Summer July 7, 2011

Design, Modeling and Control Strategy of PV/FC Hybrid Power System

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J. Electrical Systems 7-2 (2011):270-286

Regular paper

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JES Journal of Electrical Systems

This paper describes development of a general methodology of an autonomous PV/FC system composed of photovoltaic (PV), electrolyzer, hydrogen storage tank and fuel cell (FC). The aim of this paper is to determine optimum design, control strategy, economic and performance of a PV/FC hybrid power generation system without battery storage taking into account all losses in the system. The paper also presents a computer program based on Matlab software to determine optimum design, control strategy, economic and performance of an autonomous PV/FC hybrid power generation system. The computer program develops to size system components in order to match the load of the site with high operational reliability based on loss of power supply probability (LPSP). The proposed system designs for the hybrid power generation in Aswan site, southern of Egypt (24.0875^o N latitude, 32.8988^o E longitude). From simulation results the system being installed at the Aswan site consists of a 12 MW PV array coupled to a high pressure bipolar alkaline electrolyzer, rated 9.5 MW and fuel cell rated with 2MW. The results show a good optimization performance.

Key Words: Design, Control, Photovoltaic, Fuel cell, Electrolyzer.

1. Introduction

Several stand-alone power systems installed around the world, usually located in small communities or at technical installations that are not connected to a main electricity grid. The majority of these power systems are based on fossil fuel power generation. Today there is 6.4% of the world's total use of renewable energy sources. So, there has been a growing initiative to include renewable energy technologies, particularly wind and/or solar power, into stand-alone power systems. When included in stand-alone power system, wind or solar power or both often operate in combination with diesel generators and batteries, reducing the fossil fuel consumption. Replacement of diesel generators and batteries by fuel cells running on hydrogen, produced locally with renewable energy, offers a great opportunity to improve environmental standards, and reduce operation and maintenance costs [1]. This paper presents a proposed PV/FC hybrid power system consists of four components. The four system components are - the PV generator, the electrolyzer, hydrogen storage tanks and fuel cell- moreover other auxiliary components as shown in major projects in USA [2] , Germany[3~5], Italy [6] and Saudi Arabia [7]. Various optimization techniques to design renewable energy sources such as the probabilistic approach [8,9], linear programming, graphical construction method, dynamic programming, PSO [10] and iterative technique have been widely studied extensively around the world over the past decades.

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Some of studies of the stand-alone PV/FC hybrid power system have been reported in the literatures. Reference [11] optimize, analyze and compare three hybrid power systems, i.e., PV/battery system, PV/FC system, and PV/FC/battery system. Reference [12] presents several simulation of hybrid PV/FC system in remote-telecom application. Reference [13] presents several designs of hybrid PV/wind systems connected to the electrical grid, including the intermittent production of hydrogen. Reference [14] presents addressing mismatch between intermittent solar irradiation and time-varying load demand for stand-alone PV/FC system to achieve high energy efficiency. Reference [15] optimizes efficiency of the PV-electrolysis system by matching voltage and maximum power output of the PV to operating voltage of proton exchange membrane electrolyzers. The optimization process increased the hydrogen generation efficiency to 12% for a solar powered PV-PEM electrolyzer. Reference [16] presents economic study of three different configurations associating photovoltaic sources and fuel cells. Configuration 1: PV, battery, FC feed by an external hydrogen tank; configuration 2: PV, FC, electrolyzer and hydrogen tank. Finally configuration 3: PV, battery, FC, electrolyzer and hydrogen tank. Reference [17] describes a control strategy of solar photovoltaic fuel cell hybrid generation system consisting of a PV generator, a proton exchange membrane fuel cell (PEMFC), an electrolyzer, a supercapacitor, a storage gas tank and power conditioning unit. Reference [18] presents a complete model of a stand-alone renewable energy system with hydrogen storage controlled by a dynamic fuzzy logic controller. Reference [19] presents a pre-feasibility study for stand-alone hybrid energy systems with hydrogen as an energy carrier for applications in Newfoundland, Canada. Reference [20] present technical design and economic evaluation of a stand-alone PEMFC system in Sweden. Many attempts have been tried to explore a relatively simple way to design PV/FC system. But, most of them did not pay an exact identification of the system to determine optimum design, sizing of component selection, operational control strategy and performances. This paper presents a project comprises of optimal design, sizing of components, hourly operating states and operational control strategy of a PV system interconnected with hydrogen energy system in Aswan-Egypt site moreover economical study of the system. The project near to the High Dam, 20 km from Aswan center on the Coast of Nasser Lake and it can be extended to become large for supplying Egypt and Europe by Hydrogen as renewable, clean, safe energy for the next century. All components select for an optimal design with high reliability based on LPSP. When the PV system cannot provide sufficient power, stored hydrogen and oxygen are furnished to fuel cells which, smoothly and without interruption, supply the load. The paper organizes as follows: Section 2 presents system configuration. In Section 3, operational control strategies of PV/FC system, economic study, and efficiency metrics which are defined as comprehensive evaluation standards. Based on methodology, A case study implements in section 4 and 5. Finally, conclusions of the paper present in section 6.

