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Energy Management for Stand Alone Hybrid Photovoltaic – PEM Fuel Cells Systems

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Abstract

A better performance of photovoltaic (PV) generator is obtainedat high insolation. But at high insulation, the temperature of the PV system increases and leads to the drop down of the performance of the system making the system unable to supply the load. The problem becomes more difficult with irregular solar insolation, the system experience variation in his output, which is not good for the user.To overcome the problem, one of the solutions, may be the best, is to couple the PV generator with proton exchange membrane fuel cell (PEMFC) system particularly for stand-alone system for household demand. The simulation results show that with a good energy management, the PV-PEMFC hybrid system can supply the load in summer as well in winter time.This paper presents the energy management for the control of energy flow for a PV-PEMFC system in particular cases of household demand in Durban, South Africa.

Keywords: photovoltaic, fuel cell, hybrid system, energy management.

INTRODUCTION

The diminishing of fuel sources and the world-wide environmental concerns particularly on ecosystem pollution and global warming have made renewable energy systems more interesting[1][2].Apart the interested above, the increase demand of electrical energy, the green effect gas and global warming as well as the high installation cost of grid in remote area constitute the energy motivation behind the renewable energy technology[3] [4].

Many sources of renewable energy are available with popular sources listed from solar energy, hydro-energy, wind energy, fuel cell energy, battery energy, etc.… between them; solar energy is one of the most important due to his availability (mostly everywhere) and can be directly converted from solar energy to electrical energy[5].The conversion of solar energy to electrical energy is made possible by the use of photovoltaic modules. This device converts the irradiance or solar insolation into electrical energy, more details on the subject can be found in [6]. Under different insolation levels, the PV output can experience large variances [1][6]which are not good for the user. To remedy to this problem, PV systems can be integrated to two or more sources of energy with or without storage systems[1][6][7][8][9]to produce a hybrid system[10][11][12]. The purpose of a hybrid power system is to produce as much energy from renewable energy sources to ensure the load demand [13].

The fuel cell is the best candidate to be integrated with a PV system. This technology presents the advantages of being a green power source with higher efficiency than conventional power plants, very low noise and flexible modular structure[3][2][4].There are different types of fuel cells used in different applications, mainly portable, stationary and transport applications. The most used type of fuel cell for small and medium stationary application is the proton exchange membrane fuel cell (PEMFC). It can be coupled with PV array to supply electrical energy for household demand and can operate as an independent power source or as a storage system. The PEMFC as a fuel cell technology has a disadvantage of poor dynamic response to transient power demand [14]so that the battery bank or super capacitors have to be incorporated to the hybrid PV – PEMFC systems.

The main focus of this paper is on the energy management of the system for domestic use.

SYSTEM DESCRIPTION AND SIZE

The system studied is a hybrid photovoltaic-fuel cell system equipped with a battery bank, an electrolyser and ahydrogen storage tank.

The study is based on a hybrid PV – PEMFC system constitute of photovoltaic array of 24 Q-PEAK 250 monocrystalline solar modules with a fixed orientation collector for a DC STC rated power of 6000 W able to provide about 8500 kWh/year, more than the average of 8300 kWh/year needed for Durban modest household electrical demand. The parameters for the PV array generator are given in the Table 1. Details about the design and size of the PV generator can be found in [16].

Table 1: PV array parameters

Parameters	Values
Module Type	Q-PEAQK 250 Monocrystalline Silicon
Array Size	42.60 m²
Number of Strings	24
Number of Modules per String	8
Maximum Voltage at MPP (V_{PM})	180.06V
Open Circuit Voltage (V_{OC})	222.90V
Maximum Current at MPP (I_{PM})	33.64A
Short Circuit Current (I_{SC})	A

To overcome the variance of the PV array generator output under different insolation levels, a 2000 Horizon PEMFC with characteristics in table 2 is coupled to the PV array generator.

