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Optimization of PEM fuel cells for PV-Hydrogen power system

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Abstract

This paper presents photovoltaic-hydrogen power system for mobile phone station. This base transceiver station (BTS) is located in neighboring Ouargla city (in the south of Algeria). The power system includes a photovoltaic (PV) field, water electrolyzer and two fuel cells. Each fuel cell is used according to daily and seasonal load of the station. A biphasic model is adopted for the simulation of fuel cell stacks. The governing equations are solved using a program written under Matlab. Multi-criteria optimization with weighting between two opposite objectives is used to determine the compromise solutions between maximum efficiency and minimal fuel cells size. Genetic algorithm coupled with Quasi-Newton method is used to achieve optimal fuel cells operations. The optimal solutions in Pareto sense are plotted according to weighting coefficient. The obtained results show that PV modules number for the summer period is relatively high which requires introducing some technical improvements on shelter walls for reducing air-conditioning loads.

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Keywords: photovoltaic, water electrolysis, PEM fuel cell, multi-criteria Optimization, transceiver station.

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1. Introduction

Telecommunication network through developing countries, particularly in isolated zones it remains very necessary for economic development. Isolated stations of mobile phone know certain network disturbances due to their supply by diesel generator. In order to overcome these disturbances, their conventional power supplies require replacement by alternative ones like assisted photovoltaic systems. The assistance of system at night period is insured by PEM fuel cells (PEMFC) which have many environmental advantages. But, they still need some improvements concerning efficiency and cost. In industrial applications, the most number of authors adopt semi-empiric PEMFC models like S. Orçun et al. [1], L. Barilli et al. [2] and D. Candusso et al. [3]. Recent works J. Golbert et al. [4 and 5], and M. Sheila et al. [6] have studied analytical biphasic PEMFC model, but less works are oriented to apply this model on industrial equipments. This work is carried out for introducing PEMFC in power PV system for phone station to insure electricity supply at night. Numerical simulation of PEMFC analytical model and multi-objective optimization are used to evaluate optimal operating conditions for efficiency and size trade-offs investigation.

2. Base transceiver station

2.1. Station description

Base Transceiver Station (BTS) connects between mobile phone and the subsystem network. In this work we choose an isolated station (located in the neighboring of Ouargla city), it is equipped with a normal BTS (HUAWEI 2nd generation). The station is composed of metallic shelter and antennas support (see Fig. 1). The shelter contains the transmission equipments, dry storage batteries and power supply cupboard; it is cooled by mono-bloc air conditioner. The station is fed by 15 kW fuel power generator. The daily electric consumption is evaluated as follows:

- Air-conditioner (Mega Hussoto HP 8V) operate about 15 hours at full load 2,28 kW (AC current), and 9 hours at low load (fans by DC current) 10 A x 48 V.
- Transmission equipments (including AC-DC inversion) operate about 15 hours at full load 25 A x 48 V, and 9 hours for low load 10 A x 48 V.
- Charge of batteries: 20 A x 48 V (including AC-DC inversion) operate about 4 hours.

![Figure 1: Base transceiver station](image-url)
2.2. Alternative power supply

The system consists of photovoltaic panels to provide the station during the day and an assistance system to ensure the electricity supply at night and weak sunning periods.

By analyzing the characteristics of various assistance systems, we choose a system connected with water electrolysis to produce hydrogen. During dark periods, stack fuel cells is feed by hydrogen for providing the BTS station (See Fig. 2).

![Schematic of power system](image)

Produced hydrogen must satisfy the fuel cells for two different power periods:

- The first period begins approximately two hours before sunset until midnight, produced power satisfies the station at full charges (48V x 25 A DC) and air-conditioner (2280 W AC with inverter efficiency 95%) according to seasonal climate (see table 6.1). An exception is carried out for September and May when this period is divided into two parts:
  - The first part finishes approximately at 21 h (about 50% of the period): the BTS operates at full charges and with air-conditioning.
  - The second part starts approximately at 21h until 24h (about 50% of the period): the BTS operates at full charges and without air-conditioning (only fans).
- The second period starts from midnight until approximately two hours after sunrise, produced power satisfies the station at low load (48V x 10A DC) and fans (48V x 10A DC).

