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Examination, Modelling and Simulation of Hydrogen Generation Cell for Complex Renewable Energy System

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Nowadays, the growing need for energy from renewable sources and growing revulsion towards fossil and nuclear fuels turns sustainable and green energy in the foreground. Producing (electrical) energy from renewable sources hardly means difficulties but the storage of the energy not consumed immediately is a great engineering challenge. In the present paper 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. A measurement based model of a Hydrogen generating cell developed for simulation of complex energetic system is presented in this paper. The parameter estimation of the static model has been performed based on measurement data collected during the detailed examination of a demonstration cell. Series of experiments has been carried out on a HHO gas producing dry cell in order to find out if there are optimal electrolyte concentration, current value, or geometric parameter (distance between plates) values for this equipment. During the measurement KOH electrolyte solution was used while different signals has been measured, for example cell voltage, gas production value. As a result of the experiments, a cell operating in an optimal way has been developed. The novel element of this work is the temperature and concentration dependent Matlab Simulink model of the hydrogen generation cell. Using this model, a dynamic simulator of a complex domestic power plant using renewable energy source and H_2 generation cell become available. 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.

Energetic situations potentially occurring in practice have been simulated in the complex model. Several hours of simulations showed that the presented H_2 generating cell model performed well.

Producing H_2 from excess energy is not a brand new invention. This is the alternative way to store and convert renewable energy for further utilization. The produced Hydrogen can be used to store, to use in power cell to convert back to electric energy or to use in Hydrogen propulsion vehicles.

Among the numerous realized H_2 producing applications the most important class is when the energy consumption and the quantity of produced H_2 is controlled. When the power consumption and generation are continuous (and not necessarily deterministic) function of time, the H_2 production depends solely on the excess energy of the grid.

1. Introduction

Producing Hydrogen and Oxygen from water using electricity is a very simple electrochemical process that can be performed easily and in a very demonstrative way. Producing Hydrogen in large scale or industrial quantities calls for an optimized or a near-optimized cell model. In a highly energy demanding process only a few percent of variance in the efficiency could mean a significant energy surplus or shortage (Görbe et al, 2009). The so-called dry cell is used here to produce Hydrogen and Oxygen gas and henceforward the electrochemical parameters of this dry cell are discussed. 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 cells, the whole unit is underwater, while in the case of dry cells, the plates are separated with rubber seals. These seals stop the water from leaking

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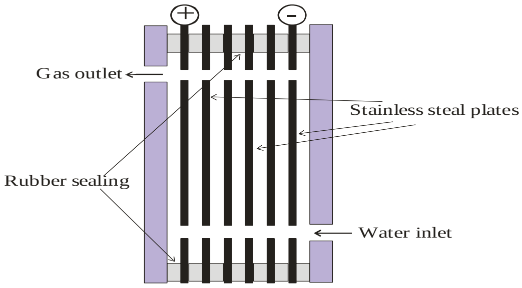

Figure 1: The setup of a HHO gas generator cell block

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.

Applications for H_2 production can be found in international literature. For example the procedure presented in (Koutsonikolasa et al., 2013). Although the described procedure is efficient and able to produce a high quantity of H_2 it is not suitable for an application like domestic power plant. The accurate solution is the usage of SCADA management system (Ziogoua et al., 2013). The domestic applicability of this technology in the future depends on the cost of SCADA system installation basically.

Applying HHO units has two main advantages:

1. The surface of the dry cell plates enables one to use smaller amount of electrolyte compared to wet cells. Therefore, the volume and weight of the cell is smaller.
2. As opposed to wet cells, where the connectors are underwater therefore their surface is slowly corroded by the electrolyte, the connectors of dry cells remain dry, i.e. they do not corrode. (Al-Rousan, 2010).

1.1 The HHO cell unit

The setup of one block of the unit can be seen in Figure 1.

