AN INVESTIGATION INTO THE EFFECT OF PHOTOVOLTAIC MODULE ELECTRIC PROPERTIES ON MAXIMUM POWER POINT TRAJECTORY WITH THE AIM OF ITS ALIGNMENT WITH ELECTROLYZER *U-I* CHARACTERISTIC

by

Mihajlo FIRAK and Ankica DJUKIĆ*

Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

Original scientific paper
UDC: 621.357:662.769.2:519.876.2
DOI: 10.2298/TSCI1003729F

In order to combine a photovoltaic module and an electrolyzer to produce hydrogen from water, an intermediate DC/DC converter can be used to adapt output power features of the module to input power features of the electrolyzer. This can also be done without using electronics, which results in saving as much as 700 USD/kW, as previous investigation has shown. A more sophisticated investigation should be carried out with the aim of improving high system efficiency, resulting in matching the photovoltaic module maximum power point trajectory (the maximum power point path in the U-I plane as a result of solar irradiance change) to the operating characteristic of the electrolyzer. This paper presents an analysis of the influences of photovoltaic module electric properties, such as series and parallel resistance and non-ideality factor, on the maximum power point trajectory at different levels of solar irradiance. The possibility of various inclinations (right – vertical – left) in relation to an arbitrary chosen operating characteristic of the electrolyzer is also demonstrated. Simulated results are obtained by using Matlab/Simulink simulations of the well known one-diode model. Simulations have been confirmed with experiments on a real photovoltaic module where solar irradiance, solar cell temperature, electric current, and voltage in the circuit with variable ohmic resistance have been measured.

Key words: *photovoltaic module, series resistance, parallel resistance, non-ideality factor, operating (U-I) characteristic, maximum power point, electrolyzer*

Introduction

Today, scientific research in this field has concentrated on systems which use direct methods of producing hydrogen (H_2) without carbon dioxide (CO_2) emissions, such as the photoelectric dissociation of water [1, 2]. However, these systems can produce only hydrogen, whereas systems that use separate processes to convert photon energy to electric energy (photovoltaic – PV – modules) and to dissociate water can be set up to produce either electric energy or

* Corresponding author; e-mail: ankica.djukic@fsb.hr

hydrogen, or both at the same time. In addition to political, economic, and ecological reasons, this is one more reason why such systems are constantly being improved. Out of 194 plants producing hydrogen for hydrogen fuel cell vehicles made until today, 68 (35%) of them produce hydrogen by means of electrolysis [3] and 15 plants (8%) produce electricity without emitting CO_2 by using PV modules, *i. e*. by using solar energy. However, in general, PV modules are commercial models with basic electrical characteristics that need not be ideal for linking them directly to an electrolyzer, so a power electronics interface unit (maximum power point – MPP – tracker with a DC/DC converter) must be used in order to enable the electrolyzer to use all the electricity created by the PV module during changing levels of solar irradiance [4]. It has already been shown that including this intermediate electronic interface unit raises the cost of the system by 700 $/kW [5]. Therefore, some authors [6, 7] have proposed the option of directly connecting a PV module and an electrolyzer without using a power electronics interface unit. The methodology according to [8] aims at designing a system to achieve an overlap between the MPP trajectory of the PV module and the *U-I* characteristic of the electrolyzer at any level of solar irradiance as much as possible. According to [8, 9], an efficiency of over 90% has been achieved when the preparation of *U-I* characteristics both of the PV system and the electrolyzer is proposed. Furthermore, the MPP trajectory of the PV system is simply adjusted to match commercial modules with known characteristics, but deeper causes of its shape or inclination have not been investigated. Hence, this paper shows that the electrical parameters, such as series and parallel resistance, R_s and R_p, respectively, and the non-ideality factor m, within a relatively narrow area of the PV cell temperature influence the position of the MPP trajectory in relation to an arbitrarily selected, but experimentally measured *U-I* characteristic of an electrolyzer. The goal was not to achieve the overlap of the characteristics, but simply to observe the influence of the above mentioned factors in the PV module. The *U-I* characteristic of the electrolyzer is not varied; the temperature and pressure in the electrolyzer, as well as the number of electrodes (*i. e*. anode – cathode pairs) are kept constant, *i. e*. this characteristic serves only as an example of the goal. Since in this study, only the solar irradiance E, the PV cell temperature T, the voltage U, the electric current I, the short circuit current I_{sc} and the open circuit voltage U_{oc} of the PV module were available during outdoor measurements, the influence of the series and parallel resistance, R_s and R_p, and the non-ideality factor m on the position of the MPP trajectory was examined by using a Simulink [10] mathematical model of a PV module. There also exist, of course, many other sophisticated methods for MPP calculations [11]. The reference mathematical model assumes a one-diode model in which these parameters are defined in such a way that the *U-I* characteristic of the PV module is reproduced, with minimal deviation and with measurements of the real *U-I* characteristic at the solar irradiance of E = 900 W/m^2 and the PV cell temperature of t = 48 °C.

