23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 2025
ISBN-13: 978-84-09-66511-2

Development and simulation of an integrated power system based on solar technologies and PEM fuel cells using MATLAB/Simulink software

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Abstract. The study will examine the possibilities for integrating two different types of renewable energy sources based on technologies for converting solar energy into electricity based on photovoltaic panels and energy obtained from hydrogen through fuel cells. These two technologies provide a completely ecologically clean source that does not pollute the environment in any way and from an environmental protection perspective represents a completely environmentally harmless technology. On the other hand, the energy sources used (sunlight and water-hydrogen) represent renewable resources that are natural and their use does not cause any pollution. The principle of operation of the system in brief would be based on the conversion of sunlight into electricity and then the application of this energy in the electrolysis process to obtain hydrogen from water. The paper will propose a MATLAB/Simulink model of an integrated system with an analysis of key parameters, the system's energy balance, the efficiency of the solar subsystem, and the fuel cell subsystem.

Key words. solar cells, fuel cells, power generator, hydrogen, solar energy, conversion

1. Introduction

We are witnessing the need for energy sources that do not pollute the environment. Continuous industrial development requires humanity to search for various forms of energy and methods for their conversion into the most commonly used electrical energy. Electrical energy has emerged as the easiest to use, and many new technological innovations in modern society are based on the use of electronics and components that rely on electrical energy as their power source. Additionally, electrical energy is slowly but surely making its way into various areas of transportation through the use of electric drives instead of traditional ones based on internal combustion engines. One of the most commonly used energy sources today is solar radiation. By using photovoltaic panels, it is possible to convert solar energy into electrical energy. This energy can then be distributed to consumers or stored in batteries. Another interesting way to store this energy is by producing hydrogen, which is stored in specially designed tanks. Hydrogen can be produced through the electrolysis of water, a process that requires electrical energy, which can be generated using photovoltaic panels. Hydrogen can later be transported to desired destinations and used as an energy source by converting it back into electrical energy using fuel cells. During this process, heat energy is released, which can be used for heating residential or business spaces. The question arises as to why this subsequent conversion of electrical energy obtained from solar radiation into energy stored in hydrogen, which would then be converted back into electrical energy, would be necessary. There are several reasons for conducting this process. It is well known that during the summer months, the energy sent by the Sun to the Earth's surface is at its highest. The length of sunny days, the intensity of radiation, and other factors are favorable for generating electricity through photovoltaic panels. However, storing the energy obtained in this way requires large battery blocks, which are extremely expensive. Additionally, long-term storage of electrical energy in batteries leads to significant losses due to self-discharge, which considerably reduces the efficiency of the process. On the other hand, if the generated electrical energy were used for consumption, and the excess energy used for hydrogen production, it could be stored for the winter months and used to generate electricity and heat spaces. This would solve the problem of environmental pollution caused by the release of toxic gases into the atmosphere from the use of fossil fuels.

2. Related Works

In paper [1] the authors study investigates the prospect of using an integrated renewable power system to enhance an unreliable grid network for sustainable electricity generation. A grid coupled microgrid comprising photovoltaic and hydrogen fuel cell system, simulated for an information and communication technology (ICT). The simulation results generated using HOMER dynamic tool, having undergone optimisation and sensitivity analysis to determine the most effective risk-mitigation and eco-friendly strategy. The results obtained by the authors indicate that the optimal system size is architecture comprising 323 kW photovoltaic array, 75 kW power converter, 25 kW fuel cell system and 26 kW electrolyser with 20 kg H2 tank. In this paper [2], authors solar powered electricity, heating and hydrogen IES based on photovoltaic (PV), photothermal (PT) and photocatalysis of hydrogen production (PH) is proposed and investigated. The results of investigated show that the solar powered IES can completely meet the electricity, heating and hydrogen energy demands and achieve cost savings for consumers. Authors in [3], investigated valuable applications of fuel cells is their use in combination with renewable systems to respond to one of the main weaknesses of these systems, namely the inability to produce electricity continuously and meet on-peak electricity demand. Hydrogen is one of the most dependable ways to store energy, especially electricity, given the essential role that energy storage devices play in today's society. When it comes to long-term energy storage, Hydrogen is also less expensive than batteries. Authors in [4], design and optimization of the hybrid renewable energy system consisting of Photovoltaic (PV)/Electrolyzer/Proton Exchange Membrane Fuel Cell (PEMFC) was investigated to provide electricity and heat for Greenhouse in Şanlıurfa (Turkey). PEMFC based hybrid system has 48% electrical and 45% thermal efficiencies. According to optimization results obtained for the proposed hybrid system, the levelized cost of energy was found 0.117 $/kWh. The obtained results show the proposed PV/Electrolyzer/PEMFC hybrid power system provides an applicable option for powering stand-alone application in a self-sustainable expedient.