Usually 5 cells make up one block, so 5 cells connected in series gives one gas-producing block. The block's electrical connections are on the two plates on the ends. Four of the six electrode plates are neutral electrodes, as there is no voltage connected to them. The potential is divided between the neutral plates according to voltage division in series connections. It means, that voltage between two electrodes is one fifth of the voltage on one whole block. In the experiment, a unit with 3 blocks connected in parallel has been used. Besides the HHO cell, a water reserve tank to infuse the electrolyte into the cell was necessary. A tube between the gas outlet and the tank has also been installed since the gas produced is not pure, it comes out as bubbles, so there is electrolyte coming out in the tube that needs to be recycled into the system. Then, as the electrolyte drips back in the tank, the gas can escape into the bottle through another hose. The produced H_2 volume and the production speed is measured with this bottle. A power supply (Manson SPS9600) has been connected to the electrical connections of the HHO unit, this way the current input was controlled during the experiment.

2. Matlab model of dry cell

The model of the measured dry cell was implemented in Matlab Simulink using the SimPowerSystems Toolbox. Two unknown functional relationships, one between the generated H_2 volume, the cell current and the KOH concentration and another one between cell voltage, cell current and KOH concentration were approximated using 4^{th} and 3^{rd} order polynomials, respectively using Matlab Surface Fitting Tool. As

Table 1: Experimental results

Electrolyte concentration (g/L)	MMW (mL/min/W)	Gas production (L/min)	Power of unit (W)	Electrolyte concentration (g/L)	MMW (mL/ min/W)	Gas production (L/min)	Power of unit (W)
1	2.13	0.2	10.8	6	2.63	2.52	119.5
2	2.66	0.75	34.44	7	2.67	2.96	140
3	2.66	1.37	55.83	8	2.65	2.76	125
4	2.59	1.51	82.15	9	2.46	2.28	105.6
5	2.72	1.9	90.6	10	1.82	2.15	103.2

the fitted polynomials do not have a physical meaning, the model is applicable to any similar electrochemical H_2 generation device with electrical two pole system (in the various linear and nonlinear physical and chemical models, different coefficients will be dominant). The voltage relationship is given by Eq(5), where i_{cell} denotes the cell current and c_{KOH} stands for the KOH concentration.

$$u_{cell}(i_{cell}, c_{KOH}) = p_{00} + p_{10}\, i_{cell} + p_{01}\, c_{KOH} + p_{20}\, i_{cell}^{\;2} + p_{11}\, i_{cell} c_{KOH} + p_{02} c_{KOH}^{\;2} + p_{30} i_{cell}^{\;3} + p_{21} i_{cell}^{\;2} c_{KOH} \tag{5}$$

The volume of the generated H_2 is given by the polynomial Eq(6).

$$H_2(i_{cell}, c_{KOH}) = p_{00} + p_{10}\, i_{cell} + p_{01}\, c_{KOH} + p_{20}\, i_{cell}^{\;2} + p_{11}\, i_{cell} c_{KOH} + p_{02}\, c_{KOH}^{\;2} + p_{30}\, i_{cell}^{\;3} + p_{21}\, i_{cell}^{\;2} c_{KOH} + p_{12}\, i_{cell} c_{KOH}^{\;2} + p_{03}\, c_{KOH}^{\;3} + p_{40}\, i_{cell}^{\;4} + p_{31}\, i_{cell}^{\;3} c_{KOH} + p_{22}\, i_{cell}^{\;2} c_{KOH}^{\;2} + p_{13}\, i_{cell} c_{KOH}^{\;3} \tag{6}$$

A Simulink block scheme of the cell model is depicted in Figure 2. This Simulink model was validated by exposing the system to the same circumstances as the original measuring layout as the original cell, i.e., a measurement procedure was implemented. In this layout we run a long range simulation (24h) with this model, lowering water and rising KOH concentration conditions. It can be seen, the generating hydrogen is reducing because of the rising KOH concentration, this, and the exact values are suiting to our measuring results exactly. The results are shown in Figure 3 and Figure 6,

Table 2: Coefficients of polynomial relationship describing the cell voltage

Coefficient	Value	Coefficient	Value	Coefficient	Value
p_{00}	1.429	p_{10}	0.2548	p_{01}	-0.1226
p_{20}	-0.008571	p_{11}	-0.01191	p_{02}	0.008257
p_{30}	0.0001141	p_{21}	-8.76e-05	p_{12}	0.0009697

Table 3: Coefficients of the polynomial relationship for the generated H_2 gas.