Experimental apparatus

Commercial PV modules built from 36 PV cells generally have a MPP trajectory that curves to the right, fig. 1(a), under STC (Standard Test Conditions: PV cell temperature t = 25 °C, reference air mass AM of 1.5, solar irradiance level E = 1000 W/m^2). However, the trajectory is sometimes vertical, fig. 1(b), and only very rarely it curves to the left, fig. 1(c). The reason for this is that manufacturers attempt to make the fill factor (*FF*) as close to 1 as possible and that these trajectory measurements assume a constant temperature (independent from solar irradiance E). The *FF* is calculated according to eq. 1.

$$FF \quad \frac{U_{\mathrm{mpp}} I_{\mathrm{mpp}}}{U_{\mathrm{oc}} I_{\mathrm{sc}}} \tag{1}$$

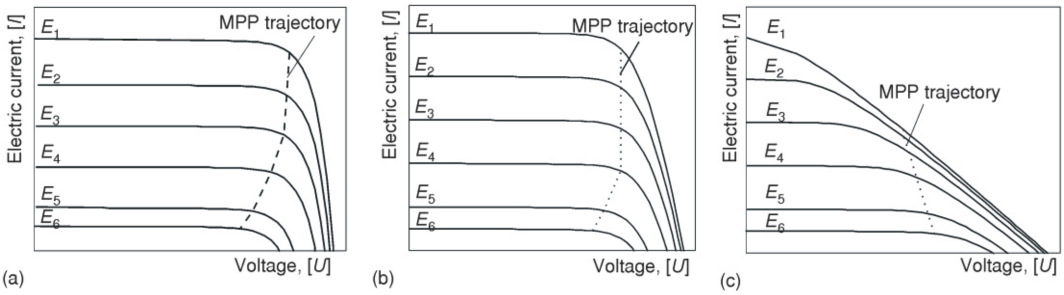

Figure 1. Examples of MPP trajectories of PV modules curving to the right, vertically, and to the left

A commercial electrolyzer can only have a *U-I* characteristic sloped to the right (fig. 2).

Figures 1 and 2 show that if the use of a power electronics interface unit is avoided, the MPP trajectory of the PV module (or array) has to be curved to the right, matching the slope of the electrolyzer and being as close as possible to its characteristic, fig. 3.

The MPP trajectory of the PV module can be aligned with the *U-I* characteristic of the electrolyzer using appropriate designs of the PV module and electrolyzer or rather by varying the number of serial connected cells and the number of parallel cell strings of the PV module. In this paper, however, only the possibility of modifying the MPP trajectory of a single PV module will be examined while the *U-I* characteristic of the electrolyzer is kept constant.

