direction north – west or south – east (angle 45°) – in Fig. 3, *b*; for the intermediate direction (angle 27°) – in Fig. 3, *c*. The patterns are designed for different angles of the strip's direction of movement from 0 to 76°. For the simulation, each of the patterns is linearly interpolated up to 48 frames. This reduces the radiation gradations for PVM accordingly.

800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800
600	600	600	600	600	600	600	600
400	400	400	400	400	400	400	400
500	500	500	500	500	500	500	500
600	600	600	600	600	600	600	600
700	700	700	700	700	700	700	700
800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800

a

800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800
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800	800	800	800	800	800	600	400
800	800	800	800	800	600	400	500
800	800	800	800	600	400	500	600
800	800	800	600	400	500	600	700
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400	500	600	700	800	800	800	800
500	600	700	800	800	800	800	800
600	700	800	800	800	800	800	800
700	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800

b

800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800
800	800	800	800	800	800	600	600
800	800	800	800	600	600	400	400
800	800	600	600	400	400	500	500
600	600	400	400	500	500	600	600
400	400	500	500	600	600	700	700
500	500	600	600	700	700	800	800
600	600	700	700	800	800	800	800
700	700	800	800	800	800	800	800
800	800	800	800	800	800	800	800
800	800	800	800	800	800	800	800

c

Fig. 3. Shading patterns of a 2 × 8 PV array: *a* — movement direction of the shading strip from north to south (angle 0°); *b* — movement direction of the shading strip north-west or south-east (angle 45°); *c* — intermediate movement direction of the shading strip (angle 27°)

The pattern frames are loaded into the array model with subsequent calculation of the power dependence $P(U)$ and a GMPP point. The simulation is performed by shifting the frame by one line. The shading pattern frames for an array with an 8S-2P (2 × 8) configuration have a size of 2 × 8 cells.

5. 3. Assessing the influence of the direction and speed of strip movement for the selected configurations; determining the recommended types of configurations

The possibility of changing the speed of passage of the shading strip (wind speed) through the PV array by four times was considered. In this case, the template arrays were scaled (compressed) with factors of 1 (normal speed 1x), 1/2 (speed 2x), 1/3 (speed 3x) and 1/4 (speed 4x).

As a result of the simulations, the trajectories of GMPP movement on the $P(U)$ curves were constructed with the averaging of the total generation power P for different directions and speeds of the shading strip movement through the PV array. At normal speed, the averaging was carried out over 48 power values at a GMPP point on the $P(U)$ curves, namely for the 2x mode – 24 points, 3x – 16 points, and 4x – 12 GMPP points.

Table 1 gives indicators for three configurations of a PVM array: P_{CP} is the average value of the generated power, ΔP_{AV} – absolute value of the difference between the average power values at a certain (1x, 2x, 3x, 4x) and single (1x) speeds.

Table 1

Averaged generation for different speeds and directions of shadow strip movement

Direction of movement	Movement speed	Power P_{AV} and ΔP_{AV} of PV arrays, W					
		16S-1P_1 (16 × 1)		8S-2P_4 (8 × 2)		8S-2P_7 (4 × 4)	
		P_{AV}	ΔP_{AV}	P_{AV}	ΔP_{AV}	P_{AV}	ΔP_{AV}
45°	1x	7,002	0	7,180	0	6,499	0
	2x	6,998	–4	7,126	–54	6,385	–114
	3x	7,005	3	7,129	–51	6,497	–2
	4x	6,991	–11	7,045	–135	6,401	–98
0°	1x	7,051	0	6,946	0	6,830	0
	2x	6,999	–52	6,946	0	6,830	0
	3x	7,050	–1	6,826	–120	6,828	–2
	4x	6,999	–52	6,949	3	6,698	–132

The average deviation of generation values ΔP_{CP} for different speeds of passage of the shading strip by the modulus does not exceed 0.5%, with the exception of individual values that are in the range of 0.7–2.0%. This is explained by the inaccuracy of interpolation of template frames and an increase in the frame step along the insolation array. Therefore, it can be considered that there is no influence of the value of the shading strip speed on the P_{CP} value. Further studies were performed for one speed of movement, based on the limitation of the number of curves $P(U)$ and the length of the shading array.