Coefficient	Value	Coefficient	Value	Coefficient	Value
p_{00}	-0.1695	p_{10}	0.1687	p_{01}	-0.01765
p_{20}	-0.007486	p_{11}	-0.03234	p_{02}	0.03446
p_{30}	-0.0001077	p_{21}	0.00412	p_{12}	-0.004094
p_{03}	-0.004061	p_{40}	-4.269e-06	p_{31}	6.169e-05
p_{22}	-0.0005518	p_{13}	0.0009544		

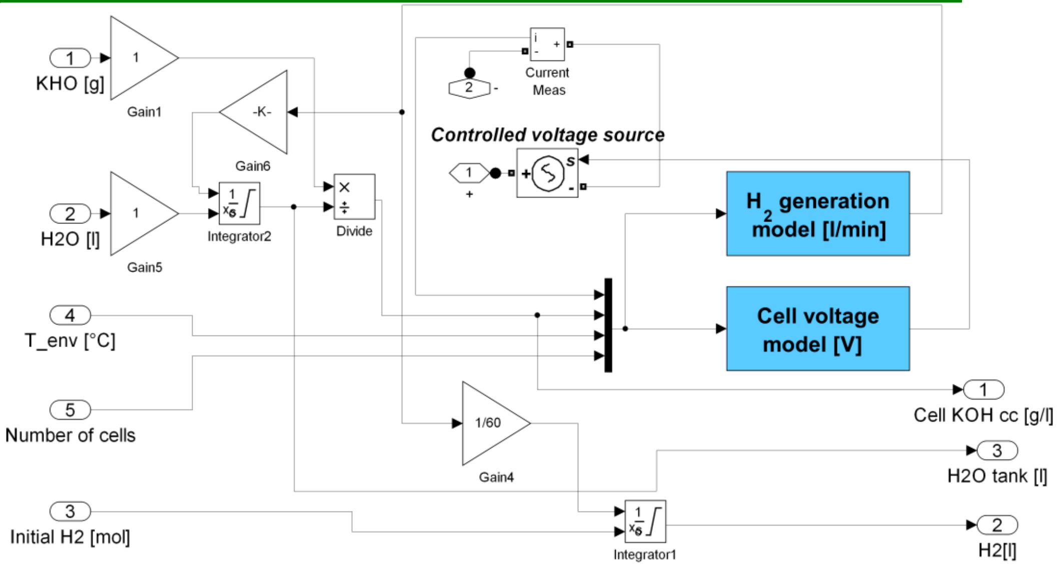

Figure 2: Matlab Simulink model of the HHO cell. The functional blocks implementing the polynomial relationships (5) and (6) are denoted with different background colour

