11th International Conference on Electrical, Electronics and Computer Engineering (IcETRAN), Nis, 3-6 June 2024

Determining the maximum power point location of the PV array under partial shading using the shading pattern recognition

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Abstract –**This paper proposes an approach for finding the maximum power point (MPP) location of the photovoltaic (PV) array in the case of partial shading based on the shading pattern recognition. Shading pattern recognition is achieved by determining the necessary solar irradiation for each part of the PV array surface to recreate the existing power-voltage (P-V) curve of the PV array. This is done using the metaheuristic particle swarm optimization (PSO) method in which criterion function is based on comparing the measured powers of the PV array (fitting power points) and the powers calculated using the PV array model for the same voltages. Model of the PV array is created from the PV cell model considering the topology and the partial shading of the PV array surface. The effect of partial shading is included by reducing the photocurrent of the PV cells in the shaded area of the PV array. When the shading pattern is known the location (voltage) of the MPP is found using the P-V curve obtained from the PV array model. Results generated for three different shading patterns show great precision of the proposed approach in determining the MPP location if the PV cell is accurately modeled, and enough number of fitting power points are used.**

Keywords – photovoltaic (PV) array, maximum power point (MPP), particle swarm optimization (PSO), shading pattern, PV cell model

I. INTRODUCTION

Solar energy is the most abundant renewable energy source with the greatest energy potential. The advantage of solar energy is that it can be directly converted to electricity using PV modules. For maximum power generation PV modules must be adequately placed and their operation properly controlled. Optimal placement includes determination of optimal tilt and azimuth angle of the PV module to maximize the solar irradiation on the PV modules surface and can be regarded as the first step in maximization of the PV modules power output. The second step, which is considered in this paper, focuses on improving the operation of the PV modules by operating in the MPP on the P-V curve [1],[2].

Location of the MPP is not hard to find if the partial shading is not present, because in that case there is only one local optimum on the P-V curve. This is the reason why conventional MPP tracking algorithms including perturb and observe, incremental inductance, hill climbing and others are quite efficient if the partial shading is not present [3]. Partial shading of the PV module surface deforms the P-V curve creating many local optima in which mentioned conventional MPP tracking algorithms can stuck [4],[5],[6]. One of the ways to overcome this problem is to use MPP tracking algorithms based on metaheuristic optimization methods [7].

Having that in mind, this paper tries to determine the location of MPP by recreating the P-V curve using the recognized shading pattern on the model of the PV array [8]. Recognition of the shading pattern is achieved by determining the necessary solar irradiation of each part of the PV array surface to fit the P-V curve through the fitting (measured) power points. In this purpose metaheuristic PSO is used [9],[10],[11]. To form the P-V curve the model of the PV array is created based on the four-parameter single diode model of the PV cell and the topology of the PV array, respecting the shading pattern [8].

Model of the PV array is made of PV strings connected in parallel, which are composed of PV modules connected in series each consisting of PV submodules [12]. In this paper each PV submodule is equipped with the bypass diode to mitigate the power generation losses and to protect the PV cells from overheating in the case of partial shading [9]. The parameters of the PV cell model are determined using the values of voltage and current in the characteristic operating points of the PV cell [12]. Partial shading effect is included by reducing the solar irradiation of the shaded area, where the smallest unit of surface that can be shaded in the model is the PV submodule. Power points through which PSO tries to fit the P-V curve are determined for different values of the voltage using the created model of the PV array [5]. Results at the end of the paper are generated using different shading patterns and the accuracy of the proposed method is determined by comparing the real and calculated location of the MPP. Influence of the different number of fitting power points and the accuracy of the determined PV cell model parameters on the calculated location of the MPP are also considered.

The paper is organized as follows: in the second chapter the used model of the PV array in the case of partial shading is presented, in the third and fourth chapter the optimization problem is defined considering the required criterion function and solved using PSO, respectively, while in the fifth chapter the simulation model parameters are determined. The results are shown and analyzed in the chapter six, while the chapter seven gives the appropriate conclusion to the paper.