To carry out an optimal design of assistance system as regards to minimize fuel consumption, we choose the use of two fuel cells stacks. The first stack has two levels of power output, so, it is composed of two separate active areas which operate according to load required (see table 1).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1st period (W)</td>
<td>1680</td>
<td>4080</td>
<td>4080</td>
<td>4080</td>
<td>1680</td>
</tr>
<tr>
<td></td>
<td>1680</td>
<td>4080</td>
<td>4080</td>
<td>1680</td>
<td></td>
</tr>
<tr>
<td>2nd period (W)</td>
<td>960</td>
<td>960</td>
<td>960</td>
<td>960</td>
<td>960</td>
</tr>
</tbody>
</table>
3. Modelisation and optimization of fuel cells

Elementary PEM fuel cell with strength gas channels at anode and cathode. It is composed of collector plate, gas diffusion layer (GDL), catalyst layer at each side of anode and cathode, as well as the polymeric membrane in the medium. In reduced model, we neglect variable space dependency in flow channels and we control outputs of gases and water in two forms vapour and liquid. Consequently, the governing differential equations will be reduced to the algebraic equations. For given current density, the species mass balances are calculated by the difference between inlet flows and flow consumed or produced by chemical reaction.

Mass balances of hydrogen, oxygen and nitrogen are respectively:

\[ M_{H_2} = M_{H_2,in} - \frac{AI}{2F} \]  \hspace{1cm} (1)

\[ M_{O_2} = M_{O_2,in} - \frac{AI}{4F} \]  \hspace{1cm} (2)

\[ M_{N_2} = M_{N_2,in} \]  \hspace{1cm} (3)

For water mass balance, the transferred water across membrane (with coefficient \(\alpha\)) is added. These equations at anode and cathode are respectively:

\[ M^V_{w,a} = M^V_{w,a,in} - M^I_{w,a} - \alpha \frac{AI}{F} \]  \hspace{1cm} (4)

\[ M^V_{w,c} = M^V_{w,c,in} - M^I_{w,c} + \alpha \frac{AI}{F} + \frac{AI}{2F} \]  \hspace{1cm} (5)

Cells effective voltage can be expressed as the difference between cells reversible thermodynamic voltage and different overvoltage losses: activation overvoltage, ohmic overvoltage and concentration overvoltage:

\[ V_{cel} = V_{rev} - V_{act} - V_{ohm} - V_{con} \]  \hspace{1cm} (6)

To evaluate fuel cell performance, generally we use the efficiency as indicator. The system efficiency is defined as the ratio of net produced output (i.e. we extract parasitic consumptions) and self fuel heating:

\[ \eta = \frac{w_{stack} - w_{prs}}{w_{fuel}} \]  \hspace{1cm} (7)

More details for model governing equations are presented in our previous work [7], also the results shows that size (active area) of PEM fuel cells and system efficiency are conflicting objectives. The first objective function to minimize is MEA total active area, while the second function to be maximized is system efficiency. Multi-objective optimization will be equivalent to resolve an unconstraint problem. Function \(f_1\) is active area "A" and \(f_2\) is system efficiency "\(\eta\". Weighting method is adopted for determining Pareto set.

The variables bounds are fixed according to the values commonly used in practice [8, 6, and 7]. Relative humidity bounds of air are taken from meteorological statistics of Ouargla city (Algeria). Superior bound of hydrogen relative humidity is slightly reduced. Vector \(x\) presents six variables: current density \(i\), cells pressure \(P\), hydrogen stoichiometric ratio \(\xi_{H_2}\), air stoichiometric ratio \(\xi_{Air}\), hydrogen relative humidity \(RH_{H_2}\), air relative humidity \(RH_{Air}\). The optimization function is expressed as:
By applying the weighted form, we obtain:
\[
\min \left[ \omega \eta(x) + (1-\omega)A(x) \right] \quad \text{with } \omega \in [0,1]
\]

3.1. Numerical procedures

Calculation start by the determination of inlet reactant flows, furthermore, outlet flows and their corresponding voltages. The numerical solution of governing equations is calculated by a program written under Matlab and optimization is carried out by Matlab "Toolbox". The optimization method of genetic algorithm (GA) was chosen with coupling by the deterministic method of Quasi-Newton. Calculation precision is fixed at relative error of $10^{-5}$. The values of the physical parameters and base case conditions are identical to those presented in our previous work [7].