The maximum P_{AV} value is for an angle of 45° for a two-row configuration 8S-2P_4 – $P_{AV} = P_{AV\text{MAX}} = 7180$ W. For a single-row configuration 16S-1P_1, the value is $P_{AV} = 0.975 \cdot P_{AV\text{MAX}} = 7002$ W, for a four-row 8S-2P_7, the value is $P_{AV} = 0.905 \cdot P_{AV\text{MAX}} = 6499$ W.

Table 2 gives general indicators for the three array configurations, averaged for all directions of the strip movement (angles 0°, 14°, 27°, 45°, 63°, 76°). To assess the efficiency, the generally accepted indicators were used: P_{array} – average potential generated power of PVS, W; L_m – average mismatched power losses, %; FF – average fill factor, %; η – average efficiency of PVS, %; $D^{*}_{PWM} = 100 D_{PWM} / U_{OC}$ – relative value of voltage range of pulse width modulation (PWM), % (U_{OC} – open circuit voltage, V; Δ_{PWM} – voltage range of the PWM algorithm of MPPT, V).

Unbalanced power losses in the PV array

$$L_m = 100\frac{P_{ideal} - P_{array}}{P_{ideal}}, \quad (1)$$

where P_{ideal} is the theoretical maximum power in the array under uniform illumination.

Fill factor

$$FF = 100\frac{P_{array}}{U_{OC} \cdot I_{SC}}, \quad (2)$$

where I_{SC} is the short-circuit current. Geometrically, FF is a measure of how close the volt-ampere characteristic (VAC) of a PVM is to a "rectangular" shape. The closer the value is to 100%, the more efficient the PVS.

PVS efficiency

$$\eta = \frac{P_{array}}{G_A \cdot A}, \quad (3)$$

where G_A is the averaged value of the array radiation per cycle of the strip movement, determined by the average values on each frame of movement, A is the area of PVM, m^2.

The range of PWM voltage change (Δ_{PWM}) of the DC-DC converter of the inverter makes it possible to estimate how "widely" the PWM controller has to work to track the maximum point. A large difference indicates that the operating point is shifted by a large distance along the voltage axis. This requires the MPPT algorithm to respond with high dynamic speed. In addition, efficiency of the DC-DC inverter depends on the ratio of the input and output voltages, and with a large duty cycle range, the inverter can go beyond its maximum efficiency zone.

Table 2

Overall performance for the three array configurations averaged across all strip directions

Configuration	P_{array}, W	L_m, %	FF, %	η, %	Δ_{PWM}, V	D^{*}_{PWM}, %
PV_16S_1P_1_1×16	6,814	19.9	70.4	22	197.4	22.8
PV_8S_2P_4_2×8	7,003	14.7	75.3	23.4	40.9	9.5
PV_8S_2P_7_4×4	6,308	11.6	69.8	22.5	94.5	21.8

Table 3 gives general indicators for the three array configurations for the prevailing directions of strip movement. Some deterioration in the performance occurs for the angle of 76°, in particular, this concerns a decrease in power to 0.994 (PV_16S_1P_1_1), 0.97 (PV_8S_2P_4_2 × 8) and 0.93 (PV_8S_2P_7_4 × 4).

The $P(U)$ curves and GMPP trajectory for the array with the 16S-1P_1 (1 × 16) configuration for the direction of the shadow strip movement for the north-south direction are shown in Fig. 4, *a* for the speed 4x. There are no (or relatively small) LMPP points on the $P(U)$ curves. A similar pattern emerges at other speeds.