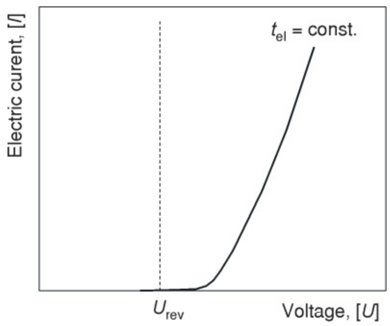

Figure 2. Example of the *U-I* characteristic of an electrolyzer

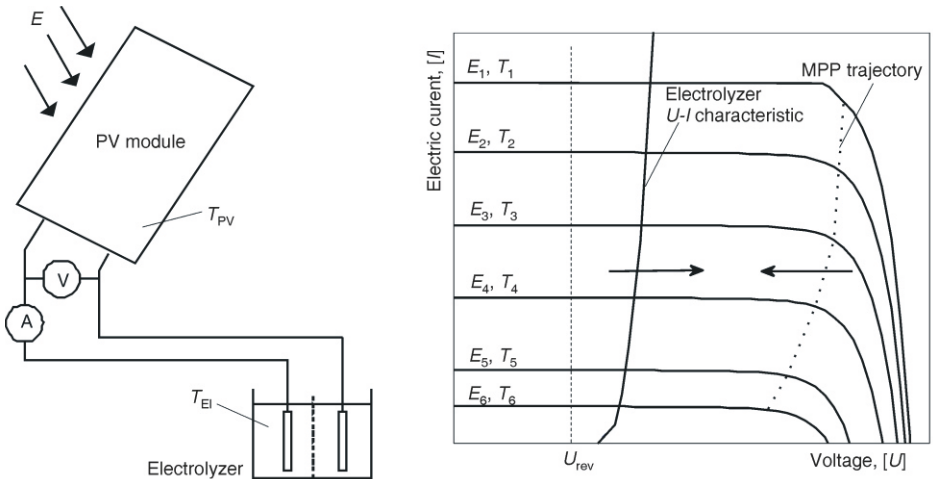

Figure 3. Example of the MPP trajectory approximately matched to the *U-I* characteristic

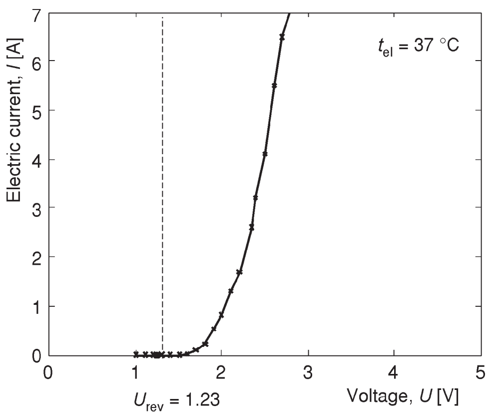

Figure 4. The reference electrolyzer *U-I* characteristic

Experiment

The experiments were performed in May/June when it was possible to make use of a large amount of solar irradiance. This is very important because the aim of this paper is to study powerful parameters on the PV module MPP trajectory. The reference *U-I* characteristic of the electrolyzer used in this paper comes from experimental measurements of a laboratory prototype of an electrolyzer with one pair of electrodes (anode and cathode). The electrode layout is 90 50 mm with thickness of 2 mm and the electrode is made of nickel (Ni) metal foam [12]. The experimental U-I characteristic of the electrolyzer is shown in fig. 4.

The real PV module used to determine the mathematical model is made of 18 PV m-Si cells of 125 65 mm, connected into two parallel strings of 9 cells (modules made by Solaris, Novigrad, Croatia; PV cells made by Helios, Padua, Italy). The *U-I* characteristics were measured in real conditions of solar irradiance. Figure 5(a) shows a diagram of the measured process which includes a PV module, a load (variable rheostat resistor), an ampermeter, a voltmeter and a solar irradiance sensor parallel to the plane of the PV module. Figure 5(b) shows the results of the measurements.

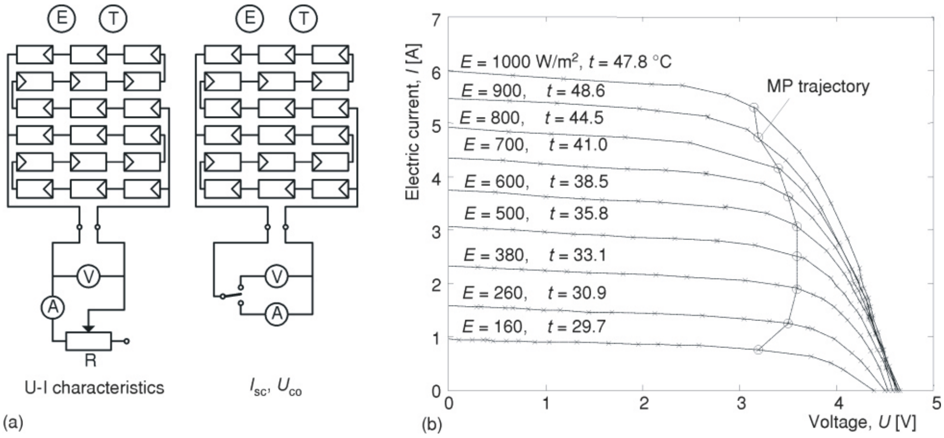

Figure 5. Diagram of the measurement process (a) and the results (b)

The temperatures shown in fig. 5 are average temperatures of the PV module during the measurement of each characteristic (the largest range is 3.5 °C and the smallest 0.7 °C with constant solar irradiance and the range is determined by wind speed). Furthermore, it can be seen that the total range of the temperature values at which the characteristics were recorded does not exceed 20 °C. A corresponding *FF* has also been calculated on the basis of these data, which are presented in tab. 1.

