Fuel Cells as Energy Storage for Photovoltaic Energy Sources in Rural Areas

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Summary: The power produced by many renewable energy sources, like photovoltaic or wind farms, is highly variable over time. In order for the electrical system to be able to receive larger share of energy from these sources some kind of energy storage is needed. The paper presents properties and simple models of PEM fuel cells and PEM electrolysers and evaluation of the possibility of using these devices for energy storage in form of hydrogen production.
Key words: smart grid, energy storage, hydrogen production, fuel cells, electrolyser.

INTRODUCTION

The solar radiation is a highly variable source of energy, as experienced on the surface of the Earth. There are three main causes of this variability. The first one is the yearly travel of our planet around the Sun, which results in differences in the duration of the day, as well as the maximum height of the Sun above the horizon between summer and winter. The second cause is the Earth's daily rotation around its axis. The third source of the radiation intensity variation is of meteorological nature – the cloud presence, the type and thickness play the major role in the energy availability on a given day.

One of the factors which make a wider use of photovoltaics difficult is discrepancy between the time when the electrical energy is needed and when it can be produced: both within a day and year. The problem of energy storage as a supplement to a renewable energy source has been a subject of numerous researches [1, 4, 17, 24]. Apart from conventional ways to store the energy like lead-acid batteries [10] and pumped hydro-storage [15], other methods including super-capacitors [23], flow batteries [7], hydrogen [29] and renewable power methane [21] production are considered.

Many of the rural areas in Europe have an untapped potential for renewable energy sources (RES) [9]. There is a relatively high potential for additional income and unemployment reduction in these areas due to the development of RES. The anticipated transformation of the conventional electrical power network into Smart Grid, among others, includes integration of energy storage devices into the grid [5]. Therefore, energy storage systems will become one more business possibility in the rural areas.

The fuel cells are promising technology in providing high quality power in distributed generation systems (including photovoltaic generation) [11]. The hydrogen generated at times when the generation exceeds power demand can be used in the fuel cells to generate the energy when needed. This approach will provide a way for better balancing the demand with RES.

FUEL CELLS

Fuel cells are devices which directly convert chemical energy contained in a fuel into electrical energy. One of the most widely used fuel is gaseous hydrogen. In a typical fuel cell the half-reactions can be written as follows [22]:

$$H_2 \rightarrow 2H^+ + 2e^-, \tag{1}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O. \tag{2}$$

The electrons removed on the anode do the work in an external circuit and the proton (the H^+ ion) is transferred through some kind of electrolyte (depending on the fuel cell type). On the cathode the proton meets the electrons coming from the circuit and combined with oxygen it forms water. One of the largely used type is the Polymer Electrolyte Membrane Fuel Cell (PEMFC). Its name comes from the construction and material used for the proton – conducting electrolyte. There are many review papers which present various types of fuel cells and their properties like [14, 25, 30].

Figure 1 presents the typical current-voltage curve of a fuel cell with its three main sections illustrated.

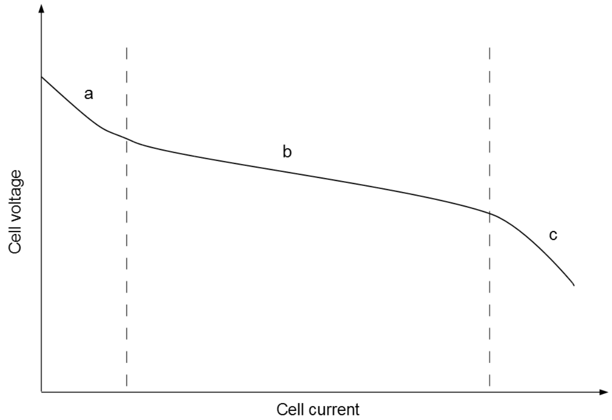

Fig. 1. Typical current-voltage curve of a fuel cell: a) activation losses dominant region, b) ohmic losses dominant region, c) concentration losses dominant region.

The fundamental equation which describes the cell voltage V_{cell} is [13]:

$$V_{cell} = E_{Nernst} - V_{Act} - V_{Ohmic} - V_{Con} \ , \tag{3}$$

the cell's reversible (Nernst) potential E_{Nernst} can be calculated as [31]:

$$E_{Nernst} = \frac{1}{2F}\left[\Delta G_e + \Delta S\left(T - T_{ref}\right)\right] + \frac{1}{2F}\left[RT\ln\left(P_H\sqrt{P_O}\right)\right]. \tag{4}$$

Where DG_{e} – free Gibb's energy, DS – entropy change, F – Faraday constant, T – operating temperature, T_{ref} – reference temperature, P_{H} – hydrogen partial pressure, P_{O} – oxygen partial pressure, V_{Act} – activation losses, V_{cell} – cell operating voltage, V_{Con} – concentration losses, V_{Ohm} – ohmic losses, R – gas constant.

