Journal of Cleaner Production 111 (2016) 17–24

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Measurement based modeling and simulation of hydrogen generation cell in complex domestic renewable energy systems

Attila Göllei, Péter Görbe, Attila Magyar*

*Department of Electrical Engineering and Information Systems, Faculty of Information Technology, University of Pannonia, Egyetem Street 10, Veszprém, H-8200, Hungary*

ARTICLE INFO

*Article history:*
Received 16 December 2014
Received in revised form
3 June 2015
Accepted 5 June 2015
Available online 16 June 2015

*Keywords:*
Clean energy
Hydrogen generation
Energy restoration
Domestic power plants
Renewable power sources
Measurement based modeling

ABSTRACT

A measurement based model of hydrogen generating cell for simulation of complex energy system is described in this paper. The model parameter estimation has been performed based on measurement data obtained during the detailed examination of a demonstration cell. A series of experiments has been carried out on a HHO (Oxyhydrogen) gas producing dry cell in order to find its optimal electrochemical, (e.g. electrolyte concentration, current value, etc.) and geometric (distance between the plates) parameters. The novel element is the current and concentration dependent Matlab Simulink model of the hydrogen generation cell. Hydrogen generation enables the long range storage of spare electric energy collected but not consumed or injected into the low voltage grid. The generated hydrogen can be consumed by vehicles for transportation purposes or it can be applied in fuel cells generating direct electrical energy for energy-deficient low voltage network situations. The potentially occurring energetic situations were simulated in a complex energetic system model. The simulations showed that the presented hydrogen generating cell model met the engineering expectations.



## 1. Introduction

Nowadays, with the growing need for energy from renewable sources and growing revulsion toward fossil and nuclear fuels sustainable and green energy in coming to the forefront. The key question of using stochastically available renewable energy sources in large scale is long time storing of energy in an efficient and safe manner. There is great potential in hydrogen, as the fuel of future in energy storing, because of its' absolutely clean, green house gas (GHG) and $CO_2$ free applications of energy recovery and lossless long time storing availability. Spreading domestic power plants (DPP) generates need for development of domestic scale hydrogen generating and storage facilities. The energy production from renewable energy sources is not a technological challenge, but the energy storage is far from being trivial, especially in domestic scale due to the safety and economical aspects.

Storing energy in hydrogen is an efficient way in renewable energy industry. There are different ways to create hydrogen from renewable sources, for example directly from biomass as wood (Iribarren et al., 2014) or molasses (Urbaniec and Grabarczyk, 2014) or from directly electric energy from direct current produced from solar or wind energy (Bhandari et al., 2014). Hydrogen generation in small size gives engineering question, e.g. technical and/or economical feasibility that can be answered with power pinch analysis method using optimal size designation proper hybrid power systems (HPS) sizing (Rozali et al., 2014). Making hydrogen and oxygen from water with electricity is a very simple electrochemical process that can be produced easily and in a very demonstrative way. Producing hydrogen in large or industrial quantities calls for an optimized or a near-optimized cell model. In a process with a big demand for energy only a few percent of variance in the efficiency could mean a significant energy surplus or shortage (Görbe et al., 2009, 2010b,a). There are application of storage electricity from solar energy at normal pressure (Bhutto et al., 2014) already. In the present work the so-called dry cells are used to produce hydrogen and oxygen gas and henceforward the electrochemical parameters of dry cell are discussed in what follows. Moreover, a complex model has been developed by investigating renewable energy sources, converting currently unnecessary energy to hydrogen for storage purposes and feeding the main grid in domestic power plant size.

Hydrogen generating (electrolyzer) cell models are mainly based on the underlying electro-chemical equations (Sarrias-Mena et al., 2015) are usually not supported by practical measurement

* Corresponding author.
*E-mail address:* amagyar@almos.vein.hu (A. Magyar).

