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A Control Methodology of Dynamic for Photovoltaic (PV)/Fuel Cell (FC) Hybrid Energy System for Standalone Usage

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***Abstract*—This paper contains the results of simulation of small photovoltaic (PV)–fuel cell hybrid energy system. Simulation consists of photovoltaic (PV) a proton exchange membrane fuel cell (PEMFC), hydrogen storage tanks and power converter. The output of the PV is highly dependent on weather conditions, so the load is supplied from the PV with a fuel cell working in parallel. Whenever the PV system cannot completely meet load demands, the FC system provides power to meet the remaining load. FC power plant uses hydrogen and oxygen to convert chemical energy into electrical energy. When excess energy produced by photovoltaic is available, electrical energy can be converted into hydrogen using an electrolyzer and store in Hydrogen storage for later use in fuel cells. PID controller is used to control fuel cell system. The model is applied in MATLAB / SIMULINK based on the mathematical and electrical models.**

***Index Terms*—Dynamic modelling, photovoltaic, fuel cell, standalone usage.**

I. INTRODUCTION

A permanent increase in energy demand, trends in new technologies and renewable power production such as permanent photovoltaic, wind and fuel cell has created. Since the electrical energy demand due to technological development and increasing population is increasing, fossil fuel energy sources is declining, and environmental concerns such as urban air pollution, global climate is increasing[1]. Recent advances in the application of hydrogen energy, hydrogen as an essential factor and many other have made. In future energy systems, renewable energy sources will be used to produce hydrogen from renewable sources, and it may be used in the topology of the fuel cell and hybrid needs to be used, because in the future hydrogen economy is very comprehensive. Therefore, other energy conversion systems such as photovoltaic cells and wind turbines with different systems can be connected to a network of independent fuel cell to reach operating. Use of photovoltaic systems for small applications such as pumping water for agricultural applications in remote locations has been much attention that doesn't have access to the network [2]. Electric power is produced by the photovoltaic, strongly depends on weather conditions. For example, when the sky is cloudy ability does not produce photovoltaic systems. In addition, photovoltaic energy stored for later use is a problem. To overcome this problem, photovoltaic systems can be used with other energy sources or storage systems such as electrolyzer, hydrogen storage tank fuel cell systems [3]. Fuel cell systems can produce hydrogen and oxygen to convert chemical energy to electrical energy they use. Due to low temperature and rapid commissioning, PEM fuel cell systems are a suitable option for commercial and residential applications in the future. PEM systems in this study to other types of fuel cell systems are preferred because these systems for use in hybrid energy systems are appropriate [4]. Block diagram of hybrid energy systems PV / FC are presented in Figure 1. In this study, the characteristic, dynamic modeling, simulation analysis system and the results will be presented in next sections. The suggested system consists of a PV, a PEMFC and a MPPT while extracting maximum power from PV, an electrolyzer, a power converter, a step load, controller. Fuel cell stack consisting of 45 individual fuel cells connected in series is present. Controller actions compensate the drop in the fuel cell stack voltage caused by the load current variations. If the PV generates more current than required by the load, then the excess current is diverted towards the electrolyzer. The hydrogen produced by the electrolyzer is stored in a tank for later use in the fuel cell stack.

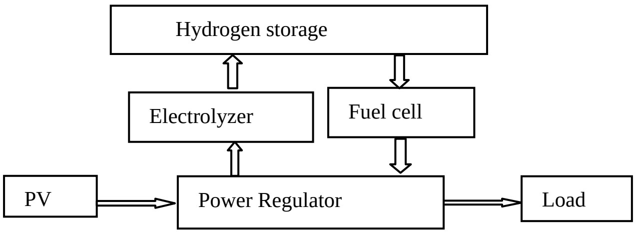

Fig. 1. Photo voltaic–fuel cell hybrid energy system

II. PV SYSTEM AND STEP LOAD

Parameters used in the mathematical modeling of the PV system are as follows:

a	Ideality or completion factor
I_0	PV cell reverse saturation current [A]
I_{PV}	PV cell output current [A]
I_{SC}	Short-circuit cell current level [A]
K	Boltzmann's constant [$J/^{\circ}C$]
N_P	The number of parallel strings
N_S	The number of series cells per string
q	Electron charge [C]
R_S	Series resistance of PV cell [Ω]
T	PV cell temperature [$^{\circ}C$]
V_{PV}	Terminal voltage for PV cell [V]

The output voltage characteristic of the PV system may be expressed as [4],

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$$V_{PV} = \frac{N_s akT}{q} \ln\left[\frac{I_{SC} - I_{PV} + N_P}{N_P I_0}\right] - \frac{N_S}{N_P} R_S I_{PV} \tag{1}$$

The maximum power output of the PV array varies according to solar radiation or load current. Therefore, a control system is needed to exploit the solar array more effectively as an electric power source by building a maximum power point tracker (MPPT) [5].

