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Design and operation of PV / FC smart electrical power system using neural networks

By

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Abstract:

This paper introduces a study of design and performance of Photovoltaic / Fuel Cells Smart Electrical Power System, PV/FC SEPS, to supply a load in a remote area has the same latitude of Elminia city. Since the output of PV system depends on solar radiation then the FC starts automatically by using Artificial Neural Network, ANN, when solar radiation is insufficient to feed the load demand. By using this operation strategy the FC works as a back- up power supply.

The performance of the system for a step change in the electrical load and solar radiation are presented. Analysis of the system's response and its limitations are discussed.

Keywords:

Solar Energy, Hydrogen, Fuel Cell, Electrolysis, Polymer Electrolyte Membrane, Photovoltaic, Artificial Neural Network, Environment

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1. Introduction:

As energy demands around the world increase, the need for a renewable energy source that will not harm the environment has been increased. Some projections indicate that the global energy demand will almost triple by 2050 and oil can only supply the world for up to 150 years [1]. Using renewable energy systems especially in the new Egyptian cities like New Minia city will reduce the cost for energy transportation and pollution. There are many types of renewable energy in a good situation among the energy types like solar energy, Hydrogen and wind energy. The price of kWh generated from some of these sources has been fallen to be lower than many conventional sources as fossil fuels. Also, the renewable energy costs will continue to decline as the industry grows and matures. Renewable energy sources presently provide significant amount of energy in many countries. Renewable energy sources currently supply about 10 % of the world energy demand [1]. These energy sources hold promise for a substantial potential contribution for the world, and they will therefore become increasingly important in the future. The renewable energy is environmental friendly compared to current level of CO_2 emission associated with electricity generation. A considerable contribution from renewable energy sources could reduce substantially the emission of CO_2 and the low level of other pollutants that cause acid rain, smog and other local environmental hazards. Fuel cells are often described as being continuously operating batteries, but this is an incomplete idea. Like batteries, fuel cells produce power without combustion or rotating machinery. They produce electricity by utilizing an electrochemical reaction to combine hydrogen ions with oxygen atoms. Hydrogen ions are obtained from hydrogen-containing fuels. Fuel cells, unlike batteries, use an external and continuous source of fuel and produce power continuously, as long as the fuel supply is maintained. Two electrodes, an anode, and a cathode form an individual cell. They are sandwiched around an electrolyte in the presence of a catalyst to accelerate and improve the electrochemical reaction.

2. Overall View of the PV-Fuel Cell Power Plant.:

Figure 1 illustrates a simplified diagram of a PV/FC SEPS including a neural network controller for the operation of electrolysis and Polymer Electrolyte Membrane, PEM, fuel cell during the night and low radiation periods. The SEPS consists of a photovoltaic array, a fuel cell plant, electrolysis plant, dc-dc Boost converter, dc-ac inverter, tank storage, power transformers, and transmission line. The PV generator operates independently and is controlled to produce maximum power point based on fuzzy logic control, which had been discussed in [2]. The PV array, composed of a set of series-

parallel connected solar cell modules, generates a dc power that is then converted to a useful ac power by the dc-ac inverter. It acts as the interface between the PV system and the ac load. The output ac power of the dc-ac inverter is provided to the ac load through the transformer and transmission line.
The neural network controller is used to operate the PEM FC and alkaline electrolysis. Its function is based on the comparison between the generated energy from PV and the energy of the load demand. Then it sends output switching signals to the electrolysis switch and PEM FC switch. If the power load demand is greater than the PV power, the ANN controller sends a signal to PEM FC switch. However if the power load demand is less than the PV power the ANN controller send a signal to alkaline electrolysis switch.