Table 3

General indicators for three array configurations for the prevailing strip movement directions

Configuration	Angle, °	P_{array}, W	L_m, %	FF, %	η, %	Δ_{PWM}, V	D^*_{PWM}, %
PV_16S_1P_1_1×16	76	6,776	22.1	67.0	21.0	218.1	25.2
	45	7,002	19.5	69.2	21.5	216.9	25.1
	0	7,051	19.0	85.0	23.9	20.9	2.4
PV_8S_2P_4_2×8	76	6,814	20.8	69.1	22.2	49.7	11.5
	45	7,180	17.3	72.2	22.9	48.1	11.1
	0	6,946	20.0	82.6	23.7	11.0	2.5
PV_8S_2P_7_4×4	76	5,890	24.0	60.3	20.6	105.6	24.4
	45	6,499	22.4	65.7	21.7	21.1	4.9
	0	6,830	21.3	82.4	23.6	9.0	2

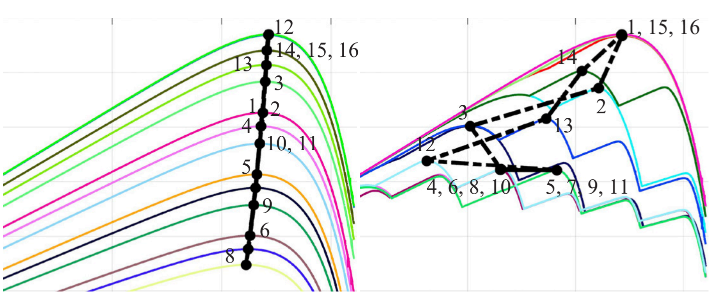
Fig. 4, *b* shows the $P(U)$ curves and GMPP trajectory for the 16S-1P (1 × 16) array at the speed 4x and the direction of the shadow strip movement is north-west. In this case, there is a large number of LMPP and the GMPP trajectory is complex. Therefore, the probability of the optimal GMPP trajectory for maximizing the generation power is quite low.

In the case of the 8S-2P_1 configuration, two parallel branches are used with the PVM distribution between the rows $n_1 = n_2 = 8$. The GMPP motion trajectories have not changed significantly, and suitable indicators are available for the angles of the direction of motion from 0 to 27°.

For the 2 × 8 series-parallel configurations (8S-2P_2, 8S-2P_3, 8S-2P_4), two parallel branches are used with the PVM distribution between the first $n_{11} = n_{12} = 4$ and the second $n_{21} = n_{22} = 4$ rows. In this case, the GMPP motion trajectories have no complications (Fig. 5, *a*); the indicators have improved (in Table 3, given for 8S-2P_4). The same applies to the 4 × 4 arrays (Fig. 5, *b*).

So, for the selected value of power for the photovoltaic system with 16 PVMs, the following configurations from two rows can be selected as recommended: 8S-2P_2, 8S-2P_3, 8S-2P_4. In this case, the parallel-connected branches contain 4 PVMs from two rows.

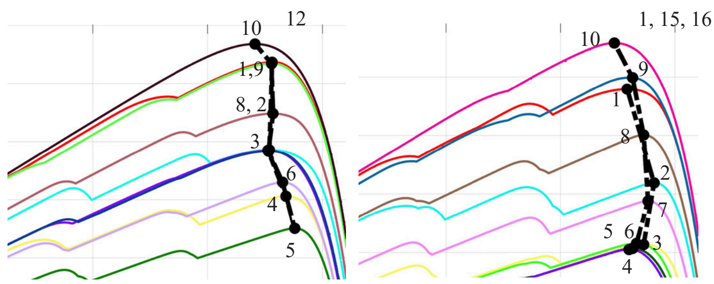
Increasing the number of rows of the array in the case of strip movement leads to a decrease in generation. Thus, the 4 × 4 configurations showed the lowest potential generation, but their GMPP trajectories are simple.



a *b*

Fig. 4. $P(U)$ curves and the trajectory of a global maximum power point for the array with the 16S-1P_1 configuration: *a* — movement direction of the shading strip in the north-south direction; *b* — movement direction of the shading strip in the north-west direction

Therefore, the general recommendation is to limit the number of PVMs in a row to $s_p \leq 4$ for a branch with a serial connection of PVMs using 2–3 rows.