ISBN 978-86-6200-001-9 ©2024 AM & ETRAN

https://doi.org/10.69994/11Ic24049

II. MODEL OF THE PV ARRAY UNDER PARTIAL SHADING

Model of the PV array is created based on the model of the PV cell, the basic building unit of the PV module. The four-parameter single diode model is used for modelling the PV cell, which is shown on Fig. 1. In this model four unknown parameters are used to describe the current-voltage (I-V) characteristic of the PV cell.

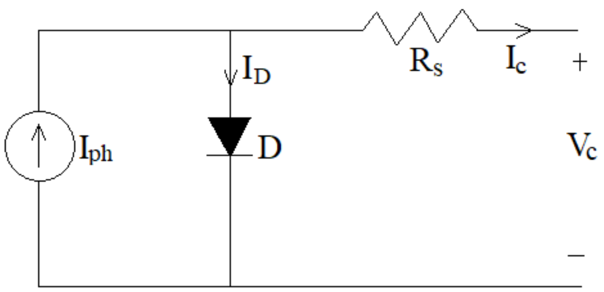

Fig. 1 PV cell model

The I-V characteristic of the PV cell can be found taking into account the electric circuit of the model shown in fig. 1. using the expression:

$$I_c = I_{PH} - I_0\left[\exp\left(\frac{V_c + I_c R_s}{aV_T}\right) - 1\right] \qquad (1)$$

Where in expression I_c and V_c are the current and voltage of the PV cell respectively, I_{PH} is the photocurrent (current proportional to the solar irradiation on the PV cell), I_0 is the diode reverse saturation current, a is the diode ideality constant, R_s is the internal resistance of the PV cell and V_T is the thermal voltage.

Considering that thermal voltage is the known parameter that depends on the temperature, PV cell model has four unkwnown parameters from which has got its name.

In the most cases PV cells of the same type (cells with the same parameters I_0, a, and R_s in PV cell model) connected in series compose the PV module. Taking this into account, if partial shading is not present and each PV cell has equal solar irradiation the I-V characteristic of the PV module is the same as (1), where the current (I_m) and voltage (V_m) of the PV module with N_{cm} PV cells, are:

$$I_m = I_c, \quad V_m = N_{cm} \cdot V_c \qquad (2)$$

The PV array model under partial shading considers the partial shading effect in the I-V characteristic of the PV module. This effect is included by decreasing the value of photocurrent in the PV cell model. Considering that in PV modules PV cells are connected in series, resulting that each PV cell has the same current. Higher photocurrents of the unshaded PV cells force shaded PV cells to operate in reverse bias, close to the reverse breakdown voltage, leading to great losses in the power generation of the PV module. Also, the negative effect of this reverse bias operation is the overheating of the shaded PV cell. To improve operation under partial shading and avoid overheating of the shaded PV cells the bypass diodes are used. Bypass diodes are connected in parallel to one or to the group of PV cells, facing the opposite direction in relation to them. The placement of bypass diodes is such that every submodule (group of PV cells connected in series) in the PV module has one bypass diode. In this paper bypass diodes are modeled using the static I-V characteristic of the real diode and are important elements in the model of the PV array under partial shading.

Also, in this paper it is assumed that the solar irradiation of each PV cell of the same PV submodule is equal. If the current of the PV submodules is greater than their photocurrents the bypass diodes of those PV submodules start to conduct. Considering I-V characteristic of the PV cell, submodule voltage (V_{sm}) in the function of submodule current (I_{sm}) for the PV submodule with N_{csm} PV cells, can be found as:

$$V_{sm} = N_{csm} \cdot \left[aV_T \cdot ln\left(\frac{I_{PH} - I_{sm}}{I_0} + 1\right) - I_{sm}R_s\right], I_{sm} \leq I_{PH} \qquad (3)$$

$$V_{sm} = -V_{BD}, \quad I_{sm} > I_{PH} \qquad (4)$$

where N_{csm} is the number of PV cells in the PV submodule and V_{BD} is the bypass diode voltage.

