Residential Hybrid Solar-Hydrogen Power System Design for A Sustainable Power Management

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Abstract

In this study, a solar-hydrogen hybrid power generation system is modelled in Matlab/Simulink, and a sustainable power flow is performed for residential solar-hydrogen hybrid power plants. A solar-hydrogen hybrid power generation system is designed to realize a sustainable power flow for the local load. The developed power management system checks the total energy demand of the hybrid power plant and operates the solar power plant or the hydrogen energy based power plant to provide a sustainable power for the local load. The designed hybrid power plant provides a sustainable energy infrastructure for the residential hybrid power plants, and it is also easy implemented and is suitable for residential real system applications.

1. Introduction

The solar energy is a significant renewable energy source which has a continuous source and available easily in the nature. Thus, the photovoltaic (PV) systems have been widely used in the applications of generating electrical energy recently instead of the fossil fuels. PV systems have an ability to generate DC current without being affected by the pollution and weather conditions [1]. Besides, the primary issue of the PV systems is having an interruptable power generation because of the weather just like in the nights and cloudy days. Therefore, a sustainable power flow is required for an off-grid PVsystem, so an energy storage device or system is essential to provide a continuous power to the consumers [2].

The hybrid renewable energy sources (HRES) are the combination of the wind, hydrogen, solar and other renewable energy sources operating at the same time [3]. The phrase of HRES is also used to provide the required electrical and thermal energy demand of the consumers by combining all of the different energy technologies [4].

A solar-hydrogen energy based hybrid power energy system is an alternative and sustainable energy solution for the residential plants which fills the deficiency of the sole PV power generation system [5]. There are several methods to produce hydrogen from the solar energy, and today the most common method for this by generating hydrogen to electrolyze the water at low temperatures [6].

A solar-hydrogen energy-based power generation system was proposed in [7]. In the study, an electrolyzer, a hydrogen storage tank and the batteries were designed to constitute the hybrid system. The daily generated and consumed power was monitored, and a new model was proposed to improve the performance of the fuel cell (FC) system in this study. A similar study was performed in [8], and the obtained experimental results from the hybrid PV-FC hybrid system was monitored by Labview. The grid connected, and standalone operational performance of the hybrid system was also researched in another study [9], and the properties of a polymer electrolyte membrane (PEM) electrolyzer were examined in the study. PV-battery, PV-FC stack and PV-FC-battery off-grid hybrid systems were designed in [10,11] to optimize and to specify the different storage technologies in this study. Most of studies focus on modelling the hybrid system and consist of simulation studies.

Another standalone hybrid system consisting of a wind türbine, a PV array and a PEM FC stack was proposed in [12]. Providing the maximum output power of the system, decreasing the voltage fluctuation and the increasing the energy quality of the hybrid system is the main design and simulation issues researched in this study. A Matlab, Simulink model of a grid, connected 1,2 kW PEM FC stack was presented in another study [13]. In this study, the analysis of the FC system is investigated, and the FC system is the sole source of the system. The simulation of a grid connected PV-FC system with Matlab, Simulink is also studied in [14]. A Matlab simulation model and the analysis of a hybrid power generation system consisting of a PV array and a PEM FC stack was also presented in [15] to supply the energy demand of a greenhouse. The general schematic of the proposed hybrid power generation system for residential plants is shown in Fig. 1.

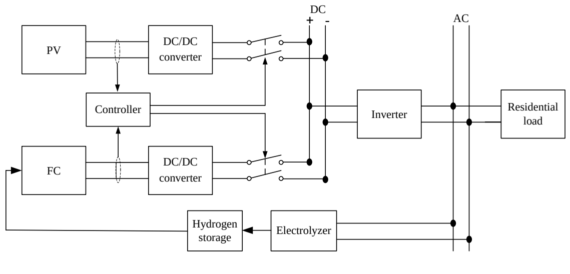

Fig. 1. The general schematic of the proposed hybrid power generation system for residential plants

This study focuses on developing a solar-hydrogen hybrid power generation system model with Matlab/Simulink. A sustainable power flow is researched for residential solar-hydrogen hybrid power plants. A solar-hydrogen hybrid power generation system is designed to realize a sustainable power flow for the local load. The developed power management system checks the total energy demand of the hybrid power plant and operates the solar power plant or the hydrogen energy based power plant to provide a sustainable power for the local load. The designed hybrid power plant provides a sustainable energy infrastructure for the residential hybrid power plants, and it is also easy implemented and is suitable for residential real system applications.