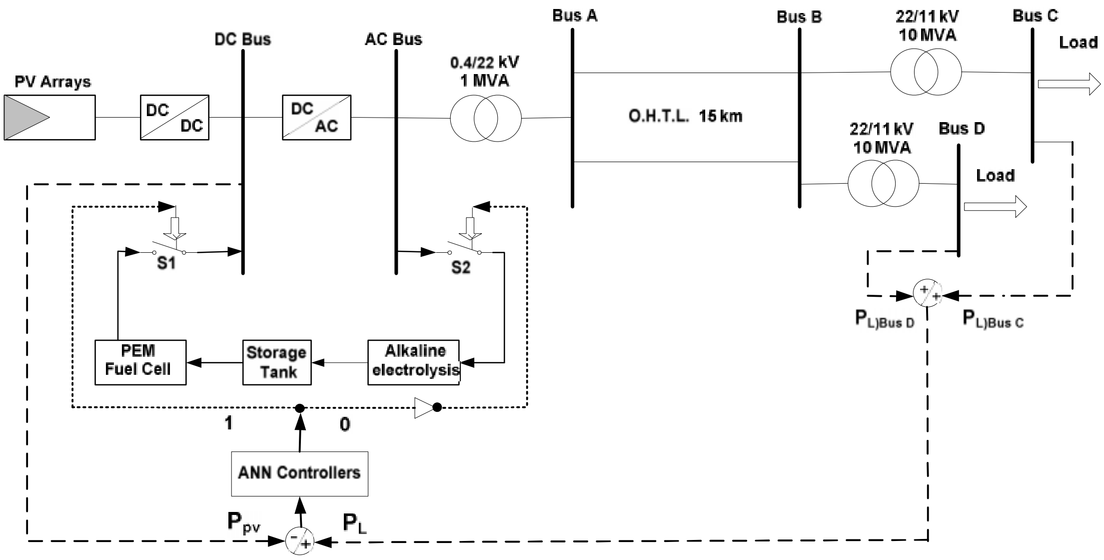

Figure (1): *Process diagram of PV / FC SEPS*

2-1. PERFORMANCE OF PEM FC MODEL:

The theoretical ideal performance of a FC depends on the electrochemical reactions that occur with hydrogen and oxygen. The ideal performance is defined by using the Nernst Equation. This equation provides a relationship between the ideal electrical potential, Eo, at standard conditions (Atmospheric pressure and 25°C), and the ideal equilibrium potential, E, at other temperatures and partial pressures of reactants and products. Once the ideal potential of standard conditions is known, the ideal voltage can be determined at other temperatures and pressures as following [3]:
(a) Open circuit voltage: The open circuit voltage has been calculated using equations in [4] and it is found as:

$$E_o = \frac{237200}{2*96485.309} = 1.2297\,V \qquad (1)$$

Figure 2 shows the basic FC inputs and outputs. The following equations represents the reactions of PEM fuel cell:

Anodic half reaction: $H_2 \Rightarrow 2H^+ + 2e^-$ (2)

Cathode half reaction: $\frac{1}{2}O_2 + 2H^+ + 2e^- \Rightarrow H_2O$ (3)

The overall reaction: $H_2 + \frac{1}{2}O_2 \Rightarrow H_2O$ (4)

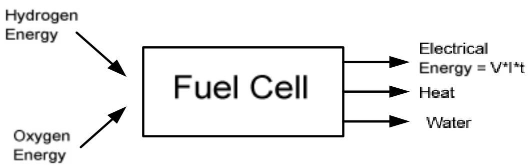

Figure (2): *Basic Fuel Cell Inputs and Outputs*

(b) Nernst equation: The Nernst equation provides the relationship between standard potential for a cell reaction and the actual voltage produced at various temperatures and pressures of the reactants and products and it can be written as:

$$E = E_o + \frac{RT}{2F}\ln\frac{P_{reac\tan t}}{P_{product}} \qquad (5)$$

Where, $P_{reactant}$, is the reactant of partial pressures of the reactants and, $P_{product}$, is the product of die partial pressures of the products produced in the cell reaction. All pressures are expressed in bars. F is Faraday's constant, R, is the universal gas constant and, T, the operating temperature of the fuel cell. In the case of the PEM fuel cell this reaction is [3, 4, 5 and 6]:

$$E = E_o + \frac{RT}{2F}\ln\left(\frac{P_{H_2} * P_{O_2}^{1/2}}{P_{H_2O}}\right) \qquad (6)$$

Alkaline electrolyses use an aqueous KOH solution (caustic) as an electrolyte that usually circulates through the electrolytic cells. Alkaline electrolyses are suited for stationary applications and are available at operating pressures up to 25 bars. Alkaline electrolysis is a mature technology allowing unmanned remote operation with significant operating experience in industrial applications. The following half reactions take place inside the alkaline electrolysis cell: [6]