2. System Configuration

The configuration of a PV/FC hybrid power generation system considered in this paper is shown in Fig. 1, which consists of a PV system with maximum power point trackers

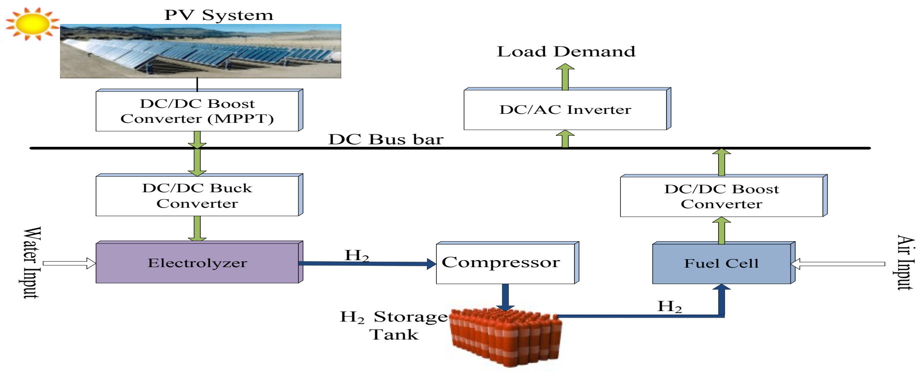

Fig. 1 Schematic diagram of PV/FC under study

(MPPT), a pressurized advanced alkaline electrolyzer with a DC/DC buck converter for H_2 production, a compressor that compresses H_2 production at high pressure, a pressurized storage tank for H_2 storage, fuel cells with a DC/DC boost converter for H_2 utilization, and a DC/AC inverter for load demand. PV system converts solar irradiations into electricity. For the increase of overall system efficiency, the DC/DC boost converter with MPPT enables the PV system to work at the maximum power point in the highly fluctuated environment. For an electrolyzer, the H_2 generation rate is proportional to the current into the water electrolysis. Due to the varying nature of the PV output, the electrolyzer designed to operate between the power ranges from 20%–100% of nominal power depending in the manufacture. For space saving and better system performance, H_2 will be produced and stored under high pressure in storage tank. The efficiency of the pressurized electrolysis is usually up to 88% with current density of several hundred mA/cm^2 while the efficiency of the fuel cell is usually about 45–65%. As an electrolyzer must be fed with direct current from PV system and the fuel cell produces direct current as well, a DC-bus bar is needed. The PV system and fuel cell are connected to DC-bus via DC/DC boost converter while the electrolyzer is connected to DC-bus bar via buck converter. On the other hand, the load is connected to DC-bus via inverter. The efficiency of the DC/DC converters is up to 95% while the efficiency of DC/AC converter is up to 90%. During solar radiation, Power will be generated by PV system to feed load demand and the excess power will be compressed and stored in the form of hydrogen in a storage tank. If there is no or low solar radiation, the PV system can't provide sufficient electricity to feed load demand, the fuel cell will utilize H_2 to produce electricity for the load demand. Note that the electrolyzer and the fuel cell will not be operated simultaneously.

3. Methodology

I. Operational control strategies

Fig. 2 shows four corresponding routes of energy flow within stand-alone PV/FC system. To ensure the highest realizable efficiency and the best possible supply security of the stand-alone PV/FC system, the operational strategies have to be stated with care, which is summarized below.

(1) When PV electrical power is equal to the load demand, P_{Load}, route A will be employed to transfer electricity from the PV system to the load demand.

(2) When PV electrical power exceeds the load demand, P_{Load}, route B will be employed to transfer electricity from the PV system to the load demand and the excess electricity would be inputted into the electrolyzer to produce H_2. If the H_2 storage tanks become full, the excess power will be diverted to another dump load.

(3) When PV electrical power less than the load demand, P_{Load}, route C will be employed to transfer electricity from both the PV system and the fuel cell.

(4) When there is no solar radiation, route D will be employed to transfer electricity from the fuel cell only to the load demand. Summary of the operational control strategies is shown in Table 1.

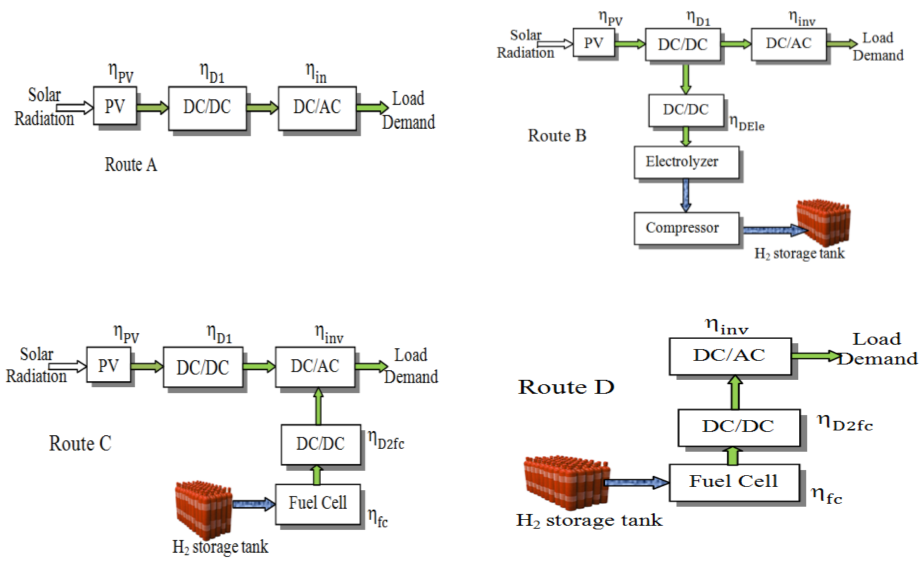

Fig. 2 Operation control strategies of the PV/FC system

Table 1 Operational Control Strategies

Route	Generated power vs. Load demand
A	$P_{pv} = P_{Load}$
B	$P_{pv} > P_{Load}$ A control signal will be sent to Electrolyzer to operate
C	$P_{pv} < P_{Load}$ A control signal will be sent to Fuel cells to operate
D	$P_{pv} = 0$ A control signal will be sent to fuel cells to feed the load demand.