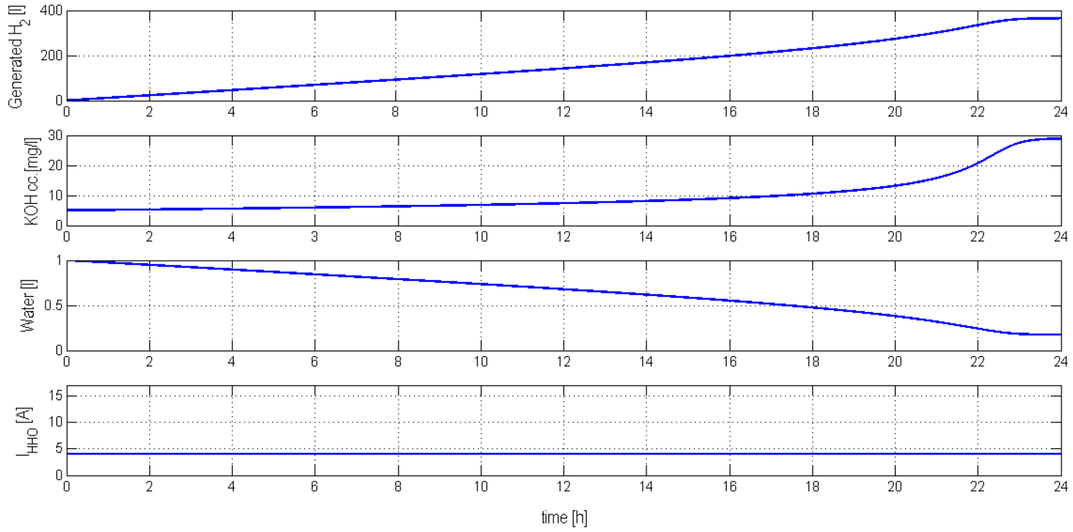

Figure 3: Simulation of cell model with constant 5 A current for 1 d. As it was expected, as the amount of water decreases and the KOH concentration increase, the H_2 generation speed decreases and the cell finally stops

3. Dry cell model in complex energy systems

The H_2 generating cell model developed in the previous section was investigated in Matlab Simulink simulation environment that simulates the energy flow conditions of a complex energy system consisting of a renewable source with a grid-synchronized inverter, a low voltage grid, an intermediate voltage controller (see Görbe et al. 2010) and a Lithium-ion battery. We replaced the lithium ion battery to this cell model. It reduces the potential energy flow modes, because this cell can only adsorb current for storing energy in developed Hydrogen, it can't reverse the electrochemical process for electrical energy from Hydrogen. The structure of the system can be seen in Fig. 4, where it is apparent that the cell model is connected directly only to the grid-synchronized inverter module of the system.