a *b*

Fig. 5. $P(U)$ curves and trajectories of the global maximum power point in the case of north-west strip movement: *a* — 8S-2P_4 (2 × 8); *b* — 8S-2P_7 (4 × 4)

5. 4. Compiling and evaluating the proposed array configurations at different power

Depending on the maximum power of PVM, the number of PVMs varies. In the case of assembling an array of two rows and limiting the number of PVMs per row in the branch to four, the following configurations can be assembled (Fig. 6): 3S-2P_2 (total number of 6 PVMs), 5S-2P_2 (10 PVMs), 6S-2P_2 (12 PVMs), 7S-2P_2 (14 PVMs). The 3S-2P_2 and 6S-2P_2 configurations are assembled with a limitation of 2 PVMs per row in the branch. The combinations 5S-2P_2 (10 PVMs), 7S-2P_2 (14 PVMs) have a different number of PVMs in the branch per row (2 + 3) and (3 + 4), respectively.

General indicators for a number of recommended array configurations are given in Table 4. In this case, (0–76°) determines that the indicators are averaged for all directions of strip movement.

In the case of assembling an array of three rows and limiting the number of PV modules per row in a branch to two, the following configurations can be assembled (Fig. 7): 6S-2P_3 (12 PV modules), 6S-3P_3 (18 PV modules) and 6S-4P_3 (24 PV modules – 15.72 kW).

The best indicators are provided by configurations with two PV modules per row. The worst configurations are: 5S-2P_2, 7S-2P_2. With the same number of PV modules (12 panels), the configuration with 2 rows has 2.7% more power. With a three-row configuration, the indicator Δ_{PWM} decreases.

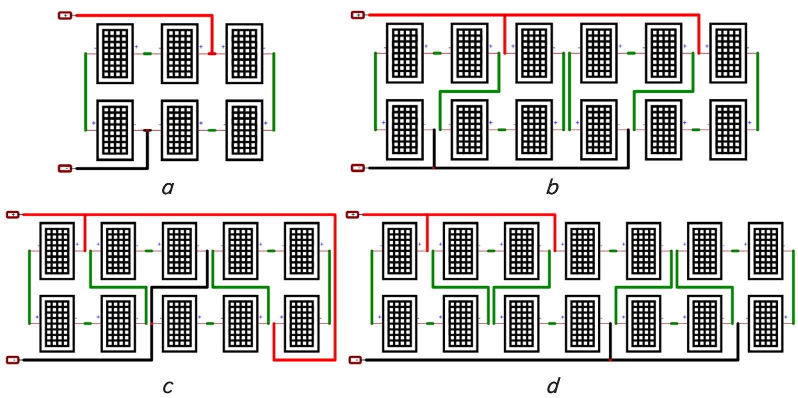


Fig. 6. Two-row array configurations: *a* – 3S-2P_2; *b* – 6S-2P_2; *c* – 5S-2P_2; *d* – 7S-2P_2

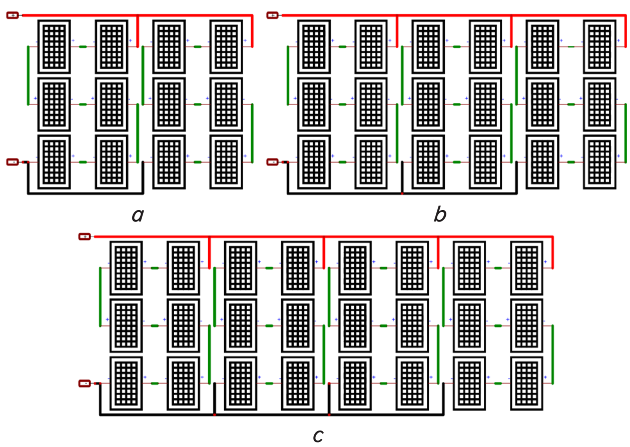


Fig. 7. Configurations of three-row arrays of photovoltaic panels: *a* – 6S-2P_3; *b* – 6S-3P_3; *c* – 6S-4P_3