3.2. Curve of Pareto set

Fig. 2 shows the optimal solutions for 50 kW PEM fuel cells. Base case solution (green point) is inside the convex space limited by Pareto curve, therefore this point presents a dominated situation. The optimal solutions are compromise solutions between efficiency and MEA area. The curve is composed of all designs which are optimal in Pareto sense. The highest point (top right) in fig. 3 represents the optimal solution for $\omega = 1$, which corresponds to the problem with simple optimization objective which consists in maximizing system efficiency without taking account of the MEA area. This solution is more profitable 23% but the size is 107% larger than that of base case. This design requires operation with low current density (thus, higher voltage), with a higher pressure, and with low stoechiometric rates of hydrogen and air compared to the base case. Consequently, it reaches a higher efficiency with low fuel consumption. However, the parasitic loss is higher due to pressure increase.

Figure 3: Pareto set and base case
3.3. Evolution of objectives

Fig. 4 shows the optimal values of objectives according to current density. At low current densities, we have solutions with big size and high efficiency; form the branches at left side. Conversely, the right branches contain the solutions which are characterized by small size and low efficiency, corresponding to high current densities. Generally, MEA area, system efficiency and cells voltage decrease according to current density.

![Figure 4: Evolution of objectives](image)

3.4. Evolution of fuel power

Fig. 5 shows the evolution of energy provided by hydrogen for different levels of fuel cells power: 1 kW, 10 kW and 50 kW. We note that for two low levels the curve increase is very slow. But, for 50 kW, the curve increase is more brutal that is due to high increase of current density which overcomes the decrease of MEA active area.

![Figure 5: Evolution of fuel power](image)
3.5. Evolution of parasitic consumption

Figure 6 shows the evolution of energy consumed by fuel cells accessories (air compressor, humidifiers …) for different levels of fuel cells power: 1 kW, 10 kW and 50 kW.

Size minimization of MEA area as unique objective (i.e. \( \omega = 0 \)) for 1 kW output power gives solution with zero efficiency. In this particular solution, produced fuel cells power is completely consumed by the system as parasitic losses (see Fig. 6). So, it is more interesting to calculate installation energy balance before choosing the supply mode. Therefore, for portable equipment (low size), with a power about 1 kW, it is preferable to design a fuel cells without air compressor.

![Figure 6: Evolution of parasite consumption](image)

4. Evaluation of hydrogen needs

The multi-objectives optimization of the 02 PEM fuel cells stacks gives the results listed in table 2. Hydrogen needs are calculated according to fuel cells power and its operating duration. Consumed hydrogen flow \( M_{H_2} \) (mol/s) is calculated as follow:

\[
M_{H_2} = \frac{AI}{2F} \quad (I: \text{current density } \text{A/cm}^2, A: \text{MEA area } \text{cm}^2)
\]

Consumed hydrogen \( Q_m \) (mol) is given by:

\[Q_m = M_{H_2} \times \text{duration}\]

By taking account of hydrogen circuit purge, previous consumption is increased by 1%. Hydrogen is assumed as ideal gas, at standard conditions (1atm, 25°C) one mole occupies 22.4 litres. So, we calculate hydrogen quantity in m³. The hydrogen needs are presented in table 3.

<table>
<thead>
<tr>
<th>PEM power (W)</th>
<th>current density A/cm²</th>
<th>MEA area (10^4) cm²</th>
<th>Efficiency %</th>
<th>Pressure atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4080</td>
<td>0.4310</td>
<td>1.2560</td>
<td>45.21</td>
<td>2.227</td>
</tr>
<tr>
<td>1680</td>
<td>0.4464</td>
<td>0.52558</td>
<td>45.33</td>
<td>2.433</td>
</tr>
<tr>
<td>960</td>
<td>0.4450</td>
<td>0.2703</td>
<td>45.055</td>
<td>2.636</td>
</tr>
</tbody>
</table>