Table 2: Fuel cell parameters

Parameters	Values
Type of fuel cell	Horizon PEM FC
Number of cells	48
Rated power	2000 W
Performance	28.8 V @ 70 A
Max stack temperature	65 ˚C
H_2 Pressure	0.45 – 0.55 bar
Hydrogen purity	≧ 99.995 % dry H_2
Flow rate at max output	36 L/min
Startup time	≦ 30 s at ambient temperature
Efficiency of stack	40 % @ 28.8 V

This fuel cell is used with an electrolyser to produce hydrogen from water using electrical energy from the PV array generator.

The lithium – ion battery bank composed of 4 batteries connected in series' is added to the system to compensate the poor dynamic response of fuel cells to transient power demand. This type of battery has a high energy density, a long cycle life and a relatively low self – discharge rate. Table 3 gives more details on the battery.

Table 3: Battery parameters

Parameters	Values	
	12 V / 120 Ah	**96 V / 120Ah**
Capacity	120 Ah	120 Ah
Output voltage	9 – 13.5 V	72 – 108 V
Continuous current (0.5C)	45 A	45 A
Energy	5.4 kWh	10.5 kWh
Life cycle (0.3C, 80% DOD)	1500	1500
Maximum discharging current (2C in 10s)	90 A	90 A

All the sub-systems and the load are connected to the busbar through different power electronic interfaces together constituting the power conditioning for the hybrid system as shown in figure 1.

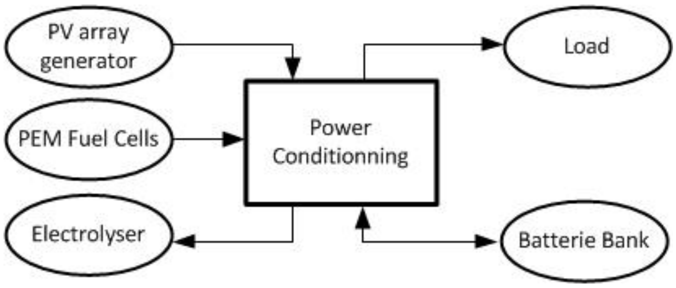


Figure 1: Hybrid PV – PEMFC electrolyser system equipped with a battery bank

SYSTEM CONFIGURATION

There are several ways to integrate different alternative energies sources to forma hybrid system. Different configurations are competing for an optimal design of hybrid photovoltaic-fuel cell systems.

Two types of configurations, the direct current (DC) coupled system and the alternating current (AC) coupled system are used based on reference busbar[2][15], each with its advantages and disadvantages [14]. In this paper the DC coupled system is used as both supplied sources are DC. To increase the flexibility of the system, an inverter is inserted between the bus bar and the load. The topology studied is given in figure 2.