II. Match calculation method

The LPSP technique [21-22] is used to match generation with load demand for sizing of the PV/FC hybrid power system. The aim of match calculation strategy for the system under study is to determine:

1. Optimum number of PV modules.
2. Optimum size of electrolyzers.
3. Optimum size of hydrogen tanks.
4. Optimum size of fuel cell.

The first aim is handled by using energy balance. The energy balance between the load plus all losses and the output from PV system must be carried out to compute the optimum number of PV modules, N_{pv} at each time step of the simulation. The hourly PV energy generated and hourly energy demand plus hourly losses of energy are compared with each other as the following equations to get the optimum number of PV modules.

$$\sum_{t=1}^{T}\left[N_{PV}.E_{PV,out}(t)-\left(E_{Load}(t)+\ E_{Loss}(t)\right)\right] > LPSP \qquad (1)$$

Where;

N_{pv} :Number of PV modules.
$E_{pv,out}(t)$: Hourly PV energy, kWh.
$E_{Load}(t)$:Hourly energy demand, kWh.
$E_{Loss}(t)$:Hourly losses energy, kWh.
LPSP : Loss of power supply probability.
t : time, hour.
T : Total time, 8760 h.

If the result of (1) greater than LPSP, then number of PV modules must be decreased by one module and repeating the foregoing process:

$$\sum_{t=1}^{T}\left[N_{PV}.E_{PV,out}(t)-\left(E_{Load}(t)+\ E_{Loss}(t)\right)\right] < LPSP \qquad (2)$$

If the result of (2) less than LPSP, then number PV modules must be increased by one module and repeating the foregoing process.

$$\sum_{t=1}^{T}\left[N_{PV}.E_{PV,out}(t)-\left(E_{Load}(t)+\ E_{Loss}(t)\right)\right] \cong LPSP \qquad (3)$$

If the result of (3) approximately equal to LPSP, then, N_{pv} is the optimum number of PV modules satisfies the energy balance condition. Once the optimum number of PV modules is determined, the number of series and parallel modules per subsystem can be estimated. Moreover, number of inverters can be determined. For a PV/FC hybrid power system, sizing of the electrolyzer is not trivial. So, the second aim is handled by calculating the power exported to all electrolyzer units through (Rout B), and it can be expressed by the following Equation:-

$$P_{Ely,rated} = \text{average}\left[\eta_{DEle}.\left(P_{PV}(t).\eta_{D1}-\frac{P_{Load}(t)}{\eta_{inv}}\right)\right] \qquad (4)$$

Where;

$P_{PV}(t)$: Photovoltaic Power, kW
$P_{Load}(t)$: Load demand Power, kW
η_{DEle} : Efficiency of buck converter,
η_{D1} : Efficiency of boost converter,
η_{inv} : Efficiency of inverter.

The electrolyzer must be able to follow sudden changes of operating conditions due to variation of the PV energy. With present technology, electrolyzer has a minimum operating point ranging from 10% to 50% of nominal power depending on the manufacturer. Electrolyzer operation power is limited by the following constraint:

$$P_{Ely}^{min} \leq P_{Ely}(t) \leq P_{Ely}^{max} \quad (5)$$

Where,
P_{Ely}^{min} *and* P_{Ely}^{max} are the minimum and maximum electrolyzer power required, kW.
$P_{Ely}(t)$: Rated power of electrolyzer, kW.

The third aim is handled by calculating daily volumetric hydrogen production as explained in the following item 3.3. Finally, the fourth aim can be handled by calculating deficit power. In this paper, electrolyzers and fuel cells should be able to retrieve all the PV power to feed load demand in the absence of PV power. The size of fuel cell can be calculated from the following Equations:

$$P_{FC}(t) = \max\left[-(P_{PV}(t)/\eta_{D1} - P_{Load}(t)/\eta_{inv}).(\eta_{D2fc}.\eta_{fc})\right] \quad (6)$$

Where; η_{D2fc} : Efficiency of fuel cell boost converter, η_{fc}: Efficiency of fuel cell.
$P_{FC}(t)$: Power produced by fuel cell, kW.
Number of fuel cell units can be determined from the following Equation:

$$N_{FC} = \frac{P_{FC}{}^{max}}{P_{FC-rated}} \quad (7)$$

Where; $P_{FC-rated}$: Fuel cell rated power, kW.