As the PV cells in PV submodules are connected in series so are the PV submodules in PV modules. Taking into account different levels of shade of the PV submodules, the I-V characteristic of the PV module with N_{sm} PV submodules, is obtained using expressions (5) and (6):

$$I_m = I_{sm}, \qquad (5)$$

$$V_m = \sum_{k=1}^{N_{sm}} V_{smk}(I_{sm}) \qquad (6)$$

Considering that PV strings are made up of PV modules connected in series the same analogy can be applied as that used for PV submodules. Taking this into account the voltage (V_{st}) and the current (I_{st}) of the PV string with N_m modules are:

$$I_{st} = I_m, \qquad (7)$$

$$V_{st} = \sum_{k=1}^{N_m} V_{mk}(I_m) \qquad (8)$$

PV array is made up from several PV strings connected in parallel. Considering this, the voltage (V_a) and the current (I_a) of the PV array composed of N_{st} PV strings can be found on the basis of expressions (9) and (10):

$$V_a = V_{st}, \qquad (9)$$

$$I_a = \sum_{k=1}^{N_{st}} I_{stk}(V_{st}) \qquad (10)$$

Finally, using (10) power generation of the PV array (P_a) is determined:

$$P_a = V_a \cdot \sum_{k=1}^{N_{st}} I_{stk}(V_a) \qquad (11)$$

III. DEFINING THE OPTIMIZATION PROBLEM

Optimization problem present in this paper can be defined as determining the necessary solar irradiations of each part of the PV array surface to minimize the difference between the power output and the measured power in the fitting points. Power generation of the PV array has a non-linear dependence on solar irradiation in the case of partial shading, which makes the optimization problem a non-linear in its nature. Control variables in this optimization problem are the solar irradiations of each part of the PV array surface. These solar irradiations must be lower than the irradiation of the unshaded part of the PV array surface (G_{max}).

$$0 < G_i < G_{max} \tag{12}$$

$$1 \leq i \leq N_{SM} \tag{13}$$

Where G_i is the solar irradiation of the i-th part of the PV array surface. In this paper minimal area of the PV array that has the same solar irradiation on its entire surface is the PV submodule. Considering this, the number of different parts of the PV array surface and the number of control variables are equal to the number of PV submodules in the PV array (N_{SM}). Criterion function (C) is defined as the sum of squared errors between actual (P_{act}) and calculated (P_{cal}) powers.

$$C = \sum_{k=1}^{N}(P_{actk} - P_{calk})^2 \tag{14}$$

N is the number of power points used for fiting the P-V curve.

IV. SOLVING THE OPTIMIZATION PROBLEM AND DETERMINING THE LOCATION OF MPP

Solving the optimization problem is done by a metaheuristic PSO method. This optimization method belongs to a group of swarm metaheuristic optimization methods, and it is inspired by the process of searching for food by the flock of birds in nature. Set of individuals create the population, in which each individual is a potential solution of the optimization problem. Each individual is represented by a set of control variables, whose values are adjusting during the execution of the PSO. Communication between the individuals allows them to move towards the individual located in the place with the largest amount of food. Quantity of food is in relation to the value of the criterion function (individuals with higher amount of food have lower value of criterion function). To improve the search of the solution space, individuals move taking into account not only the location with the largest amount of food found so far (g_{best}), but also the location which has the largest amount of food which that individual has found so far (p_{best}). In this way individuals in each subsequent iteration are getting closer to the place with largest amount of food, which represents the optimal solution. PSO can be analytically described using expressions (15) and (16).

$$v_i(t+1) = w \cdot v_i(t) + C_1 \cdot r_1 \cdot (p_{besti}(t) - x_i(t)) + \\ + C_2 \cdot r_2 \cdot (g_{best}(t) - x_i(t)) \tag{15}$$

$$x_i(t+1) = x_i(t) + v(t+1) \tag{16}$$

Where are: t – ordinal number of iteration (generation), x_i– location vector of the i-th individual, v_i- displacement vector of the i-th individual, w – inertia coefficient, C_1, C_2- acceleration coefficients, r_1, r_2- random numbers from interval $[0,1]$.

Each individual in the population is represented by the vector of control variables. Number of coordinates of this vector is equal to the number of control variables, in this case that is the number of PV submodules in the PV array, while each coordinate represents the solar irradiation of a different PV submodule. Using the model of the PV array in the case of partial shading the optimization method can determine the value of criterion function for each individual. Optimization method changes the values of solar irradiations of each individual through iterations to minimize their criterion function. The solution to the optimization problem is found after required number of iterations when the change in criterion function of the best individual is negligible.