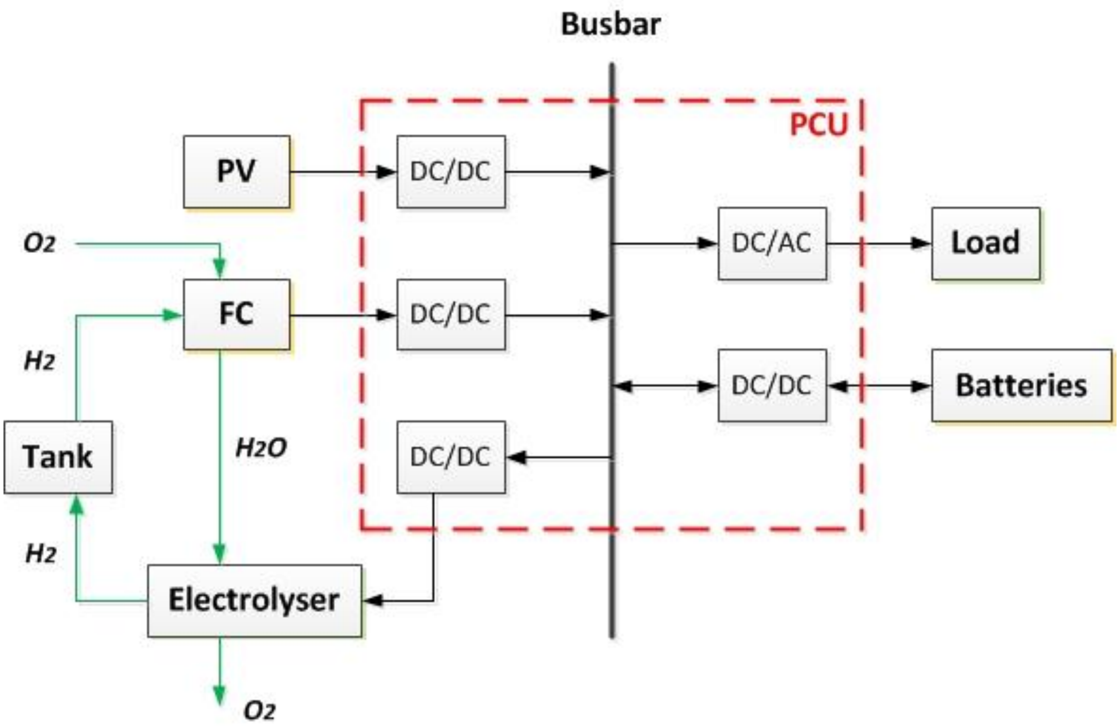


Figure 2: Hybrid PV – PEMFC Topology

To obtain a correct coupling of different sources to the busbar, they must have equal voltage. This is realised by using electronic interface systems.

SYSTEM MODELLING

Photovoltaic model :

The PV model is based on the calculation of the output current as function of the voltage. To simulate this generator coupled to PEM fuel cells stack and battery bank, the one diode-one resistance model is used.This model presents the advantage of low number of parameters to be determinate and low simulation time compared to one diode model two resistances and two diode model two resistances.The two resistances models are more accurate compare to one resistance model, but the difference between results are insignificant. More details on different models are given in [17][18]. For the simplicity andshort running time, the one diode one resistance model is used and mathematic the model is given in the Equation (1):

$$I = I_{sc} - I_o\left(e^{q\left(\frac{V+IR_s}{AkT}\right)} - 1\right) \qquad (1)$$

where Iis cell current (the same as the module current) (A); I_{sc} is short circuit current which is equal to photocurrent (A); I_o is dark saturation current (A); q is electronic charge (1.602x10^{-19}C); k *is* Boltzmann's constant (1.381 × 10^{-23} J/K); A is idealizing factor; T is cell temperature (K); V is cell voltage (V) and R_s is shunt resistance (Ω)

The equation for R_s is derived by differentiating the Equation (1) and then rearranging it in terms of R_s:

$$R_s = -\frac{dV}{dI} - \frac{AkT/q}{I_o e^{q\left(\frac{V+IR_s}{AkT}\right)}} \qquad (2)$$

At the open circuit, the voltage V = V_{oc} and the current I=0 so thatEquation (2) gives the value of R_s as:

$$R_s = -\left.\frac{dV}{dI}\right]_{V_{oc}} - \frac{AkT/q}{I_o e^{\frac{qV_{oc}}{AkT}}} \qquad (3)$$

where $-\left.\frac{dV}{dI}\right]_{V_{oc}}$ is slope of the *I-V* curve at the V_{oc}obtained from the I-V curve in the solar cell datasheet; V_{oc} is the open-circuit voltage of cell, found in the solar cell datasheet.

1.1. Fuel cell model

The FC model is based on the calculation of the output voltage as a function of the current. The most popular model for PEM fuel cell is the algebraic sum of Nernst voltage, the activation voltage, the ohm's voltage drop and the concentration voltage[19][20]. Its mathematic model is given in the Equation (4):

$$V_{fc} = E_{oc} - NAln\left(\frac{i_{fc}}{i_o}\right) - i_{fc}r_{fcin} \qquad (4)$$

Where E_{oc} is the open circuit voltage (V); N is the number of cells; A is the Tafel slope; i_{fc} is fuel cell output current (A); i_o is fuel cell exchange current (A) and r_{fcin} is internal resistance (Ω)

The ideal open circuit voltage for a fuel cell is obtained by the Nernst relation given in Equation (5):

$$E_{oc} = K_c E_n \tag{5}$$

where K_c is voltage constant (-) and E_n is Nernst voltage (V).