2. The Proposed Sustainable Power Management System

The general schematic of the proposed hybrid power generation system for residential plants is shown in Figure 1. The proposed hybrid system consists of a PV array and PEM FC stack, and an electrolyzer and a hydrogen storage tank as a fuel processing unit. The electrolyzer is supplied from the AC bus, and the DC/DC converters and the inverter are the power conditioning units of the proposed hybrid system.

The implemented electronic control card manages the active power flow of the hybrid system to provide a sustainable power demand of the local load. The developed control card also maintains the active power flow of the hybrid power plant. Thus, the proposed management system provides a sustainable energy infrastructure for the residential hybrid power plants. Besides, the current energy demand of the residential power plants can be viable in the lack of the sun or hydrogen, thanks to the developed hybrid power plant and the management system.

The developed electronic control card shown in Figure 3, measures the input voltage of the buck converter where is located at the output of the PV array. If the measured voltage is below the defined threshold value, the PV array is switched off and PEM FC stack is switched on to provide the continuous power. The related led is also red that indicates the load is supplied from the PEM FC stack. The PV array is operated when the input voltage of the buck converter over the defined threshold value, and the led is green in this condition. There is a hysteresis band for the defined threshold values to provide a sustainable energy management, thus the sudden and indecent changes of the system can be omitted. The developed control card also detects the power lack of the FC stack, and if the measured output voltage of the FC stack is below 5 V, the condition has drawn attention by a buzzer.

Fig. 3. The developed electronic control card for a sustainable power management

3. The Proposed Sustainable Hybrid Power Generation System Model

The proposed hybrid power generation system designed for residential plants is modelled in Matlab/Simulink. Figure 2 shows the developed model. The proposed model consists of a 100 Wp PEM FC stack, and a 160 Wp PV module, and the proposed control system are developed to compare the both simulation and experimental results. A detailed model of the proposed system is presented in this section.

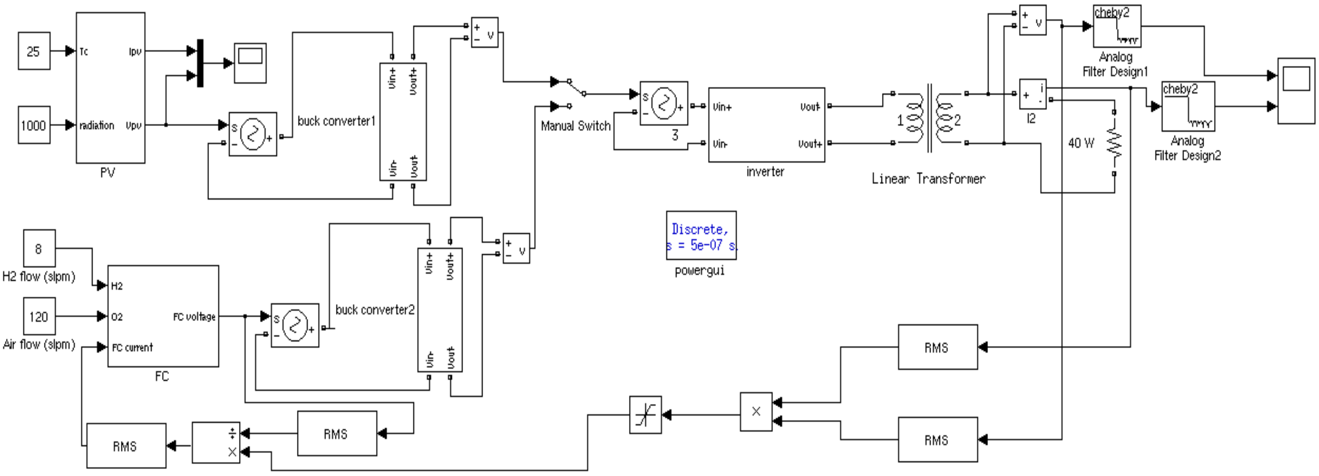

Fig. 2. The general schematic of the proposed hybrid power generation system for residential plants

3.1. PEM Fuel Cell Model

The mathematical models are used to obtain the characteristics of an FC stack, and the polarization curve is obtained by evaluating the developed mathematical model of the PEM FC stack in Matlab/Simulink. The operation of an FC in a stack is nonlinear that is clearly indicated by the polarization curve in Figure 4. This characteristic also depends on many factors, just like current density, cell temperature, membrane humidity and the partial pressure of the reacted gases.