Anodic half reaction: $2OH^- \Rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$ (7)

Cathode half reaction: $2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$ (8)

The overall reaction: $H_2O \Rightarrow H_2 + \frac{1}{2}O_2$ (9)

3. Overall Application and Results:

3-1. Design of Fuel Cell and Electrolysis Subsystems:

To design alkaline water electrolysis subsystem the maximum hourly surplus power that generated from PV system and the characteristics of the PV module must be known.
The maximum hourly surplus is 23323 kW, and from Table (1) we consider the nominal of flow rat of hydrogen production is, 50 Nm^3/h, and the HySTAT™-conversion efficiency is 4.8 kWh/Nm^3.

Table (1): *The characteristics of the electrolysis under study. [7]*

Module Type	***HySTAT™-A 1000Q-60-10***	
Hydrogen production	Number of cell stacks	4
	Nominal flow rate	32 - 60 Nm^3/h
	Flow range	25 – 100 %
	Output pressure range	6 to 10 Bar
Oxygen production	Nominal flow rate	50 % of H_2 flow
	Minimum & Maximum Flow rate	25 – 100 %
	Output pressure range	1 to 8 Bar
Conversion efficiency	Cell stack Conversion efficiency	4.2 kWh / Nm^3
	HySTAT Conversion efficiency	4.8 kWh / Nm^3
Electrical power supply (EPS)	Voltage	400 VAc
	Frequency	50 Hz
	phase	3 Phase
Electrolyte	Type	30 % KOH in H_2O
	Quantity	Approx. 650 liter
Operating Conditions	Ambient Temperature Range	2^oC to 35^oC

From the above parameter can be calculating the number of subsystem modules as a following:
The power consumed in alkaline water electrolyses = 4.8*50=240 kW
Then; The number of HySTAT™-A modules = 23323/240 = 97.1792 ≈ 98 modules.

As the same to design the alkaline water electrolysis, the maximum hourly deficits and the characteristic of PEM FC must be known.
The maximum hourly deficits is 6000 kW, moreover the rated power of PEM FC is 50 kW as shown in Table (2). Then; The number of PEM FC modules = 6000/50 = 120 modules.

***Table (2):** The characteristics of PEM FC under study. [8]*

Type	120 kW fuel cell system / PEM Power Plant Unit	Ned Stack PS50
	Net Rated Electrical Nominal Power	50– 72 kW
	Output voltage	600 V (DC)
	Operating current range	84–120 A (DC)
	Typical Beginning of Life Voltage Range	640 V (DC)
	Efficiency – LHV	55–57 % (stack) / 48 – 50 %(system)
	Maintenance routine	2.000 h
	Operational ambient temperature	-20–+40 °C
Fuel	H2	
	Purity	99.95 % (no sulphur compounds)
	Supply pressure	0.5–5 bar
	Stack Operating Pressure	ambient
	Nominal H2 Consumption at 50 kW	11 slpm/

Since Inverter with rating of 500 kW, input voltage of 600 ± 5 % Vdc and efficiency of 95 %, at unit power factor has been selected in this study. Using this inverter unit the design parameters of FC / alkaline water electrolysis electrical hybrid system has been calculated as shown in Table (3).

Table (3): *The design parameters of Fuel Cell / alkaline water electrolysis electrical hybrid system*

Items \ **Module**	**Ned Stack PS 50**	***HySTAT™-A 1000Q-60-10***
Total No. of modules	120	98

3-2.Hydrogen Storage:

The yearly hydrogen storage = 414295 Nm^3
Then; Gallons H_2 =414295 cu. m. H_2 x 264.1721gal H_2 /cu. m. = 1.0944518*10^8gallons H_2
The Ideal Gas Law
Pressure in the ideal gas law must include atmospheric pressure, (1 atm or 1.01325 bar or 14.69595 psi). We have 1.0944518*10^8gallons of hydrogen at just above atmospheric pressure. If we choose to store the hydrogen at 9 bar or 130.534 psi above atmospheric pressure, we can determine the resulting volume by applying the ideal gas law:

$$P_i\, V_i = P_f\, V_f \tag{10}$$

$V_f = \frac{P_i * V_i}{P_f}$ =14.69595 psi x 1.0944518*10^8gal H_2/130.534 psi= 12.321701*10^6 gal H_2
The 1.0944518*10^8gallons of hydrogen we produce can be stored in a 12.321701*10^6 gallon storage tank at 130.534 psi. The advantage of the higher pressure tank is the low volume storage tank. Hydrogen at 130.534 psi could be stored in a xerxes fiberglass aboveground Storage tank. The size available of xerxes storage tank at horizontal tank is, 43110 gallon, at and then can be calculate the number of the xerxes storage tanks that will used. [9]
The number of the ASME storage tanks = 12.321701*10^6 /43110 = 285.8 ≈ 286 tanks.
From the above the yearly hydrogen storage is 305592 Nm^3, can be calculate the electrical energy that stored as following;
Electric energy stored = Hydrogen storage * NCV*efficient of PEM fuel cell
Where; NCV is Net Calorific Value or Lower Calorific Value (LHV), is equal to 11.920*10^3 kJ/Nm^3 or 3.31 kWh/$Nm^3$for hydrogen at NTP condition. [3]
Then; Electric energy stored = 414295 Nm^3 *3.31 kJ/Nm^3 *0.55 =754.2441 MWh /year
From the above we Can be feed the demand load about seven days per year when the low radiation period.

4. Design of ANN for PV/FC Hybrid System:

A computer program has been written to generate training cases. The training data have been processed with Back-Propagation [10], BP, learning algorithm to compute the weights for the network architectures under study. Many ANN configurations have been analyzed to determine, the most suitable ANN. Figure 3 shows this proposed ANN which consists of one neuron in input five neuron in the hidden layer and one neuron. The difference, DEF, between PV power generated and the load power represents,(Equ.(11)), the input of ANN. If DEF is +ve the output of ANN will be (0), then the electrolysis will operate. If DEF is -ve the output of ANN will be (1), then the FC will operate. Table (4) shows the weights and base for the ANN.

$$DEF = PV_O - P_L \tag{11}$$

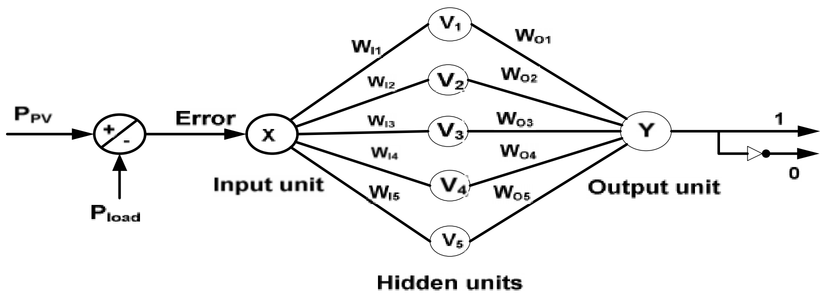

Figure (3): *Structure of the Proposed Three Layers NN used for Control Strategy of PV/FC Hybrid system*

Table (4-a): *Weights W1 and Biases for 1+5+1 NN for PV/ FC hybrid system*

W_{INPUT}	0.020526	-8.7664e-005	0.16958	22.5718	0.089718
base	21.7504	0.14514	7.8905	-10.443	5.5218

Table (4-b)*: Weights W1 and Biases for 1+5+1 NN for PV/ FC hybrid system*

W_{OUTPUT}	-1.177	38.7759	-2.5089	-10.3083	-18.6561
base	- 18.7368				

Figure 4 shows the evaluation of the 1+5+1 ANN errors. Figure 5 displays the optimal operation of the PV/FC and electrolysis hour by hour through the day which represents the months of January, April, July and October respectively

