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MEASUREMENT-BASED MODELLING AND SIMULATION OF A HYDROGEN-GENERATING DRY CELL FOR COMPLEX DOMESTIC RENEWABLE ENERGY SYSTEMS

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Nowadays, the growing need for energy from renewable sources and growing revulsion towards fossil and nuclear fuels puts sustainable and green energy in the limelight. Producing (electrical) energy in domestic power plants from renewable sources (mainly solar and wind) hardly results in difficulties, but the storage of energy not consumed immediately is a great engineering challenge. In the present paper a complex model has been developed by investigating renewable energy sources, the surplus energy not actually consumed and stored in electrical vehicle (EV) batteries, the conversion to hydrogen for storage purposes and how the main grid is fed. A measurement-based model of a hydrogen generating cell developed for the simulation of complex energetic systems. The parameter estimation of the static model was based on the collected measurement data coming from the detailed examination of a built demonstration cell. The novel element of this work is the Matlab Simulink model for the hydrogen generation cell. Using this model, a dynamic simulator of a complex domestic power plant is made available using renewable energy sources and hydrogen generation cells. Hydrogen generation enables the lossless long-term storage of surplus electric energy collected, but not consumed or injected into the low voltage grid. The generated hydrogen can be consumed for transportation purposes in suitable vehicles 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 were simulated in our complex model. Simulations showed that the presented model is suitable for domestic scale low voltage complex energetic systems.

Keywords: hydrogen generation, renewable energy sources, domestic power plants, modelling and simulation, measurement-based modelling

Introduction

Producing hydrogen gas (H_2) from excess energy is not a new idea. This is an alternative way to store and convert renewable energy for further utilization. The produced hydrogen can be stored or used in power cells to be converted back to electric energy or in vehicles for hydrogen propulsion [1]. Although the described procedure is efficient and able to produce a high quantity of H_2 it is not suitable for application in combination with domestic power plants.

The most relevant from of H_2 production is when the energy consumption and quantity of produced H_2 are controlled. When power consumption and generation are continuous (and not necessarily deterministic) functions of time, the H_2 production depends solely on the excess energy of the grid. The best solution is the usage of Supervisory Control and data Acquisition Systems (SCADA) of management [2]. The domestic applicability of this technology in the future depends on the cost of SCADA system installation.

Producing hydrogen and oxygen gases from water using electricity in a laboratory is a simple electrochemical process that can be performed easily and in a very demonstrative way. Producing hydrogen on a large scale or in industrial quantities calls for an optimized or near-optimized cell model. In an energy demanding process only a few percent of variance in efficiency could mean a significant energy surplus or shortage [3]. The electrochemical parameters of a dry cell (*Fig.1*) that are used here are discussed to simulate hydrogen and oxygen gas production. Compared to wet oxyhydrogen (HHO) cells where the entire unit is underwater, the plates of dry cells are separated with rubber seals. These seals stop the water from leaking from the cell. The electrical connections and edges of

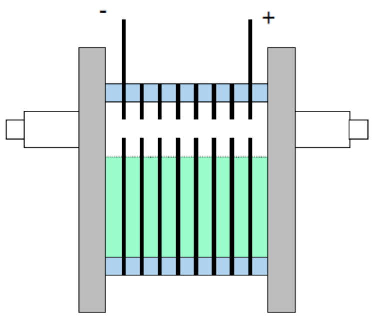

Figure 1: The theoretical setup of a dry HHO block

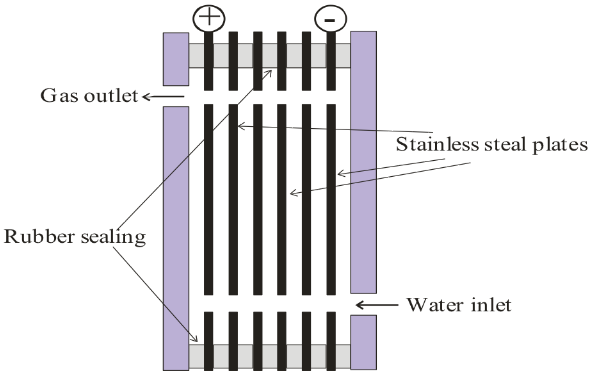

Figure 2: The setup of a HHO gas generator cell block

the plates do not touch the electrolyte. These parts of the unit stay dry, thus the name dry cell. To make sure the gas made from the electrolyte gets out of the cell and the solution flows between the plates, there are holes on the top (for the gas) and bottom (for the electrolyte) on the metal slats (*Fig.1*).