Table 1. Experimental measurement data of PV module

E [Wm^{-2}]	U_m [V]	I_m [A]	U_{oc} [V]	I_{sc} [V]	t [°C]	FF
1000	3.15	5.3	4.615	5.98	47.8	0.605
900	3.2	4.74	4.64	5.460	48.6	0.599
800	3.4	4.16	4.59	4.92	44.5	0.626
700	3.5	3.63	4.66	4.348	41.0	0.627
600	3.6	3.075	4.64	3.748	38.5	0.636
500	3.6	2.5	4.64	3.075	35.8	0.631
380	3.6	1.88	4.54	2.32	33.1	0.642
260	3.5	1.245	4.51	1.575	30.9	0.613
160	3.2	0.75	4.39	0.95	29.7	0.575

Figure 5 also shows the corresponding real-valued MPP trajectory which has a curve that is suitable for matching with the *U-I* characteristic of the electrolyzer at low solar irradiance and very unsuitable at high values. The question instantly presents itself: would it be possible to curve that part of the MPP trajectory to the right and which parameters of the PV module determine the slope? Answers to these questions are examined later. Figure 6 shows the measurements of the relationship of the parameters of the short circuit current I_{sc} and the open circuit voltage U_{oc} to solar irradiance in real outdoor conditions.

Figure 6 shows that the PV cell temperature is lower at lower levels of solar irradiance as this can be seen in fig. 5. This effect is documented in literature [13] and is expressed by the following equation:

$$T \quad T_a \quad \frac{NOCT \quad 20}{800} E \qquad (2)$$

Some manufacturers of PV modules give diagrams of the relationship of short circuit current and open circuit voltage to solar irradiance and PV cell temperature [14].

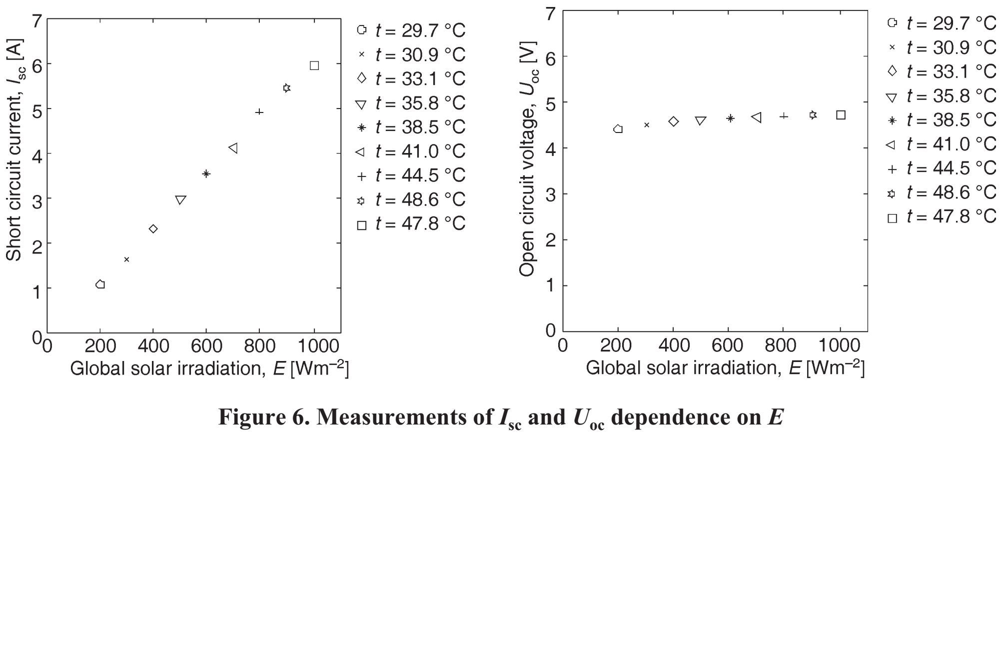

Figure 6. Measurements of I_{sc} and U_{oc} dependence on E

Mathematical models of the electrolyzer and the *U-I* characteristics of the photovoltaic module

