Revue des Energies Renouvelables Vol. 20 N°3 (2017) 497 - 503
DOI: https://doi.org/10.54966/jreen.v20i3.643

Optimal coupling of a PEM electrolyser to a PV generator: Case of Adrar

Djamila Ghribi-Diaf [1*] , Said Diaf [2], Abdellah Khelifa [3] and Nouamane Kellil [1]

[1] Unité de Développement des Equipements Solaires, UDES
Centre de Développement des Energies Renouvelables, CDER
42415, Tipaza, Algérie

[2] Centre de Développement des Energies Renouvelables, CDER
Route de l'Observatoire, 16340 Bouzareah, Algérie

[3] Laboratoire de Génie Chimique, Université Saâd Dahlab
B.P. 270, Route de Soumaâ, 09000 Blida, Algérie

(reçu le 20 Septembre 2017 - accepté le 30 Septembre 2017)

Abstract - *An optimization method is proposed and applied to study a PV-electrolyzer system consisting of Solarex MSX60 modules and PEM electrolyser H-Tec StaXX7 stacks. A total of 41 series-parallel combinations of PV modules and electrolyser stacks were analyzed. The configuration of 05 stacks of electrolyser in series connected with 04 PV modules in series is identified as optimal configuration for the site of Adrar. This configuration presented a value of 0.2 % in terms of annual energy losses and an annual production of hydrogen of 125* m^3.

Résumé - *Une méthode d'optimisation est proposée et appliquée à l'étude d'un système d'électrolyse photovoltaïque composé de modules Solarex MSX60 et d'un électrolyseur de type PEM H-Tec StaXX7. Un total de 41 combinaisons de stacks d'électrolyseurs et de modules PV série-parallèle ont été analysées. La configuration comportant 5 stacks d'électrolyseurs en série connectés à 4 modules PV en séries a été identifié comme étant la configuration optimale pour le site d'Adrar. Cette configuration présente des pertes annuelles d'énergie de 0.2 % et une production annuelle d'hydrogène de 125* m^3.

Keywords: PV array - PEM electrolyser - Optimal coupling - Maximum power point.

1. INTRODUCTION

Hydrogen as an energy currency, carrier and storage medium may be a key component of the solution to problems of global warming, poor air quality and dwindling reserves of liquid hydrocarbon fuels. Renewable energy–hydrogen systems for remote area power supply potentially constitute an early niche market for zero-emission hydrogen energy technology, because of the high costs of conventional energy sources in such applications.

Solar-hydrogen systems mainly consist of a photovoltaic (PV) array, electrolyser, hydrogen storage and fuel cell. Hydrogen is a flexible storage medium for intermittent renewable energy and can be generated by the electrolysis of water. It is particularly advantageous if an electrolyser may be simply and efficiently coupled to a source of renewable electrical energy system.

The direct integration of a PV array and an electrolyser without interfacing electronics such as a maximum power point tracker (MPPT) / dc-to-dc converter would lead to a significant cost reduction and thereby enhance the economic viability of solar-hydrogen systems in remote area applications.

Unfortunately, in PV-hydrogen systems, the direct coupling problem lies in the transfer of the maximum power from the PV array to the electrolyser, which often suffers from poor adaptation. The resulting operating point is sometimes very far from

* ghdiaf@yahoo.fr

the maximum power point (MPP). To overcome this problem, several methods, theoretical and experimental, have been proposed in the literature to determine the optimal configuration between a PV array and an electrolyser.

In this study and in order to study the direct coupling of a StaXX7 50 PEM electrolyzer and Solarex MSX60 PV modules, we opted for the method [1] which consists to vary the series-parallel configurations of individual PV modules, and individual PEM electrolyser cells (or small stacks), to achieve the closest possible matching between the resulting MPP curve of the PV array, and the characteristic current (I) - voltage (V) curve of the electrolyser bank.

To find the optimal matching condition in the case study, fourty-one different series–parallel combinations of PV modules and electrolyser stacks for direct-coupling were evaluated in terms of the percentage of the maximum available PV power transferred to the electrolyser at various solar irradiance values, the amount of energy loss over the year due to direct-coupling compared to the maximum energy transfer achievable, and the amount of annual hydrogen production. These parameters were calculated by a computer simulation model developed as part of this study.