III. Control Strategy of hydrogen production

For each hour of the year, the surplus electrical power will be used for the production of hydrogen by electrolyzer power. The control strategy of Hydrogen production can be done as follows:-

$P_{surplus}(t) = P_{PV}(t).\eta_{D1} - P_{Load}(t)/\eta_{inv}$, kW
If $P_{surplus}(t) > 0$ then $P_{Fc-to-Load}(t) = 0$
$P_{Ely}(t) = P_{surplus}(t)$
If $P_{Ely}(t) \geq P_{Ely}^{min}$ and $\leq P_{Ely}^{max}$ then
$\dot{V}_{H2}(t) = \frac{P_{Ely}(t)}{SPC_{Ele}}$ Else $\dot{V}_{H2}(t) = 0$
End else
$P_{FC-to-Load}(t) = \dot{V}_{H2-fc}(t) * \eta_{fc} * SPC_{Ele}$ kW
end
Where,

$\dot{V}_{H2}(t)$: Rate of hydrogen production, Nm^3/h.

$P_{FC-to-Load}(t)$: Power produced by the fuel cell (kW).

The hydrogen storage balance can be expressed by the following equation:-

$$V_{H2}(t+1) = V_{H2}(t) + \dot{V}_{H2}(t).\Delta t - \dot{V}_{H2-fc}(t).\Delta t \qquad (8)$$

Where, $\dot{V}_{H2-fc}(t)$: The hydrogen consumption by fuel cell to feed the load demand during deficit PV power, Nm^3/h.

The amount of H_2 that can be stored and extracted from tank is limited by the minimum and maximum allowable storage levels and is given by the following Equation:-

$$V_{H2}^{min} \le V_{H2}(t) \le V_{H2}^{max} \qquad (9)$$

Where;

V_{H2}^{max} : Maximum storage capacity, Nm^3, V_{H2}^{min} : Minimum storage capacity, Nm^3

IV. Readability of PV/FC system based on LPSP Concept

Because of the intermittent solar radiation characteristics, which highly influence the resulting energy production, reliability analysis has been considered as an important step in PV/FC hybrid power system design process. The LPSP technique is considered to be the criteria for sizing and evaluating a hybrid PV/FC power system. The objective function of the LPSP from time 0 to T can be described by [23]:-

$$LPSP = \frac{\sum_{t=1}^{T} Time\left(P_{availability}(t) < P_{Load}(t)/\eta_{inv}\right)}{T} \qquad (10)$$

Where the power available from the PV/FC hybrid power system at each hour can be expressed as:-

$$P_{availability}(t) = P_{PV}(t) + P_{FC}(t) \qquad (11)$$

V. Economical Calculations based on ACS Concept.

Economical calculations of the system are performed after the unit-sizing program has been run. Three economic metrics are developed to evaluate economics of PV/FC hybrid system which are called Initial Cost of the system (IC), Annualized Cost of System (ACS), and Cost of Electricity (COE). The initial cost of the system is the sum of the products of component cost and its size. Six main components are considered: PV array, Electrolyzer, Compressor, Hydrogen tank, Fuel cell and the other devices. The other devices include controller, inverter and rectifier. The IC can be expressed by the following Equation:-

$$IC = \sum_{k=Componet} C_{cap}(k) * S(k) \qquad (12)$$

Where; $C_{cap}(k)$: Initial capital cost of each component, US$. S(k) :Size of each component, kW, k means each of the components of the system; the PV array (k= PV), the electrolyzer (k= Ele), the compressor (k =Comp), Hydrogen storage tank (k=H2T), the fuel cell (k =FC), the other devices (k=other). The annualized cost of system is composed of the annualized capital cost C_{acap} and the annualized replacement cost C_{arep} for each components. It can be expressed by the following Equation:

$$ACS = \sum_{k=Componet} C_{acap}(k) + C_{arep}(k) \qquad (13)$$

$$C_{acap}(k) = C_{cap}(k).CRF\left(i, Y_{proj}\right).S(k) \qquad (14)$$

$$\mathrm{CRF}(\mathrm{i}, \mathrm{Y_{proj}}) = \frac{\mathrm{i}.(1+\mathrm{i})^{\mathrm{Y_{proj}}}}{(1+\mathrm{i})^{\mathrm{Y_{proj}}}-1} \quad (15)$$

$$\mathrm{i} = \frac{\acute{\mathrm{i}}-\mathrm{f}}{1+\mathrm{f}} \quad (16)$$

$$\mathrm{C_{arep}}(\mathrm{k}) = \mathrm{C_{rep}}(\mathrm{k}).\mathrm{SFF} \quad (17)$$

$$\mathrm{SFF}(\mathrm{i}, \mathrm{Y_{rep,k}}) = \frac{\mathrm{i}}{(1+\mathrm{i})^{\mathrm{Y_{rep,k}}}-1} \quad (18)$$

Where;

$C_{acap}(k)$: Annualized capital cost of each components taking into account the installation cost (including PV array racks, cables, electrolyzer and fuel cell etc.).

$C_{arep}(K)$: Annualized replacement cost of a system component which is the annualized value of all the replacement costs occurring throughout the lifetime of the project. In the studied PV/FC hybrid system, only the electrolyzer and fuel cell need to be replaced periodically during the project lifetime.

i :The annual real interest rate which is related to the nominal interest rate í (the rate at which you could get a loan) and the annual inflation rate f.

Y_{proj} :The component lifetime, year;

CRF :The capital recovery factor.