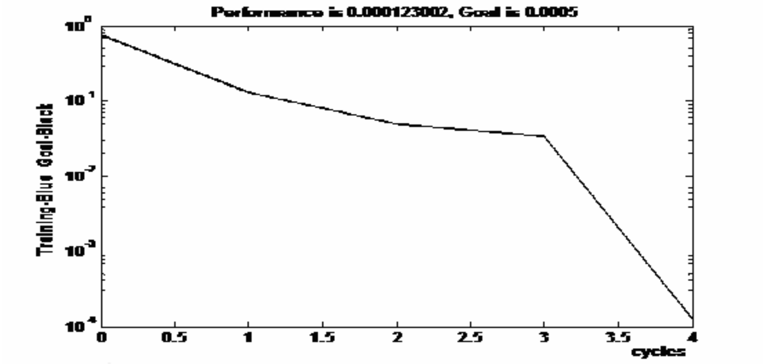

Figure (4)*: Relation between Error and Epoch*

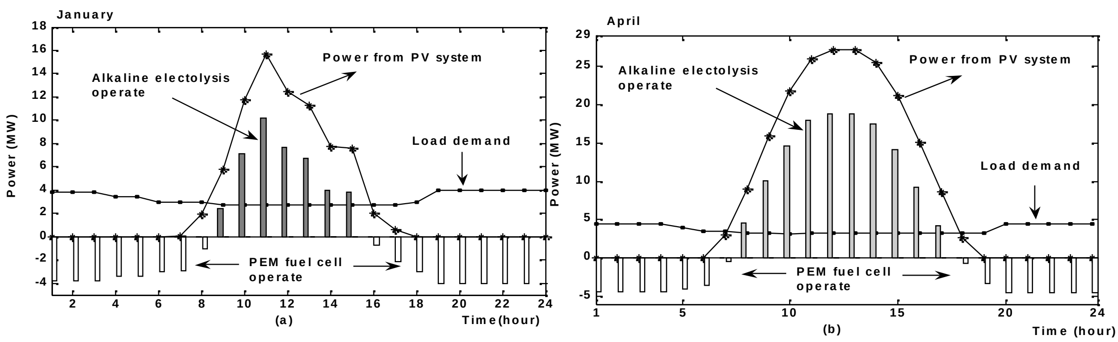

Figure (5-a)*: optimal operation of PV/FC SEPS and electrolysis hour by hour through the day for January and April months.*

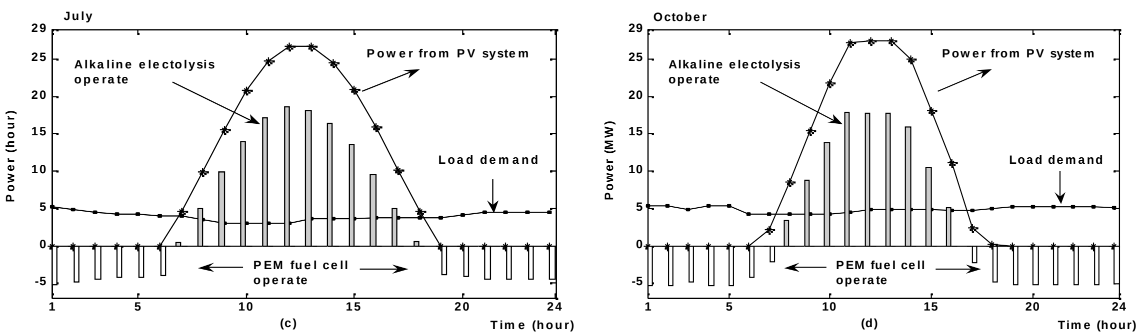

Figure (5-b) *optimal operation of PV/FC SEPS and electrolysis hour by hour through the day for July and October months.*

From figure **5** it can be seen that the deficit energy has been taken from PEM fuel cell (i.e. the ANN send a trip signal to switches S1 to turn ON, S2 to turn OFF). On the other hand, the surplus energy has been injected to alkaline water electrolysis through the day (i.e. the ANN send a trip signal to switches S2 to turn ON and S1to turn OFF).

Figures **6**, **7**, 8 and 9 displays the output of the proposed ANN of 1+5+1 for month of January, April, July and October respectively using test data. This output may be 1 or 0 for each switch.