2. SOLAR PV COUPLING TO PEM ELECTROLYSER

2.1 Photovoltaic generator model

In this study, an explicit model [18] is used to simulate current (I) - voltage (V) characteristics of the modules. The relation between the current I and the voltage V, in this model, under standards conditions is given by:

$$I = I_{SC,ref} \left(1 - C_1 \left(\exp\left(\frac{V}{C_2\, V_{OC,ref}} \right) - 1 \right) \right) \tag{1}$$

where

$$C_1 = \left(1 - \frac{I_{max,ref}}{I_{SC,ref}} \right) \exp\left(\frac{-V_{max,ref}}{C_2\, V_{OC,ref}} \right) \tag{2}$$

$$C_2 = \frac{\left(V_{max,ref} \;/\; V_{OC,ref} \right) - 1}{\ln\left(1 - \left(I_{max,ref} \;/\; I_{SC,ref} \right) \right)} \tag{3}$$

Under the variable operating conditions of temperature and solar irradiance, the new values of the current (I_{pvn}) and the voltage (V_{pvn}) of the PV module/generator are obtained by:

$$I_{pvn} = I + \Delta I \tag{4}$$

$$V_{pvn} = V + \Delta V \tag{5}$$

ΔI and ΔV represents respectively the variation of the current and voltage according to the temperature and solar radiation, there are given by the following equations:

$$\Delta I = \mu_{Isc} \left(G_\beta \;/\; G_{ref} \right) \Delta T + \left(G_\beta \;/\; G_{ref} - 1 \right) I_{SC,ref} \tag{6}$$

$$\Delta V = -0.0539\, V_{max,ref} \ln\left(G_\beta \;/\; G_{ref} \right) - \mu_{V_{OC}} \left(T_c - T_{c,ref} \right) \tag{7}$$

$$\Delta T = T_c - T_{c,ref} \tag{8}$$

G_β represents the solar radiation on tilted module plane (W/m^2) and G_{ref} reference solar radiation (1000 W/m^2), $T_{c,ref}$ is reference cell temperature (25°C), μ_{Isc}, μ_{Voc} are coefficients given by manufacturer's. T_c, cell operating temperature, is approximately proportional to the incident solar irradiance and is given by:

$$T_c = T_a + G_\beta\left(\frac{NOCT - 20}{800}\right) \tag{9}$$

where T_a is ambient temperature and $NOCT$ is the normal operating cell temperature, which is generally given in the manufacturer's specifications. For a PV generator consisting of N_s modules in series and N_p modules in parallel as shown in figure 1, the equation describing the characteristic (I_{GEN}, V_{GEN}) becomes as follows:

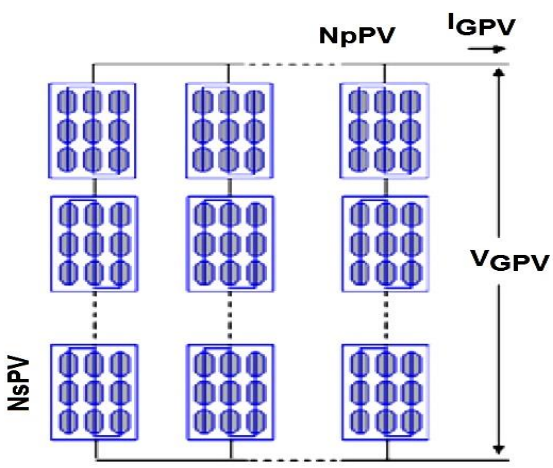

Fig. 1: Synoptic diagram of a PV generator

$$I_{GEN} = N_{pPV}\, I_{SC}\left(1 - C_1\left(\exp\left(\frac{V_{GEN} - \Delta V}{N_{sPV} \times C_2\, V_{OC}}\right) - 1\right)\right) + \Delta I \tag{10}$$

$$\Delta I = \mu_{Isc}\left(G_\beta / G_{ref}\right)\Delta T + \left(G_\beta / G_{ref} - 1\right) I_{SC,ref}\, N_{pPV} \tag{11}$$

$$\Delta V = -0.0539\, V_{max,ref}\, N_{sPV} \log\left(G_\beta / G_{ref}\right) + \mu_{V_{OC}}\, \Delta T \tag{12}$$

In this paper, the studied photovoltaic generator consists of a photovoltaic module type Solarex MSX60 of 60 W. The electrical characteristics of the module provided by the manufacturer are the open circuit voltage, $V_{OC,ref} = 21\,V$, the short circuit current, $I_{sc,ref} = 3.87\,A$, the maximum power delivered $P_{max,ref} = 60\,W$, and the maximum power voltage and current respectively, $V_{mp,ref} = 16\,V$ and $I_{mp,ref} = 3.56\,A$.

