

Dynamic Analysis of Photovoltaic-Fuel Cell-Electrolyzer System at Stand Alone Operation

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Abstract—The Introduced Hybrid System (HS) consists of Solar Photovoltaic (PV) system, the Fuel Cell (FC) System. The HS is used to supply the required electricity to a Single Phase load with the help of Pulse Width Modulation Voltage Source Inverter (PWM-VSI). In this paper, the PV supply some loads while it's power are available (as irrigation load) and provide the FC system with the required power to be used when it is needed to fed another loads (important load). The FC system generates the hydrogen, H_2 , from Electrolyzer which takes PV energy and water as input elements. The generated H_2 is stored in a tank which provides the FC stack by the required hydrogen level. The output voltage from the FC stack then boosted and converted to AC voltage suitable for the loads using a PWM-VSI. The complete modeling of the individual components is simulated in MATLAB/Simulink environment and also the results obtained are found to be satisfactory.

Index Terms— Photovoltaic; Fuel cell; Electrolyzer; Dynamic modeling.

I. INTRODUCTION

The photovoltaic (PV) energy has been widely used in low power applications among the renewable energy sources. PV generator converts solar radiation directly into electrical power. PV generators have many advantages such as being pollution free, silent, long life time etc. From an operational point of view, a PV power generation has large variations in its output power due to the variations at weather conditions [1, 2]. This fluctuating nature of solar radiation means that purely PV power generators for off grid applications must be large and also expensive. One method to overcome this problem is to integrate the PV plant with other power sources such as Fuel cell (FC), or battery backup. The FC beak-up power supply is a very attractive option to be used with an intermittent power generation source like PV power due to many attractive features of FC such as efficiency, fast load response [3, 4]. Therefore, the FC power system has a great potential for being coordinated with the PV generator as a Hybrid System (HS) to smooth out the PV power's fluctuations.

A HS consisting of combination of PV-wind-diesel is used in [5, 6]. But due to increasing cost of diesel and use of the diesel environmental pollution is created that makes the operation of diesel engine prohibited.

Other types of Hybrid Systems (HSs) consisting of a wind-hydro are connected to the grid where the power converters are used to improve the reliability of the power system [7, 8].

A HS also called as standalone system supplies electricity to the load without being connected to the centralized power stations, or electric grid. HSs have applications in remote and some inaccessible areas where there are no electricity sources available. In remote and rural areas, the grid connection is not technical feasible and also a cost effective option. Therefore, HSs are well suited for such areas. The purpose of this paper is to model and simulate the different components of a Photovoltaic Fuel Cell (PVFC) HS which may fulfill the electric demands for remote and rural areas. Therefore, PV generator and FC are connected to the load to fulfill the electrical requirements to these areas. This HS consists of a PV generator and a Proton Exchange Membrane Fuel Cell (PEMFC) coupled together to form a system which is connected to the load. The system design and performance analysis were achieved through a computer software programs. Modeling and simulations for the presented system are performed using MATLAB/Simulink package and results are presented to verify the effectiveness of that system.

II. MODELING HS

A. A Dynamic Model of PV Generator

PV arrays are built up with combined series/parallel combinations of PV solar cells, which allow extracting the characteristic parameters of the one-diode equivalent model for a single solar cell. As shown in Fig. 1, the equivalent circuit of the general model is composed of photo current source, diode, and parallel resistor expressing the leakage current, and series resistor describing the internal resistance to the current flow.

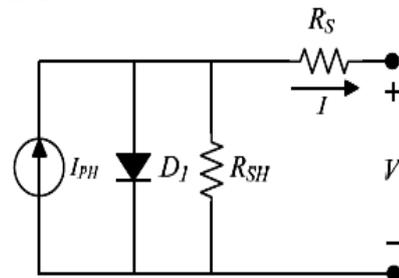


Fig. 1. The equivalent circuit of a PV cell.