3. Methods

For the implementation of the system, low-power components were selected. As a solar source, a photovoltaic module with a power of 0.375W (output voltage of 5V, output current of 75mA) was chosen. Additionally, a system based on a PEM fuel cell was selected, which has a reversible function, operating both as an electrolyzer and as a converter of hydrogen energy into electrical and thermal energy.

Figure 1. presents the block diagram of the complete system.

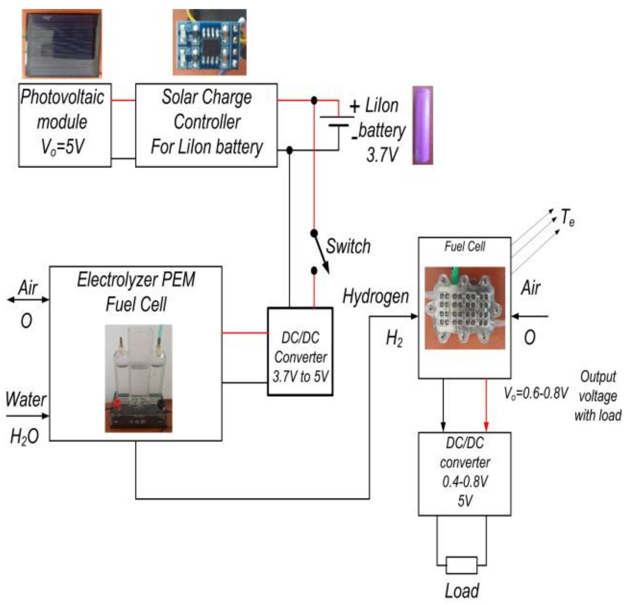

Fig.1.Block diagram of integrated subsystems based on solar and fuel cells

For the analysis of electrical properties of the fuel cell can be very useful knowledge of current voltage characteristics of fuel cells. It has already been mentioned above that the value of the output voltage is influenced by factors that are divided into three main groups [5]. The effect of each parameter is reflected in the voltage drops from the effects of activation polarization, ohmic, and at the end of concentration polarization. The model of the PV system and the PEM fuel cell will be developed based on well-known semiconductor electronic components.

Taking into account the impact of these factors for a mathematical model of voltage-current characteristics can be written [5]:

$$V = E_{oc} - i \cdot r - A\ln(i) + m \cdot e^{(n \cdot i)} \qquad (1)$$

where: E_{oc} real practical value of the open circuit voltage, and output power density fuel cell, *r* the specific resistance of the surface of the fuel cell, *A* slope factor of the curve, *m* constant, *n* is a constant.

Based on equation (1), it is possible to model a PEM fuel cell using existing electronic components. Figure 2 shows the model of a PEM fuel cell utilizing basic electronic components [5,6].