http://dx.doi.org/10.1016/j.jclepro.2015.06.025
0959-6526/

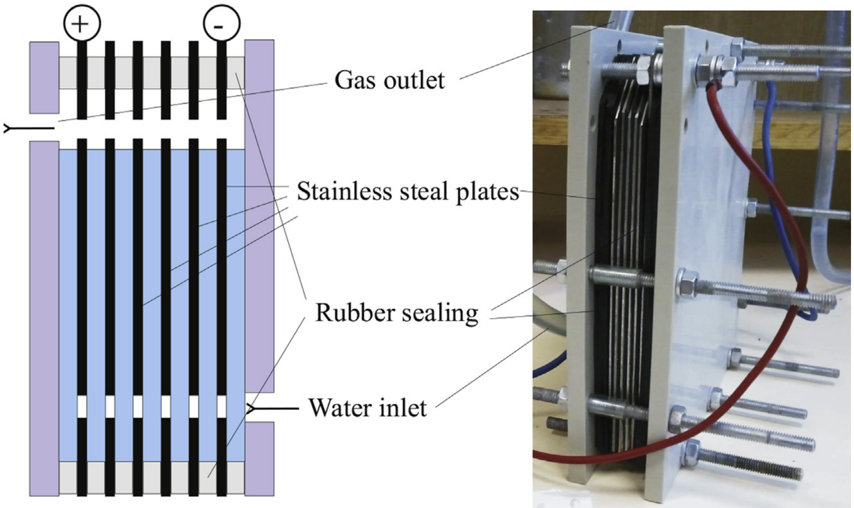


**Fig. 1.** Hydrogen generator block schematics (left) and a photo of the measured dry cell (right).

data. This paper presents a black box modeling method applicable for implemented dry cells. Moreover, exact simulation models are also available as a by-product of this method.

## 2. Hydrogen generating dry cell

The name could be misleading as this electrolyzing cell uses water just like any other electrolyzing unit. There are, though, some attributes of this cell that makes it easier to design and handle. With wet HHO (Oxyhydrogen, i.e. 2:1 mixture of hydrogen ($H_2$) and oxygen ($O_2$) gases) cells, the whole unit is underwater, while in the case of dry cells, the plates are separated with rubber seals. This sealing stop the water from leaking from the cell, the electrical connections and the edges of the plates are not touching the electrolyte. These parts of the unit are staying dry, thus the name dry cell. To make sure the gas made from the electrolyte gets out of the cell and the solution to flow between the plates, there are holes on the top (for the gas) and bottom (for the electrolyte) on the metal slats (Fig. 1). There are two main advantages to the application of the HHO units:

- With the dry cell generator, considering the surface of the plates in the unit, much less electrolyte is used compared to wet cells. Therefore, the volume and weight of the cell can be smaller.
- As the electronic connections are underwater in the wet cell model, their surface is slowly corroded by the electrolyte. In HHO cells, the connections are situated on the outside, i.e. not corroding.

### 2.1. Electrochemical basis of calculations

Electrochemical cells can be galvanic battery or an electrolyzing cell. Cells are called electrolytic cells are when they are using external current supply to create chemical reactions. The electrochemical cell is made up of two electrodes and a liquid, current-carrying electrolyte. The electrolyte can be a watery solution or molten salts (solvation). The chemical reaction happening on the surface of the electrodes (reduction or oxidation) is called an electrode reaction. If the electrode's material is not participating directly in the electrode reaction, it is called an indifferent electrode (e.g. graphite electrode). The oxidation happens on the anode, the other electrode is the cathode, on which the reduction happens. In the process of electrolysis, if there is more than one possible type of electrical reaction, then a simple anion will detach form the positive anode (e.g. chloride), lacking this anion, OH- will be created by water splitting. Water's dissolution voltage at 25 °C (room temperature) is 1.23 V (electromotive force, EMF), the temperature coefficient is −0.85 mV/K, meaning that at 100 °C this voltage goes down to 1.17 V. Therefore, in the light of these data, the specific energy demand to make hydrogen through electrolysis at 25 °C can be calculated as follows (White, 1984). The amount of charge needed to detach 1 kg hydrogen gas is

$$q = \frac{z\,F}{M} = \frac{2 \cdot 96,487}{2} = 96,487\ \mathrm{As/mol} = 26,801\ \mathrm{Ah/kg}, \tag{1}$$

where $z$ is the charge number of the specific ion, $F$ is the Faraday constant (approximately 96,500 C/mol) and $M$ is the standard atomic weight.

$$W_{H_2} = q\,E_{MF} = 26,801 \cdot 1.23 = 32,966\ \mathrm{Wh/kg} \tag{2}$$

Since the volume of 1 kg standard state $H_2$ is 12,474 L, the amount of energy required to produce 1 L hydrogen is

$$W_{H_2} = \frac{32,966}{12,474} = 2.64\ \mathrm{Wh/L}. \tag{3}$$

To produce 1 L of hydrogen 1.5 L HHO gas is needed. The energy demand of producing 1 L HHO gas (using (3)) is

$$W_{H_2HHO} = 0.667 \cdot 2.64 = 1.76\ \mathrm{Wh/L}. \tag{4}$$

**Table 1**
Experimental data.

| KOH cc. [g/L] | MMW [mL/min/W] | Gas production [L/min] | Power [W] |
|---|---|---|---|
| 1 | 2.13 | 0.2 | 10.8 |
| 2 | 2.66 | 0.75 | 34.44 |
| 3 | 2.66 | 1.37 | 55.83 |
| 4 | 2.59 | 1.51 | 82.15 |
| 5 | 2.72 | 1.9 | 90.6 |
| 6 | 2.63 | 2.52 | 119.5 |
| 7 | 2.67 | 2.96 | 140 |
| 8 | 2.65 | 2.76 | 125 |
| 9 | 2.46 | 2.28 | 105.6 |
| 10 | 1.82 | 2.15 | 103.2 |