The I - V characteristic equation of a PV cell is given as, [9]:

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$$I = I_{PH} - I_s \left(\exp \left[\frac{q(V + IR_s)}{kTA} \right] - 1 \right) - \frac{(V + IR_s)}{R_{SH}} \quad (1)$$

Where, I_{PH} is a light-generated current or photocurrent,
 I_s is the cell saturation of dark current,
 q ($= 1.6 \times 10^{-19}$ C) is the electron charge,
 k ($= 1.38 \times 10^{-23}$ J/K) is Boltzmann constant,
 T is the cell working temperature,
 A is the ideal factor,
 R_{SH} is the shunt resistance, and
 R_s is the series resistance.

For an ideal PV cell (no series loss and no leakage to ground, i.e., $R_s = 0$ and $R_{SH} = \infty$, respectively). The equivalent circuit of PV cell can be further simplified [10, 11], where Eq. (1) can be rewritten as:

$$I = I_{PH} - I_s \left(\exp \left[\frac{qV}{kTA} \right] - 1 \right) \quad (2)$$

The equivalent circuit for a PV module arranged in N_p parallel and N_s series cells. The terminal equation for the current and voltage of the simplified model of a generalized PV array is described as:

$$I = N_p I_{PH} - N_p I_s \left(\exp \left[\frac{qV}{N_s kTA} \right] - 1 \right) \quad (3)$$

Using the data given at appendix, the voltage-current (V - I) characteristics of the PV module are simulated at different irradiance and constant temperatures (25°C). Figure 2 shows the V - I curves of the simulated module at different irradiance levels. While, Fig. 3 shows the V - I curves of the module at different cell temperatures. It is seen that at constant cell temperature, increasing the irradiance will increase the short circuit current largely and the open circuit voltage increase slightly. The influence of temperature on the V - I characteristics can also be observed where it is shown that at fixed irradiance level, increasing temperature will decrease the open circuit voltage widely and slightly increases the short circuit current.

B. A Dynamic Model of PEMFC

The PEMFC is an electro-chemical device which convert the chemical energy contained in a reaction between a fuel, the hydrogen, and an oxidizer, the oxygen into electric energy.

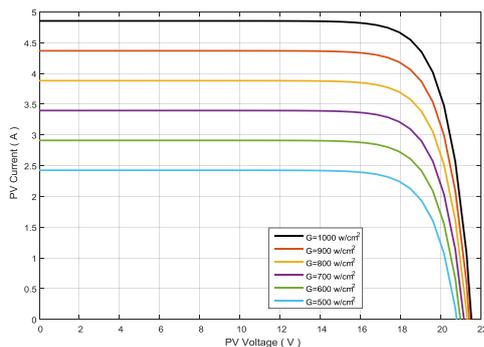


Fig. 2. V-I characteristic curves of the PV module at different irradiances.

A bias voltage is applied across the electrochemical cell in order to induce electrochemical reactions at both electrodes (Cathode and Anode). Water is introduced at the anode and dissociated into oxygen, protons, and electrons. The protons are driven by an electric field through the PEM to the cathode where they combine with the electrons arriving through the external circuit to form hydrogen gas.

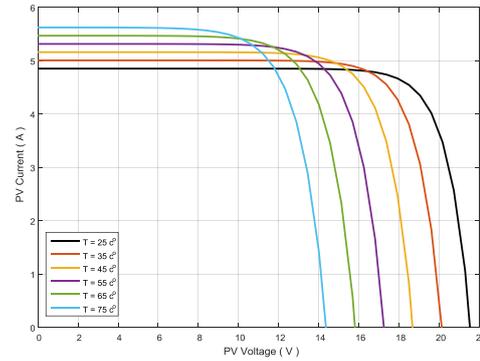


Fig. 3. V-I characteristic curves of the PV module at different temperatures.

The assessment of these two half reactions produces water, heat, and electricity as Figure 4 shows, [12].