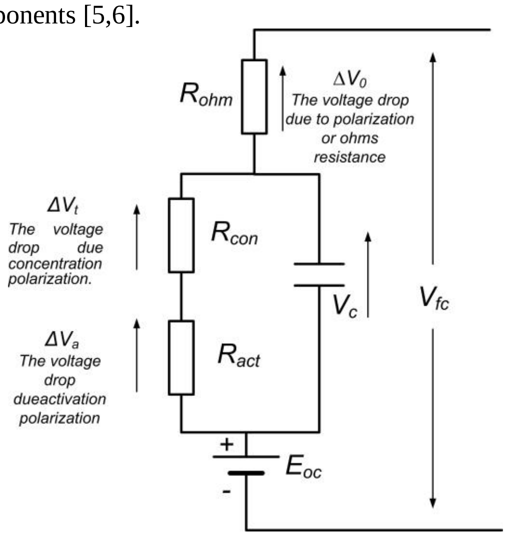

Fig.2. Equivalent electrical circuit model of PEMFC

The voltage drop at the exit of the fuel cell effect as previously mentioned three main groups of parameters. The first sharp decline caused by activation losses, ohmic and concentration and in the end. The default value of individual fuel cell voltage output is 0.6 V. By attaching more cells are obtained the necessary voltage levels [7].

The fuel cell can be modeled with simple electronic components. The resistor R_{ohm} models the ohmic losses. A change in current gives an immediate change in the voltage drop across this resistor. The resistor R_{act} models the activation overvoltage and the capacitor 'smoothes' any voltage drop across this resistor.

Generally speaking, the effect of this capacitance resulting from the charge double layer gives the fuel cell a 'good' dynamic performance in that the voltage moves gently and smoothly to a new value in response to a change in current demand [6,7,8].

Based on equation (1) and equation (2), a model of the PEM fuel cell has been developed in the MATLAB/Simulink software package, fig.3. [8].

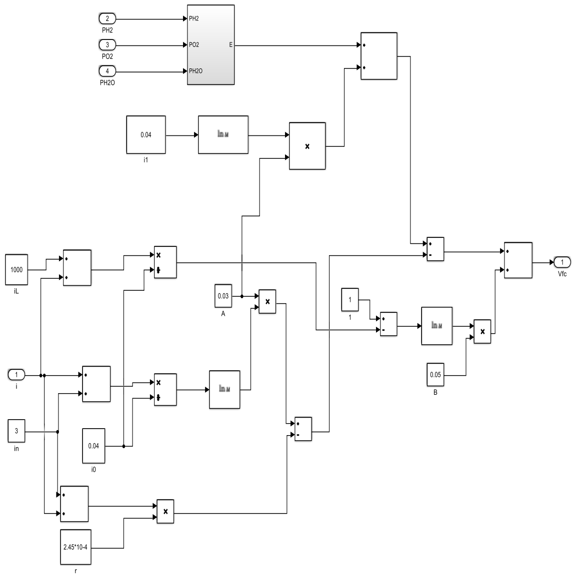

Fig.3. MATLAB/Simulink model of PEMFC

For the purpose of modeling photovoltaic systems under different environmental conditions, where ambient temperature and radiation intensity vary, a solar cell model—and consequently, a photovoltaic module model that does not account for temperature and radiation intensity is not sufficiently accurate [9,10]. Such models are based on data provided by manufacturers under standard test conditions, which often differ from the variable conditions in which the system operates [9].

The shortcomings of such a model can be addressed by using a "behavioral" model of the photovoltaic module, which takes into account the effects of temperature and radiation intensity on the voltage and current of the photovoltaic module.

This modeling approach utilizes the N_{OCT} (Nominal Operating Cell Temperature) concept, which considers conditions where the radiation intensity is 800 W/m², ambient temperature is T = 20°C, and wind speed is 1 m/s. When transitioning from one set of conditions to another, the following expression is used:

$$T_c - T_a = \frac{N_{OCT} - 20}{800} \cdot G \qquad (2)$$

where: G is the radiation intensity given in W/m², T_a is the ambient temperature, T_C is the solar cell temperature. All temperatures are given in °C.

The N_{OCT} value depends on the type of module. Testing a large number of modules has led to the following N_{OCT} value:

$$T_c - T_a = 0{,}035 \cdot G \qquad (3)$$

It corresponds to the N_{OCT} value of 48°C.

The short-circuit current of the module, depending on the radiation intensity and temperature, is given by the following equation [11]:

$$I_{scM} = \frac{I_{scMr}}{1000} \cdot G + \left(\frac{dI_{scM}}{dT} \right) \cdot \left(T_c - T_r \right) \qquad (4)$$

where: I_{SCM} is short circuit photovoltaic modules, the G intensity of incident radiation on the surface of photovoltaic modules, I_{scMr} short circuit at the reference temperature, T_r reference temperature, T_c temperature of solar cells and modules.