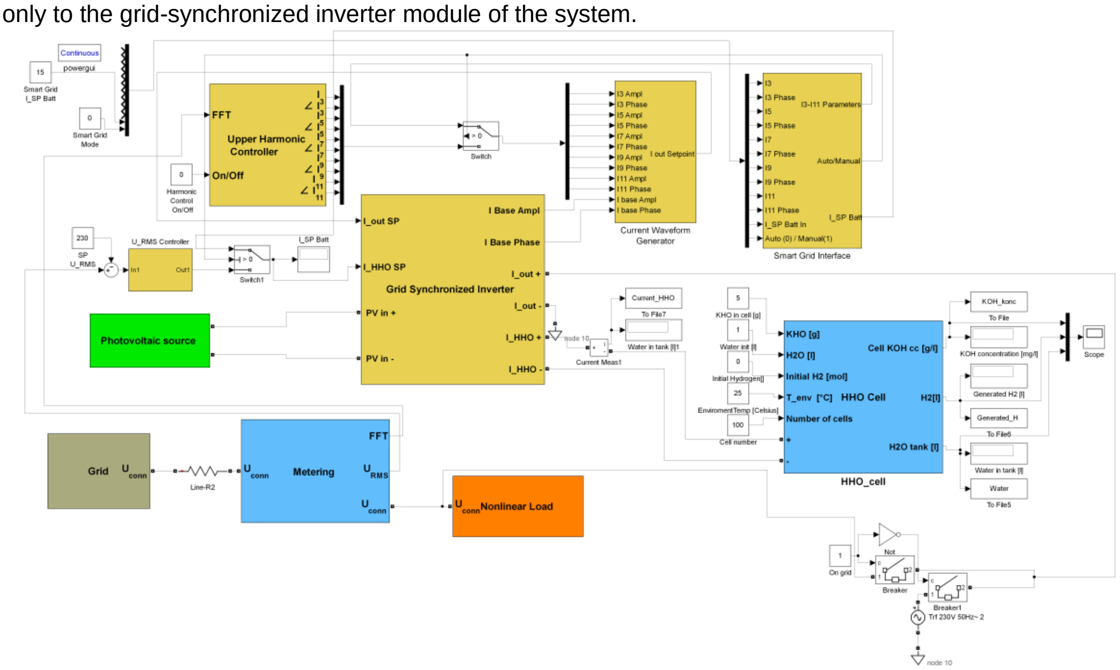

Figure 4: Matlab Simulink model of a complex energetic system with HHO cell model inside

Table 4: Parameters of the complex energetic system energy mode simulation

Time	0-1 s	1-2 s	2-3 s	3-4 s	4-5s
I Outer Load Peak	0A	50A	0A	-20A	30A

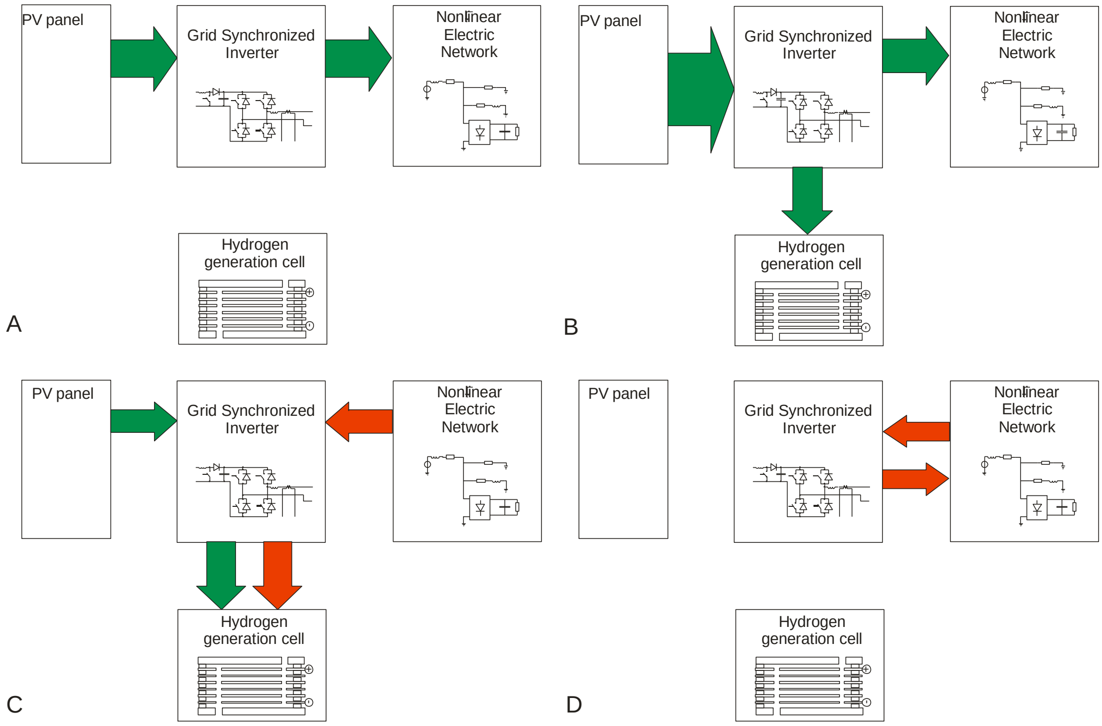

Fig. 5: Complex energetic system energy flow modes: A:Normal inverter mode, B: inverter and Hydrogen generator mode, C: Hydrogen generation only mode, D: Distortion reduction only mode

The system depicted in Figure 4 operates in different discrete states according to the energy flow direction. Four cases can be defined:

- *Normal inverter mode:* The energy flows from the renewable source to the grid only (Figure 5.A).
- *Normal inverter and Hydrogen generation mode:* The energy flows from the renewable source to both the dry cell and the grid (Figure 5.B).
- *Hydrogen generation only mode*: The energy flows from the grid to the dry cell only (Figure 5.C).
- *Distortion reduction only mode*: The energy flows from the grid into the intermediate capacitance and from the intermediate capacitance into the grid. The energy balance is zero for any whole period, and the active power is zero. (Figure 5.D).