Table 2: Results of optimisation
Table 3: Hydrogen needs

<table>
<thead>
<tr>
<th>Month</th>
<th>1st period (m³)</th>
<th>2nd period (m³)</th>
<th>Total (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>7.65</td>
<td>5.23</td>
<td>12.88</td>
</tr>
<tr>
<td>Feb.</td>
<td>7.65</td>
<td>4.95</td>
<td>12.6</td>
</tr>
<tr>
<td>Mars</td>
<td>7.17</td>
<td>4.95</td>
<td>12.12</td>
</tr>
<tr>
<td>April</td>
<td>6.70</td>
<td>4.95</td>
<td>11.65</td>
</tr>
<tr>
<td>May</td>
<td>10.8</td>
<td>4.68</td>
<td>15.48</td>
</tr>
<tr>
<td>June</td>
<td>14.20</td>
<td>4.40</td>
<td>18.6</td>
</tr>
<tr>
<td>Jul.</td>
<td>14.20</td>
<td>4.40</td>
<td>18.6</td>
</tr>
<tr>
<td>Aug.</td>
<td>14.20</td>
<td>4.40</td>
<td>18.6</td>
</tr>
<tr>
<td>Sept.</td>
<td>10.80</td>
<td>4.68</td>
<td>15.48</td>
</tr>
<tr>
<td>Oct.</td>
<td>6.70</td>
<td>4.95</td>
<td>11.65</td>
</tr>
<tr>
<td>Nov.</td>
<td>7.17</td>
<td>4.95</td>
<td>12.12</td>
</tr>
<tr>
<td>Dec.</td>
<td>7.65</td>
<td>5.23</td>
<td>12.88</td>
</tr>
</tbody>
</table>

5. Water electrolysis system

Hydrogen production by water electrolysis consists of decomposing water molecules into hydrogen and oxygen. In present work, we choose alkaline electrolysis which uses hydroxide aqueous solution of potassium (KOH) as electrolyte [9]. The major quantity of water used in electrolysis is recovered from fuel cells exhaust, only periodic supplements will be carrying out by stocked distilled water. Hydrogen purification is insured by water washing, so that the gases (hydrogen and oxygen) pass through the washers supplied by clean water, and the solution of potassium hydroxide is turned towards the electrolyzer by two external circuits [10]. Then, hydrogen passes in Deoxo-desicator where oxygen is eliminated by heating with resistance. Furthermore, two desiccators remove humidity from hydrogen [11]. Lastly, hydrogen is forwarded to the compressor before being stored in the tank.

The estimation of electrolyzer energy needs is based on correlations between the electrolyzer and data base concerning the industrial station of hydrogen production in "Line Gas Algeria" company (centre of Skikda) [12]. Standard electric consumption of industrial electrolyzer varies between 4 to 6 kWh/Nm³ (including consumption of auxiliaries). Water electrolysis operates by direct current and it represents 92% of total consumption, so, consumption ratio will be about 84% of its initial value [12]. By taking the maximum value of ratio we obtain:

\[
\text{Ratio} = 6 \times 0.84 = 5.04 \text{ kWh/Nm}^3
\]

Daily electricity needs for electrolyzer:

\[
B_{ele} = Q_{mT} \times \text{Ratio}
\]

6. Photovoltaic panels

6.1. Total electricity needs

Photovoltaic generator (PV) transforms sun light directly into electricity. It is composed by several photovoltaic modules. We choose modules with polycrystalline cells which are less expensive and their efficiency is about (11 to 13%) [13]. PV panels need some accessories such as MPPT which ensures searching for maximum power point [14]. In addition, the electric inverter (DC/AC) converts direct current into alternative current to ensure providing certain equipments by alternative current.

Total produced energy by photovoltaic panels \(B_{total}\) includes electricity needs for transceiver equipments \(B_{fs}\) during sunny period and needs for water electrolyzer \(B_{ele}\). During sunny period the
station operates at full load (1200 W) with air-conditioning or ventilation (according to the month), all these loads operate approximately since two hours after sun rise until two hours before sunset. The solar panels must be directed towards the south and present an optimal monthly slope ($\beta_{op}$ [°]) to collect maximal energy [15] (see table 4).