After solving the optimization problem solar irradiation of each part of the PV array surface is obtained. Now, using the model of the PV array in the case of partial shading the P-V curve of the PV array can be created. Analyzing the P-V curve the location of MPP is determined as the voltage for which the generated power of the PV array is maximal.

V. DETERMINING THE PV CELL AND THE SIMULATION MODEL PARAMETERS

PV cell model is the building block of the PV array model, so the values of its parameters (a, I_{ph}, I_0 and R_s) need to be determined. For better understanding the results and drawing conclusions, parameters of the PV cell model are expressed per unit (p.u.), where the base unit (equal to 1 p.u.) for current is the short circuit current (I_{sc}) of the PV cell without shading and for voltage is the open circuit voltage (V_{oc}). The value of 1.3 is chosen for ideality factor, which is usually in range from 1 to 2. Other three parameters are determined using the open circuit, and short circuit mode, as well as the operation in MPP. In the MPP operation typical values of fill factor and voltage of the MPP are used: FF_c=0.76 and V_{cMPP}=0.815 p.u. Taking this into account three equations are obtained:

$$I_c(V_{oc}, 0) = 0 \tag{17}$$

$$I_c(0, I_{sc}) = 1 \tag{18}$$

$$I_c(V_{cMPP}, I_{cMPP}) = \frac{FF_c}{V_{cMPP}} \cdot I_{sc} \cdot V_{oc} \tag{19}$$

To solve this non-linear system of equations the Newton-Raphson iterative method is used. The solution found at the end of the iterative method contains the values of the second, third and fourth unknown parameter: $I_{ph} = 1$ p.u, $I_0 = 4.914269 \cdot 10^{-10}$p.u. and $R_s = 0.059655$ p.u.

In this paper impact of temperature on the operation of the PV cell is not taken into account. The temperature of the cell is assumed to be constant with the value $T_c = 45$ °C (normal operating cell temperature). Also, to determine the thermal voltage in relative units, typical value of open circuit voltage in absolute units is used: V_{oc} =0.764 V.

Simulation model of the PV array is created using two PV strings connected in parallel, each having six PV modules connected in series. Each of these PV modules have 36 PV cells connected in series. Group of six PV cells represents the PV submodule, each having the bypass diode connected in parallel.

Parameters of the bypass diodes are equal to the parameters of the diode in the PV cell model.

Metaheuristic PSO method is implemented using the population of 100 individuals, and in all considered cases the solution is found after 100 iterations. Considering the results of test simulations values for coefficient of inertia and acceleration coefficients are obtained. Acceleration coefficients are constant $C_1 = 0.8$ and $C_2 = 0.7$, while coefficient of inertia is linearly decreasing by iterations, from 0.8 to 0.3.

VI. RESULTS AND DISCUSSION

To verify the efficiency of the proposed approach for determining the location of MPP three different shading patterns are considered, labeled as:

SP1. 0.7(1)1, 0.5(1)1.
SP2. 0.6(1)1, 0.5(0.5)1, 0.75(1)2, 0.45(1)2.
SP3. 0.5(1)1, 0.35(1)1, 0.35(1)1, 0.6(1)1, 0.65(1)2.

The shading pattern label consists of three numbers refering to the solar irradiation of the shaded area comparing to the solar irradiation of the area without shade, the share of the shaded area in the total surface of the PV module, and the number of the PV string in which shaded module is located, respectively.

For each of these shading patterns impact of different number of fitting points and accuracy of PV cell model parameters on the location of MPP obtained by the proposed approach is considered.

Table I contains the actual locations (voltages) and power of MPP of the PV array for all three shading patterns. In all considered cases the location and power of the MPP are represented per unit, using the open circuit voltage of the PV array without partial shading (V_{oc}) and the power in MPP of the PV array without partial shading (P_{max}) as the base units.