The application of dry HHO units has two main advantages. The surface of the dry cell plates enables one to use smaller amounts of electrolyte compared to with wet cells; therefore, the volume and weight of the cell is smaller. Furthermore, the connectors of dry cells remain dry, i.e. they do not corrode unlike to wet cells, where the connectors are underwater therefore their surface slowly corrodes [4].

Electrochemical Foundations

Electrochemical cells can be considered as galvanic batteries where the electrochemical reactions are supported by an external current supply. They are composed of two electrodes and a conductive electrolyte fluid. If the electrode material does not participate directly in the electrode reaction, it is called an indifferent electrode (e.g. graphite). During electrolysis, if there is more than one possible type of electrochemical reaction, then a simple anion will detach from the positive anode (e.g. chloride), without this anion, HO^- will be created by water splitting. The dissolution voltage of water is 1.23 V at 25 °C, the temperature coefficient is -0.85 mV/K, which means that at 100 °C this voltage decreases to 1.17 V. Therefore, in the light of these data, the specific energy demand to make hydrogen *via* electrolysis at 25°C can be calculated from *Eqs.(1–4)*.

The amount of charge needed to evolve 1 kg of H_2 gas is

$$q = z\mathrm{F}M = 2\cdot 96487\cdot 0.5 = 96487 \text{ A s mol}^{-1} = 26801 \text{ Ah kg}^{-1} \quad (1)$$

$$w_{H_2} = q\mathrm{E}_{\mathrm{MF}} = 26801\cdot 1.23 = 32966 \text{ Wh kg}^{-1} \quad (2)$$

Since the volume of 1 kg of standard state H_2 is 12474 dm^3, the amount of energy required to produce 1 dm^3 of H_2 gas is:

$$w_{H_2} = \frac{32966}{12474} = 2.64 \text{ Wh dm}^{-3} \quad (3)$$

Table 1: Experimental results

Electrolyte concentration, g dm^{-3}	MMW[a], cm^3 min^{-1} W^{-1}	Gas production, dm^3 min^{-1}	Power of unit, W
1	2.13	0.20	10.8
2	2.66	0.75	34.4
3	2.66	1.37	55.8
4	2.59	1.51	82.2
5	2.72	1.90	90.6
6	2.63	2.52	119.5
7	2.67	2.96	140.0
8	2.65	2.76	125.0
9	2.46	2.28	105.6
10	1.82	2.15	103.2

[a] millilitres per minute per watt

To generate 1 dm^3 of hydrogen gas, 1.5 dm^3 of HHO gas is needed and thus the energy demand of producing 1 ldm^3 of HHO gas (0.667 dm^3 H_2) is:

$$w_{\mathrm{H_2(HHO)}} = 0.667\cdot 2.64 = 1.76 \text{ Wh dm}^{-3} \quad (4)$$

The unit has been measured at 10 different electrolyte concentrations, using different currents. At the same time, the voltage on the plates and amount of gas produced by electrolysis has also been measured.

The HHO Cell Unit

The setup of one block of the unit is shown in *Fig.2*. Usually five cells make up one block giving one gas-producing block. The block's electrical connections are on the ends of two plates (*Fig.1*). 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 the voltage between two electrodes is one fifth of the voltage on one whole block. In the experiment, a unit with three 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 due to bubbling, electrolyte comes out of the tube that needs to be recycled back into the system. Then, as the electrolyte drips back into the tank, the gas can escape into the bottle through another hose. The produced H_2 volume and the production speed are measured with this bottle. A power supply (Manson SPS9600) has been connected to the electrical connections of the HHO unit, in this way the input current was controlled (*Table 1*).