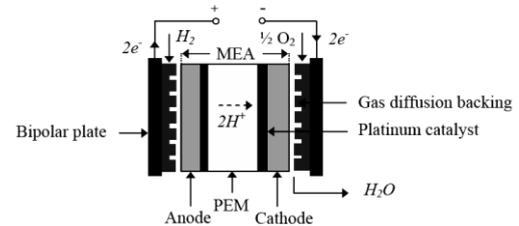


Fig. 4. Basic description of a PEMFC operation.

C. Theoretical Cell Voltage

The theoretical voltage of PEM fuel cell is, [13]:

$$E = 1.2297 + \frac{\Delta S_0}{n \cdot F} (T - T_r) + \frac{R \cdot T}{n \cdot F} \ln \left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_0} \right) \quad (4)$$

Where: T : is the operating temperature

ΔS_0 : is the change of entropy at STP equal to: -0, 1634 kJ/(K mol)

n : are the number per electrons per mole. i.e. $n=2$

F : is Faraday's Constant and is equal to 96485,309 C/mol

R : is the Universal Gas Constant and equals to 8.31451 J/(K mol)

P_{H_2} : is the Hydrogen supply pressure

P_{O_2} : is the Oxygen supply pressure. If air is used 100 kPa pressure may be assumed

P_0 : is the reference pressure that is 100 kPa

This is called Nernst equation. This value is the maximum voltage that the cell can give, because there are losses or over potentials, which can be divided into four types:

Activation losses; and it is given by a semi empirical equation:

$$E_{act} = -[\xi_1 + \xi_2 * T + \xi_3 * T * \ln(C_{O_2}) + \xi_4 * T * \ln(i_{FC})] \quad (5)$$

Ohmic losses; this loss represents the resistance of the membrane this loss is given by:

$$E_{ohm} = i_{FC} * (R_m + R_C) \quad (6)$$

Concentration losses; it is also called mass transportation loss, which represents the limit of reactants mass transfer. This loss is given by:

$$E_{conc} = -B * \ln(1 - \frac{i}{i_L}) \quad (7)$$

The cross over loss; this loss comes from crossing hydrogen and electrons over the membrane. Now, we can obtain the equation that defines the fuel cell voltage as:

$$V_{FC} = E + E_{act} + E_{ohm} + E_{conc} \quad (8)$$

The voltage-current density (V-I) characteristic of the FC module is simulated and the result is indicated at Figure 5. It is seen that increasing the current density for the fuel cell will decrease the actual output voltage of the fuel cell and the theoretical voltage of the fuel cell is approximately constant [5, 6, 13-15].

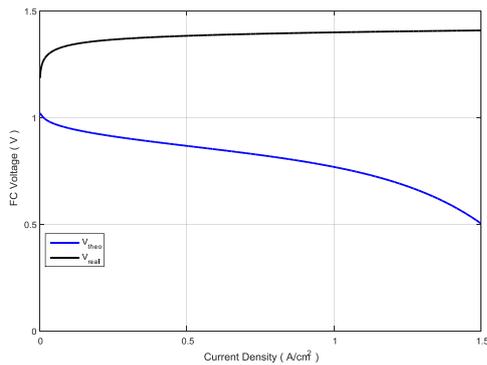


Fig. 5. Characteristic curve of the FC module for the theoretical and actual voltage.

D. Modeling of Electrolyzer

The water is decomposed into hydrogen (H₂) and oxygen through the Electrolyzer by using the extra power from PV. According to Faraday's law, there is direct relation between hydrogen production through the electrolyzer and electrical current given below [16-19].

$$n_{H2} = \frac{\eta_F \eta_C I_e}{2F} \quad (9)$$

- Where: I_e : Current of an electrolyzer, [A]
- n_c : No. of series connected electrolyzer cells
- n_{H2} : Amount of hydrogen generated in moles per second, [mol s-1]
- F : Faraday constant, [C kmol-1]
- η_F : Faraday efficiency

Faraday efficiency is given in terms of hydrogen generation and its theoretical value which is shown as;

$$\eta_F = \frac{(I_e/A)^2}{k_{f1} + (I_e/A)^2 k_{f2}} \quad (10)$$

A complete Simulink model for the Electrolyzer is shown at Figure 6.