Electrolyzer

The structure of the mathematical model of the electrolyzer is given according to [15] and the parameters, such as the parameter related to ohmic resistance of electrolyte *a*, coefficient for overvoltage on electrodes *b*, and coefficient for overvoltage on electrodes *c*, are determined by using the curve fitting tool of the Matlab Software on the basis of the measurement results shown in fig. 4.

$$U \quad U_{\mathrm{rev}} \quad \frac{a}{A} I \quad b \log \quad \frac{c}{A} \quad 1 \tag{3}$$

PV module MPP trajectory

The mathematical model of the PV module is a one-diode model [16-18] given in the equation:

$$I \quad I_{\mathrm{ph}} \quad I_{\mathrm{s}} \exp \frac{U \quad IR_{\mathrm{s}}}{U_{\mathrm{T}}} \quad 1 \quad \frac{U \quad IR_{\mathrm{s}}}{R_{\mathrm{p}}} \tag{4}$$

where

$$I_{\mathrm{ph}} = (c_1 + c_2 T)E \tag{5}$$

$$I_{\mathrm{ph}} = I_{\mathrm{sc}} \text{ (for } U = 0 \text{ V)} \tag{6}$$

$$I_{\mathrm{s}} \quad \frac{I_{\mathrm{sc}}}{\exp \dfrac{U_{\mathrm{oc}}}{U_{\mathrm{T}}} \quad 1} \tag{7}$$

$$U_{\mathrm{T}} \quad m \frac{n_{\mathrm{s}} k T_{\mathrm{c}}}{e} \tag{8}$$

It should be emphasized that in this model, the quantities of series and parallel resistance and the non-ideality factor are constants, and short circuit current, open circuit voltage, and saturation dark current are dependent on solar irradiance and PV cell temperature. The values for these constants are: R_{s} = = 0.099 Ω, R_{p} = 20 Ω, m = 1.6, determined at E = 900 W/m² and t = 48 °C. This model will be referred to as the *reference model*. A comparison of the mathematical models and the measurements of the PV module MPP trajectories and the electrolyzer U-I characteristics is given in fig. 7.

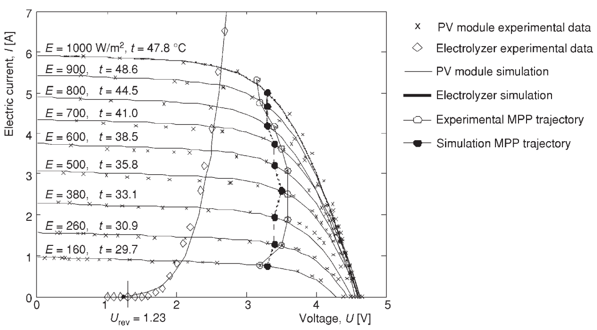

Figure 7. Comparison of mathematical models of the PV module and the electrolyzer with measurement values

Figure 7 shows that in real conditions the experimental PV module has a complicated (curved) incline (slope) increasing to the left with the rising of the PV cell temperature and solar irradiance. Furthermore, the MPP trajectory of the reference model (calculated for the measured irradiance, measured PV cell temperature and measured open circuit voltage) shows a satisfactory agreement with the measured trajectory. This confirms that our reference model presented in this paper can be used in further analyses.

The effect of electric photovoltaic module parameters on maximum power point trajectory

