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Determination of the photovoltaic system efficiency using the optimization method

Abstract*. This paper deals with determination of photovoltaic system efficiency using the differential evolution algorithm. The significance of this method is to determine the efficiency of the photovoltaic system, taking into account the solar irradiance, photovoltaic module temperature and the air mass factor. The aim of the paper is to determine the functional dependence of the overall efficiency of photovoltaic system, efficiency of the PV module and efficiency of DC/AC inverter under real working conditions using the differential evolution algorithm. The results in this paper show that the smallest deviation is achieved by considering all three variables in the calculation of efficiency.*

Streszczenie. *Artykuł dotyczy określenia wydajności układu fotowoltaicznego przy użyciu algorytmu ewolucji różnicowej. Znaczenie tej metody polega na określeniu wydajności układu fotowoltaicznego z uwzględnieniem natężenia promieniowania słonecznego, temperatury modułu fotowoltaicznego i współczynnika masy powietrza. Celem artykułu jest określenie zależności funkcjonalnej ogólnej wydajności układu fotowoltaicznego, wydajności modułu fotowoltaicznego i wydajności falownika DC / AC w rzeczywistych warunkach pracy z wykorzystaniem algorytmu ewolucji różnicowej. Zgodnie z osiągniętymi wynikami najmniejsze odchylenie osiąga się, biorąc pod uwagę wszystkie trzy zmienne w obliczeniach wydajności. (****Wyznaczanie wydajności systemu fotowoltaicznego z wykorzystaniem metody optymalizacji****).*

Keywords: efficiency, photovoltaic system, differential evolution, solar irradiance, temperature, air mass
Słowa kluczowe: sprawność, system fotowoltaiczny, ewolucja różnicowa, promieniowanie słoneczne, temperatura, masa powietrza.

Introduction

Renewable energy sources have shown significant growth over the last few decades. In particular, the photovoltaic (PV) systems have become very popular renewable energy source due to its long term economic prospect and ease of maintenance [1]. However, due to high investment price [2], optimization of PV system has to be performed, in order to achieve maximum energy yield. In addition to optimizing the inclination angle, azimuth angle, and other parameters it is also necessary to analyse the efficiency of the entire PV system as well. The efficiency of electricity generation from the PV system depends on various factors, such as the efficiency of PV modules, the efficiency of inverters and the efficiency of other parts of the PV system. However, the total efficiency of the PV system can only be determined under the operating conditions. For this reason, the paper presents the determination of the efficiency of the PV system, efficiency of the PV module and efficiency of the DC/AC inverter based on various factors using the optimization method called differential evolution (DE). The DE is a direct search stochastic algorithm capable of solving global optimization problems, subject to nonlinear constraints and operates on a population of candidate solutions and does not require a specific starting point [3]. Usually, DE is used to solve continuous optimization problems, where the candidate solutions are numerical vectors of dimension, but there exist many adaptions to solve combinatorial optimization problems, where the solutions are discrete objects [4]. Seme et al. [5] presents the optimization of a dual-axis PV tracking system, using differential evolution. The main goal was to maximize the production of electricity of a PV tracking system, by considering the consumption of a PV tracking system. On the basis of the measurements obtained from the PV system consisting of 6 mono-crystalline silicon PV modules of the Solar World SW175 type, installed capacity 1,050 kW_p and a total area of 7,83 m^2, an analysis of the results of solar irradiance and photovoltaic module temperature in dependence on efficiency was performed. The paper is organized in the following way: I. introduction, II. section describes the efficiency model; III. section presents and explains the obtained results; and the conclusion is discussed in the IV. section.

The efficiency model of the photovoltaic system

The efficiency η is in general as a function of solar irradiance G, the photovoltaic module temperature T and the relative air mass AM. Determination of efficiency η under different conditions was carried out using the semi-empirical efficiency model developed by Wilhelm Durisch [6]. This paper presents the determination of efficiency η based on the dependence of the individual factors. The efficiency calculations for different factors are described by (1) – (4).