Maximum power has been given in Figure 2 using MPP to visualizing the dynamic response of system to load variations and input radiation. Also as it is shown in Figure 3, the load has been given by putting the breaker and switching.

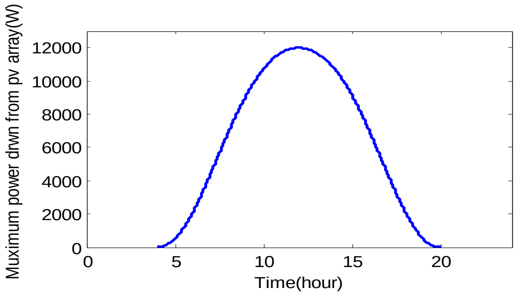

Fig. 2. Maximum cell power regarding input radiation differences

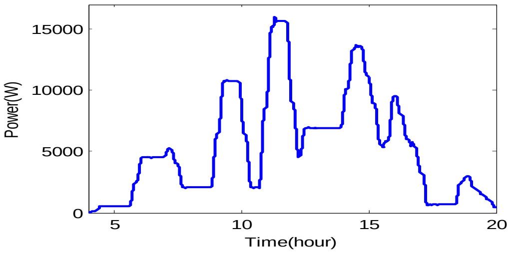

Fig. 3. Load variation state

Maximum current value and maximum voltage have been calculated regarding to input radiation which these magnitudes are shown in Figures 4 and 5. As it is evident in figure, by increasing the solar input radiation, maximum current of power will be increased.

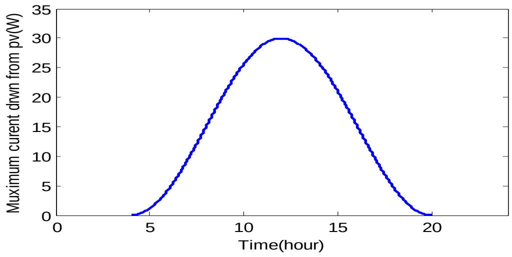

Fig. 4. Maximum cell current regarding to input radiation differences

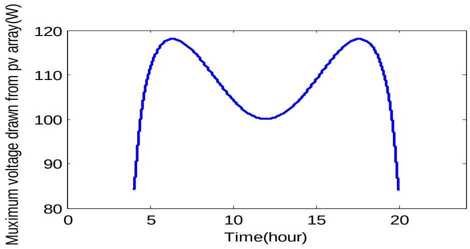

Fig. 5. Maximum cell voltage regarding to input radiation differences

III. FUEL CELL STACK MODEL

The FC is an electrochemical device that produces direct current electricity through the reaction of hydrogen and oxygen in the presence of an electrolyte. The several FC available for use in systems, the Proton Exchange Membrane FC (PEMFC) has drawn the most Application due to its simplicity, quick start up, higher power density, and operation at lower temperatures [6]. The ideal standard potential of a H_2/O_2 fuel cell (E_0) is 1.229 V with liquid water product. The actual cell potential is reduce from its reference potential because of irreversible losses. The thermodynamic potential E is defined via a Nernst equation in expanded form as [7].

$$\begin{aligned} E &= 1.229 - 0.85\times10^{-3}(T - 298.15) + \\ &4.3085\times10^{-5} \times T\left(\ln \mathrm{P}_{\mathrm{H}_2} + 0.5\ln \mathrm{P}_{\mathrm{O}_2}\right) \end{aligned} \tag{2}$$

where P is the effective pressure in atmospheres and T is the temperature in Kelvin. The concentration of dissolved oxygen at the gas/liquid interface can be clarify by a Henry's law expression of the form [8]

$$CO_2 = PO_2 / 5.08\times10^6 \times \exp(-498/T) \tag{3}$$

The parametric equation for the over voltage due to activation and internal resistance improve from the empirical analysis [8] is given as:

$$\begin{aligned} \eta_{act} &= -0.9514 + 0.00312T - 0.000187T \times \ln(i) + \\ &7.4\times10^{-5}T \times \ln(co_2) \end{aligned} \tag{4}$$

$$R_{in} = 0.01605 - 3.5\times10^{-5}T + 8\times10^{-5}i \tag{5}$$

where i is the fuel cell current and the activation resistance is determined as:

$$R_a = -\eta_{act} / i \tag{6}$$

The combined effect of thermodynamics, mass transport, kinetics, and ohmic resistance determines the output voltage of the cell as defined by [9].

$$V = E - v_{act} + \eta_{ohmic} \tag{7}$$

The model of steady state fuel cell describe above indicates that the current drawn, cell temperature, H2 pressure, and O2 pressure will affect the fuel cell output voltage.