$C_{rep}(k)$:The replacement cost of the component (H_2 tank and fuel cell), US$;

$Y_{rep,k}$:The component (H_2 tank and fuel cell) lifetime, year;

SFF :The sinking fund factor.

The COE ($/kWh) can be calculated form the following equation [21]:-

$$\mathrm{COE} = \frac{\mathrm{ACS} + \sum_{\mathrm{k=Componet}} \mathrm{C_{amain}}(\mathrm{k}, Y_{rep,k})}{\mathrm{AEG}} \quad (19)$$

Where;

AEG : Annual energy generated form PV and Fuel cell, kWh.

$C_{amain}(k, Y_{rep,k})$: The system maintenance cost of the $Y_{rep,k}$ year, which includes the operation and maintenance, staff cost, the spare costs etc, it can given by:-

$$C_{amain}(k, Y_{rep,k}) = C_{amain}(k, 1).(1+f)^{Y_{rep,k}} \quad (20)$$

VI. System Efficiency

Overall monthly and yearly efficiency of hydrogen system and PV/FC hybrid power system can be calculated by the following Equations:

$$\eta_{PV/H2\ system} = \frac{\sum_{t=1}^{8670}\left(E_{Load}(t) + E_{Loss}(t)\right)}{\sum_{t=1}^{8670} E_{PV,out}(t)} \quad (21)$$

$$\eta_{H2\ system} = \frac{\sum_{t=1}^{8670}\left(E_{Ele}(t)\right)}{\sum_{t=1}^{8670}\left(E_{fc}(t)\right)} \quad (22)$$

Where;

$E_{Ele}(t)$:Hourly electrolyzer energy, kWh. $E_{fc}(t)$:Hourly fuel cell energy, kWh.

4. APPLICATIONS AND RESULTS

A Matlab computer program developed based on the above methodology. Fig. 3 shows the flowchart of this program.

The input data of this program are:

- Hourly solar radiation, kW/m^2

The average radiation of the horizontal surface for the selected site is the first data required for design of PV/FC hybrid system. The data have obtained from the Egyptian Metrological Authority for Aswan site. Table 2 shows the monthly radiation on the horizontal surface.

- Characteristics of PV module type

Based on reference [24], the mono-Si-HIP-205BA3 PV-module from Sanyo with 205W peak capacity is selected in this study.

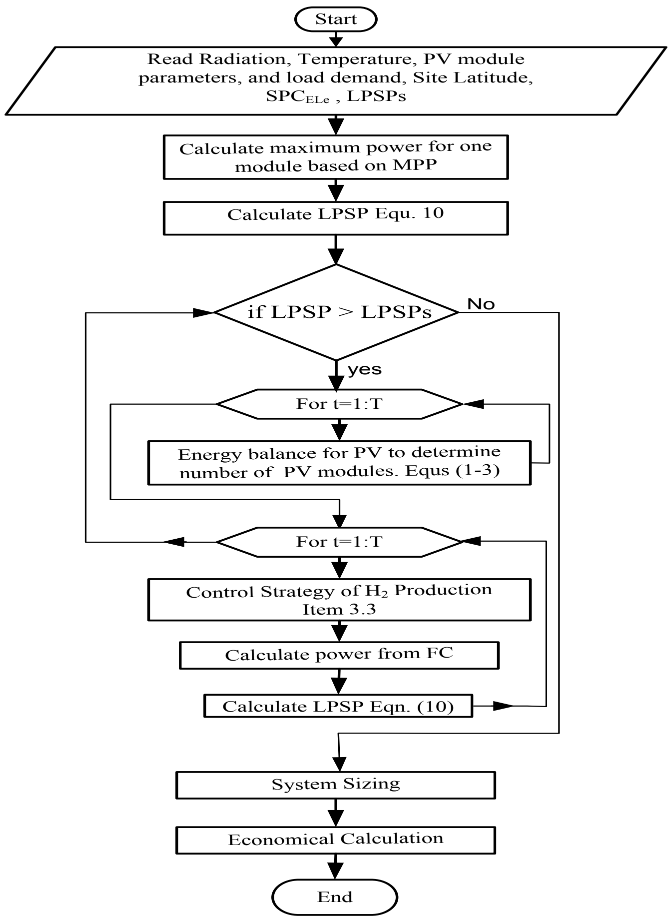

Fig. 3 Flowchart of PV/FC energy system.

Table 2 Global solar radiation values (kW/m^2) at Aswan

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Values	4.7	5.78	6.58	7.87	8.03	8.25	7.9	7.70	7.20	6.50	5.59	4.77

- Site latitude, Degrees.

A PV/FC hybrid system is assumed to be installed at Aswan site, Egypt (24.0875 latitude, 32.8988 longitude) which has the highest profitability, energy production.

- Hourly load demand, kW

The load demand in Aswan city have been evaluated along one complete year of operation, for each month a reference day has been constructed. Fig. 4 shows some of the assumed load demand during January, April, July and October. The minimum and maximum loads are set to 2000 kW and 4000 kW respectively with an average load demand of 2481.11 kW. Yearly energy demand equal to 10.465 GWh.

Given input data, the outputs of this program are:

1. Optimum number of selected PV modules.

The first output of the proposed computer program are the optimum total number of PV modules to feed the whole load demand plus losses, number of modules per panel, and finally number of inverter units. The inverter has an input voltage 600±5% V_{dc}, efficiency 95% at unity power factor and rating 600 kW.