Table 4

General indicators for recommended array configurations

Angle, °	P_{array}, W	L_m, %	FF, %	η, %	Δ_{PWM}, V	D^*_{PWM}, %
6S-2P_2						
0–76	5,221	19.5	75.2	23.5	9.7	3
0	5,206	20.0	82.6	23.0	8.3	2.56
45	5,391	17.2	73.7	23.3	10.9	3.3
76	5,095	20.8	70.7	22.7	10.9	3.3
7S-2P_2						
0–76	6,058	20.0	73.7	23.2	47.5	12.6
6S-2P_3						
0–76	5,081	19.9	75.1	23.6	7.5	2.3
0	5,121	21.3	80.2	23.0	9.5	2.9
45	5,248	19.1	73.2	23.3	8.0	2.46
76	4,956	18.1	72.0	23.1	6.7	2.06
6S-4P_3						
0–76	10,729	16.4	77.8	23.0	6.3	1.9
0	10,242	21.3	80.2	23.0	9.5	2.9
45	11,157	14.1	76.8	23.8	7.3	2.25
76	10,893	13.1	76.7	23.8	5.6	1.72

Fig. 8 shows the trajectories of GMPP motion for configurations 6S-2P_2 for an angle of 45° (Fig. 8, *a*) and 6S-3P_3 for an angle of 76° (Fig. 8, *b*).

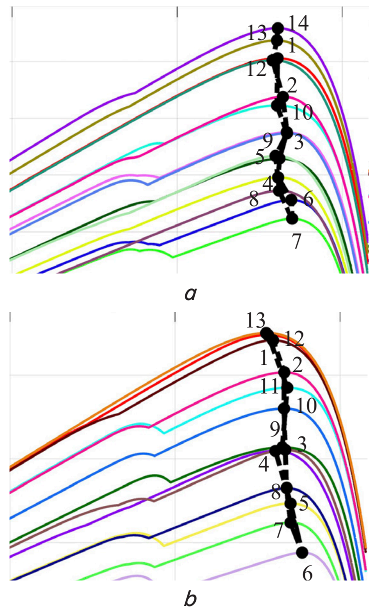


Fig. 8. $P(U)$ curves and trajectories of the global maximum power point in the case of strip direction for the following configurations: *a* – 6S-2P for an angle of 45°; *b* – 6S-3P for an angle of 76°

The trajectories shown in Fig. 8 demonstrate the monotonic nature of GMPP motion at a small Δ_{PWM} value.

6. Discussion of results based on the study on minimizing the impact of shading on the energy efficiency of a photovoltaic array

The possibility of minimizing the impact of partial shading on the energy efficiency of a photovoltaic array for a local facility's PVS is achieved by:

– using series-parallel configurations of the 2×8 PV array, which are the least critical to the movement direction of the shading strip (Fig. 3) without reducing energy efficiency (Table 3);

– using two-row and three-row configurations with the recommended limitation of the number of PVMs to 4 per row in the branch. These configurations along the GMPP trajectory (Fig. 8) have no complications, the range of operation of MPPT PWM is small; therefore, they can be tracked by the simplest MPPT algorithms.

A feature of our research method is the transition from individual to further generalization and compiling recommendations. In this case, the features of energy processes for specific 12 configurations of a fixed-power array are analyzed. Based on the analysis, recommendations are defined for limiting the impact of partial shading, according to which recommended configurations of arrays of different power are compiled with an assessment of the indicators (given in Table 4 and Fig. 8). Most available studies [8–11, 13, 15] consider solutions for arrays with a fixed dimension of 2 × 4, 4 × 4, 5 × 5, 6 × 6, 9 × 9. An important feature of our study is the consideration of the movement of the shading strip. Different directions of movement of the strip are considered, including according to the movement of clouds along the prevailing wind directions with a generalization of indicators and determination of the GMPP trajectory. Solar radiation gradations and directions of movement are justified in accordance with specific climatic conditions. In addition, radiation gradations change from almost zero depending on the speed of movement. Most works in this area of research consider static shading with a defined shading scheme. To some extent, paper [17] is close, in which the solar radiation of the array changes over time. However, the radiation for all PVMs is the same. The gradations of radiation in the process of change are not justified.