The fuel cell system consists of a stack of 45 similar cells connected in series. Therefore, the total stack voltage is given by:

$$V_{stack} = 45V_{cell} \tag{8}$$

Fuel cell current and internal resistance can be used to calculate internal heat losses as internal heat generation:

$$\mathrm{i}^2(\mathrm{R}_\mathrm{a} + \mathrm{R}_{\mathrm{int}}) \times 45 \tag{9}$$

Regarding to Fig. 6 Which depicts the difference between power of solar cell and load power, the places of curves which are in negative sections are showing the point of entry of fuel cell in system. Fig. 7 show remain power should be prepared using fuel cell.

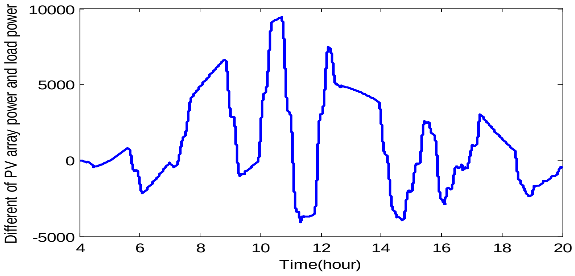

Fig. 6. Difference of PV power and load power

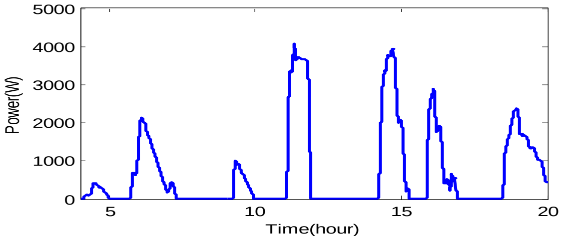

Fig. 7. Provided power by fuel cell

IV. ELECTROLYZER AND HYDROGEN STORAGE MODEL

Water can be decomposed into its elementary components by passing electric current between two electrodes separated by an aqueous electrolyte. The electrochemical reaction of water electrolysis is given by:

$$H_2O(l) + \text{electrical energy} \Rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{10}$$

A water electrolyzer consists of several electrolyzer cells connected in series. The current in comparison to voltage feature of an electrolyzer depend on its working temperature [10]. According to Faraday's law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn is equivalent to the electrical current in the circuit.

$$n_{H_2} = \frac{\eta_F . n_n . i_e}{2F} \left(mol/s \right) \tag{11}$$

where i_e is the electrolyzer current, n_c is the number of electrolyzer cells in series, and η_F is the Faraday efficiency. Faraday efficiency is the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyzer.

Assuming an electrolyzer working temperature of $40^{\circ}C$ [10], Faraday efficiency (in percent) can be given as:

$$\eta_F = 96.5 \times exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2} \right) \tag{12}$$

The difference between the produced and consumed hydrogen is sent to the storage tank. Hydrogen can be stored both of the compressed hydrogen gas or liquid hydrogen. In this study, the storage model described in Ref. [13] is used.

The parameters used in the hydrogen storage system are:

M_{H_2} Molar mass of hydrogen [$kg\ kmol^{-1}$]

N_{H_2} Hydrogen moles per second delivered to the storage tank [$kmol / s$]

P_b Pressure of tank [pascal]

P_{bi} Initial pressure of the storage tank [pascal]

R Universal (Rydberg) gas constant [$J / kmol\ K$]

T_b Operating temperature [K]

V_b Volume of the tank [m^3]

z Compressibility factor as a function of pressure

One of the hydrogen storage techniques is physical hydrogen storage, which include using tanks to store both of the liquid hydrogen or compressed hydrogen gas. The hydrogen storage model is based on Eq. (13) and it directly calculates the tank pressure using the ratio of hydrogen flow to the tank. The produced hydrogen is stored in the tank, whose system dynamics can be expressed as follows [12]

$$P_b - P_{bi} = z\frac{N_{H_2} R T_b}{M_{H_2} V_b} \tag{13}$$

Figures (8) and (9) show the amount of H2 consumption and production from electrolyzer and hydrogen tank respectively.