The PEM fuel cell operates at a temperature between 40^0C - 80^0C, and for fuel cells operating at temperatures below 100^0C, the Nernst equation is given by Equation (6)[32]:

$$E_n = 1.229 + (T - 298)\frac{-44.43}{2F} + \frac{RT}{2F} ln\left(p_{H_2} p_{O_2}^{1/2}\right) \tag{6}$$

where T is temperature of operation (K); R is gas constant (8.3145 J/molK); F is Faraday constant (96485 As/mol); p_{H_2} is partial pressure of H_2 (atm) and p_{O_2} is partial pressure of O_2 (atm). More details about fuel cell model can be found in [21][22][20].

Battery model:

The battery model depends on the operating mode of the battery in the system. Two models are defined based on the discharge mode and the charge mode of the battery and are given in Equations (7) and (8):

- Discharge mode (i*>0) model:

$$V_b = E_o - K\frac{Q}{Q - it} i^* - K\frac{Q}{Q - it} it + Aexp(-Bit) - r_b i_b \tag{7}$$

- Charge mode (i* < 0) model:

$$V_b = E_o - K\frac{Q}{0.1Q - it} i^* - K\frac{Q}{Q - it} it + Aexp(-Bit) - r_b i_b \tag{8}$$

where E_o is constant voltage (V); K is polarization constant (V/Ah); i^* is low frequency current dynamics (A); i_b is battery current (A); Q is maximum battery capacity (Ah); A is exponential voltage (V) and B is exponential capacity (Ah).

In hybrid PV – PEMFC equipped with battery bank, the state of charge (SOC) of the batteries is the parameter used as gauge of the electrical energy stored in the batteries. The SOC of the battery is given by Equation (9) [25]:

$$SOC\ (t) = \frac{\int_{t_o}^{t} I_b(\tau)\, d\tau}{Q_o} * 100 \tag{9}$$

where $I_b(t)$ is the charging current, t_o is the initial charging time, t is the final charging time, Q_o is the total charge the battery can hold.

In practice, the SOC of the batteries is kept in certain limits to improve the life time of the batteries.

Electrolyser model:

Different V-I models for electrolyser have been developed [9]. The basic form of V-I curve for a known operating temperature is given by Equation (10):

$$V = V_{rev} + \frac{I}{A} r + slog\left(\frac{I}{A} t + 1\right) \tag{10}$$

where V is operating cell voltage (V); V_{rev} is reversible cell voltage (V); r is ohmic resistance of electrolyte (Ω); s and t are coefficients for over-voltage on electrodes (Ωm^2); A is area of electrode (m^2) and I is current through cell (A).

The electrolyser operate at the inverse of fuel cell stack, the quantity of hydrogen produced is set by the current consumed by the electrolyser. This current is obtained by the power allocated to the electrolyser by the energy management system.

Power conditioning :

The power conditioning unit (PCU) is constituted by the electronic interfaces [14]connecting different components to the busbar[9]. The PV generator, the FC and the electrolyser are connected to the busbar via one direction DC/DC converters, while the battery bank is connected to the busbar via a bi-directional DC/DC converter. The DC/AC inverter is used to connect the load to the busbar and increase the flexibility of the system. This is related to the configuration or topology adopted and represent in figure2.

ENERGY MANAGEMENT

Generally, in photovoltaic hybrid systems, PV subsystem works as a primary source. It converts solar irradiance into electricity provided to a DC bus. During periods in which the PV system cannot provide the full charge, especially when the load exceeds the power produced by the PV generator, the PEM fuel cell then supplies the electrical energy to overcome the load demand by sharing the load with the PV generator. In case of worse scenario, during night for example, the load is then supplied with the energy produced exclusively by the fuel cell subsystem which produces electrical energy using hydrogen to supply the DC bus. As the fuel cell subsystem needs more time to provide the rated power and the output should only be increased slowly after start up, batteries are used to assist the fuel cell subsystem. As well batteries are used to back up the fuel cell subsystem at peak load or transient load.