Table 4: Electricity needs and solar radiation

<table>
<thead>
<tr>
<th>Month</th>
<th>Load (kWh)</th>
<th>$\beta_{op}$ [°]</th>
<th>$\bar{H}_{cp}$ [W/m²·J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>75.8</td>
<td>60</td>
<td>6.10</td>
</tr>
<tr>
<td>Feb.</td>
<td>75.3</td>
<td>51</td>
<td>6.30</td>
</tr>
<tr>
<td>Mars</td>
<td>73.7</td>
<td>36</td>
<td>6.07</td>
</tr>
<tr>
<td>April</td>
<td>72.2</td>
<td>18</td>
<td>6.43</td>
</tr>
<tr>
<td>May</td>
<td>114.7</td>
<td>4</td>
<td>6.54</td>
</tr>
<tr>
<td>June</td>
<td>134.5</td>
<td>-2</td>
<td>6.70</td>
</tr>
<tr>
<td>Jul.</td>
<td>134.5</td>
<td>0</td>
<td>7.01</td>
</tr>
<tr>
<td>Aug.</td>
<td>134.5</td>
<td>12</td>
<td>6.72</td>
</tr>
<tr>
<td>Sept.</td>
<td>117</td>
<td>29</td>
<td>6.12</td>
</tr>
<tr>
<td>Oct.</td>
<td>72.2</td>
<td>47</td>
<td>6.00</td>
</tr>
<tr>
<td>Nov.</td>
<td>73.7</td>
<td>58</td>
<td>6.17</td>
</tr>
<tr>
<td>Dec.</td>
<td>75.8</td>
<td>62</td>
<td>5.38</td>
</tr>
</tbody>
</table>

6.2. Peak power and number of photovoltaic modules

By knowing the electric power needs ($E_m = B_{total}$, calculated in previous section) and the average daily solar radiation, the corresponding peak power of photovoltaic generator $P_c$ is calculated as follow [15]:

$$P_{cc} = \frac{G}{F_m \left[1 - \gamma (T_{moy} - T_r)\right]} \bar{H}_{cp} (\beta) \cdot E_m$$

With:

- $G$: Standard solar radiation (1000 W/m²).
- $\bar{H}_{cp} (\beta) [\text{Wh/m}^2]$: Daily average radiation corresponding to optimal modules slopes.
- $F_m$: Coupling factor, generally when we use an MPPT this factor is taken 0.9.
- $\gamma$: Temperature coefficient, for mono crystalline cells $\gamma = 0.004$.
- $T_{moy}$: Daily average of ambient temperature during sunny periods.
- $T_r$: Referential temperature 25 °C (given by manufacturer)

We choose photovoltaic modules with 300 W peak power ($P_{cm}$). The number of modules $N_m$ is calculated as follow:

$$N_m = \frac{P_{cc}}{P_{cm}}$$

Table 5 shows peak powers and number of corresponding modules. In order to ensure system operation over all the year, we choose the number maximal of modules (80 modules).

Table 5: Peak power and number of modules

<table>
<thead>
<tr>
<th>Month</th>
<th>Ambient temperature °C</th>
<th>Peak power (kW)</th>
<th>Number of modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>19</td>
<td>13.5</td>
<td>45</td>
</tr>
<tr>
<td>Feb.</td>
<td>21</td>
<td>13.1</td>
<td>44</td>
</tr>
</tbody>
</table>
7. Conclusion

Optimization stochastic method is adequate to the present complicated objective function; also it leads to reach the global minima. But since the obtained result is an approximate value, it requires refining operation by deterministic method.

Before choosing fuel cells supply mode, it is necessary to calculate installation energy balance, because, for portable equipment (too small size), for power less than 1 kW, it is preferable to design fuel cells without air compressor.

Integration of photovoltaic system assisted by fuel cell and electrolyzer in antenna power supply represents a good solution to solve fuel logistic problems. The number of photovoltaic modules is relatively high (80 modules of 300W) which increases the investment cost, nevertheless, we plan to use passive cooling and new shelter materiel in order to reduce air-conditioning load. In addition, the generalization of using new BTS equipments (HUAWEI 3rd generation) by mobile company will contribute to decrease energy consumption and equipments released heat. Consequently, it leads to reduce the number of PV modules.

References