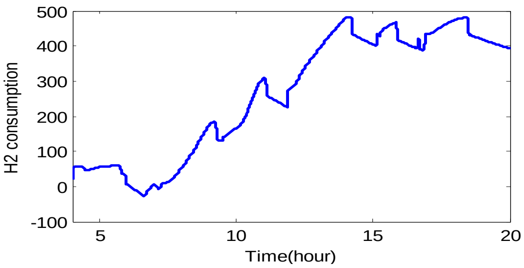

Fig. 8. The amount of H2 consumption from hydrogen tank

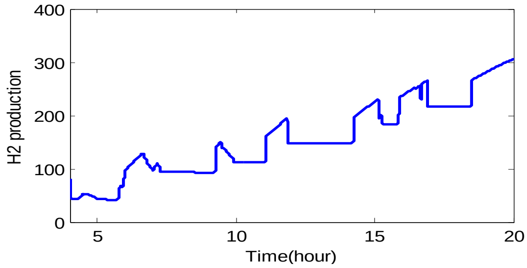

Fig. 9. The amount of hydrogen production from electrolyzer

V. CONTROLLERS AND POWER CONVERTER MODEL

PID type controllers are used in the fuel cell, the boost converter, and the inverter. The general transfer function of a PID controller may be written as [12]

$$G_r(s) = \left(s + T_d s^2 + \frac{1}{T_i} \right) . \frac{K_P}{s} \tag{14}$$

The fuel cell controller controls the fuel cell voltage by varying the H_2 and O_2 flow rates. Limiters are used at the output of each controller to limit gas pressure in the fuel cell. The controller in the boost converter maintains a 200 V DC at the inverter's input. The inverter is controlled for maintaining 170 V, 60 Hz AC by adjusting the modulation index of the PWM scheme.

The Ziegler–Nichols open loop method for determining the parameters of a PID controller was used [11]. Suitable controller parameters are given in Table I.

TABLE I: CONTROLLER PARAMETERS

	Fuel cell flow controller			
	O_2 flow	H_2 flow	Boost converter	inverter
K_p	2	5.00	5.00	0.05
T_i	0.5	1.00	2.00	0.015
T_d	0	0	0	0

The fuel cell flow controller SIMULINC contain two PID controllers to regulate the flow of reactants depending on the stack output voltage is shown in Fig. 10.

The ‘power controller’ SIMULINK make a comparison of available PV power with required load and divert access energy to the electrolyzer for producing hydrogen is shown in Fig. 11.

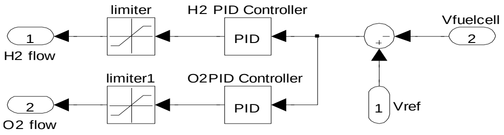

Fig. 10. Fuel cell flow controller subsystem

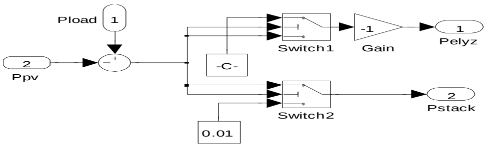

Fig. 11. Power controller subsystem

The hybrid energy system is considered for standalone mode of operation and a two stage power converter modules are considered to regulate the output voltage at a Standard magnitude and frequency. The first stage consists of a boost converter, Which converts the variable DC output of the fuel cell (in parallel with the ultra capacitor bank) into a high voltage constant DC. Here, the boost converter is controlled with a PID controller to regulate the high voltage bus at 200 V. This could be achieved by adjusting the duty ratio, D, as generally given by the equation:

$$\frac{V_{boost}}{V_{ucap}} = \frac{1}{1-D} \qquad (15)$$

A pulse width modulated (PWM) single-phase voltage source inverter (VSI) is operated through a PID controller that adjusts the modulation index towards achieving 200 V, 60 Hz output.

Output voltage of DC/DC convertor, output voltage of PWM and filtered voltage of load are shown in Figures 12, 13 and 14 respectively. Using a booster convertor, output DC voltage of fuel cell is keeping fixed in 200 volts and using a PWM convertor and filter, load get current in 170 volts of AC and 60 Hz frequencies.