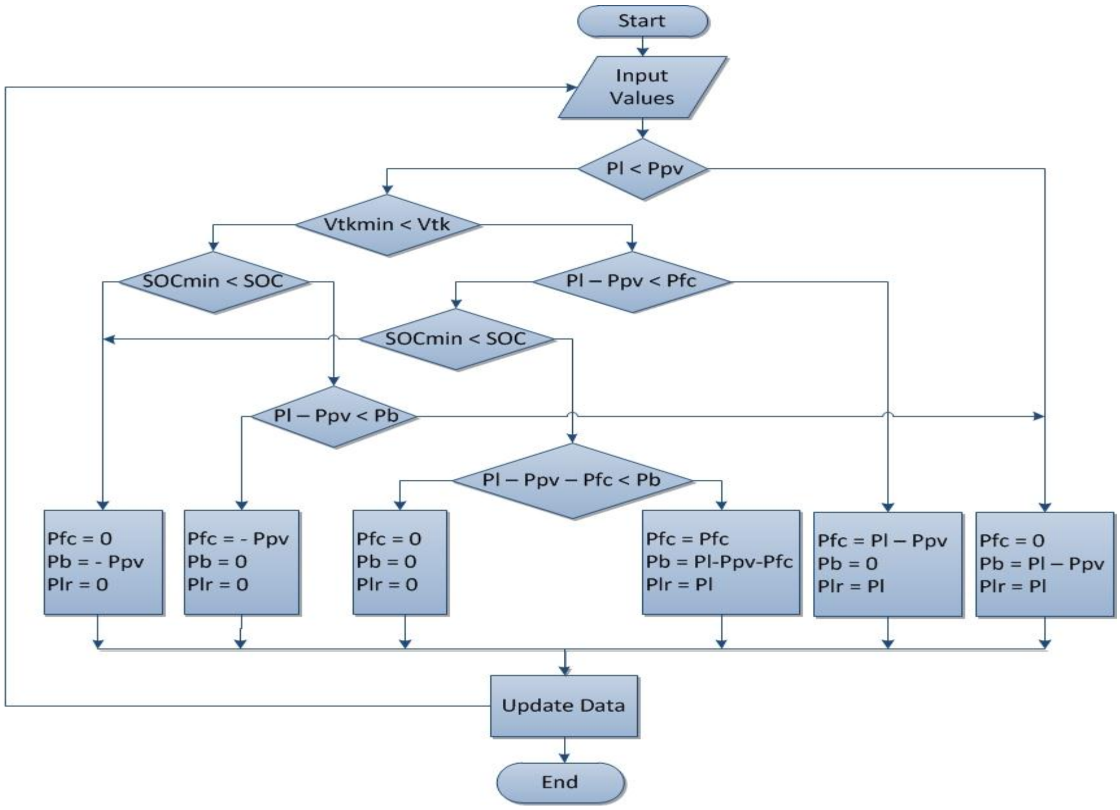


Figure 3: Flowsheet diagram of the PV-PEMFC hybrid system energy management

Over a short period of time, if the PV-FC cannot cover the full load or neither the PV nor the FC subsystems deliver energy to the load, battery bank automatically starts feeding the load with energy stored and disconnect if the SOC reach the minimum. In the case of high insulation with a low load connected to the system, the PV generator supplies electrical energy to the load. The extra energy produced by this subsystem is used to charge batteries until the maximum SOC of batteries is reached than to produce hydrogen from water by the electrolyser. The hydrogen produced is stored in a tank and can be used by the fuel cell to produce electricity in case of need.

SIMULATIONS AND ANALYSIS OF RESULTS

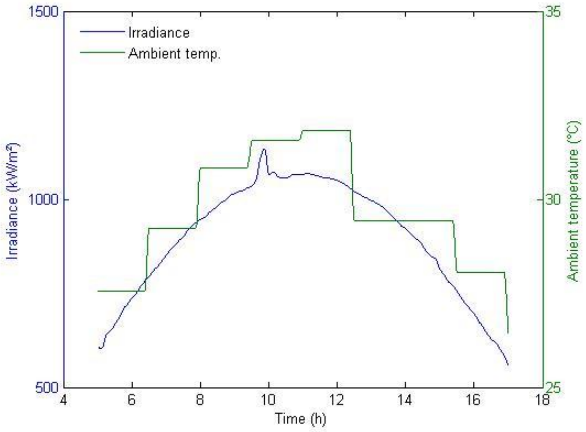
The simulation of the system is done using Matlab package. Four different days are used, two winter days and two summer days. The same load is used for simulation for four particular days, two summer days and two winter days. For each season, one day correspond to the regular insolation and the other to the irregular insolation. Results for simulation are given in Figure4 to Figure7.