2.2 PEM electrolyser model

In this paper, an empirical model is used to approach electrical behavior of unit of commercial H-tec 50 W StaXX7 PEM electrolyser. The unit comprises a stack of seven PEM cells in series. The $I-V$ characteristic curve of the electrolyser, established in previous study [4, 5], is expressed by a polynomial equation as follows:

$$I_{1S} = \begin{cases} 0 & V_{1S} \leq 10 \\ \sum_{i=0}^{4} a_i V_{1S}^i & V_{1S} > 10 \end{cases} \tag{13}$$

where I_{1S}, V_{1S} current and voltage of one stack electrolyser, the a_i are the polynomial coefficients $a_0 = 498.128$; $a_1 = -159.199$; $a_2 = 18.824$; $a_3 = -0.90817$; $a_4 = 0.0191867$ with quadratic error, $R^2 = 0.0012353$.

For an electrolyser composed of N_{sEL} stacks in series and N_{pEL} stacks in parallel as shown in figure 2, the equation (10) can be expressed as follows:

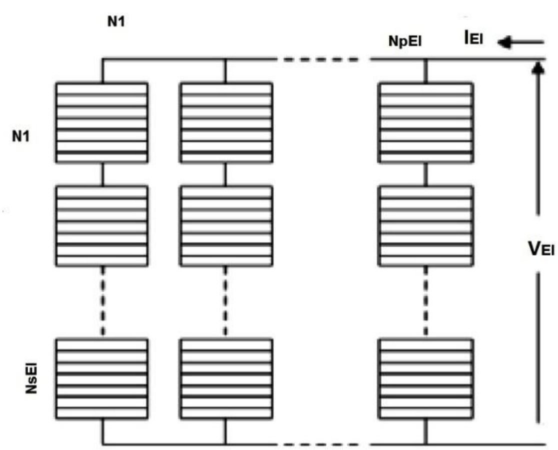

Fig. 2: Block diagram of PEM electrolyser

$$I_{EI} = \begin{cases} 0 & V_{EI} \leq 10 \times N_{sEI} \\ N_{pEI} \times \sum_{i=0}^{4} a_i (V_{1S} \times N_{sEI} & V_{EI} > 10 \times N_{sEI} \end{cases} \tag{14}$$

<u>*Estimation of the hydrogen produced*</u>

The volume of hydrogen generation (l/h) for one electrolyser stack is estimated by following equation [5]:

$$V_{H_2,1S} = 3.1939 \times I_{1S} \times \eta_f \tag{15}$$

where I_{1S} is the input current of the electrolyser in (A) and η_f is the faradic efficiency of the electrolyser {considered in this study equal to 99%).

For an electrolyser composed of N_{sEL} stacks in series and N_{pEL} stacks in parallel, the equation (15) can be expressed as follows [22]:

$$V_{H_2,1S} = 3.1939 \times N_{sEI} \times I_{EI} \times \eta_f \tag{16}$$

2.3 Optimising the coupling between a PV array and PEM electrolyser in terms of energy transfer

The amount of power loss, ΔP_j, due to direct-coupling of the PV array and PEM electrolyser in relation to maximum power point of PV is given by:

$$\Delta P_j = P_j^{mPV} - P_j^{EL} \qquad (17)$$

where P_j^{mPV} is the maximum power point of PV output at solar energy $G = G_j$, and P_j^{EI} is the electrolyser power input from the PV panels at $G = G_j$; $j = 1, 2, 3, \ldots, N$ refersto the different solar radiation data frequency distribution.

Thus over a full year the total electrical energy loss compared to the maximum achievable energy transfer is:

$$E = \sum_{j=1}^{N} (P_j^{mPV} \times f_j) \qquad (18)$$

The total electrical energy loss compared to the maximum achievable energy transfer over a full year is:

$$\Delta E = \sum_{j=1}^{N} (P_j^{mPV} - P_j^{EL}) \times f_j \qquad (19)$$

The percentage of overall annual loss of energy compared to perfect matching based on maximum power point is:

$$\Delta E(\%) = \left(\frac{\sum_{j=1}^{N} (P_j^{mPV} - P_j^{EL}) \times f_j}{\sum_{j=1}^{N} (P_j^{mPV} \times f_j)} \right) \times 100 \qquad (20)$$

2.4 Solar data frequency histogram

For a direct-coupled PV-electrolyser system the difference in energy transfer between the PV array and the PEM electrolyser stack in the maximum power point condition and the actual condition varies with the solar irradiance. Hence, in order to calculate the total difference in energy transfer on an annual basis, it is necessary to know the number of hours per year that the solar irradiance is within each range.