Table 3 shows the construction of the designed PV system under selected type of PV module. From Table 3, it can be seen that, the total number of PV modules to feed whole load demand is equal to 52740 modules divided into 18 inverters. Number of series module per panel is equal to 10. On the other hand, number of parallel panel per string is equal to 293. Total number of modules per subsystem is equal to 2930.

2. Optimum number of selected Electrolyzer

The next output is size of electrolyzer. From computer program it can be found that, the maximum input power to electrolyzer is 9.5 MW to be capable of producing approximately 2001 Nm^3 per hour. Table 4, column six, shows the monthly hydrogen production, from column six, Table 4, it can be seen that the yearly hydrogen production is equal to 48.94833 ton Nm^3.

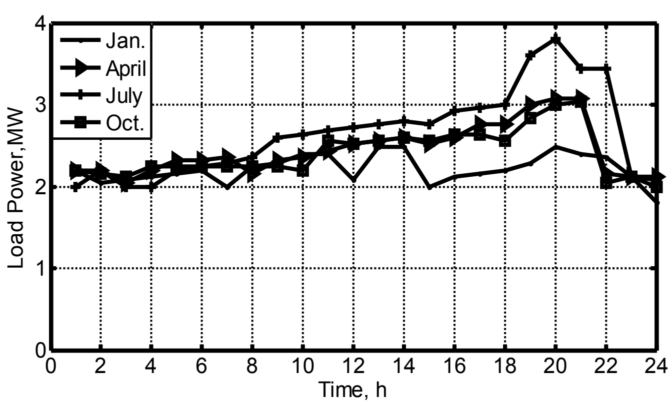

Fig. 4 Variation of the load demand

The electrolyzer should produce enough hydrogen for backup power in the absence of PV power. So, optimum number of electrolyzer unit consists of 19 units with rated 500kW for each one. The limited operational range of the electrolyzer is (20 -100% of rated power). The flow rate of hydrogen gas through hydrogen compressor is equal to 105.32 Nm^3/h (0.00262 kg/s).

3. Sizing of Hydrogen Compressor

The compressor is chosen based on the requirements for the inlet and outlet pressures (30 bar inlet and 200 bar outlet) and gas flow rate (0.00262 kg/ s). Hence, taking a reasonable efficiency value of 0.6, the rated power of the compressor will be 13.22 kW as obtained by (23) as shown as follows:

$$W_c = 14304 \times \frac{293}{0.6} \times \left\{ \left(\frac{220}{30} \right)^{\frac{1.4-1}{1.4}} - 1 \right\} \times 0.00262 = 13.22kW \quad (23)$$

The compressor will run whenever the electrolyzer is at work. The power to operate the compressor will be derived from the PV modules.

Table 3 Design Parameters of PV system

Parameters	Unit
Total Number of Modules	52740
Number of series Module/panel	10
Number of parallel panel /String	293
Number of Modules /subsystem	2930
Number of Converter unit	18

Total number of compressor needed is equal to number of electrolyzers.

4. Sizing the H_2 Storage Tanks

The fourth output of the proposed program is the capacity of the hydrogen storage tank. The hydrogen storage tank is a daily storage; hence it should withhold the amount of hydrogen required by the fuel cell in the absence of radiation. Fig. 5 emphasizes the period of working electrolyzer through route B during sun hours and full in H_2 storage tank. On the other hand, it shows that the fuel cells are working during route C and D. From this figure it can be seen that the maximum storage value equal to 12840 Nm^3-H_2 which is equal to the sizing of the storage tank. According to Van der Waals equation, size of storage tanks is 80 m^3 are installed and are rated for use up to 200 bar, which gives a maximum storage of 12840 Nm^3 hydrogen gas. A 13.22 kW compressor is used to raise the pressure from the electrolyzer to that of the store.

5. Optimum size of Fuel Cell

The size of the fuel cell is the fifth output of the computer program. According to control strategy of H_2 production, the size of fuel cell is equal to 2MW. Optimum number of fuel cell unit consists of four units with rated 500 kW for each one. Table 4, column three, shows the monthly fuel cell energy produced from hydrogen. From Table 4, column three, it can be seen that the yearly fuel cell energy is equal to 4811.74 MWh.

Table 4 Monthly energy and hydrogen production

Month	PV Energy MWh	FC Energy MWh	Load Demand MWh	Electrolyzer Inputted, MWh	H_2 kNm^3	Deficit Energy MWh	$\eta_{H2,sys}$
January	1954.03	224.17	776.8415	1579.92	3067.28	-402.73	14.18
February	2107.14	421.01	787.4873	1740.66	4106.16	-421.01	24.18
March	1973.92	406.23	820.0332	1560.12	4312.33	-406.23	26.03
April	1967.78	372.57	861.3998	1478.96	4174.7	-372.57	25.19
May	2127.45	438	932.5748	1632.88	4697.37	-438	26.82
June	2174.3	386.53	950.2165	1610.62	4580.94	-386.53	23.99
July	2018.68	393.59	936.2248	1476.04	5003.74	-393.59	26.66
August	1967.61	442.57	901.2456	1508.95	4588.19	-442.57	29.32
Sept.	1905.7	445.96	851.6665	1499.99	3752.36	-445.96	29.73
October	2022.73	397.55	847.104	1573.17	3487.68	-397.55	25.27
Nov.	2083.95	443.24	850.754	1676.44	3746.51	-443.24	26.43
Dec.	1982.25	440.32	949.304	1473.27	3446.63	-440.32	29.88
Total (Yearly)	24285.54	4811.74	10464.852	18811.02	48963.89	-4990.3	25.58

