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Dynamic Modeling of a Hybrid Photovoltaic System with Hydrogen/Air PEM Fuel Cell

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Abstract: In this study, a photovoltaic-electrolyser-fuel cell system was considered and simulated. This hybrid system produces hydrogen in the daytime and stores it in the storage tank in order to supply the required energy for the peak period of demand. Dynamic behavior of the process components was analyzed under different conditions. Transient simulation represents performance of the components and the system. Results can be used for improving the component's efficiency and optimizing component's size. The results obtained in this work, consist of hourly values of hydrogen produced by electrolyser unit, generated fuel cell energy to cover the energy demand, generated PV energy, dynamic behavior of the PEM fuel cell and tank pressure level.

Key words: Hybrid system · Photovoltaic · PEM fuel cell · Hydrogen storage · PVFC

INTRODUCTION

There has been increasing interest in research and development of the hybrid renewable energy systems (using two or more different types of renewable energy systems and/or sources) for hydrogen production, for example, using both solar and wind or solar and geothermal, or maybe other combinations. One solution may be solar hydrogen systems [1]. Renewable energy resources - such as wind and solar energies - cannot produce power steadily, since their power production levels change with the season, the month, the day, the hour, etc [2]. Hydrogen can be used to store variable renewable energy (RE), such as solar and wind energy [3].

The fuel cell generator is a good option to integrate with the PV power since it is characterized with many good features such as high efficiency, fast response, modular production and fuel flexibility [4]. A complete model for hydrogen PVFC hybrid system was implemented in computer codes and utilized to predict its operational performance through numerical simulation [5]. The potential for both heat and power extraction from a PEM fuel cell was investigated experimentally and a computer simulation was applied to improve the economics of a solar hydrogen system supplying energy to a remote household [6].

The aim of this study is to develop dynamic behaviors of a stand-alone PVFC components and hydrogen production efficiency using TRNSYS software.

Simulation Structure: The whole system is divided into two main parts: solar PV subsystem and hydrogen/air PEM fuel cell subsystem. The second part consists of an alkaline water electrolyser, a storage hydrogen tank, a PEM fuel cell (PEMFC) and power conditioning units (PCU). The hydrogen storage tank considered here is mainly used to store the additional solar energy, as schematically shown in Figure 1. During the peak periods of electricity demand, fuel cells switched by the stored hydrogen to produce electricity.

Photovoltaic or fuel cell power systems, which generate power as a direct current (DC), require power conversion units to convert the power from DC to alternating current (AC) [5]. The power conditioning

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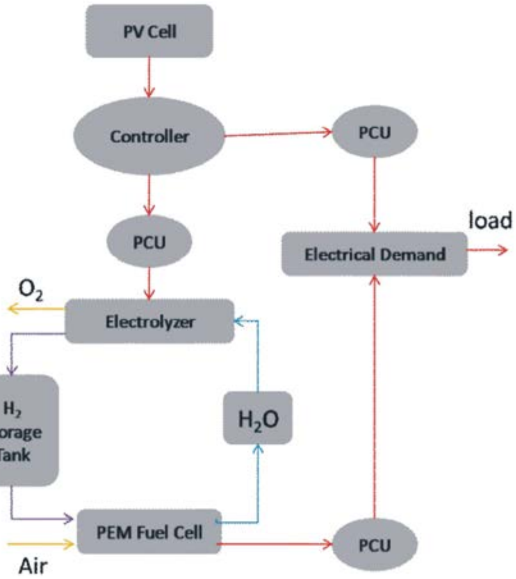

Fig. 1: Schematic of hydrogen PVFC hybrid system.

Table 1: Operating parameters for hybrid system [5, 7]

PV panels	Maximum power: 85 W
	Voltage at P_{max}: 18.0 V
	Current at P_{max}: 4.72 A
	Short circuit current (I_{sc}): 5.0 A
	Open circuit voltage (V_{oc}): 22.1 V
	Total surface area: 230 m^2
PEM Fuel Cell	Peak power: 2.5 kW
	Operating voltage: 45 V
	Open circuit voltage: 65V
Alkaline Electrolyser	Nominal Voltage: 62 V
	Maximum operating current: 35 A
Hydrogen Storage Tank	Total volume: 30 m^3
	Maximum pressure level: 100 bar
	Minimum Pressure level: 10 bar

unit helps the electrolyser to receive constant power (DC or AC input), by combination of the output from the PV cells [1].