The open-circuit voltage is given by the approximate equation [11]:

$$V_{ocM} \approx V_{ocMr} + \left(\frac{\partial V_{ocM}}{\partial T} \right)_G \cdot \left(T_c - T_r \right) + V_T \cdot \ln \frac{I_{scM}}{I_{scMr}} \qquad (5)$$

where: V_{ocM} is circuit voltage photovoltaic modules, V_{ocMr} circuit voltage of photovoltaic modules at the reference temperature, T_r reference temperature (27^0C), T_c temperature of photovoltaic modules, V_T temperature potentials.

Figure 4 shows the MATLAB/Simulink model of the photovoltaic module used in the experiment.

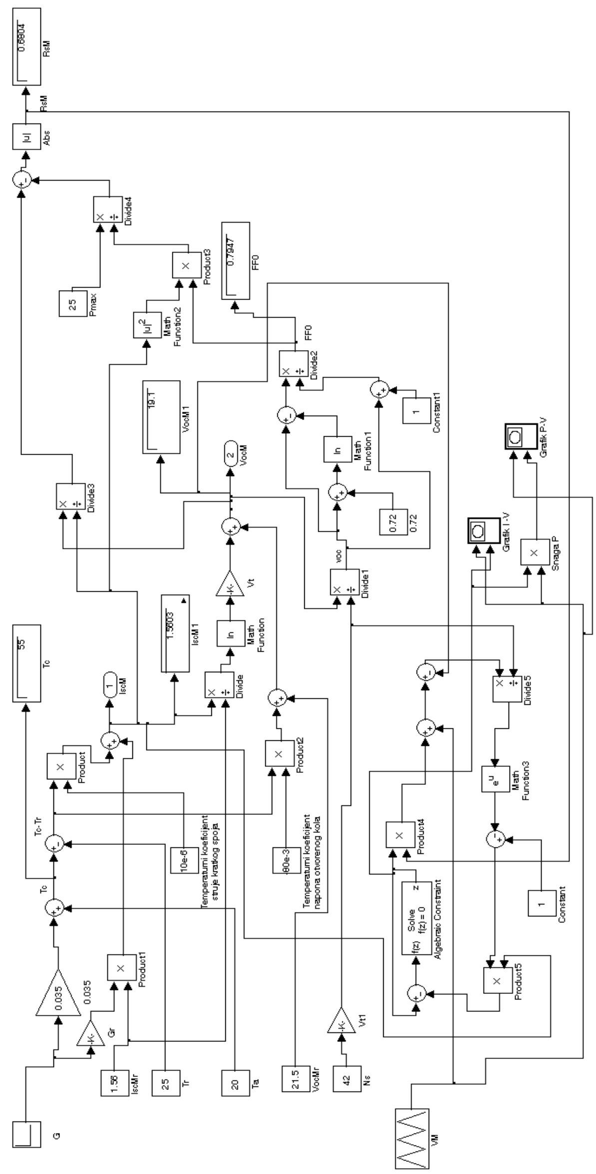

Fig.4. MATLAB/Simulink model of photovoltaic module

Figures 3. and 4. show the MATLAB/Simulink models of the utilized photovoltaic module and PEM fuel cell. The DC-DC converter model is taken from the literature as a standard DC-DC converter with voltage boost at the output. The utilized photovoltaic module model takes into account temperature variations and their impact on the conversion efficiency factor.

4. Results and Discussion

For the experimental research, a small hybrid PV/PEMFC system was utilized. The system consists of a photovoltaic module with a solar charge controller for a Li-Ion battery, a water electrolysis system for separating air and hydrogen molecules, and a PEMFC system for converting hydrogen into electrical energy. The system is equipped with two measuring devices for voltage and current measurement, as well as a small DC motor as a low-power load. Figure 5. shows the complete integrated PV/PEMFC hybrid system used for experimental research.