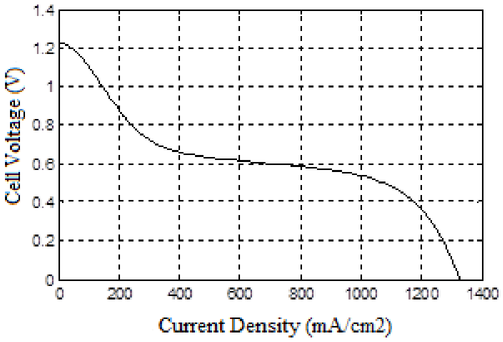

Fig. 4. The polarization curve obtained from the developed PEM FC stack model

A PEM FC stack consists of an anode, a cathode, electrolyte layer and the gas flow channels. The inputs of an FC stack are hydrogen, oxygen, steam pressure and the current density of an FC. The cell voltage equals to the multiplication of the number of FC. The stack voltage is obtained from this multiplication. The developed model of the PEM FC stack is indicated in Figure 5.

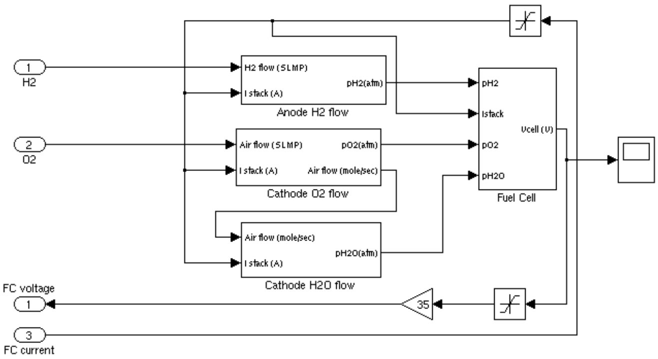

Fig. 5. The developed model of a PEM FC stacks

The cell voltage (Vcell) can be determined in any conditions by using equation (1). When a cell operates with a load, no load voltage (E) decreases with the increment of the voltages defined as (Vact). It is the activation voltage. (Vohm) is the ohmic voltage, and (Vconc) is the concentrate voltage.

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \qquad (1)$$

The Nerst equation (2) gives the open circuit cell voltage (E). It is the function of the cell temperature (T) and the reactant partial pressures to obtain the characteristic curve of an FC.

$$E = E_0 - 0{,}85.10^{-3}\,(T - 298{,}15) + \frac{R.T}{2.F}\ln\left(\frac{P_{H2}.P_{O2}{}^{0.5}}{P_{H2O}.P^{0.5}}\right) \qquad (2)$$

E_0 is the reference voltage, R is the universal gas constant, and F is the Faraday constant. P_{H_2}, P_{O_2} and P_{H_2O} is the hydrogen, oxygen and steam pressures, and the P is the total pressure in the stack. The activation decrease can be analyzed by the Tafel equation.

$$E_{act} = -0{,}9514 + 0{,}00312T - 0{,}000187.T.[\ln(I)] + 7{,}4.10^{-5}.T.[\ln(C_{O_2})] \qquad (3)$$

The current density in equation (3) is defined as “I”. C_{O_2} is also oxygen concentration and it is determined as a function of the stack temperature in equation (4).

$$C_{O2} = \frac{P_{O2}}{5{,}08.10^{6}\exp(-498/T)} \quad \text{mol.cm}^{-3} \qquad (4)$$

The over activation voltage is indicated in equation (1) as a voltage drop, and Eact is negative in all of the arrays in equation (3). The equation (5) is used to avoid the adverse effect of this term

$$V_{act} = -\,E_{act} \quad V \qquad (5)$$

3.2. Solar Plant Model

The PV modules consist of solar cells, which are connected in series and parallel to each other. Figure 6 shows the PV modules in the proposed simulation model, and each branch of the module consists of many N_{pc} cells in parallel and number of N_{sc} cells in series. The number of series and parallel cells also appears in the catalogs of the commercial PV modules .