A 85-watt monocrystalline PV cell, a 2.5kW PEM fuel cell system, an alkaline electrolyser and simple models of PCUs and storage tanks was considered. Technical data of system components was taken from literatures [5, 7].

Next size of all components of system – that is, the number and total area of PV panels, number of the fuel cell stack and electrolyser, tank volume, etc. – were calculated. All of the components in the solar-hydrogen system were modeled separately as follow:

- Photovoltaic panel submodel

The photovoltaic cell array studied here is 85 watt mono-crystalline PV cell. The open circuit voltage (V_{OC}) is 22.1 V and the short circuit current (I_{SC}) is 5.0 A under the condition of 1000 W/m2 (G) and 298 K as presented in Table 1. Essential parameters for the system sizing were the average daily solar radiation energy and the load consumption energies. To size the PV power generator, the following equation is usually used: [5].

$$A_{PV} = \frac{E_{ld}}{\eta_{sys} \times E_{sd}} \quad (1)$$

The PV production at standard and maximum power condition is calculated as:

$$P_{max} = V_{max} \cdot I_{max} = FF.\ V_{OC} \cdot I_{SC} \quad (2)$$

$$P_{PV} = E_0 \times \eta_{PV} \times A_{PV} \quad (3)$$

The efficiency of PV cell is defined as:

$$\eta = \frac{P_{\max}}{P_{radiation}} \quad (4)$$

- PEM Fuel cell submodel

According to Faraday's law, the consumption rates of hydrogen in a fuel cell is directly proportional to the transfer rate of electrons to the electrodes, which in turn is equivalent to the electrical current in the external circuit. Hence, the total consumption rate of hydrogen in a fuel cell, which consists of several cells connected in series, can be expressed as: [8]

$$\dot{m}_{H2,C} = N_{cells} \cdot \frac{I_{Fuel\ Cell}}{n\ .F} \quad (5)$$

The required number of PEM fuel cells and number of stacks can be derived as: [9]

$$N_S = \frac{PEM\ Fuel\ Cell\ System\ Voltage}{PEM\ Fuel\ Cell\ Stack\ Voltage} \quad (6)$$

$$N_P = \frac{PEM\ Fuel\ Cell\ System\ Power}{PEM\ Fuel\ Cell\ Stack\ Power} \quad (7)$$

In this study, the number of cells and stacks are optimized and arranged as 1 stack and 55 cells, which successfully covered the excess demand.

Total efficiency of fuel cell, which consists of hydrogen loss that will not heat up the fuel cell, is expressed as: [10]

$$\eta_{eff}=\frac{V_{fC}.I_{fC}}{V_{ref}.(I_{fC}+k_{kurloss}.V_{OC}+k_{hydloss}.I_{min})} \tag{8}$$

By neglecting hydrogen losses the fuel cell efficiency will have simple form, as:

$$\eta_{eff}=\frac{V_{fC}}{V_{ref}} \tag{9}$$

- Electrolyser submodels

An alkaline water electrolyser consists of a number of electrolyser cells connected in series. An electrolyser with one stack and 70 cells is used here. The equation that describes the required operation voltage is: [4]

$$V_{actual}=V_{OC}+\eta_{anode}+\eta_{cathode}+\eta_{ohm} \tag{10}$$

The total hydrogen production rate in electrolyser, which consists of several cells connected in series, can be expressed as: [8]

$$\dot{m}_{H2,p}=\eta_{f}.N_{cells}.\frac{I_{Electrolysev}}{n.F} \tag{11}$$

Again by neglecting hydrogen losses, total efficiency of electrolyser is calculated as:

$$\eta_{eff}=\frac{V_{ref}}{V_{ely}} \tag{12}$$

- Hydrogen Storage tank Submodel

The equation of state is either the ideal gas or the Van-der-Waal equation of state for real gases. According to the Van Der Waals equation of state, the pressure of a real gas in a storage tank can be calculated from [10] as follows:

$$p=\frac{n.R.T_{gas}}{Vol-n.b}\quad a.\frac{n}{vol^{2}}\quad - \tag{13}$$

The hybrid system under study has two controller valves to protect the hydrogen storage tank from over pressure inside the tank. In this work operating pressure of hydrogen tank was considered between 10-100 bar. The selected volume in the storage tank in this study was kept at 30 m^3.