The evaluation was performed under the same conditions for configurations with 16 PV modules (Tables 1–3 and Fig. 4, 5), as well as in the case of the number of PV modules (6, 8, 10, 12, 14, 16, 18, 24), which are compiled according to the compiled recommendations (Table 4 and Fig. 8). In the case of using PV modules with a maximum power of 655 W, this makes it possible to generalize our results for different PVS capacities from 3.93 kW to 15.72 kW (Table 4), which are sufficient for private households and other small facilities. It is important to ensure the monotony of GMPP movement at a small Δ_{PWM} value, which does not require additional requirements for the MPPT controller.

Limitations in our solutions relate to the suitability of recommendations only for the two-row and three-row structure of PV module configurations.

The disadvantages are:

– the adopted simplification regarding the same temperature of different PVMs with a small area of the array;

– the possibility of arrays with a row of more than three was not considered, which is associated with the adopted geometric location on the southern slope of the building;

– the complexity of forming shading patterns for different directions of strip movement for different configurations of a PVM array, which complicates the implementation of the modeling process.

Using the proposed model taking into account the shading strip could make it possible to assess the effectiveness of solutions regarding PVM array configurations when designing PVSs and for improving MRRT algorithms. In this case, improving the model with the expansion of its functionality is a further continuation of our work.

7. Conclusions

1. According to the accepted maximum power of a PVS, 12 possible configurations of arrays with 16 PV modules and the arrangement of panels in 1–4 rows according to the corresponding connection schemes have been compiled. The configurations were determined for the limiting characteristics of the inverter and the panel array in terms of current and voltage.

2. A methodology for modeling the movement of a shading strip is based on linking its direction to the wind direction. The range of radiation value changes is accepted from the maximum, on a clear day, to 0.5 of the maximum. Gradations of radiation values between PV modules range from 12.5% to practically 0. The speed of movement varies from 1 to 4 times.

3. The location and connection of modules (PVMs) in the model according to the studied 12 configurations correspond to the accepted maximum power of PVS, 10480 W. The radiation gradations for the modules are set by a template of values according to the movement direction of the shading strip, and the speed is set by changing the frame frequency of the template. The movement direction is set by a series of angle values – from 0° to ±76°. The GMPP trajectory is determined by calculation according to the frames in the order of their alternation and reflects the possibilities of its tracking in dynamics.

For the basic version with 16 PVMs, it was established that the possibility of obtaining maximum energy efficiency under conditions of partial shading is provided by series-parallel configurations of the type 2 × 8 with 4 PVMs in a branch per row. The total generated power P practically does not depend on the speed of movement of the shading strip, which makes it possible to extend the results to static shading. With an increase in the number of rows in the array to 4, the generation decreases. The GMPP trajectory is monotonic and can be processed by a conventional P&T MPPT controller.

4. Similar results under the same conditions were obtained for the proposed configurations with 6, 10, 12, 14, 18 PV modules at 655 W with the values of the maximum PVS power, respectively, from 3.93 to 11.790 kW. This makes it possible to formulate a recommendation for two-row series-parallel configurations to limit the number of PV modules in a branch to four per row. In the case of the proposed three-row configurations with 6, 12, 18, 24 PV modules, two PV modules are used in a branch per row, which ensures a decrease in Δ_{PWM}. The power reduction in this case is up to 3%.

The generation power in the preferred directions relative to the average generation value in all directions of movement is not less than 96%.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Olexandr Shavolkin: Conceptualization, Writing – original draft, Investigation, Supervision, Formal analysis, Writing – review & editing; **Hennadii Kruhliak**: Methodology, Software, Validation, Investigation, Data Curation, Formal analysis, Writing – original draft; **Iryna Shvedchykova**: Writing – review & editing, Project administration, Resources; **Tetiana Bila**: Writing – review & editing, Formal analysis; **Andrii Pisotskyi**: Visualization, Writing – original draft, Data curation.

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