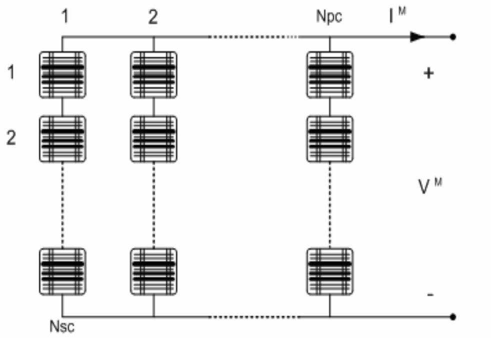

Fig. 6. The PV modules in the proposed simulation model

The total voltage of the series connected PV cells is determined by summing the each PV cell voltage that has the same current. Similarly, the total current of the parallel connected PV cells is determined by summing the each PV cell current which has the same voltage. In Equations (6) and (7); the module voltage is V_M , and the module current is I_M .

$$V_M = N_{sc}.V_{new} \qquad (6)$$

$$I_M = N_{pc}.I_{new} \qquad (7)$$

The output power of the module is a function of the solar irradiance and the ambient temperature. I_D is an internal current flow from the p-n junction that constitutes the semiconductor material of a PV cell. It depends on the absolute temperature of the diode and the function of the current flowing through the load and the voltage. The saturation current (I_0) is defined in (8) as a function of the temperature;

$$I_0 = I_{0ref}\left(\frac{Tc}{T_{cref}}\right)^3 .exp\left[\left(\frac{qE_g}{nk_b}\right)\left(\frac{1}{T_{cref}}-\frac{1}{T_c}\right)\right] \tag{8}$$

In equation (8);

I_{0ref}= The reference current,

E_g= The bandwidth of the PV cell material.

The photon current of the PV cell depending to the solar irradiance is explained in (9):

$$I_{ph} = [I_{sc} + \alpha(T_c - 25)]\frac{G}{G_{ref}} \tag{9}$$

In equation (9);

- G: Solar Irradiance (W/m^2),
- G_{ref} : Reference Solar Irradiance (W/m^2),
- Tc: The Effective PV Module Temperature (K),
- T_{cref} : The Reference PV Module Temperature (K),
- A: The short current temperature coefficient of PV module (mA/K).

There are several mathematical determination methods in the literature to obtain I-V characteristics of a PV module. Equations (10)-(12) define one of these methods. Vref and Iref are the reference values of the I-V characteristic curve. The open circuit voltage, the short circuit current, the voltage temperature coefficient (α) and the current temperature coefficient (β) are the fixed values obtained from the catalog of a PV module. The new current and voltage values are determined by the equations (10)-(12).

$$I_{new} = I_{ref} + \left[\alpha\left(\frac{G}{G_{ref}}\right)(T_c - T_{cref}) + \left(\frac{G}{G_{ref}} - 1\right)I_{sc}\right] \tag{10}$$

$$\Delta I = \left[\alpha\left(\frac{G}{G_{ref}}\right)(T_c - T_{cref}) + \left(\frac{G}{G_{ref}} - 1\right)I_{sc}\right] \tag{11}$$

$$V_{new} = -\beta(T_c - T_{cref}) - R_s\Delta I + V_{ref} \tag{12}$$

The constituted PV modules in the experimental study (DPS-160) are also modelled in Matlab/Simulink in the light of the data sheet of this module. Equations (10), (11) and (12) are used to obtain the PV module model.

The developed PV module model shown in Figure 7, have the temperature and the solar irradiance as inputs, and the current and the voltage as outputs. PV module is modelled as a subsystem, and the module generates 4.44 A and the 36 V at the conditions of 25 C° temperature and 1000 W/m^2 solar irradiance. That means 160 Wp power generated from the PV module, thus the results are compatible with the data sheet of the PV module. This is also the maximum power point of the PV module.