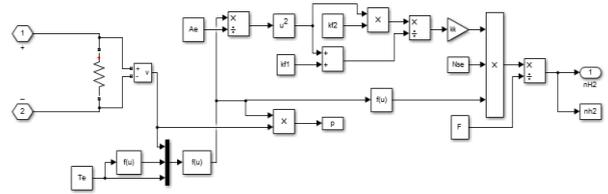


Fig. 6. A brief model of electrolyzer model using Simulink.

E. A Hydrogen Storage System

Storage tank is used to store the H₂, which is generated from the Electrolyzer. Further this H₂ is used as a Fuel of the PEMFC. The remaining amount of hydrogen is stay at the storage tank. The dynamic of the storage is obtained as follows [18, 20]:

$$(P_b - P_{bi}) = Z \frac{N_{H2} \cdot R \cdot T_b}{M_{H2} \cdot V_b} \quad (11)$$

- Where: Z: Pressure compressibility factor
- N_{H2} : Amount of hydrogen stored in the storage tank in moles per second, [kmol s-1]
- M_{H2} : Hydrogen molar mass, [kg kmol-1]
- T_b : operating temperature, [oK]
- P_{bi} : Storage tank pressure at initial stage, [Pa]
- P_b : Storage tank pressure, [Pa]
- R: Rydberg/Universal gas constant, [J (kmol oK)-1]
- V_b : Storage tank volume, [m³]

All auxiliary power requirements such as pumps; valves were ignored in the dynamic model. The Simulink version of the hydrogen storage model is depicted in Figure 7.

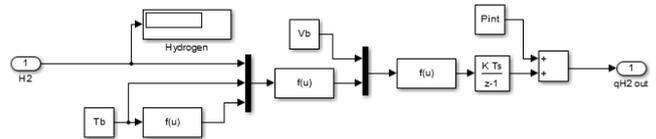


Fig. 7. A brief model of hydrogen storage model using Simulink.

F. The DC/DC Buck Converter

The buck converter is a step-down DC-DC voltage converter. The average output voltage is always less than or equals to the input voltage. The purpose of buck converter is used with Maximum Power Point Tracking (MPPT) technique to get the maximum power from the PV and regulate DC power supplies from the PV to provide the electrolyzer with the required DC power. The relation between the input and output voltage given by the following equation, [13]:

$$\frac{V_o}{V_{in}} = D \quad (12)$$

Where, V_o and V_{in} are output and input voltages, respectively. In this work, the PV output is designed to be 72 V and about 20 A. Since the electrolyzer load is designed for 72 V and 20 A, it becomes necessary to select a buck converter in order to regulate the voltage and current. The

buck converter model is generated in MATLAB/Simulink in order to control the output and input between the PV and electrolyzer as shown in Fig. 8.

G. Boost DC/DC Converter

Boost DC/DC Converter is a step-up converter which steps up voltage (while stepping down current) from its input (supply) to its output (load) according to the conversion equation below. Figure 9 indicate the MATLAB/Simulink model for that Boost DC/DC Converter with a PID controller and a Pulse Generator to regulate the Boost Converter output voltage, [9].