(1) $$\eta(G)=x_1\left[x_2\frac{G}{G_0}+\left(\frac{G}{G_0}\right)^{x_3}\right]\left[1+x_4+x_5+1\right]$$

(2) $$\eta(G,T)=x_1\left[x_2\frac{G}{G_0}+\left(\frac{G}{G_0}\right)^{x_3}\right]\left[1+x_4\frac{T}{T_0}+x_5+1\right]$$

(3) $$\eta(T)=x_1\left[x_2+1\right]\left[1+x_4\frac{T}{T_0}+x_5+1\right]$$

(4) $$\eta(G,T,AM)=x_1\left[x_2\frac{G}{G_0}+\left(\frac{G}{G_0}\right)^{x_3}\right]\left[1+x_4\frac{T}{T_0}+x_5\frac{AM}{AM_0}+\left(\frac{AM}{AM_0}\right)^{x_6}\right]$$

where G_0, T_0 and AM_0 are the solar irradiance, photovoltaic module temperature and air mass under standard test conditions (G_0=1000 W/m^2, T_0=25°C and AM_0=1.5). The parameters x_1, x_2, x_3, x_4, x_5 and x_6 are determined by minimizing the root mean square error (RMSE) differences between measured and modelled values of the overall efficiency. Fig. 1 presents the block diagram for the entire efficiency calculation.

Results

The efficiency parameter determination using the selected DE is correlated with the solar irradiance G, photovoltaic module temperature T and air mass AM. The optimal set parameters of the DE are: the optimal values of population size (NP), mutation factor (F) and crossover rate

(*CR*) are set to be 70, 0.7 and 0.6 respectively. Maximum number of iterations/generations is set to be 100.000 and the selected DE strategy is set to be the DE/rand-to-best/1/exp.

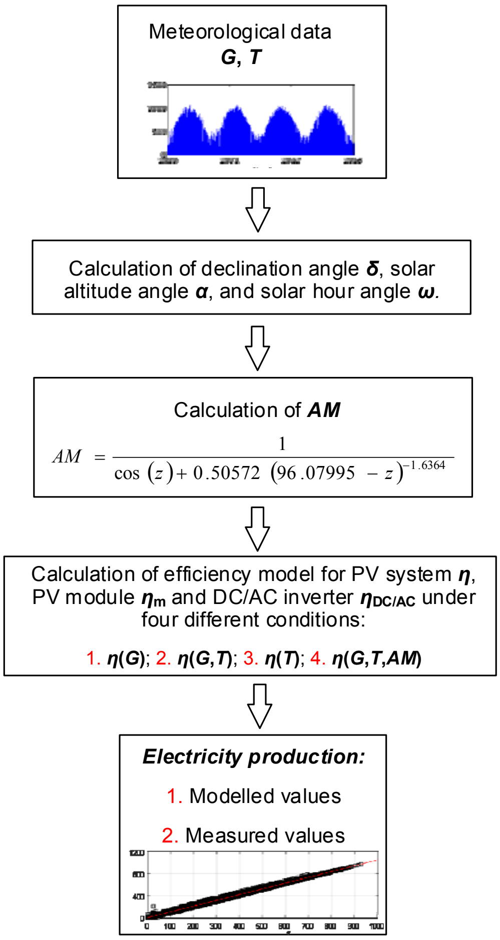

Fig.1. Block diagram for the entire efficiency calculation

The obtained measurements of solar irradiance *G*, photovoltaic module temperature *T* and air mass *AM* from the operating PV systems for a period of eight months are presented in Fig. 2. Based on the equations presented in the previous chapter, an analysis between measured and modelled data was conducted. Figs. 3 to 6 present a comparison of measured and modelled results of efficiency of PV system in dependence on solar irradiance and photovoltaic module temperature. In the following results, the efficiency model is calculated on the basis of four different correlations between the involved factors.

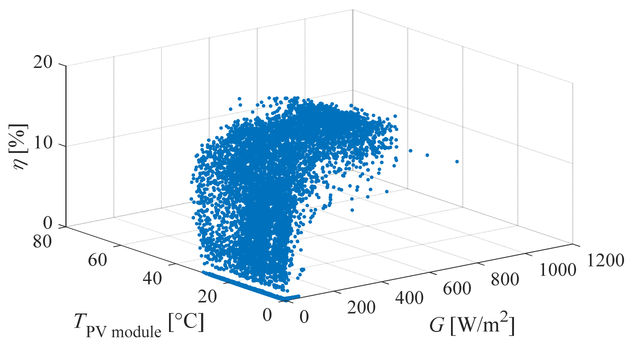

Fig.2. The efficiency of PV system *η* as a function of solar irradiance *G* and photovoltaic module temperature *T*.