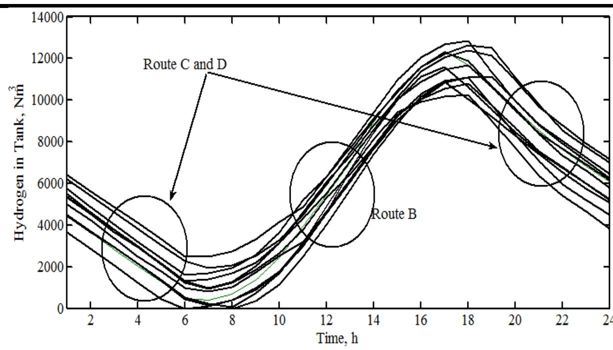

Fig. 5 Hourly Hydrogen flow during simulation time for 12 months

Design of air compression subsystem needed for fuel cell based on mass flow rate of air, inlet temperature, operating pressure of fuel cell and air pressure. The inlet air flow rate can be estimated by the following equation:-

$$\dot{m}_{air,in} = \frac{S_{O2}.M_{air}.P_{fc}}{4.r_{O2}.V_{cell}.F} \quad \frac{kg}{s} \qquad (24)$$

Where;

F : Faraday constant, the charge on one mole of electrons, 96,485 Coulombs.

S_{O2} : Oxygen stoichiometric ratio, 1.5.

M_{air} :Molar mass of air which is equal to $28.85 \times 10^{-3}\ kg\ mole^{-1}$

r_{O2} : Oxygen content in the air, 0.2095.

P_{fc} : Rated power of fuel cell, 500kW. The amount of the inlet air flow rate is equal to 0.3823 kg/s as obtained from (24).

$$\dot{m}_{air,in} = \frac{1.5 \times 28.85 \times 10^{-3} \times 500 \times 1000}{4 \times 0.2095 \times 0.7 \times 96485} = 0.3823 \; kg/s$$

The rated power of the air compressor is equal to 41.70 kW as obtained from the following equation:-

$$W_c = 1004 \times \frac{293}{0.6} \times \left\{ \left(\frac{2}{1}\right)^{\frac{1.4-1}{1.4}} - 1 \right\} \times 0.3823 = 41.7 \; kW$$

The compressor will run whenever the fuel cell is at work. Total number of compressors needed is equal to number of fuel cells. Table 4 shows monthly energy load demand, PV energy, fuel cell energy, electrolyzer energy and deficit energy, monthly hydrogen and monthly PV/FC system efficiency. Negative power is taken from fuel cell and positive power sent to load demand and electrolyzer. Table 4, column two, shows the monthly PV energy produced from solar radiation during day hours. From Table 4, column two, it can be seen that the yearly PV energy is equal to 24285.54 MWh. On the other hand, the yearly energy of load demand is equal to 10464.852 MWh. Form Table 4, it can be seen that the designed PV system, which used the solar cells modules type of mono-Si-HIP-205BA3 PV-module, satisfies the load demand during the year. Deficit energy as shown in Table 4 column seven will be supplied from fuel cell. From table 4 it can be seen that, there is a best matching between the load demand, electrolyzer, PV generation and fuel cell. Fig. 6 shows the Hydrogen system efficiency and PV/FC system efficiency. Exact values for Hydrogen system efficiency are in Table 4 column eight. From Fig. 6, the system has high efficiency compared with diesel system.

Cost Result

The cost of PV/FC needs to be competitive with similar to non-renewable energy source. As a prototype, constructing a system today is relatively expensive. However, efficient and cost effective design can significantly reduce future production costs.

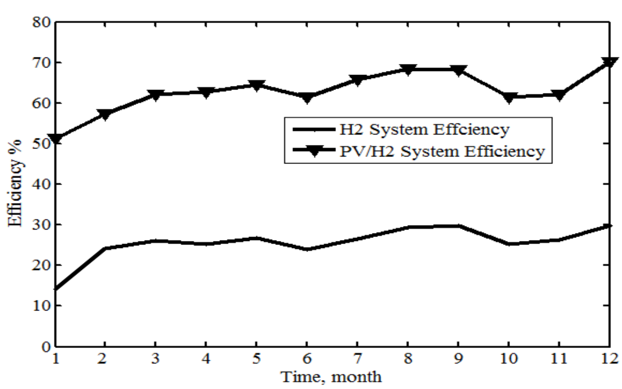

Fig. 6 Monthly efficiency of Hydrogen system

The efficiencies, initial capital cost, replacement cost, operation & maintenance cost in the first year and the lifetime of key components (PV array, Electrolyzer, H_2 tank, Fuel cell and other devices) in this study are listed in Table 5. As seen in the table, PV module cost \$6000/kW while fuel cell and electrolyzer cost \$500/kW and \$500/kW respectively.