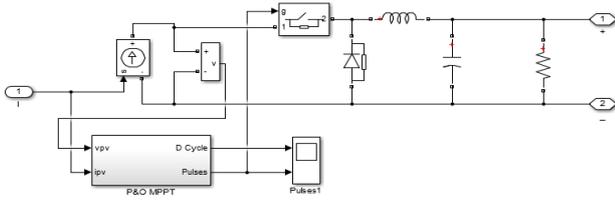


Fig. 8. Buck DC/DC Converter

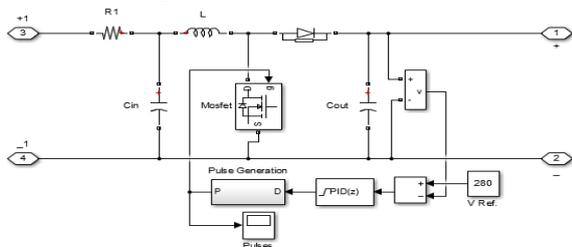


Fig. 9. Boost DC/DC Converter

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{13}$$

H. Modelling of the Inverter

This is a simple topology with a MOSFET H-bridge inverter and a linear transformer which is simple to be implemented and completely isolated. The inverter converts the DC input to AC output with RMS value and Frequency suitable for the connected loads. Figure 10 indicate the MATLAB/Simulink model for the single phase PWM H-bridge VSI with linear transformer, [16].

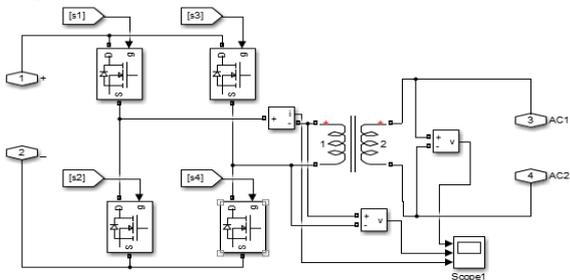


Fig. 10. Single Phase PWM Inverter

III. COMPLETE SYSTEM MODEL

The simulation is done in MATLAB/Simulink environment by creating each component separately then combines them together. Each system block has been implemented and studied to ensure that each one is

sufficiently precise to run the simulation and to give adequate results. The module for PV solar panels, Buck DC/DC converter, electrolyzer, Hydrogen tank, Fuel Cell Stack, Boost DC/DC Converter and the single phase inverter have been created and well matched with each other. The simulation is valid to model different cases. Fig. 11 shows the Simulink model for the whole renewable energy system. The PV Array used to supply its loads through a Boost DC/DC converter and a single phase H-bridge Inverter. Also the PV system provide the FC system with its requirements from the power through the Electrolyser which generate the required Hydrogen which is used as input for the FC Stack to generate its output terminal voltage to fed another loads connected to its terminals.

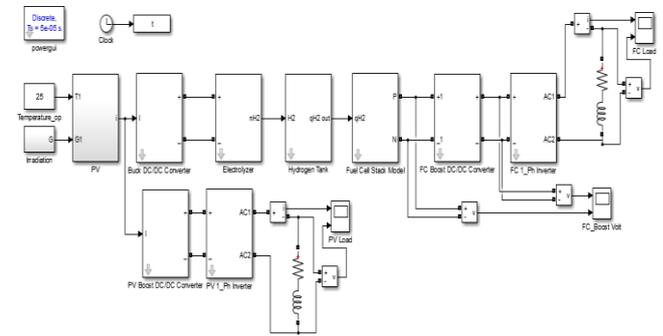


Fig. 11. Simulink model for the whole renewable energy system.

IV. RESULTS AND DISCUSSION

In this work, the maximum voltage from the PV is designed to be 72 V and the current is reaching 20 A, however the maximum power of the PV panel is varying due to the weather a perturb and observe (P&Q) for MPPT algorithm is used to get the maximum power from the PV panels. Figure 12 is shown the output voltage of buck converter supply from PV. The maximum voltage and current from the PV panel were obtained and the electrolyzer was able to generate hydrogen with maximum output. The generated Hydrogen is stored at storage tank (as shown in Fig. 13) which is connected to the FC Stack. The FC Stack when fed with the required Hydrogen level it produces its Actual output voltage which depends on the value of the Hydrogen pressure and its current density.