Matlab Model of the Dry Cell

The model of the dry cell considered was implemented in Matlab Simulink using the SimPowerSystems Toolbox. Two unknown functional relationships between the generated H_2 volume, the cell current and the KOH concentration and between cell voltage, cell current and KOH concentration were approximated using fourth and third order polynomials, respectively

Table 2: Coefficients of the polynomial relationship describing the cell voltage

	Value		Value		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

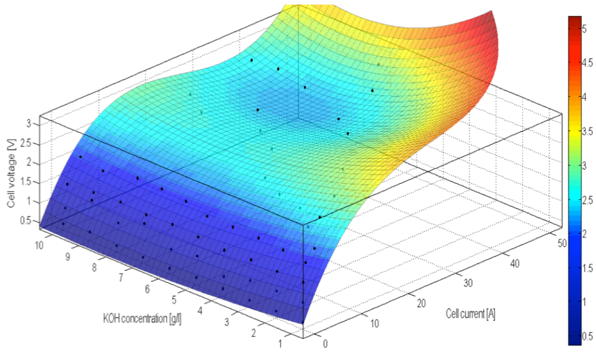

Figure 3: Simulation of the cell model with a constant current of 5 A for 1 day

using the Matlab Surface Fitting Tool. As the fitted polynomials do not have a physical connection to the given device, the model is applicable to any similar electrochemical H_2 generation device with an electric two-pole system. In the different linear and non-linear physical and chemical models different coefficients become dominant. The voltage relationship is given by *Eq.(5)*, where i_{cell} denotes the cell current and c_{KOH} stands for the KOH concentration. Parameters can be found in *Table 2*.

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

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

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

Table 3 and *Figs.3-4* show representative results for the model. As expected, the H_2 generation speed decreases and the cell finally stops working as the amount of water decreases and the KOH concentration increases.

A Simulink block scheme of the cell model is depicted in *Fig.5*. This Simulink model was validated by considering a system with the same parameters as the layout of the experimental cell. In this layout, we ran a simulation for 24 h using this model, decreasing water and increasing KOH concentrations. The results of this simulation can be seen in *Fig.6*. It can be seen that the hydrogen gas generated is reduced because of the rising KOH concentration. The exact values are in good agreement with our measurements.

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

	Value		Value		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_{13}	6.169e-05
p_{22}	-0.0005518	p_{13}	0.0009544		

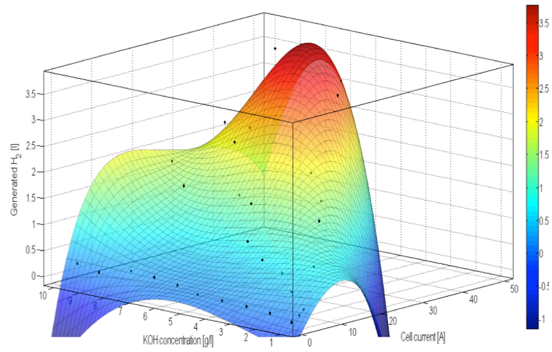

Figure 4: Generated H_2 as a function of KOH concentration and dry cell current

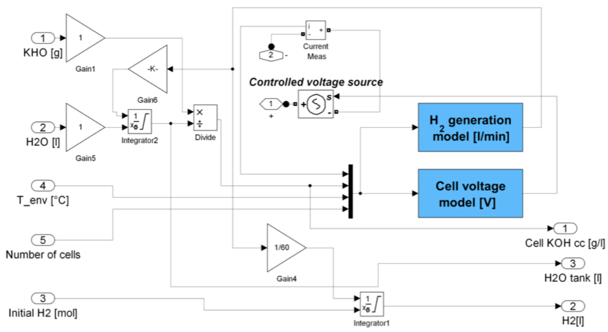

Figure 5: Matlab Simulink model of the HHO cell. The functional blocks implementing *Eqs.(5)* and *(6)* are denoted by different background colours