Model verification was performed by changing the energy flow modes in subsequent time intervals, and this was implemented by changing the energy balance of the system with outer current loads (I outer load). The different values for the simulations as parameters can be seen in Table 4. The simulation results are shown in Figure 6, where U_{conn} is the effective value oft the voltage at the connection point, I_{HHO} is the current value of the dry cell, H_2 *generated* is the volume of the generated Hydrogen, *KOH conc* is the KOH concentration of the electrolyte and Water is the volume of the water inside the cell system. These values are plotted as a function of time.
The results of the simulation show that the behaviour of the simulated electronic two-pole system is identical to that of the measured database.

4. Conclusion

We developed a complex model investigating renewable energy sources, converting currently unnecessary energy to hydrogen for storage purposes and feeding the main grid. We built a measurement based model of hydrogen generating cell for simulation of complex energy system in MATLAB SIMULINK

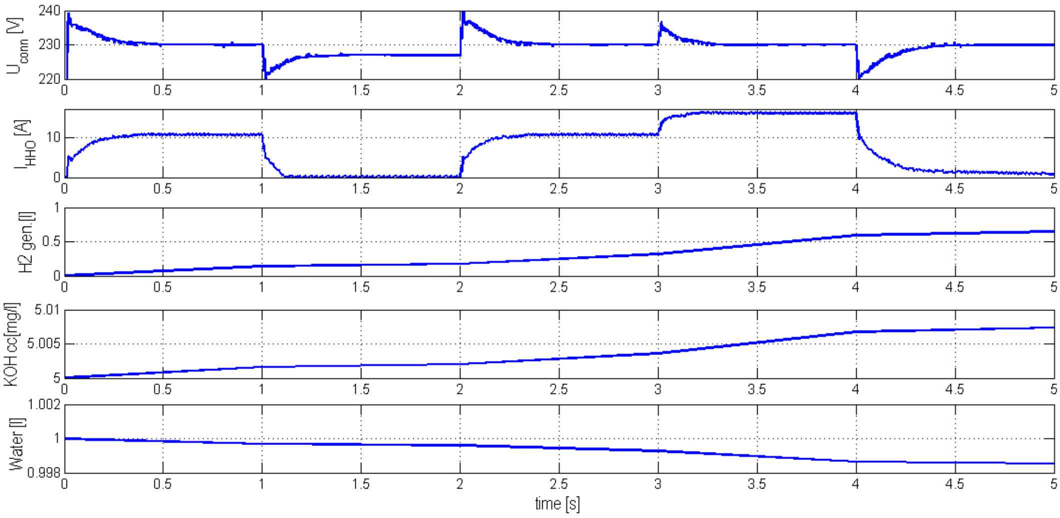

Figure 6: Simulation results of a complex energetic system with Cell model short time range (5 sec)

environment. We estimated the model parameters based on measurement data collected during the detailed examination of a demonstration cell. We carried out a series of experiments on a HHO gas producing dry cell to find the optimal electrolyte concentration, current value, etc. or changing the setup by alternating the distance between the plates with KOH electrolyte solution. We monitored it in several regards, for example cell voltage, gas production, mL/min/W value. The novel element is the temperature and concentration dependent Matlab Simulink model of the hydrogen generation cell. This is suitable for simulation purposes. We tested it in a simulation of a complex domestic power plant using renewable energy source and 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.
We simulated all the potential energetic situations in this complex energetic system model. The simulations showed that the presented hydrogen generating cell model performed well.

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