The PV generator supplied the load with interruptions in summer regular insolation day. The power supplied to the load is higher compared to winter days as seen in figures4A, with a mean power supplied relative error of 38.4% and rms value of 32.0%. While in summer irregular insolation, the load is supplied by intermittence with a power supplied main relative error of 45.7% and rms value of 32.0% as seen in Figures 5A.

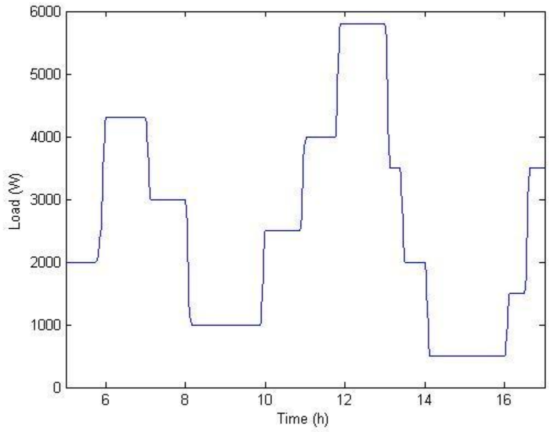
In winter irregular insolation day, the load is supplied by interruption by the PV generator due to variations of insolation reaching very low values that can't provide enough power to the load in winter regular insolation as seen in Figures 6A. The power supplied mean value is 89.5% and the rms value is 81.5%. The PV generator supplies with interruptions in winter regular insolation day. The power supplied error mean value is 77.7% and the rms value of 67.8% as seen in Figures 7A.

Compared to the PV generator, the PV-PEMFC hybrid system supplies the load almost continuously in summer regular insolation day with interruption between 11:45 and 12:30 due to the load peak before storage system to produce sufficient energy to compensate the PV generator as seen in Figures 4B. The power relative error mean value is 16.6% and the rms value is 12.2%. In summer irregular insolation day the PV-PEMFC supplies the load by intermittence with high output energy. The power supplied relative error mean value is 14.3% and the rms value is 7.6%. Those values are low compared to the summer regular insolation day because of high insolation reaching sometimes 1300W/m^2 as seen in Figures 5B.

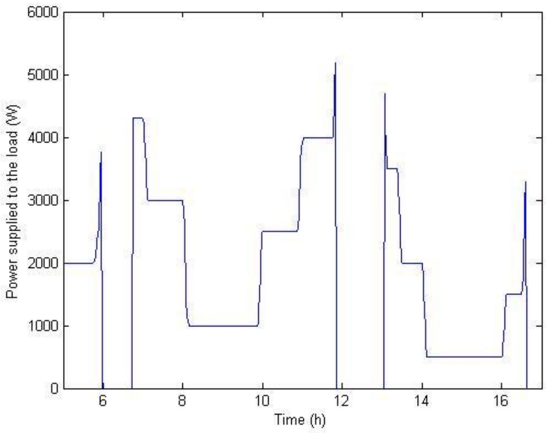
The performance of the PV-PEMFC hybrid system in winter irregular insolation day is shown in Figures 6B. The load is supplied by intermittence with good performance obtained before 11:00. The power supplied relative error mean error is 45.3% and the rms value is 34.9%. The winter regular insolation day is characterised by a better performance of the system providing almost the total energy need by the load as seen in Figures 7B. This is meanly justified by the regularity of the insolation, the low operating temperature and the impact of storage systems. The power supplied relative error mean value is 13.6% and the rms value is 6.2%.