TABLE I. ACTUAL LOCATIONS AND POWER OF MPP OF THE PV ARRAY FOR DIFFERENT SHADING PATTERNS

Shading pattern	Location (V_{MPP}/V_{oc})	Power (P_{MPP}/P_{max})
SP1.	0.710	0.7798
SP2.	0.595	0.6403
SP3.	0.880	0.5694

These three shading patterns are chosen for testing the proposed approach because they have different shapes of P-V curves and the location of MPP is well distributed along the voltage and power axes. Locations and power of the MPPs obtained by the proposed approach are shown in Tables II, III, IV and V. Results in Table II are generated for different number of fitting power points (3, 5, 10, 20) using accurate values for PV cell model parameters. Voltage of the fitting power point per unit is calculated using the ordinal (i_{fPP}) and the total number of fiting power points (N_{fPP}) based on expression:

$$V_{fPP} = \frac{i_{fPP}}{N_{fPP+1}} \tag{20}$$

TABLE II. LOCATIONS AND POWER OF THE MPP DETERMINED BY THE PROPOSED APPROACH FOR DIFFERENT NUMBER OF FITTING POWER POINTS

	SP1	SP2	SP3
Location-3	0.670	0.680	0.690
Power-3	0.7422	0.5989	0.5498
Location-5	0.795	0.515	0.785
Power-5	0.7597	0.6307	0.5128
Location-10	0.765	0.595	0.875
Power-10	0.7400	0.6403	0.5676
Location-20	0.710	0.595	0.885
Power-20	0.7798	0.6403	0.5692

Table II shows that increasing the number of fitting points improves the accuracy of determining the location of MPP for all three shading patterns. Although in the case with 20 fitting points MPP location practically matches its actual location, losses in the power generation resulting from not determining the accurate location of MPP are less than 10% in the cases with 3, 5 and 10 fitting points, which can be seen comparing the results from Table I and II. Also, it must be point out that accuracy of the proposed method in determining the location of MPP improves if actual location of the MPP is closer to the location of fitting power point. This is the reason why certain results in Table II are better in the case with lower number of fitting points.

Tables III, IV and V are the results generated using the proposed approach with 20 fitting power points while acknowledging different levels of inaccuracies in the PV cell model parameters including diode ideality constant (a), inverse saturation current (I_0) and internal resistance (R_s), respectively. The following errors in percentages are used: -20, -10, -5, 5, 10 and 20.

Comparing the results from Tables III, IV and V it can be seen that the location of the MPP determined by the proposed approach is most sensitive to the value of the diode ideality constant from all other parameters in the PV cell model.

TABLE III. CALCULATED LOCATIONS AND POWER OF MPP OF THE PV ARRAY FOR DIFFERENT ERRORS OF DIODE IDEALITY CONSTANT OF THE PV CELL

	SP1	SP2	SP3
Location (-20%)	0.650	0600	0.685
Power (-20%)	0.7204	0.6404	0.5518
Location (-10%)	0.760	0.605	0.700
Power (-10%)	0.7366	0.6399	0.5435
Location (-5%)	0.825	0.565	0.835
Power (-5%)	0.7717	0.6276	0.5454
Location (5%)	0.840	0.545	0.860
Power (5%)	0.7726	0.6211	0.5605
Location (10%)	0.870	0.550	0.870
Power (10%)	0.7612	0.6190	0.5660
Location (20%)	0.840	0.615	0.860
Power (20%)	0.7726	0.6369	0.5605

TABLE IV. CALCULATED LOCATIONS AND POWER OF MPP OF THE PV ARRAY FOR DIFFERENT ERRORS OF INVERSE SATURATION CURRENT OF THE PV CELL

	SP1	SP2	SP3
Location (-20%)	0.825	0.605	0.890
Power (-20%)	0.7717	0.6399	0.5678
Location (-10%)	0.815	0.595	0.870
Power (-10%)	0.7689	0.6403	0.5660

Location (-5%)	0.710	0.620	0.890
Power (-5%)	0.7798	0.6338	0.5678
Location (5%)	0.710	0.595	0.885
Power (5%)	0.7798	0.6403	0.5693
Location (10%)	0.700	0.590	0.875
Power (10%)	0.7725	0.6393	0.5676
Location (20%)	0.795	0.585	0.685
Power (20%)	0.7597	0.6379	0.5518