In equation (4) the pressures are assumed to be in bars, otherwise each of the pressures should be divided by the value of pressure in standard conditions. Assuming standard pressure and temperature, the above equation can be transformed into [31]:

$$E_{Nernst} = 1.229 - 8.5\times10^{-4}(T - 298.15) + 4.308\times10^{-5}\ln\left(P_H\sqrt{P_O}\right). \tag{5}$$

Activation losses can be calculated using an empirical equation [26]:

$$V_{Act} = -\left(\alpha_1 + \alpha_2 T + \alpha_3 T\ln C_O + \alpha_4 I\right), \tag{6}$$

in which $a_{1\ldots4}$ are empirical coefficients and I is the cell current. The oxygen concentration in the catalytic interface of the cathode C_{O} can be expressed by[26, 31]:

$$C_O = \frac{P_O}{5.08\times10^6 \times e^{-\frac{498}{T}}}. \tag{7}$$

According to Sharifi and others [26]:

$$V_{Ohmic} = I(R_P + R_E)\ , \tag{8}$$

with resistance for electrons R_{E} assumed to be constant and small. The resistance for protons R_{P} is calculated by the classical expression:

$$R_P = \frac{\rho_P L}{A}. \tag{9}$$

The resistivity of the membrane depends on water activity and cell temperature T. For Nafion it is expressed by the empirical formula as [8]:

$$\rho_P = \frac{181.6\times\left[1 + 0.03J + 0.062\left(\frac{T}{303}\right)^2 J^{2.5}\right]}{\left(\lambda - 0.634 - 3J\right)e^{4.18\frac{T-303}{T}}}$$

J is the current density within the cell. The value of l can be fitted for a particular cell. Sharifi [26] proposes the following way of obtaining the value of l:

$$\begin{cases} \lambda = 0.0045 + 17.81a - 39.85a^2 + 36a^3 & \text{for } 0 < a \le 1 \\ \lambda = 14 + 1.4(a-1) & \text{for } 1 < a < 3 \\ \lambda = 16.8 & \text{for } a = 3 \\ \lambda = 22 & \text{for } a > 3 \end{cases} \tag{10}$$

where:

$$a = \frac{P_{H_2O,out}}{P_{H_2O}^{sat}}, \tag{11}$$

$P_{\text{H2O.out}}$ is the partial pressure of water in the system. The last factor in equation (3) is called concentration losses [12]:

$$V_{Con} = -\frac{RT}{nF}\ln\left(1 - \frac{J}{J_{\max}}\right), \tag{12}$$

The efficiency of the fuel cells is a variable depending on its operating conditions: temperature, current density and rate of fuel delivered and it is reported to be within the range of 20 to 75 % [27].

HYDROGEN GENERATION

Hydrogen can be produced in many ways. The most popular technology in a large scale production is steam gasification. Its variation is the steam gasification of biomass [20]. For the application of the fuel cell system as the energy storage for renewable sources this technology is not appropriate. A better solution is producing hydrogen by the water electrolysis using the electrical energy from the RES. The advantages include high purity, which is important for the fuelling of fuel cells.

The main technologies used for electrolysis are: solid oxide high temperature [19], alkaline [16] and PEM [6] electrolysers. As an example a summary of a simple PEM electrolyser model will be presented here.

The current – voltage (I-V) curve of the single cell of an electrolyser can be modelled by the following equation [2]:

$$I = \begin{cases} 0 & \text{for } V \le 1.476\text{ V} \\ 3.064(V - 1.476) & \text{for } V > 1.476\text{ V} \end{cases} \tag{13}$$

The hydrogen flow in litres per second can be expressed by [3]:

$$v_H = \frac{RTI}{p2F}, \quad (14)$$

where:
p is the gas pressure and other variables as defined earlier. The relationship (14) can be approximated by a linear expression [2]:

$$v_H = K_H P, \quad (15)$$

in which K_H is a coefficient (equal to 4,1 ml W^{-1} A^{-1} in [2]) and P is electrical power delivered to the electrolyser.

The electrical-to-chemical (hydrogen) energy conversion efficiency is reported around 50 % [2], whereas light-to-chemical efficiency (using photovoltaic generators) is approximately 5 % – mainly due to relatively low efficiency of the photovoltaic generator.

CONCLUSIONS

Assuming the realistic medium values of energy conversion efficiencies (50 % for electrical energy-to-hydrogen for an electrolyser and 50 % for hydrogen-to-electrical energy for the fuel cells) the overall efficiency in the chain electrical energy from photovoltaic generator – hydrogen production (storage) – electrical energy from fuel cells will be equal to 25 %. This efficiency can be increased by utilising the heat produced both within the electrolyser and the fuel cell and operating as a combined heat and power (CHP) system.

The anticipated evolution of the electrical grid as known today into a smart grid will include, among others, energy storage systems [18]. The decentralised energy storage should be preferably placed in locations which would prevent the need to upgrade the existing electrical grid [28]. One of the available options is storing the energy by the hydrogen production.

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OGNIWA PALIWOWE JAKO MAGAZYN ENERGII DLA ŹRÓDEŁ FOTOWOLTAICZNYCH W OBSZARACH WIEJSKICH

Streszczenie: Moc wytwarzana przez wiele odnawialnych źródeł energii, jak na przykład farmy fotowoltaiczne czy wiatrowe, jest wysoce zmienna w czasie. Aby system elektroenergetyczny mógł przyjąć większą ilość energii z tego rodzaju źródeł konieczne jest zastosowanie magazynu energii. Artykuł przedstawia właściwości i uproszczone modele ogniw paliwowych typu PEM oraz elektrolizerów PEM oraz ocenę możliwości wykorzystania tych urządzeń w celu przechowywania energii w formie wytwarzania wodoru.
Słowa kluczowe: smart grid, magazyn energii, wytwarzanie wodoru, ogniwa paliwowe, elektrolizer.