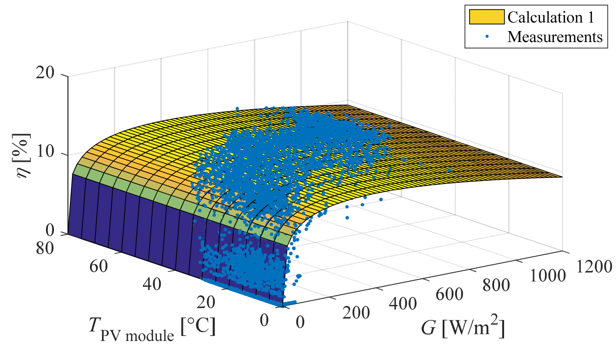

Fig. 3. Calculation 1: The efficiency of PV system *η* as a function of solar irradiance *G* at constant photovoltaic module temperature *T* and constant air mass *AM*.

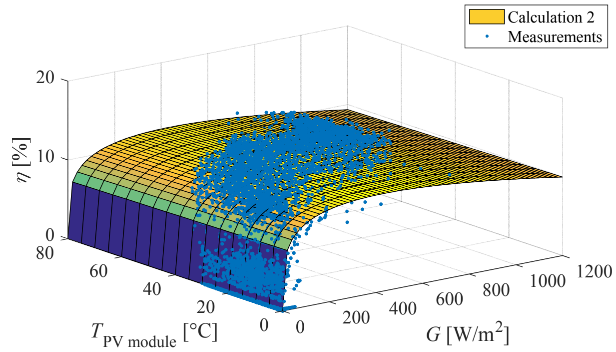

Fig. 4. Calculation 2: The efficiency of PV system *η* as a function of solar irradiance *G* and photovoltaic module temperature *T* at constant air mass *AM*.

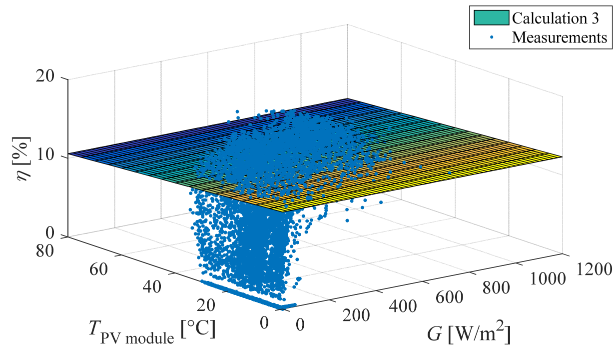

Fig. 5. Calculation 3: The efficiency of PV system *η* as a function of photovoltaic module temperature *T* at constant solar irradiance *G* and constant air mass *AM*.

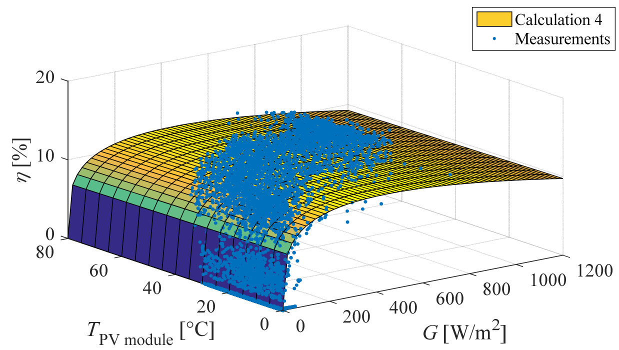

Fig. 6. Calculation 4: The efficiency of PV system *η* as a function of solar irradiance *G*, photovoltaic module temperature *T* and air mass *AM*.

The RMSE method was used to calculate the deviation between measured and modelled results of the efficiency. The efficiency calculation for all four cases (see Eq. 1 - 4) was also carried out in the case of PV module and DC/AC inverter. The values of efficiency model parameters and RMSE values for PV system, PV module and DC/AC inverter are presented in Table 1 – 3. Optimization results show that the smallest RMSE is achieved by considering all three variables in the calculation of efficiency (solar irradiance *G*, temperature of the photovoltaic module *T* and air mass *AM*).