TABLE V. CALCULATED LOCATIONS AND POWER OF MPP OF THE PV ARRAY FOR DIFFERENT ERRORS OF INTERNAL RESISTANCE OF THE PV CELL

	SP1	SP2	SP3
Location (-20%)	0.710	0.605	0.890
Power (-20%)	0.7798	0.6399	0.5678
Location (-10%)	0.815	0.600	0.890
Power (-10%)	0.7689	0.6402	0.5678
Location (-5%)	0.705	0.595	0.875
Power (-5%)	0.7761	0.6403	0.5676
Location (5%)	0.700	0.595	0.885
Power (5%)	0.7724	0.6403	0.5693
Location (10%)	0.815	0.590	0.885
Power (10%)	0.7689	0.6393	0.5693
Location (20%)	0.885	0.590	0.880
Power (20%)	0.7697	0.6393	0.5694

Taking into account the similarities between the results from Tables IV and V with those from Table II generated for 20 fitting points, it is clear that inaccuracies up to 20% in values of inverse saturation current and internal resistance in the PV cell model have low impact on the location of MPP determined by the proposed method. Explanation for the results in Tables III, IV and V can be found in the fact that diode ideality constant is in the exponential function in the expression for the current of the PV cell and thus has high impact on its value. Internal resistance is also in the exponential function but it has low impact considering that the voltage drop which creates is only a few percent of the voltage of the PV cell.

On Figs 2, 3 and 4 are shown P-V curves obtained for 3, 5, 10 and 20 fitting power points, using first (SP1), second (SP2) and third (SP3) shading pattern, respectively. To see the ability of the proposed approach in recreating the existing (real) P-V curve, for the appropriate shading patterns real P-V curves are also shown on figs 2, 3 and 4.

Analyzing the figs 2, 3 and 4 it can be seen that the best recreatinon of the exisitng P-V curve (best matching between the real P-V curve and the one obtained using the proposed approach) is achieved in the case with 20 fitting points for all three shading patterns. Also, these figs show that results obtained in the case with 10 fitting points are quite good and that 10 fitting points can be better choice in applications where time response needs to be shorter.

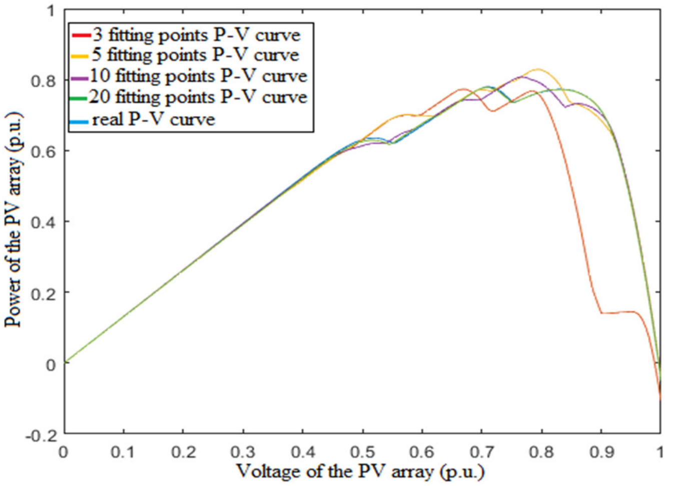

Fig. 2 P-V curves obtained for different number of fitting power points and the real P-V curve of the SP1

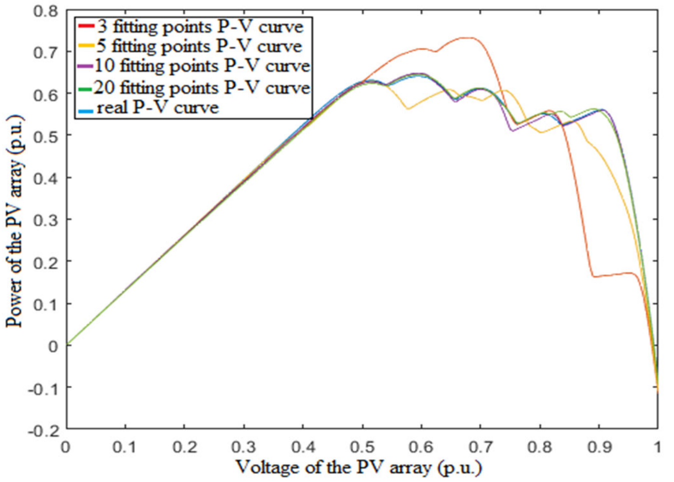

Fig. 3 P-V curves obtained for different number of fitting power points and the real P-V curve of the SP2