In this case study, the solar irradiation data of Adrar for an inclined surface [3] were used to obtain a frequency histogram for an annual period as shown in figure 3. In this distribution, fj is the number of hours in a year solar irradiance in the interval between $(G_j - 0.5\Delta G)$ and $(G_j + 0.5\Delta G)$, where $\Delta G = 200 W/m^2$ for $j = 2$ to 6; j=2 to 6. f_1 is the number of hours for which $G = 0 W/m^2$, and F_7 is the number of hours $G \geq 1000 W/m^2$.

3. SIMULATION RESULTS AND DISCUSSION

To find the optimal matching condition between a direct coupled PV array and electrolyser, various series–parallel combinations of standard PV modules and electrolyser stacks have been investigated. All results are summarized in **Table 1**.

For each combination the percentage of the maximum available PV power transferred to the electrolyser at various solar irradiation values, and the amount of energy loss over the year due to direct coupling compared to the maximum energy transfer achievable, are presented.

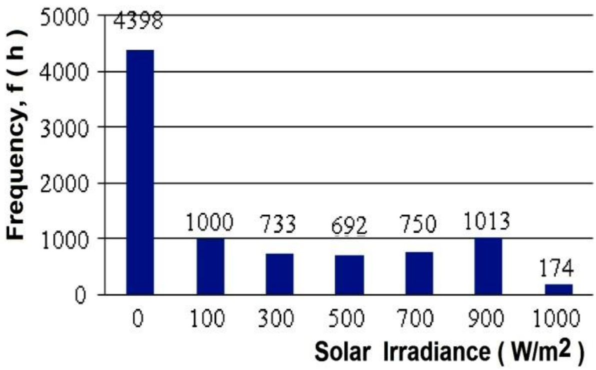

Fig. 3: Solar data frequency histogram (Adrar)

The optimum combination in terms of annual energy transfer as well as hydrogen production identified for the particular PV module (Solarex MSX60) and electrolyser stack (StaXX7) coupling combinations investigated, is four PV modules connected in series directly coupled to five electrolyser stacks in series.

The amount of overall energy loss over the year compared to the maximum power point condition is only 0.2 % and the calculated annual hydrogen production is 125 m^3 for the site of Adrar [3].

4. CONCLUSION

The theoretical analysis presented and applied to a case study of direct coupling of a number of different combined series-parallel configurations of both PV modules (Solarex MSX60) and electrolyser stacks (StaXX7), has shown that it is possible to operate the electrolyser near the maximum power point of the PV array over a range of solar irradiances without any intervening electronics such as a DC-to-DC converter and maximum power point tracker.

The case study has shown that coupling an array of four PV modules connected in series with the bank of five electrolyser stacks in series gives an overall energy loss over the year compared to the MPP condition of only 0.2 %.

REFERENCES

[1] O. Atlam, F. Barbir and D. Bezmalinov, '*A Method for Optimal Sizing of an Electrolyser Directly Connected to a PV Module*', International Journal of Hydrogen Energy, Vol. 36, pp. 7012 - 7018, 2011.

[2] B. Paul and J. Andrews, '*Optimal Coupling of PV Arrays to PEM Electrolysers in Solar-Hydrogen Systems for Remote Area Power Supply*', International Journal of Hydrogen Energy, Vol. 33, N°2, pp. 490 - 498, 2008.

[3] D. Ghribi, '*Etude, Modélisation et Simulation d’un Système de Production d’Hydrogène par Voie Solaire Photovoltaïque*', Thèse de Doctorat, Université Saâd Dahleb, Blida, 2016.

Table 1: Power delivered to electrolyser, annual potential available PV energy and energy loss for different PV-electrolyser configuration