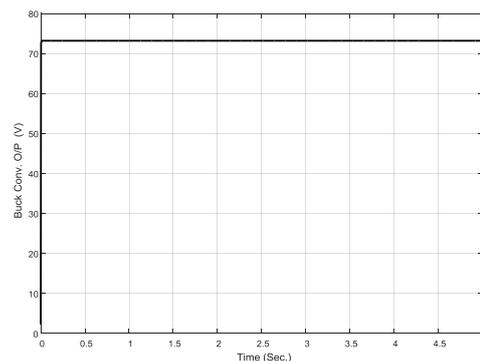


Fig. 12. Output voltage of buck converter

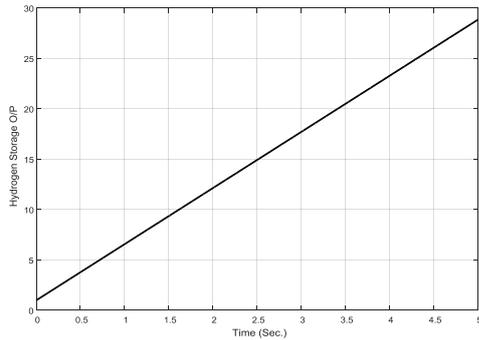


Fig. 13. Hydrogen in storage tank

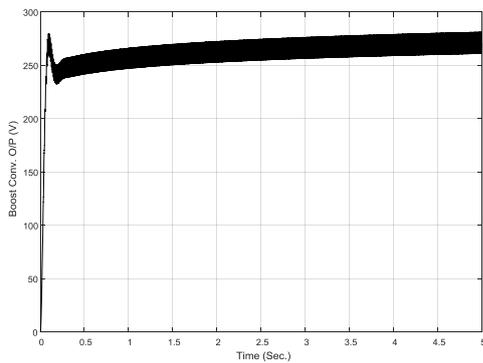


Fig. 14. Output voltage of boost converter.

The output voltage from the FC input to a boost DC/DC converter to step-up (as shows in Fig. 14), its voltage to a stabilized level suitable for the inverter input terminals. Figure 15 shows the output voltage of output voltage of FC inverter. At irrigation load, the output voltage of single inverter shows in fig. 16.

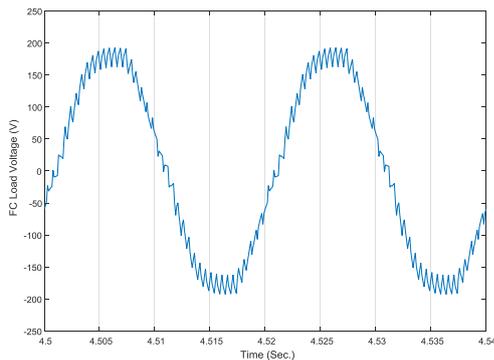


Fig. 15. Output voltage of FC inverter.

V. CONCLUSION

In this work, the renewable energy system has been developed. The PV solar panels were examined in order to supply a certain loads as long as it is available and to supply the FC System with its required power to generate the required Hydrogen value for its operation when it needed. The electrolyzer is used to consume some of the power that is generated from PV panels.

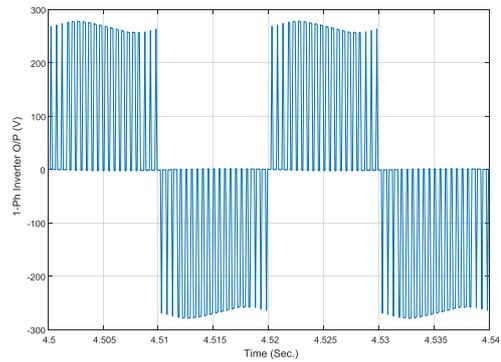


Fig. 16. Output voltage of single inverter.

The DC/DC buck converter with a MPPT algorithm is used along with the system to regulate and maintain the current values which are fed to the electrolyzer. MATLAB/Simulink provides the simulation environment helping to integrate such system. The simulation results for some models are shown which indicate the validity of the hall system.

APPENDIX

Table The PV Cell Parameters.

Parameter	Value	Parameter	Value
A	1.6	I _{SC}	4.75 A
T	298 K	V _{OC}	0.6 V
T _r	298 K	C	1 kW/m ²
R _s	15*10 ⁻³ Ω	R _{SH}	30 Ω

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