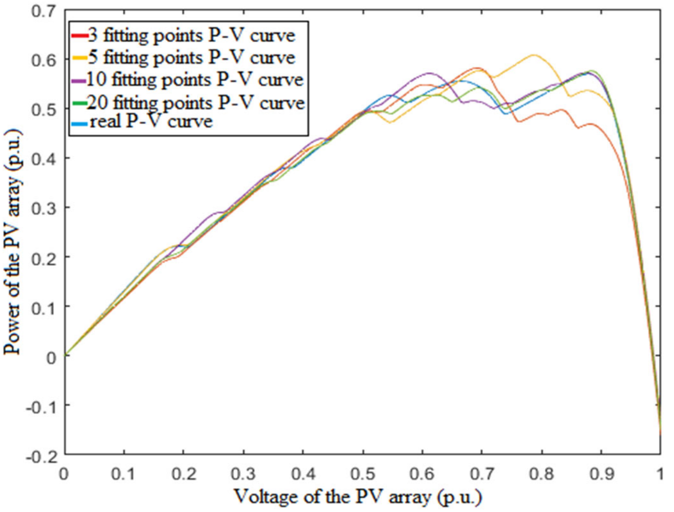

Fig. 4 P-V curves obtained for different number of fitting power points and the real P-V curve of the SP3

In general, increasing the number of fitting power points improves the accuracy of the proposed approach, but is more time consuming which can have negative impact on the energy production of the PV array on a time scale (energy lost in the calculation time can not be replaced by the additional power generation achieved by the better MPP location).

Fig. 5 represent P-V curves generated by the proposed method for different inaccuracies in the value of the diode ideality constant (cases with 20%, 10%, -10% and -20% mismatch between the actual and the value used in the model of the PV array are shown) using second shading pattern and 20 fitting power points.

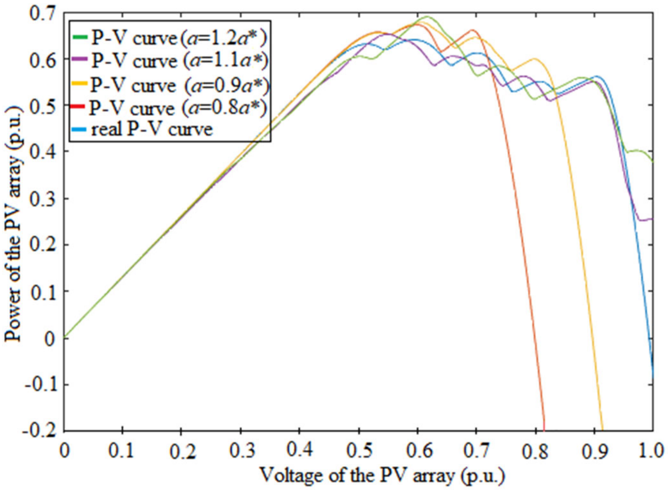

Fig. 5 P-V curves generated for different inaccuracies in the value of the diode idelity constant

Comparing P-V curves generated for different errors in diode ideality constant estimation with the real P-V curve from the fig. 5, it can be seen great mismatch between the curves, especially in cases when estimated value is lower than the real one ($a = 0.8a^*, a = 0.9a^*$). Also, fig 5 shows that proposed approach is not capable to recreate P-V curve accurately if diode ideality constant is not properly estimated, especially for voltages close to 1 p.u. and when estimated value is lower than the real one. This is because diode ideality constant greatly changes the open circuit voltage of the PV cell making the recreation of the P-V curve in most cases impossible using only the solar irradiations of the PV array surface as a control variable like in the proposed approach.

Figures representing P-V curves generated for inaccuracies in inverse saturation current and internal resistance are not shown because they are very similar to those on the figs 2, 3 and 4 obtained for the case with 20 fitting points.