PV/FC hybrid power system cost includes the following:-

- IC from (12) equal to \$79089353.44
- The annualized cost of a component includes annualized capital cost and annualized replacement cost.

The calculations proceed as follows

The capital recovery factor= $CRF(i, Y_{proj}) = \frac{i.(1+i)^{Y_{proj}}}{(1+i)^{Y_{proj}}-1} = \frac{0.0222.(1+0.0222)^{25}}{(1+0.0222)^{25}-1} = 0.0525$

Where; $i = \frac{i-f}{1+f} = \frac{0.0375-0.015}{1+0.015} = 0.0222$

The sinking fund factor for compressor

$= SFF(i, Y_{rep,Comp}) = \frac{i}{(1+i)^{Y_{rep,k}}-1} = \frac{0.0222}{(1+0.0222)^{15}-1} = 0.0178$

The sinking fund factor for electrolyzer, compressor and other devices can be calculated as follows:

$$SFF(i, Y_{rep,k}) = \frac{i}{(1+i)^{Y_{rep,k}}-1} = \frac{0.0222}{(1+0.0222)^{15}-1} = 0.0178$$

Annual replacement cost and totals ACS by (13) for the system is shown in Table (5).

- Cost of Electricity, COE

The COE can be calculated from (19) which equal to

$$\text{COE} = \frac{5481077}{24285540} = 0.22569 \text{ US \$/kWh}$$

The calculations proceed as follows:

Operating and maintenance annual costs of the system can be calculated using (20) as shown in Table 6 which is equal to 976568.04 US \$. On the other hand, ACS of system which is equal to 4504602.59 US \$, while AEG is equal to 24285540 kWh.

Fig. 7 shows the breakdown of the annualized costs of the proposed PV/FC system. From this Figure, it can be seen that the PV panels have the largest cost component. COE is very high compare to diesel one. But PV power generation with fuel cell is considered a green power supply source, an environmental benefit (savings) may be considered.

Table 5 Expected costs and lifetime for the system components (2015-2020) [25-27]

	Eff. %	Initial capital cost	Replacement cost	O&M cost in first year	Life time (year)	Interest Rate i %	Inflation Rate %
PV array	14	6000US \$/kW	Null	50 US \$/kW	25	3.75	1.5
Electrolyzer	74	500 US \$/kW	400	10 US \$/kW	15		
Compressor	70	150US \$/kW	100 US \$/kW	1 US \$/kW	15		
H_2 Storage Tank	100	22.8US \$/Nm^3	15 US \$/Nm^3	1 US \$/Nm^3	10		
Full Cell	47	500 US \$/kW	400 US \$/kW	10 US \$/kW	10		
Other components	95	300 US \$/kW	250 US \$/kW	5 US \$/kW	15		

Table 6 Summary of results for system cost

Cost / Comp.	IC, US $	$C_{acap}(k)$, US $	$C_{arep}(k)$, US $	$C_{amain}(k)$, US $	ACS, US $	ACS+ $C_{amain}(k)$	Eff. %
PV	66398400	3488107	0	802837.1	3488107.27	4290944.37	77.43
Electrolyzer	4750000	249531.8	101045.7	137839.8	350577.5	488417.30	7.78
Comp.	171000	8983.14	3031.37	1654.08	12014.51	13668.59	0.27
H2 Tank	1824	95.82	207.27	58.04	53.41	111.45	0.00119
FC	1000000	112592.8	35606.22	29018.91	148199	177217.91	3.29
Others	6769800	355637.9	150013	5160.11	505650.9	510811.01	11.23
Total US $	79091024	4214948.46	289903.56	976568.04	4504602.59	5481170.63	100

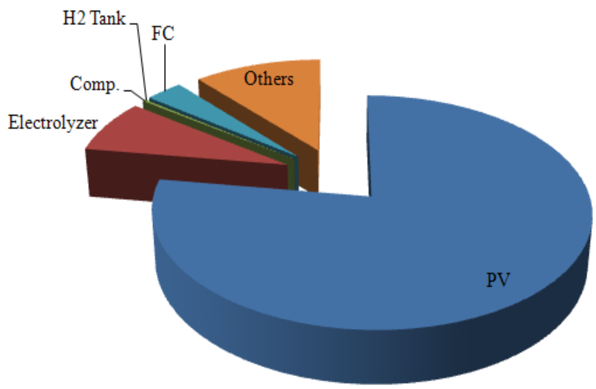

Fig. 7 Break down of annualized cost of PV/FC system

5. Conclusions

The PEM fuel cells are a viable alternative to diesel engine generators as renewable, clean, safe energy and high efficiency for the next century. 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 power system generation. PV/FC hybrid power system is proposed as an ultra low emission energy system. Computer program and control strategies have been developed to coordinate the optimal design and operation of the PV/FC hybrid power system components. The proposed control strategy can be easily adapted and applied to similar renewable energy systems which contain multiple components working together. Moreover a complete economic picture of the system under study has been proposed. Performance of the system components and control strategies were found to be satisfactory. From simulation results the system being installed at the Aswan site consists of a 12 MW PV array coupled to a high pressure bipolar alkaline electrolyzer, rated 9.5 MW and fuel cell rated with 2MW. The proposed method can be broadly implemented in different cases of the optimization of hybrid PV/FC power system for varieties of load profile and meteorological condition.

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