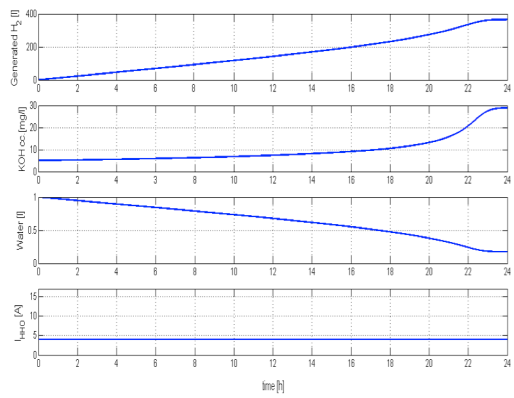

Figure 6: Simulation of a cell model with a constant current of 5 A for 1 day

Dry Cell Model in Complex Energetic Systems

The model for H_2 generating cells described in the previous section was investigated in the Matlab Simulink simulation environment that studies the energy flow conditions of a complex energetic system consisting of a renewable source with a grid-

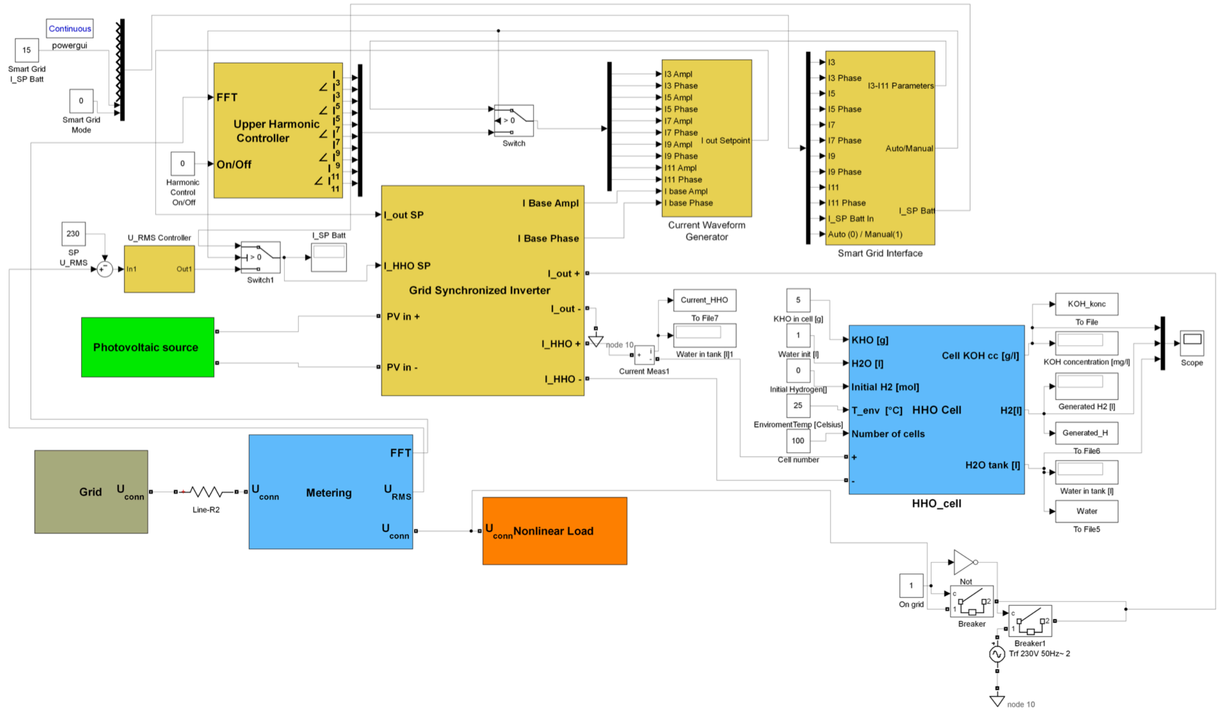

Figure 7: Simulink model of a complex energetic system with an HHO cell model inside

synchronized inverter, a low voltage grid, an intermediate voltage controller [3,5] and a lithium ion battery. We replaced the lithium ion battery in this cell model, which reduces the potential energy flow modes, because this cell can only adsorb current for storing energy in hydrogen production. It cannot reverse the electrochemical process for electrical energy generation from hydrogen gas. The structure of the system can be seen in *Fig.7*, where it is apparent that the cell model is connected directly only to the grid-synchronized inverter module of the system. The system depicted in *Fig.7* 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 (*Fig.8A*).
- Normal inverter and hydrogen generation mode: The energy flows from the renewable source to both the dry cell and the grid (*Fig.8B*).
- Hydrogen generation only mode: The energy flows from the grid to the dry cell only (*Fig.8C*).
- 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 a period, and the active power is zero (*Fig.8D*).