PV-electrolyserConfiguration		Maximum potential PV power delivered to the electrolyser %						Annual maximum potentially available PV energy (kWh)	Annual energy delivered to electrolyser (kWh)	Annual energy loss (kWh)	Pertes annuelles totales d'énergie ΔE(%)
Stack electrolyseur	Module PV	G=100 (W/m²)	G=300 (W/m²)	G=500(W/m²)	G=700 (W/m²)	G=900 (W/m²)	G=1000 (W/m²)				
1	1	96,9	91,6	92,3	94,2	96,3	97,5	111,2	105,5	5,7	5,1
1	2‖	97,9	95,8	97,9	Excess power	Excess power	Excess power	221,7	–	–	–
1	2+	49,8	45,4	44,8	45,4	46,3	46,8	240,7	110,5	130,2	54,1
2‖	1	96,8	88,8	88,2	89,0	90,7	91,8	111,2	100,1	11,0	9,9
2‖	2‖	97,0	91,7	92,4	94,3	96,5	97,4	221,7	210,6	11,1	5,0
2‖	3‖	97,4	93,7	95,4	97,8	Excess power	Excess power	332,3	–	–	–
2‖	2+ ‖ 2+	49,9	45,2	44,8	45,3	46,2	46,9	480,1	220,2	259,9	54,1
2+	1	–	–	–	–	–	–	111,2	–	–	–
2+	2+	94,8	88,4	87,9	88,7	90,3	91,2	240,7	215,8	24,9	10,4
2+	2‖	–	–	–	–	–	–	221,7	–	–	–
3‖	1	96,6	87,5	86,6	87,5	88,4	89,3	111,2	98,0	13,1	11,8
3‖	2‖	95,6	90,0	90,0	91,0	92,9	94,1	221,7	203,9	17,8	8,0
3‖	3‖	97,0	91,7	92,0	94,0	96,5	97,5	332,3	315,3	17,0	5,1
3‖	2+ ‖2+	49,4	44,0	43,4	43,3	43,8	44,2	480,1	210,7	269,4	56,1
3+	2+	25,4	72,2	76,8	75,7	72,5	70,5	240,7	173,4	67,3	28,0
3+	3+	94,1	87,4	86,5	86,9	88,2	88,9	370,3	325,2	45,1	12,2
3+	2+ ‖2+	18,8	57,0	58,3	54,5	49,7	47,2	480,1	247,1	233,0	48,5
4‖	2‖	94,8	88,9	88,3	89,2	90,9	91,9	221,7	199,8	21,9	9,9
4‖	3‖	96,5	90,2	90,3	92,0	94,0	95,0	332,3	308,3	24,0	7,2
4‖	4‖	97,0	91,7	92,0	94,0	96,6	97,5	442,8	420,3	22,5	5,1
4‖	5‖	97,4	92,8	93,8	96,0	Excess power	Excess power	553,4	–	–	–
2+ ‖2+	2‖	–	–	–	–	–	–	221,7	–	–	–
4+	3+	85,6	98,4	99,2	98,8	97,9	97,3	370,3	362,5	7,8	2,1
4+	4+	93,8	86,9	85,7	86,0	87,1	87,8	499,9	434,3	65,6	13,1
2+ ‖2+	2+ ‖2+	94,9	88,5	88,0	88,7	90,3	91,3	480,1	430,5	49,6	10,3
2+ ‖2+	2+ ‖2+‖2+	95,9	91,0	91,4	Excess power	Excess power	Excess power	719,5	–	–	–
5‖	3‖	95,5	89,8	89,3	90,5	92,1	93,3	332,3	303,4	28,9	8,7
5‖	4‖	96,4	91,0	90,6	92,4	94,6	95,6	442,8	413,1	29,8	6,7
5‖	5‖	97,0	91,7	92,1	94,0	96,6	97,5	553,4	525,3	28,1	5,1
5‖	6‖	97,0	92,4	93,4	95,8	97,9	Excess power	664,0	–	–	–
5‖	3+ ‖ 3+	32,0	28,5	27,5	27,0	27,0	26,9	738,6	202,3	536,3	72,6
5+	3+	0,0	27,5	41,8	45,5	45,6	45,0	370,3	154,8	215,5	58,2
5+	**4+**	**97,1**	**99,9**	**99,7**	**99,7**	**100,0**	**100,0**	**499,9**	**498,8**	**1,2**	**0,2**
5+	5+	93,6	86,6	85,3	85,5	86,4	87,0	629,5	543,5	86,0	13,7
5+	2+ ‖2+	–	–	–	–	–	–	480,1	–	–	–
6‖	4‖	95,7	90,1	89,4	91,1	93,0	94,1	442,8	407,1	35,7	8,1
6‖	5‖	96,0	90,6	90,8	92,6	94,7	95,9	553,4	516,8	36,6	6,6
2+ ‖ 2+ ‖ 2+	2+ ‖ 2+	94,3	86,5	85,1	85,2	86,2	86,7	480,1	413,6	66,5	13,9
3+ ‖ 3+	3+	92,6	84,5	82,2	81,6	81,6	81,7	370,3	304,9	65,4	17,7
6+	3+	–	–	–	–	–	–	370,3	–	–	–
6+	4+	32,5	78,1	83,6	83,8	82,2	81,0	499,9	403,0	96,9	19,4
6+	5+	99,6	98,7	97,8	98,1	98,6	98,9	629,5	619,5	10,0	1,6
6+	6+	93,4	86,4	85,0	85,1	86,0	86,6	759,1	652,6	106,5	14,0
3+ ‖ 3+	2+ ‖ 2+	25,4	72,1	76,8	75,7	72,5	70,5	480,1	345,9	134,2	27,9
3+‖3+	3+‖3+	94,2	87,5	86,4	86,9	88,2	88,9	738,6	648,6	90,0	12,2