Some hydrogen losses are expected such as hydrogen losses in the electrolyser or fuel cell during start-up and shut down, hydrogen losses in the gas storage tank and hydrogen losses in the fuel cell during operation, but these will not be included in the simulation. [5]

- Controller Submodel

The controller actually set a power set point for a power device that is linking the electrolyser and fuel cell. The power set point is adjusted to maintain the state of charge of a storage tank within the target range [8]. The control strategy which is required to split electricity generated by PV cells is considered as:

- If $P_{PV} < P_{Load}$, then: $P_{Load} - P_{PV} = P_{Fuel\ Cell}$. This means that, the load is connected directly to the PV cell and the excess power must be supplied by the fuel cell system.
- If $P_{PV} > P_{Load}$, then: $P_{PV} - P_{Load} = P_{Electrolyser}$. This means that, the power from the PV cell is more than requested load and the excess power is stored in hydrogen tank by the electrolyser.
- If $Pressure_{H2} > Pressure_{max}$, then: $P_{electrolyser} = P_{idle}$ This means that, pressure of hydrogen tank level is more than maximum value and the electrolyser is switched off.
- If $Pressure_{H2} < Pressure_{min}$, then: $P_{fuel\ Cell} = P_{idle}$. This means that, pressure of hydrogen tank level is less than minimum value; then, the fuel cell is switched off.

Total energy efficiency of hybrid PV-PEM fuel cell system by neglecting hydrogen losses, may be written as: [7].

$$Energy\ Efficiency=\frac{Output\ Energy+Stored\ Energy}{Input\ Energy} \tag{14}$$

RESULT AND DISCUSSION

Figures 2 to 11 show the simulation results of stand-alone photovoltaic fuel cell system with different parameters. Daily data of the solar radiation and the ambient temperature are shown in Figure 2.