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

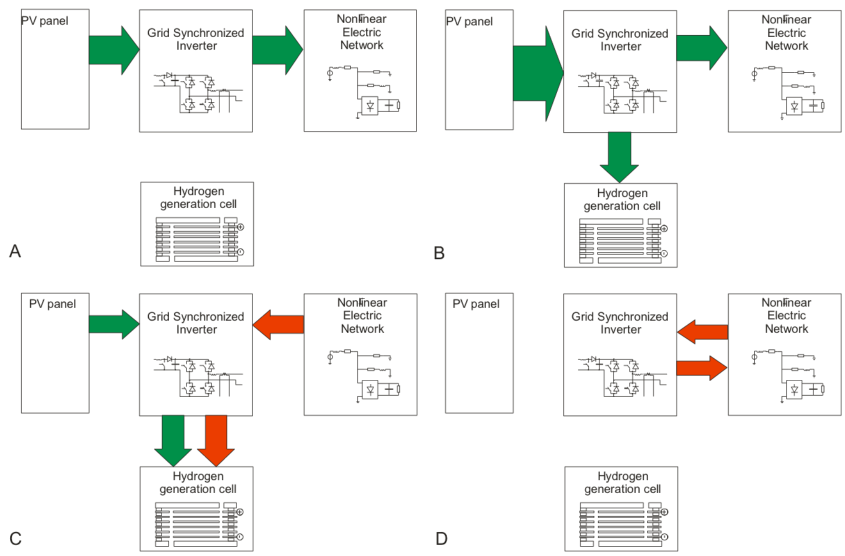

Figure 8: Complex energetic system energy flow modes: A: normal inverter mode, B: inverter and hydrogen generator mode, C: hydrogen generation only mode, D: distortion reduction only mode

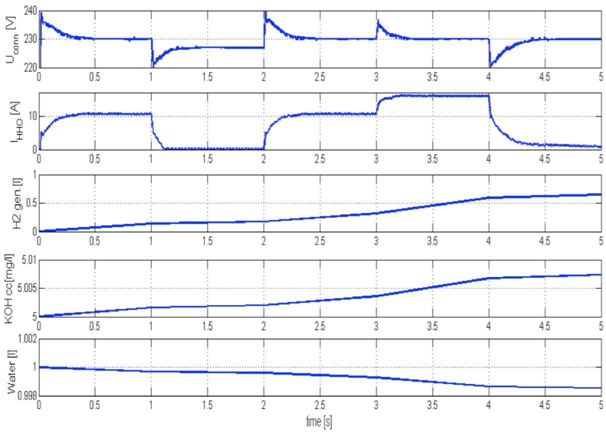

Figure 9: Simulation results of a complex energetic system using a cell model short time range (5 sec)

seen in *Table 4*. The simulation results are shown in *Fig.9*, where U_{conn} is the effective value of the voltage at the connection point, I_{HHO} is the current value of the dry cell, V_{H_2} is the volume of generated hydrogen gas, c_{KOH} is the KOH concentration of the electrolyte and V_{water} is the volume of 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.

Conclusion

We developed a complex model to investigate renewable energy sources, for the conversion of surplus energy to hydrogen gas for storage and to represent how a main grid is fed. We built a measurement-based model of a hydrogen-generating cell for the simulation of complex energy systems in MATLAB SIMULINK environment. We estimated the parameters of the model based on measurements 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 change the setup by altering the distance between the plates with KOH electrolyte solution. We monitored the experimental setup in several regards, for example cell voltage, and gas production. The novel element is the temperature and concentration dependent Matlab Simulink model of the hydrogen generation cell, which was found to be suitable for simulation purposes. We tested it in a simulation of a complex domestic power plant using a renewable energy source and hydrogen generation cell. Hydrogen generation enables the long-term storage of surplus electrical 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 model of an energetic system. The simulations showed that the presented model of a hydrogen-generating cell performed well.

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