It is well known that the electrical parameters in the one-diode PV cell model, solar irradiance E and PV cell temperature T, are dependent [19]. In the investigation presented in this paper, the exact dependence of the PV cell model electrical parameters, such as series and parallel resistance, R_s (E, T) and R_p (E, T), the non-ideality factor m (E, T) and the saturation dark current I_s (E, T), was not known and the main electrical parameters, such as the open circuit voltage U_{oc} (E, T) and the short circuit current I_{sc} (E, T) as well as the PV cell temperature and solar irradiance, were measured only within the very restricted solar irradiance and PV cell temperature range. By using eq. (7) it is possible to express the reverse cell saturation current I_s using the measured variables of the open circuit voltage and the short circuit current, which are readily dependent on solar irradiance and PV cell temperature. In this way, the basic input variables in the reference model are solar irradiance, PV cell temperature, and open circuit voltage. To obtain the MPP trajectory [20] the solar irradiance value in a certain range should be used. The chosen values are the same as those in the outdoor measurements: 1000, 900, 800, 700, 600, 500, 380, 260, and 160 W/m^2. Each of the corresponding *U-I* characteristics was calculated at the mean measured PV cell temperature (this is the arithmetic mean of the measured load points of the PV cell temperatures) for the respective solar irradiance. Thereafter, the reference MPP trajectory was plotted (the curve *simulation MPP trajectory* in fig.7). According to [16] it is known that the ranges of the PV cell electrical parameters can be roughly estimated as follows: $0.001 < R_s <$ < 0.2, $0.1 < R_p < 1000$, and $1 < m < 5$. In addition to the above mentioned dependency on solar irradiance and PV cell temperature, these values also depend on PV cell production technology [16]. This fact allows the authors to use arbitrary values within the ranges stated in this investigation of the influence of these values on the curvature and the slope of the MPP trajectory. Figures 8, 9, and 10 show the influence of series and parallel resistance and the non-ideality factor on the reference MPP trajectory in comparison with the simulated MPP trajectories obtained for different values of these parameters. Each figure is divided into three diagrams. The reference diagram presenting the reference MPP trajectory is in the middle (fig. 7 without the electrolyzer characteristics) while the simulated trajectories for smaller and larger values of the series and parallel resistance and the non-ideality factor are positioned on the left-hand and the right-hand side. The isolated effect of the PV cell temperature on the MPP trajectory could be investigated in a similar way by using this reference model; this, however, would be beyond the scope of this paper. According to [19] it can be seen that the series resistance increases with higher PV cell temperature, especially if solar irradiance is decreasing. This is an unwanted influence on the upper part of the MPP trajectory and the effect can be clearly seen in fig. 7. The parallel resistance decreases with higher PV cell temperature and this can also be seen as an unwanted influence on the curvature of the MPP trajectory. The non-ideality factor decreases with higher PV cell temperature and increases with higher solar irradiance [19]. This can explain the fact that

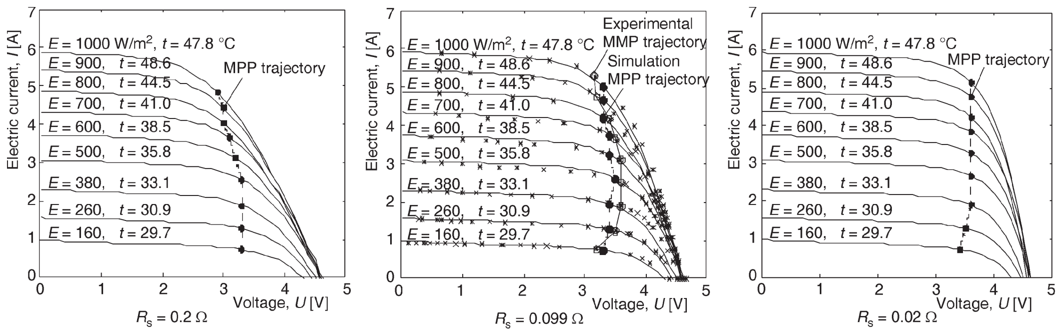

Figure 8. Influence of R_s on MPP trajectory

changes in the non-ideality factor do not affect the MPP trajectory curvature (fig. 10). Figure 8 shows the influence of a series resistance change on the MPP trajectory if series resistance is 0.2, 0.099 and 0.02 Ω. It can be seen that a decrease in the series resistance moves the upper part of the trajectory to the right if the other two parameters (parallel resistance and non-ideality factor) are kept constant.