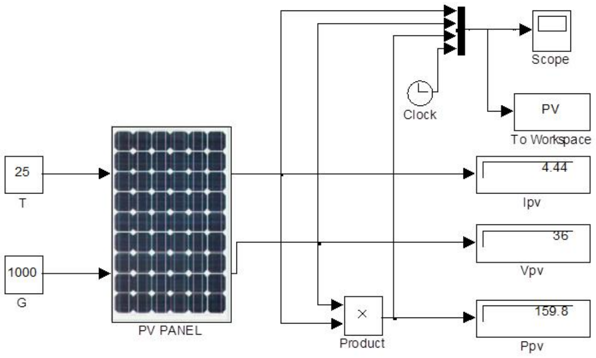

Fig. 7. The Simulink model of the DPS-160 PV Module

The developed PV module model includes a subsystem indicated in Figure 8. This subsystem determines the current and voltage according to the temperature and solar irradiance by using the related equations in Section 3.2.

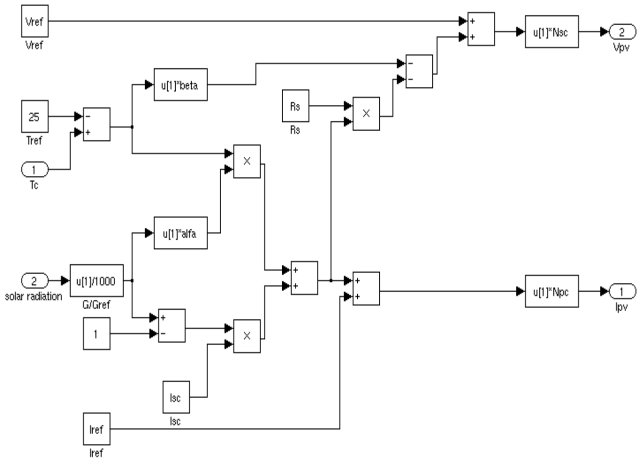

Fig. 8. The Simulink subsystem model of the PV Module

The developed model is simulated to obtain the I-V curves of the PV module. The PV module generates 4.44 A and the 36 V at the conditions of 25 C° temperature and 1000 W/m^2 solar irradiance. The Figure 9 shows the I-V curve of the PV module, and the short circuit current (4.98 A) and the open circuit voltage (43.3 V) can also be indicated in this figure. The developed model is also simulated in different solar irradiance values, and the simulation results are indicated in Figure 9.

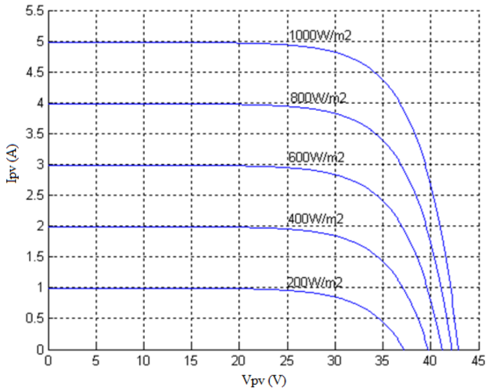

Fig. 9. I-V curves of the PV Module in different solar irradiance values

4. Obtained Results from the Matlab Model

In this section, the proposed model was simulated under different load conditions. Table 1 shows the operating conditions of the proposed hybrid system in the simulation.

Table 1. The operating conditions of the hybrid system

Operating Condition	**Load**	**Solar Irrad. (W/m^2)**	**Hydrogen (lt/s)**	**FC Stack Operation**	**PV Array Operation**
		Conv-1 support	**Conv.-2 support**		
Q1	25 W	-	+	Yes	No
Q2	40 W	+	-	No	Yes
Q3	75 W	+	+	1st source	2nd source
Q4	125 W	-	-	No	No
- : Insufficient energy source (lack of hydrogen or solar irradiation) + : Sufficient energy source (enough hydrogen or solar irradiation)					

4.1. The FC Stack Operation

The developed model was simulated under different load conditions. The FC stack is operated with a resistive load. Figure 10 and Figure 11 show the simulation results obtained from the proposed model when the load is resistive (25 W). The output voltage of the FC stack is indicated in Figure 10, and the load current in Figure 11. The obtained voltage is a smooth sinusoidal signal, and there is a small peak because of switching.