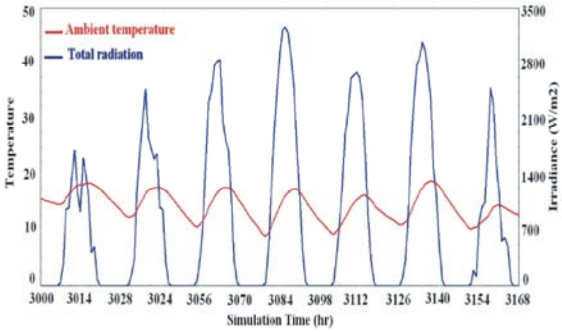

Fig. 2: Ambient temperature and total radiation

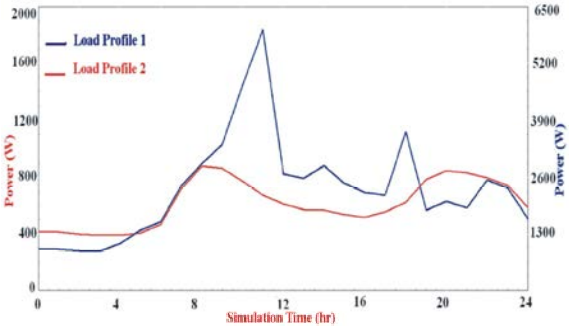

Fig. 3: Considered load profile 1, 2

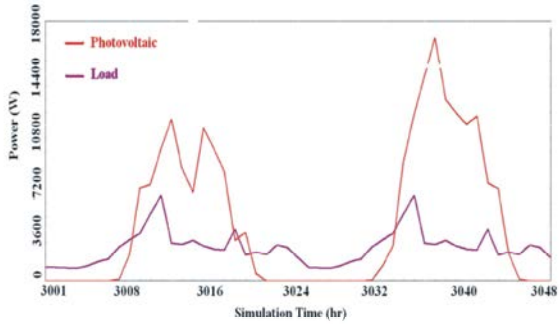

Fig. 4: Requested load profile and generated power by photovoltaic

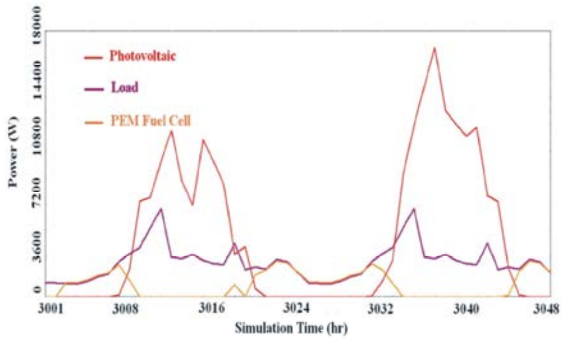

Fig. 5: Power used by fuel cell to cover the requested load

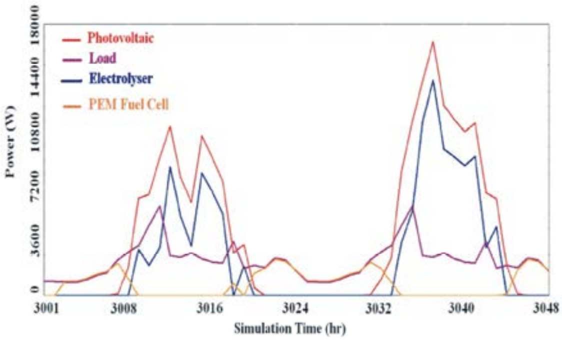

Fig. 6: Hybrid system PV-PEM fuel cell power

Figure 3 shows two types of profile, which are given as daily electrical demand. These load profiles are taken from [9, 11]. In profile No. 1 the peak load during the day is 6.05 kW occurring between 8 a.m. and 10 a.m. The demand for load No. 2 is lower, which the average requested load is about 0.6 kW.

The output power of photovoltaic panel is controlled by a maximum power point tracking method (MPPT) neural network [12]. Figure 4 shows the load profile and electric energy provided by the photovoltaic panel at maximum power point. When, $P_{pv}>P_{load}$, there is excess power available for the hydrogen production. Also, when $P_{pv}<P_{load}$, fuel cell switched and generate electricity to cover the demand by the stored hydrogen. Figure 5 shows the power which fuel cell must compensate the deficit in photovoltaic generator energy. The excess value of photovoltaic energy generated is used by the electrolyser to produce hydrogen.

The performance of the whole system components is illustrated in Figure 6, which shows the comparison of the PEM fuel cell output power and value of energy used for hydrogen storage by electrolyser. According to Figure 6, after 8: 00 the PV panels begin to generate electricity. Until around 10:00 both PV and fuel cell provides electricity to the user, then fuel cell stack turns off and PV panels supply electricity. The extra power produced by the PV panels between 8:00 and 20:00 supplied to the electrolyser stack. After 20:00 pm fuel cell stack starts up again and produces electricity during the night hours. This Figure although expresses the operation of each component to satisfy the requested load and process of producing and consuming hydrogen.

Variation of hydrogen pressure is due to gas flow at input or output of the storage tank as was shown in Figure 7. It was found that the behavior of the volumetric flow rates of hydrogen is similar to the power behavior of the fuel cell generator and electrolyser.

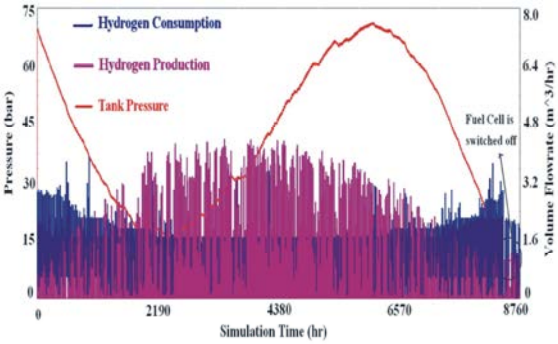

Fig. 7: Hydrogen volumetric flow rate and annual tank pressure level for load profile 1