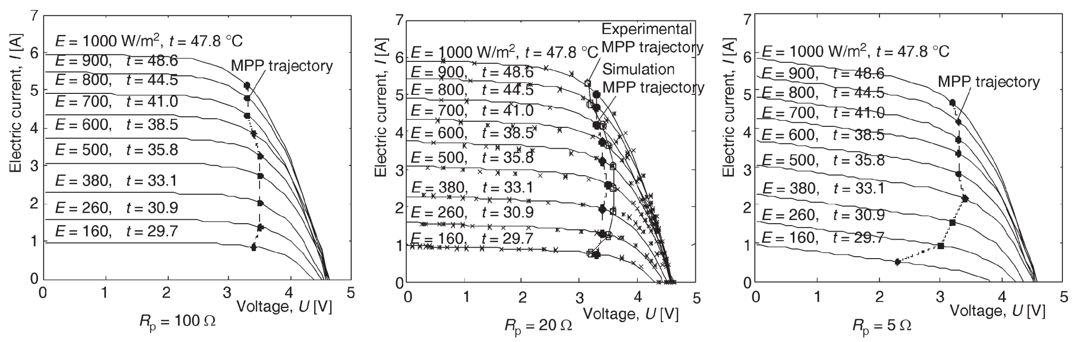

Figure 9. Influence of R_p change on MPP trajectory

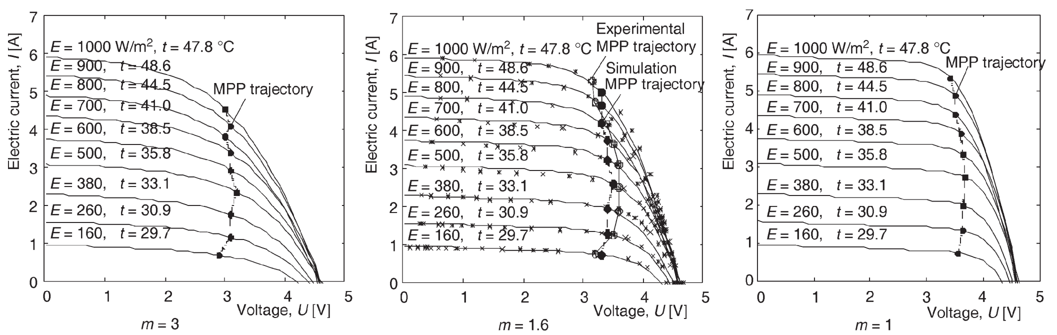

Figure 10. Influence of *m* on MPP trajectory

Figure 9 shows the influence of a parallel resistance change on the MPP trajectory in a range of values of 100, 20, and 5 Ω. It can be seen that an increase in the parallel resistance moves the lower part of the trajectory to the left. The upper part is much less affected.

Figure 10 shows the influence of the non-ideality factor m for $m = 1$, 1.6, and 3. It can be seen that a decrease in this value shifts the whole trajectory to the right, but the upper and the lower curvature are not affected.

Conclusions

The aim of this paper was to investigate the effects of the most powerful parameters on the operating (*U-I*) characteristics and the MPP trajectory of a PV module. These parameters were defined in a range of values acceptable for PV modules in general. The results were completed after a number of simulations performed by using Matlab/Simulink software. All dependences of the PV module operating characteristic on every single parameter were taken into consideration. According to the performed simulations and experiments, it should be emphasized that for an effective PV module operation directly connected with an electrolyzer, a detailed design analysis is necessary. This is important because of potential losses in the sensitive connections of the system design which leads to unwanted slopes of the PV module operating characteristics and the MPP trajectory. In this paper, the possibility and consequences of variations of these parameters are explained in theory and proved with simulations and experimental results. It is not simple to define the actual values of the mentioned parameters and the knowledge of and how to use different methods of calculating values is required because there is no manufacturer's information about measured or simulated values of these powerful parameters, such as series resistance, parallel resistance, and non-ideality factor, especially under variable solar irradiance. From the graphs of the MPP trajectories, the following can be concluded regarding the influence of electrical parameters of PV modules on the MPP trajectory and its overlapping with the *U-I* characteristic of the electrolyzer: it is generally preferable if the series resistance R_s tends to be smaller, the parallel resistance R_p tends to be higher, and the non-ideality factor m closer to 1 (smaller m generally moves the whole trajectory to the right). Some of these parameters can be controlled (minimizing R_s and maximizing R_p increases the efficiency of the module) while others are determined by factors, such as solar irradiance and PV cell temperature, that can not be influenced. An increase in solar irradiance generally increases the solar cell temperature which has an unwanted effect of increasing the series resistance. This leads to the conclusion drawn by the authors that when using a PV module together with an electrolyzer without a power electronics interface unit it might be advisable to add a cooling system to the module. This leaves room for further investigations into PV module and electrolyzer systems without power electronics interface units.

Nomenclature

A	– electrode area, 0.0045 m^2
a	– parameter related to ohmic resistance of electrolyte, 0.5e-4 Ωm^2
b	– coefficient for overvoltage on electrodes, 0.28 V
c	– coefficient for overvoltage on electrodes, 0.09953 $A^{-1}m^2$
c_1	– parameter for temperature dependence, 3e-3 m^2/V
c_2	– parameter for temperature dependence, 0.1e–6 m^2/VK
E	– solar irradiance, [Wm^{-2}]
e	– elementary charge, 1.60219e–19 C
FF	– fill factor (< 1)