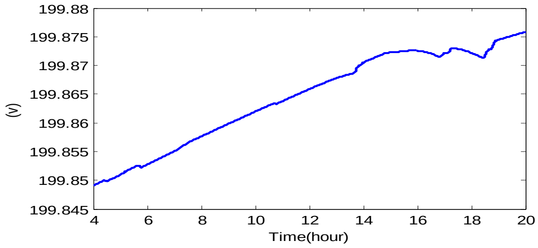

Fig. 12. Output voltage of DC/DC convertor

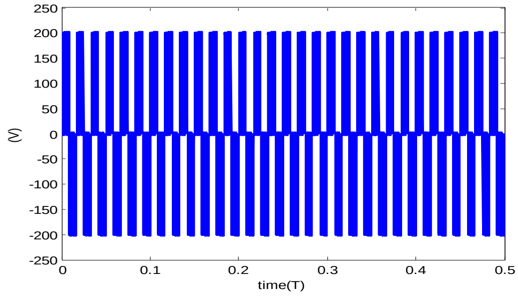

Fig. 13. Output voltage of PWM

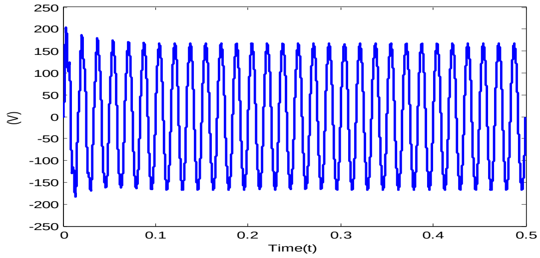

Fig. 14. Output filtered voltage of PWM

As it is shown in Fig. 14, by implementing a filter in output of PWM convertor, voltage has became clearer. Load current is also different with regarding to switching which in greater current, power of load become greater Fig. 15 and Fig. 16, verify the results.

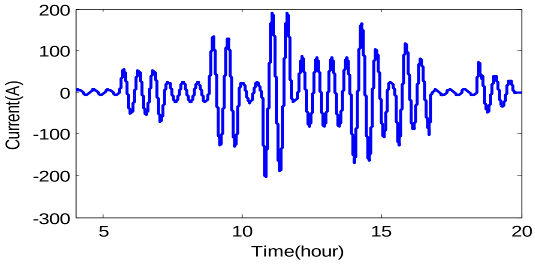

Fig. 15. Load current variations

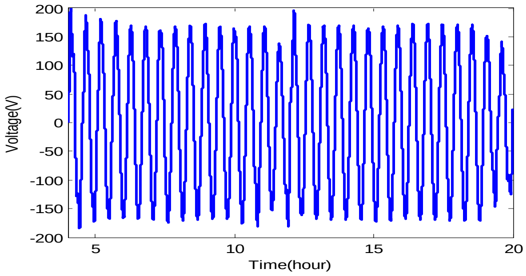

Fig. 16. Load voltage variations

It is obvious from Fig. 17 that from the time which request power of load become greater than creating power of photovoltaic, fuel cell begins to provide the power.

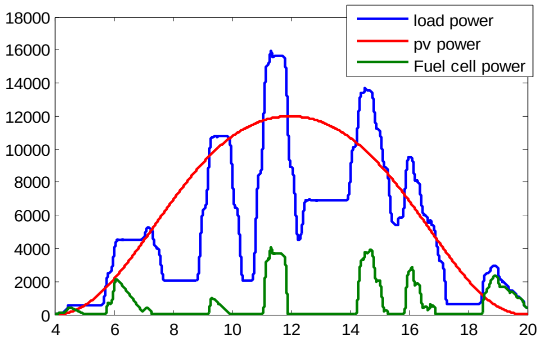

Fig. 17. Providing power of photovoltaic, fuel cell and consuming load

In the present study simulation of electric potential and electric field for the actual composite insulators of 20kV, has been carried out using 3-D analysis in Comsol program. The result shows that increasing the number of droplets on the insulator surface causes non-uniform field in insulator. As can be seen from result, the magnitude of the E-field close to the energized end is higher than that at the grounded end. Thickness and conductivity of pollution layer on polymer insulator change magnitude of the E-field at the head and end of insulator.

VI. CONCLUSION

The PV/FC hybrid power system is modeled for small grid users with appropriate power flow controllers. We integrated PV system with the FC system. The PV system feeds the electrolyzer to produce hydrogen for future use and transfers energy to the load side if possible. Whenever the PV system cannot completely meet load demands, the FC system provides power to meet the remaining load. The developed system and its control strategy exhibit excellent performance for the simulation of a complete day or longer periods of time. The model is applied in MATLAB / SIMULINK.

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Hossein Mohseni received the Dipl. Ing and Dr. Techn from Technical University Graz, Austria in 1971 and 1975, respectively. From 1971 to 1976 he was with ELIN UNION AG Austria, working as testing and research engineer in the High Voltage Laboratory and the Transformer R and D Department. In 1976 he joined the Faculty of Engineering, University of Tehran, Department of Electrical Engineering where is currently a Professor and teaches high voltage engineering, high voltage insulation technology, and transients in power System and Apparatus. During 1981/82 he was the chairman of Department of electrical engineering at the University of Tehran. Since 1980 he has been a technical consultant of the Iran Power Generation and Transmission Company (TAVANIR). Also since 1998 he is the dean of the High Voltage and Pulsed Power research center, at the University of Tehran.