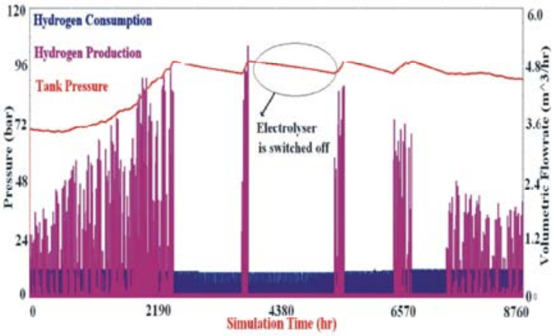

Fig 8: Hydrogen volumetric flow rate and annual tank pressure level for load profile 2

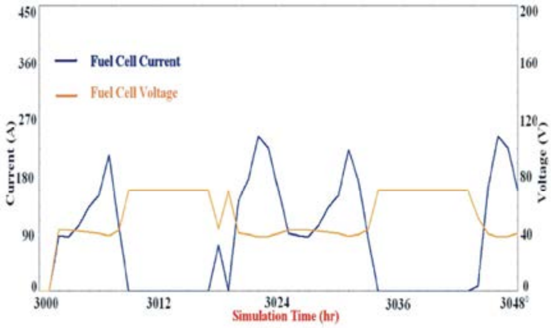

Fig. 9: Electrical dynamics of the fuel cell

Fig. 10: Electrical dynamics of the electrolyser

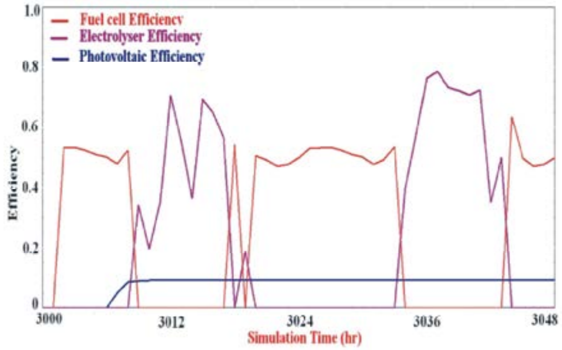

Fig 11: Component energy efficiency of hybrid system

Distribution of current and voltage of the fuel cell and electrolyser are shown in Figures 8 and 9. In Figure 9, it was observed that the voltage decreases as the current increases. In the daytime, the PEM fuel cell keeps at its open-circuit voltage without any current extracted from the fuel cell stack. The general trend shown in Figure 10 was an increase of current passing through the electrolyser with increasing the operational voltage. The difference between the operational voltage and the open-circuit voltage represents the over potentials in the electrolyser [4]. Both figures show that the current profile is similar to the load profiles.

The energy efficiency of electrolyser and PEM fuel cell is presented in Figure 11 during 48 hours. It is seen that energy efficiency of these components is averagely 50% during the considered operation time. Finally, total energy efficiency of the whole hybrid system is calculated and shown in figure. It can be observed that the overall energy efficiency is very low (about 5%) due to high value of solar energy as input parameter in comparison with load and hydrogen storage required energy.

Nomenclature:

a, b	Van der Waals equation's constants [-]
η_f	Faraday efficiency [-]
η_{sys}	Total system efficiency [-]
η_{PV}	PV generator rated efficiency [-]
P_{PV}	PV production power at standard test conditions [W]
E_0	Solar radiation at standard test condition [1kW/m^2]
p	Pressure [bar]
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
FF	Fill factor
V_{max}	Voltage at maximum power point
I_{max}	Current at maximum power point
V_{fc}	Voltage over fuel cell

I_{fc}	Current for fuel cell
$Vref$	Reference voltage
A_{PV}	PV generator surface area [m^2]
E_{ld}	Daily mean load energy consumption [kWh/d]
E_{sd}	Daily mean solar radiation energy [$kWh/m^2/d$]

CONCLUSION

In this work the dynamic behavior of hybrid photovoltaic system with hydrogen/air PEM fuel cell was simulated with TRNSYS software, which consist variation of hydrogen tank pressure, PEM fuel cell power, electrolyser power, PV cell electricity generated and etc, during 48 hours. The results drawn by this work can get better understanding the dynamic behaviors of the each components of the whole system that helps in improving component's efficiency. The present hybrid system was successfully covered the daily power demand and the required load of the energy was managed successfully using mentioned control strategy.

Investigation of solar stirling power plant using hydrogen/Air fuel cells will be as a recommendation for future work. This system may be a future competitor of hybrid solar/fuel cell systems.

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