I – electrolyzer operating current, [A]
I_{ph} – photo current, [A]
I_{PV} – PV module operating current, [V]
I_s – saturation dark current, [A]
I_{sc} – short circuit current, [A]
k – Boltzmann's constant, 1.3806e-23 [JK^{-1}]
m – non-ideality factor
$NOCT$ – normal operating cell temperature, [K]
n_p – number of parallel strings of PV cells
n_s – number of series-connected PV cells
PV – photovoltaic
R_p – parallel resistance, [Ω]
R_s – series resistance, [Ω]
T_a – atmospheric temperature, [K]
T_c, t – photovoltaic (PV) cell temperature, [K] [°C]
U – electrolyzer and/or PV module operating voltage, [V]
U_{oc} – measured PV module open circuit voltage, [V]
U_{PV} – PV module operating voltage, [V]
U_{rev} – reversible voltage, 1.23 V
U_T – thermal voltage, [V]

References

[1] Grimes, C. A., Varghese, O. K., Ranjan, S., Light, Water, Hydrogen, Springer-Verlag, Berlin, Heidelberg, 2008
[2] Gibson, L. T., Kelly, A. N., Optimization of Solar Powered Hydrogen Production Using Photovoltaic Electrolysis Devices, *International Journal of Hydrogen Energy, 33* (2008), 21, pp. 5931-5940
[3] http://www.fuelcells.org/info/charts/h2fuelingstations.pdf
[4] Bilgen, E., Solar Hydrogen from Photovoltaic-Electrolyzer Systems, *Energy Convers Manage, 42* (2001), 9, pp. 1004-1057
[5] Khan, M. J., Iqbal, M. T., Pre-Feasibility Study of Stand-Alone Hybrid Energy Systems for Applications in Newfoundland, *Renewable Energy, 30* (2005), 6, pp. 835-54
[6] Barbir, F., PEM Electrolysis for Production of Hydrogen from Renewable Energy Sources, *Solar Energy 78* (2005), 5, pp. 661-669
[7] Shapiro, D., *et al*., Solar Powered Regenerative PEM Electrolyzer/Fuel Cell System, *Solar Energy,79* (2005), 5, pp. 544-550
[8] Biddyut, P., Andrews, J., Optimal Coupling of PV Arrays to PEM Electrolysers in Solar-Hydrogen Systems for Remote Area Power Supply, *International Journal of Hydrogen Energy, 33* (2008), 2, pp. 490-498
[9] Clarke, R. E., *et al*., Direct Coupling of an Electrolyser to a Solar PV System for Generating Hydrogen, *International Journal of Hydrogen Energy, 34* (2009), 6, pp. 2531-2542
[10] ***, The MathWorks Inc., Using Simulink, 2000
[11] Salas, V., *et al*., Review of the Maximum Power Point Tracking Algorithms for Stand-Alone Photovoltaic Systems, *Solar Energy Materials & Solar Cells, 90* (2006), 11, pp. 1555-1578
[12] ***, MitsubishiMaterials, http://www.mmc.co.jp/alloy/english/products/happou/kouzou.html#hyou
[13] Markvart, T., Solar Electricity, John Wiley & Sons Inc., Chichester, UK, 1994
[14] http://www.solarcentury.co.uk/content/download/3163/26112/file/Sharp-ND-Series.pdf
[15] Ulleberg, Q., Modeling of Advanced Electrolyzers: a System Simulation Approach, *International Journal of Hydrogen Energy, 28* (2003), 28, pp. 21-33
[16] Quaschning, V., Understanding Renewable Energy Systems, Bath Press, London, UK, 2005
[17] Kulišić, P., Vuletin J., Zulim, I., Solar Cells (in Croatian), Školska knjiga, Zagreb, Croatia, ISBN: 953–0–31631-3, 1995
[18] Chenni, R., *et al*., A Detailed Modeling Method for Photovoltaic Cells, *Energy, 32* (2007), 9, pp. 1724-1730
[19] Karatepe, E., Boztepe, M., Çolak, M., Estimation of Equivalent Circuit Parameters of PV Module Using Neural Network, *IJCI Proceedings*, International XII Turkish Symposium on Artificial Intelligence and Neural Networks, 2003, Vol. 1, No .1, pp. 214-221
[20] Tafticht, T., *et al.*, An Improved Maximum Power Point Tracking Method for Photovoltaic Systems, *Renewable Energy, 33* (2008), 7, pp. 1508-1516

Paper submitted: March 22, 2009
Paper revised: May 14, 2010
Paper accepted: June 6, 2010