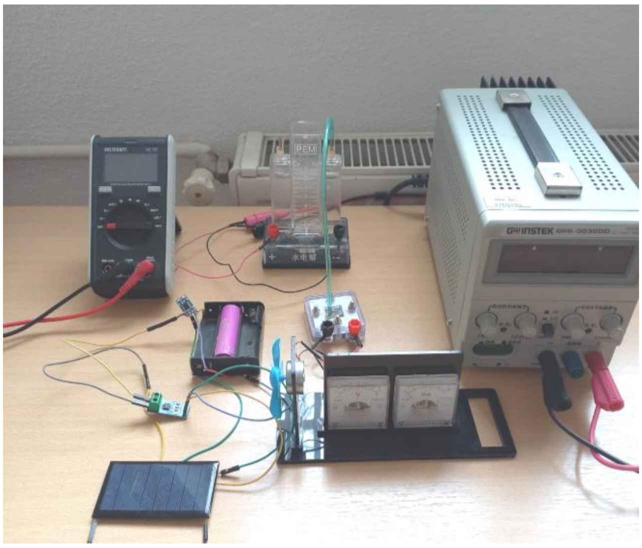

Fig.5. Integrated PV/PEMFC power system

A DC motor with a power of P = 1 mW was used as the load in the experiment. For powering the electrolyzer, a single Li-Ion battery was used, connected to the water electrolysis device via a DC/DC (3.7V-5V) converter. The power of the electrolyzer is 1.2 W. The hydrogen storage capacity is V = 2.5 cm³. The calculation of the energy contained in the volume V = 2.5 cm³ of hydrogen is given by the following equation (for the Lower Heating Value L_{HV}=119.96MJ/kg):

$$E_{H2} = V \cdot \rho \cdot L_{HV} \qquad (6)$$

where: E-energy in MJ/kg, ρ - hydrogen density in g/cm³ (at 22^{0}C and 1bar, ρ = 0.00008375 g/cm^3)
L_{HV}-Lower Heating Value L_{HV} = 119.96MJ/kg, V- volume in cm^3, V = 2.5cm^3.

The obtained energy of hydrogen in joules, from the given volume is $E_{H2}[J]$ = 25.12 J. Using equation (7), it is possible to convert the obtained energy from joules to Wh.

$$E_{H2}[Wh] = \frac{E_{H2}[J]}{3600} = \frac{25.12J}{3600} = 0.00698Wh \qquad (7)$$

To produce 2.5 cm³ of hydrogen, the electrolyzer operated for 60 seconds, consuming 19.2 mWh of electrical energy. The electrolyzer's supply voltage comes from the output of the DC/DC converter and is 5V, while the current consumption is 0.24A. Using equation (8), the efficiency of the electrolyzer is obtained.

$$\eta = \frac{E_{H2}[mWh]}{E_{input}[mWh]} \cdot 100\% = \frac{6.98}{19.2} = 36.3\% \qquad (8)$$

where: E_{H2} is energy obtained from the produced hydrogen in mWh, E_{input} energy obtained from the power source (Li-Ion battery).

Professional water electrolysis devices based on PEM technology typically have an efficiency of 60-80%. It is evident that the used electrolyzer has a lower efficiency (36.3%) since it is an educational kit for students and not intended for professional use. The efficiency of the fuel cell is calculated using the formula:

$$\eta = \frac{E_{electric}}{E_{chemical}} = \frac{2.78Wh}{6.98Wh} \cdot 100\% = 39.8\% \qquad (9)$$

where: $E_{electric}$ produced electrical energy, $E_{chemical}$ input chemical energy.
Typical efficiency values for fuel cells based on PEM technology range from 40% to 60%. From the obtained result, it is evident that the used fuel cell falls within this range of results. The efficiency of a small DC electric motor with a power of 1mW is 37%. The estimated efficiency of the used PV system ranges between 12% and 15%.
The energy produced by the PV system on a monthly basis is shown in Figure 6.