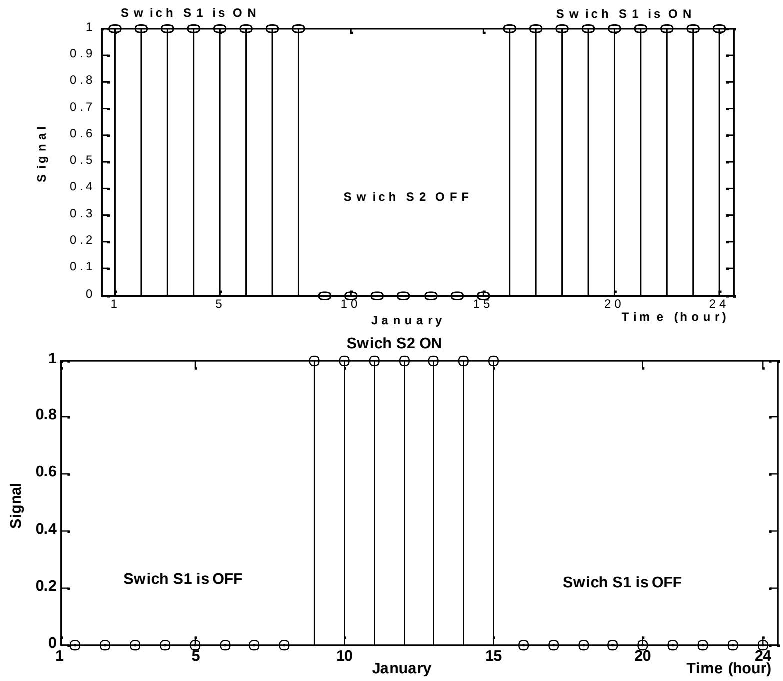

Figure (6) The output of the proposed ANN of 1+5+1 for month of January.

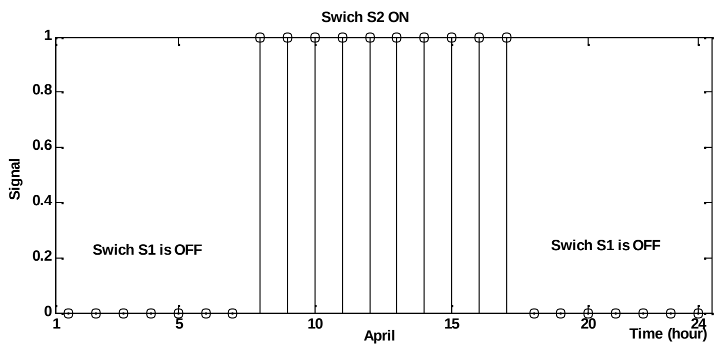

Figure (7) Display the output of the proposed ANN of 1+5+1 for month of April.