Table 1. Photovoltaic system

	Efficiency model parameters						RMSE
	x_1	x_2	x_3	x_4	x_5	x_6	
1.	0.0568	-0.4678	0.2368	-2.7297	4.1496	/	2.0727
2.	0.1235	-0.4544	0.2420	-0.0309	-0.3854	/	2.0217
3.	-0.0732	-1.7987	-0.0925	0.1063	/	/	3.0412
4.	0.0928	-0.4813	0.2679	-0.0350	0.2248	-0.2802	1.9534

Table 2. Photovoltaic module

	Efficiency model parameters						RMSE
	x_1	x_2	x_3	x_4	x_5	x_6	
1.	0.0647	-0.3578	0.1370	-0.0684	0.7812	/	2.2377
2.	0.1162	-0.3389	0.1414	-0.0311	-0.4529	/	2.1723
3.	0.0307	-0.0737	-0.2333	2.7288	/	/	2.8813
4.	0.0837	-0.3659	0.1643	-0.0383	0.2085	-0.2619	2.1031

Table 3. DC/AC inverter

	Efficiency model parameters						RMSE
	x_1	x_2	x_3	x_4	x_5	x_6	
1.	0.0356	-22.802	-2.8484	-0.5935	0.0171	-0.8249	5.1045
2.	0.0356	-22.689	-0.0000	1.1634	0.3094	1.0499	5.1046
3.	0.2708	1.0748	0.0404	-2.4989	-0.2063	-1.0425	4.9468
4.	35.917	0.0197	10.365	0.0098	-7.4417	-0.0142	4.9319

Based on the results from Table 1 – 3, the calculation of efficiency for PV system, PV module and DC/AC inverter was conducted, taking into account the efficiency model parameters with the smallest RMSE (Calculation 4: The efficiency as a function of solar irradiance *G*, photovoltaic module temperature *T* and air mass *AM*).

The RMSE calculation of deviation between the measured and modelled values of power was also performed (see Fig. 12), using the efficiency of PV system η, PV module η_m and DC/AC inverter $\eta_{DC/AC}$. The RMSE values of the power of PV system using the efficiency of PV system P_η and the power of PV system using the efficiency of PV module and efficiency of DC/AC inverter $P_{\eta_m + \eta_{DC/AC}}$ are 2.8129 and 2.9835, while the power of the PV system using the efficiency of PV module P_{η_m} is much higher 10.0787. The conclusion can be made from the fact that the calculation of efficiency requires consideration of as many factors as possible.

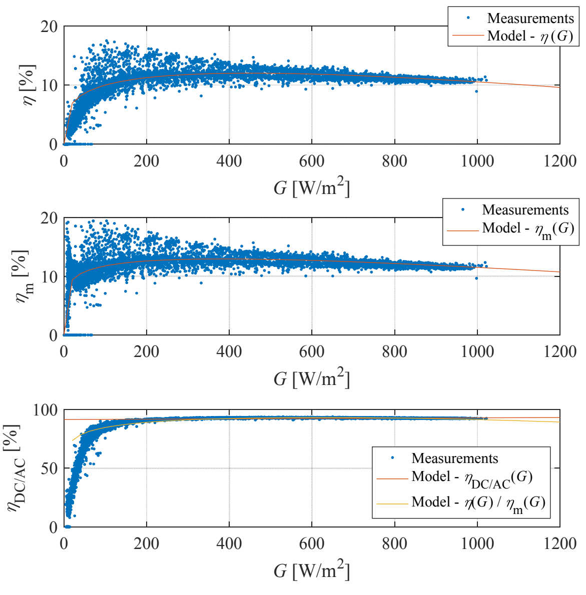

Fig. 7. The efficiency of PV system η, PV module η_m and DC/AC inverter $\eta_{DC/AC}$ as a function of solar irradiance *G*.

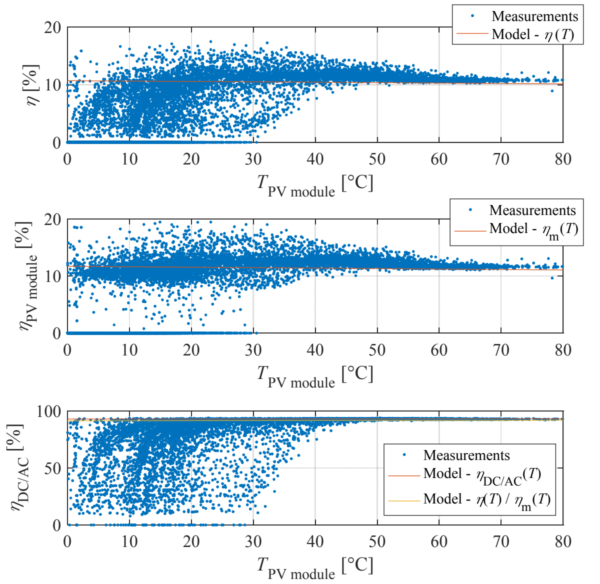

Fig. 8. The efficiency of PV system η, PV module η_m and DC/AC inverter $\eta_{DC/AC}$ as a function of PV module temperature *T*.