VII. CONCLUSION

This paper presents an approach for determining the MPP location of the PV array in the case of partial shading based on the shading pattern recognition achieved by metaheuristic PSO method. The efficiency of the proposed approach is verified on the MATLAB simulation model of the PV array using three different shading patterns. The results show that accuracy of determining the MPP location is improved if the number of fitting power points is increased. It is important to notice that as the number of fitting points increases time needed for optimization method to recognize the shading pattern also increase, which is the main constraint for not using too many fitting points. Also, it is proven that accuracy of the proposed approach and its ability to properly recreate the P-V curve is sensitive to errors in estimation of some parameters in the PV cell model, especially of diode ideality constant. At the end it can be concluded that proposed approach can precisely determine the location of the MPP if enough number of fitting power points are used and the PV cell model parameters are accurately determined.

ACKNOWLEDGMENT

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia [grant number 451-03-65/2024-03/200102].

REFERENCES

[1] M. Jalil, S. Khatoon, I. Nasiruddin and R. Bansal, “Review of PV Array Modelling, Configuration and MPPT Techniques”, International Journal of Modelling and Simulation, vol. 42, no. 4, pp. 533-550, 2022.

[2] M. Afzal Awan, “A Technical Review of MPPT Algorithms for Solar Photovoltaic System: SWOT Analysis of MPPT Algorithms”, Sir Syed University Research Journal of Engineering & Technology, vol. 12, pp. 98-106, 2022.

[3] D. Sera, L. Mathe, T. Kerekes, S. V. Spataru and R. Teodorescu, “On the Perturb-and-Observe and Incremental Conductance MPPT Methods for PV Systems”, IEEE Journal of Photovoltaics, vol. 3, no. 3, pp. 1070-1078, 2013.

[4] B. Yang, T. Zhu, J. Wang, H. Shu, T. Yu, X. Zhang, W. Yao and L. Sun, “Comprehensive Overview of Maximum Power Point Tracking Algorithms of PV System Under Partial Shading Condition”, Journal of Cleaner Production, vol. 268, pp. 121983, September 2020.

[5] K. Lappalainen and S. Valkealahti, “Number of Maximum Power Points in Photovoltaic Arrays During Partial Shading by Clouds”, Renewable Energy, vol. 152, pp. 812-822, 2020.

[6] J. Li, Y. Wu, S. Ma, M. Chen, B. Zhang and B. Jiang, “Analysis of Photovoltaic Array Maximum Power Point Tracking under Uniform Environmental and Partial Shading Condition: A Review”, Energy Reports, vol. 8, pp. 13235-13252, 2022.

[7] M. Mohamed, A. Zaki Diab and H. Rezk, “Partial Shading Mitigation of PV Systems via Different Meta-heuristic Techniques”, Renewable Energy, vol. 130, pp. 1159-1175, 2019.

[8] E. Moshksar and T. Ghanbari, “A Model-Based Algorithm for Maximum Power Point Tracking of PV Systems Using Exact Analytical Solution of Single-Diode Equivalent Model”, Solar Energy, vol. 162, pp. 117-131, 2018.

[9] K. Ishaque and Z. Salam, “A Deterministic Particle Swarm Optimization Maximum Power Point Tracker for Photovoltaic System Under Partial Shading Condition”, IEEE Transactions on Industrial Electronics, vol. 60, no. 8, August 2013.

[10] T. Sen, N. Pragallapati, V. Agarwal and R. Kumar, “Global Maximum Power Point Tracking of PV Arrays Under Partial Shading Conditions Using a Modified Particle Velocity-Based PSO Technique”, IET Renewable Power Generation, vol. 12, no. 5, pp. 555-564, 2018.

[11] J. Zhang, K. Ding, R. Mei and Y. Cai, “Global Maximum Power Point Tracking Method Based on Sorting Particle Swarm Optimizer”, International Journal of Green Energy, vol. 15, no. 13, pp. 821-836, 2018.

[12] J. Prasanth Ram and N. Rajasekar, “A New Robust, Mutated and Fast Tracking LPSO Method for Solar PV Maximum Power Point Tracking Under Partial Shaded Conditions”, Applied Energy, vol. 201, pp. 45-59, September 2017.