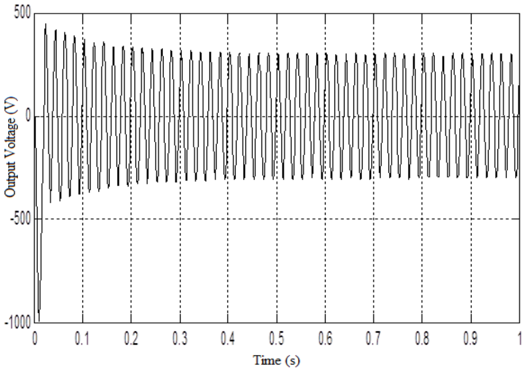

Fig. 10. Output voltage of FC stack

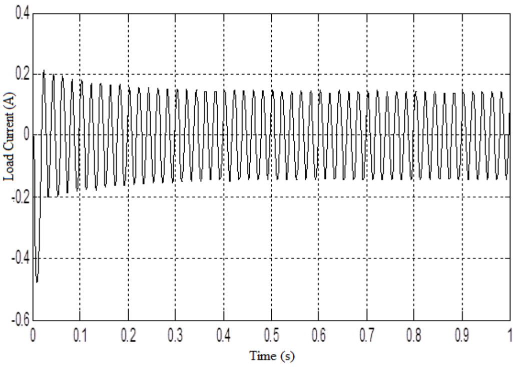

Fig. 11. The load current

4.2. The PV Array Operation

The developed model was also simulated with the single operation of the PV array. Figure 12 and Figure 13 shows the simulation results obtained from the proposed model when the load is resistive (40 W). The output voltage of the PV array is indicated in Figure 12 and the load current in Figure 13. There is a small fluctuation in the load current, but the current provides the stability in a short time.

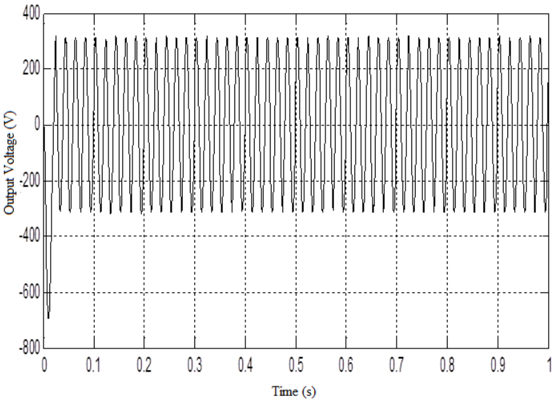

Fig. 12. Output voltage of PV array

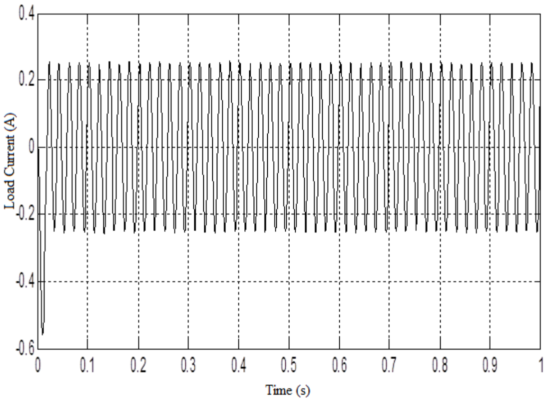

Fig. 13. The load current

6. Conclusions

This study focuses on developing a sustainable power management system for residential solar-hydrogen hybrid systems. In the study, the required energy demand of the hybrid power plant is simulated by using Matlab/Simulink. A solar-hydrogen hybrid power generation system was also performed in to check the proposed system. The proposed management system provides a sustainable energy infrastructure for the residential hybrid power plants. Besides, the current energy demand of the residential power plants can be viable in the lack of the sun or hydrogen, thanks to the developed hybrid power plant and the management system. The developed hybrid energy management system is proposed to meet the electrical energy demand of the customers in residential power plants, and it is also easy implemented and is suitable for residential real system applications.

7. References

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