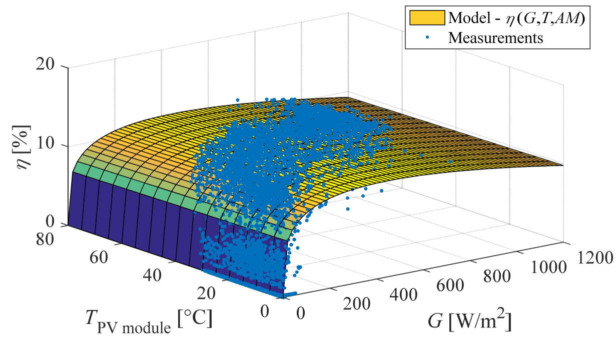

Fig. 9. The efficiency of PV system η as a function of solar irradiance *G*, PV module temperature *T* and air mass *AM*.

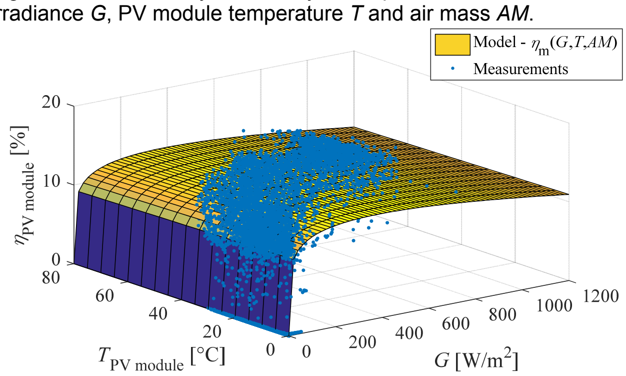

Fig. 10. The efficiency of PV module η_m as a function of solar irradiance *G*, photovoltaic module temperature *T* and air mass *AM*.

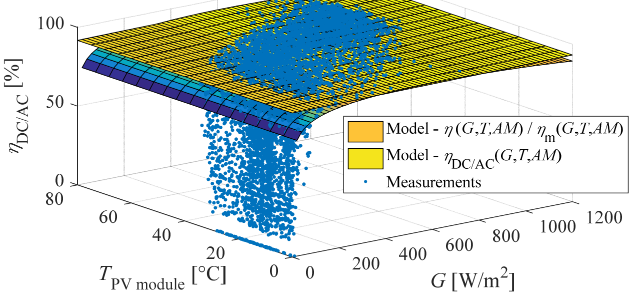

Fig. 11. The efficiency of DC/AC inverter $\eta_{DC/AC}$ as a function of solar irradiance *G*, photovoltaic module temperature *T* and air mass *AM*.

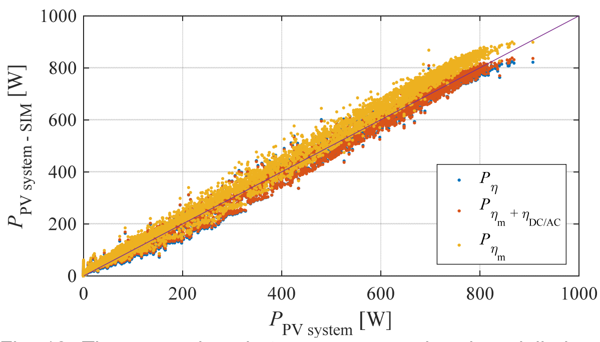

Fig. 12. The comparison between measured and modelled values of power of the PV system.

Conclusion

This paper deals with determining the efficiency of the PV system, PV module and DC/AC inverter using the optimization method. The objective function or the efficiency model takes into the account different factors, such as solar irradiance, photovoltaic module temperature and air mass. It can evident that more factors we use in the calculation, the smaller is the deviation between the measured and the modelled values.

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