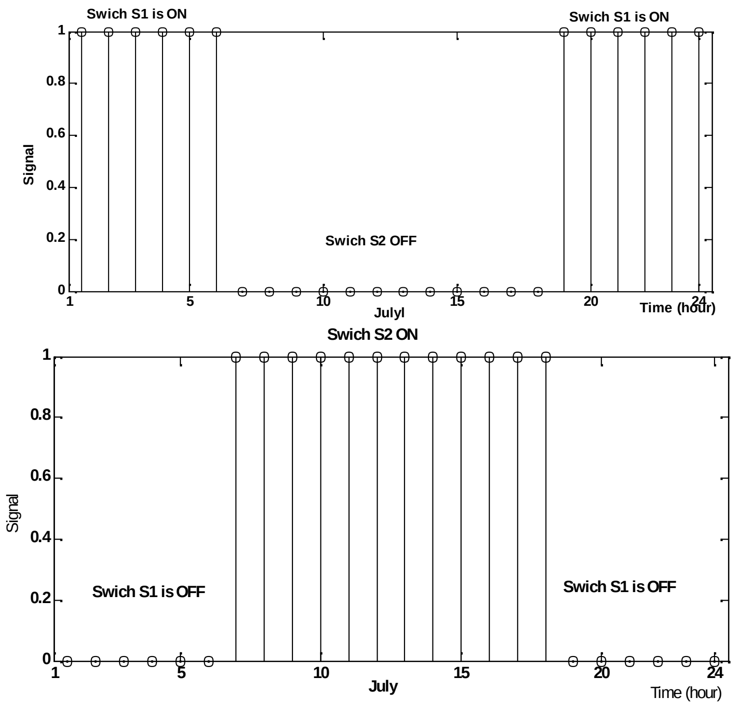

Figure (8) Display the output of the proposed NN of 1+5+1 for month of July

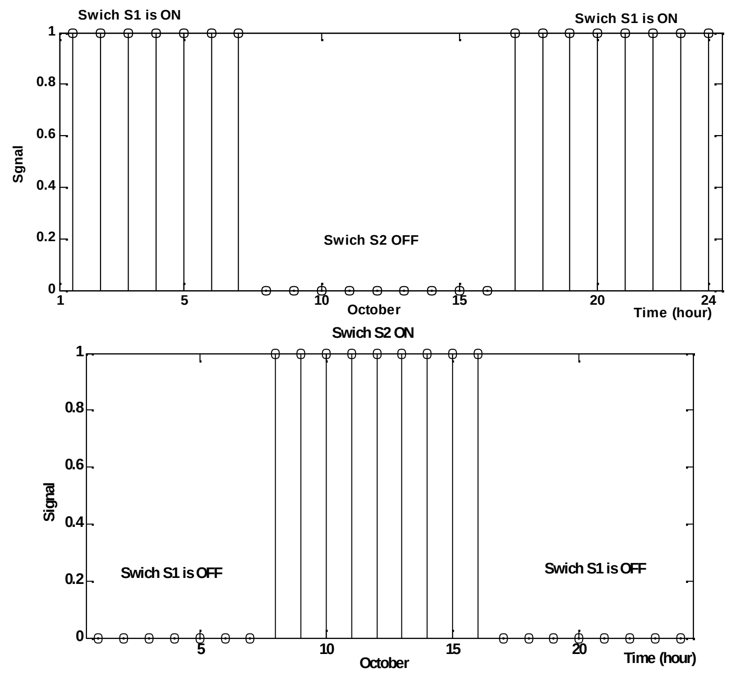

Figure (9) Display the output of the proposed ANN of 1+5+1 for month of October

From Figures 5a and 6 (January) it can be noticed that the trip signal which produced from ANN send to switch S1 to OFF and S2 to ON at hours 9, 10, 11, 12, 13, 14, and 15. This means that the PV system feed the load demand at these hours, and the surplus will injected to the electrolysis. On the other hand, switch S2 to OFF and S1 to ON, at hours 1, 2, 3, 4, 5, 6, 7, 8, 16, 17, 18, 19, 20, 21, 22, 23 and 24. This means that the PEM FC should supply the load demand at these hours.

From Figures 5b and 7 (April) it can be noticed that the trip signal which produced from ANN send to switch S1 to OFF and S2 to ON at hours 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17. This means that the PV system feed the load demand at these hours, and the surplus will injected to the electrolysis. On the other hand, switch S2 to OFF and S1 to ON, at hours 1, 2, 3, 4, 5, 6, 7, 18, 19, 20, 21, 22, 23 and 24. This means that the PEM FC should supply the load demand at these hours.

From Figures 5b and 8 (July) it can be noticed that the trip signal which produced from ANN send to switch S1 to OFF and S2 to ON at hours7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 and 18. This means that the PV system feed the load demand at these hours, and the surplus will injected to the electrolysis. On the other hand, switch S2 to OFF and S1 to ON, at hours 1, 2, 3, 4, 5, 6, 19, 20, 21, 22, 23 and 24. This means that the PEM FC should supply the load demand at these hours.

From Figures 5b and 8 (October) it can be noticed that the trip signal which produced from ANN send to switch S1 to OFF and S2 to ON at hours 8, 9, 10, 11, 12, 13, 14, 15, and 16. This means that the PV system feed the load demand at these hours, and the surplus will injected to the electrolysis. On the other hand, switch S2 to OFF and S1 to ON, at hours 1, 2, 3, 4, 5, 6, 7, 17, 18, 19, 20, 21, 22, 23 and 24. This means that the PEM FC should supply the load demand at these hours.

5. Conclusions:

The PEM FC is a viable alternative to engine generators as a backup for PV power at remote, unattended locations. PEM fuel cell technology, while still facing economic and technical hurdles on the way to becoming a popular energy supply alternative, can now claim to be a durable and reliable choice for specialized applications. PV/FC HPS is proposed as an ultra low emission energy system.
On the other hand, it can be concluded that the PV/FC is more reliable energy system comparing with another energy storage.
A proposed control strategy based on the ANN has been developed to control the

operation the PV/FC HPS. For this purpose the 1+5+1 ANN has been designed in an accurate manner. By using this proposed strategy the PV/FC HPS becomes more reliable generation system.

The proposed PV/FC HPS can be built at any site to feed a load instead of the conventional generation system to protect the environment from any pollution.

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