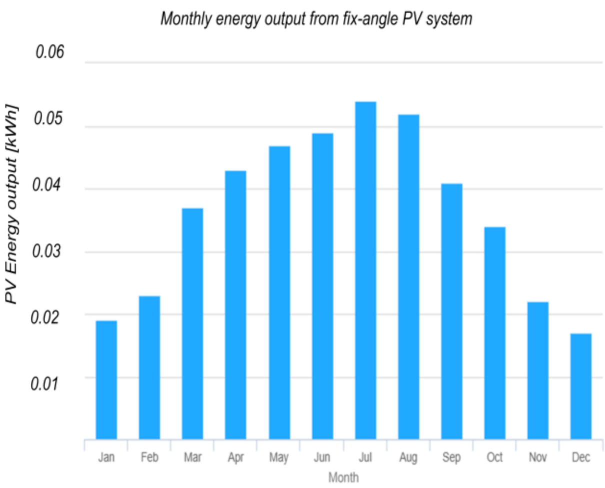

Fig.6. Monthly energy output from PV system

Figure 6. shows the total electricity production for the PV system, which is a part of the hybrid PV/PEMFC system. The following diagram.
Figure 7, shows an off-grid PV system with a battery capacity of 2Wh and a battery depth of discharge of up to 20%. The battery will be fully charged 31% of the days. The energy consumption by the electrolyzer would be

1.2Wh/daily, and the expected operating time of the electrolyzer is 1 hour per day.

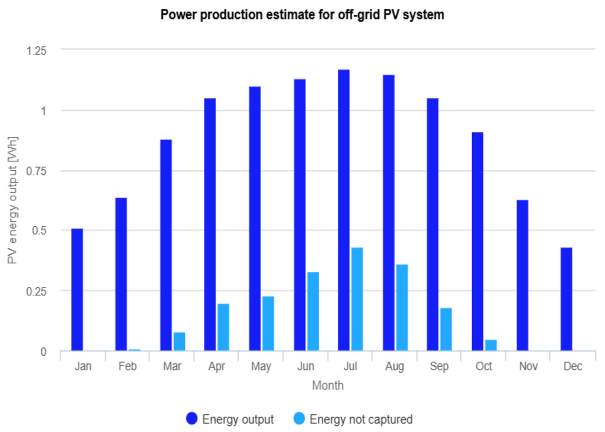

Fig.7. Off-grid PV system output production

Table I shows the energy produced by the PV system, as well as the portion of energy that was not used for charging the battery. The third column indicates the additional operating time that can be added to the electrolyzer's runtime in order to utilize the excess generated energy.

Table I.- Extended operating time of electrolyzer

MOUNTH	ENERGY OUTPUT [Wh]	ENERGY NOT CAPTURED [Wh]	EXTENDED OPERATING TIME OF ELECTROLYZER [min]
Jan	0.51	0	0
Feb	0.64	0.01	0.49
Mar	0.88	0.08	3.6
Apr	1.05	0.2	9.6
May	1.1	0.23	11.49
Jun	1.13	0.33	16.5
Jul	1.17	0.43	21.5
Avg	1.15	0.36	18
Sep	1.05	0.18	9
Oct	0.91	0.05	2.49
Nov	0.63	0	0
Dec	0.43	0	0

It is evident from Table I that the operation of the electrolyzer will be extended in the months when the PV system production exceeds consumption, specifically from February to November, in a range from 0.49 to 21.5 minutes.

5. Conclusion

Based on the proposed model, it is possible to design systems of different power levels. The test model demonstrates the potential for implementing a hybrid PV/PEMFC system that would serve as an autonomous converter of solar and water energy into electrical energy. The paper presents the results of research conducted on a small integrated PV/PEMFC hybrid system composed of semi-professional components. The obtained results indicate that the efficiency of individual subsystems is in accordance with data found in the literature. Based on the energy generated by the PV subsystem, which powers the electrolyzer, the operating time of the electrolyzer was calculated for optimal utilization of the energy produced by the PV subsystem. It should clearly indicate the advantages, limitations, and possible applications.

Acknowledgement

We would like to express our special gratitude to the Ministry of Scientific and Technological Development and Higher Education of the Republic of Srpska, Bosnia and Herzegovina, for supporting the implementation of the project titled "Development of an Autonomous Integrated Power Supply System Based on Solar Technologies and Hydrogen Fuel Cell Systems."

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