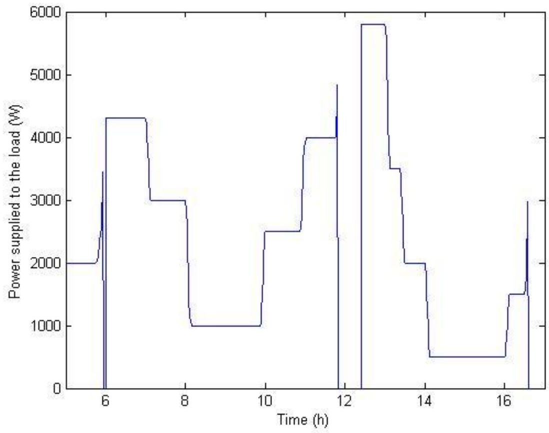
A1) Environmental data



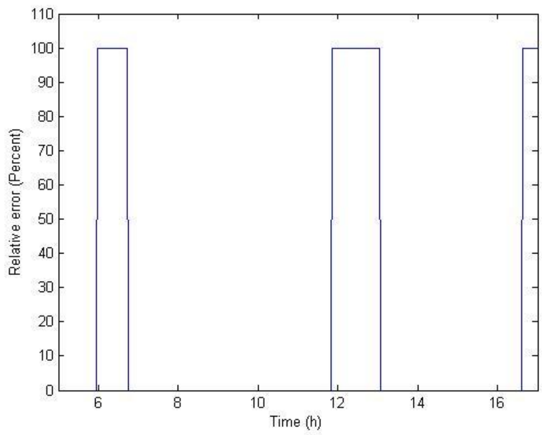
B1) Load profile for simulation



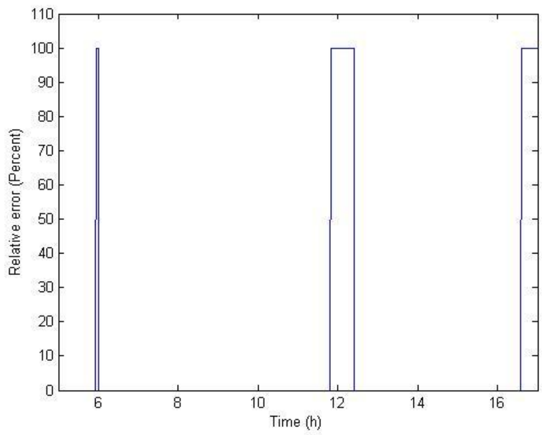
A2) Stand-alone PV generator power supplied to the load



B2) Stand-alone hybrid PV-PEMFC generator power supplied to the load

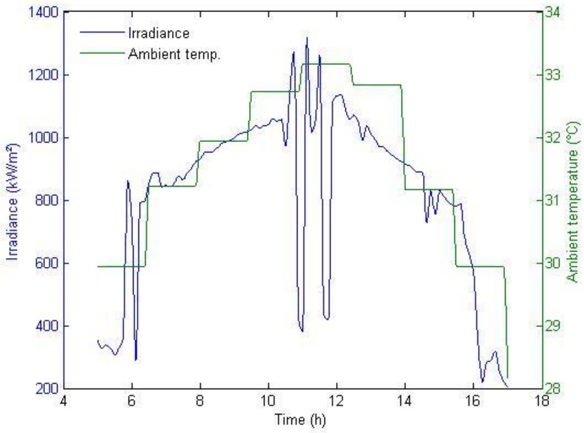


A3) Stand-alone PV generator power relative error

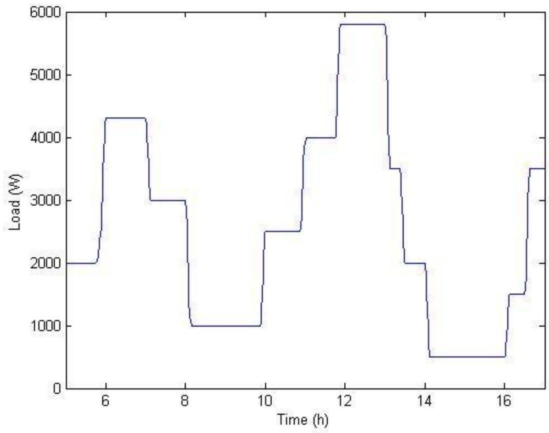


B3) Stand-alone hybrid PV-PEMFC generator power relative error

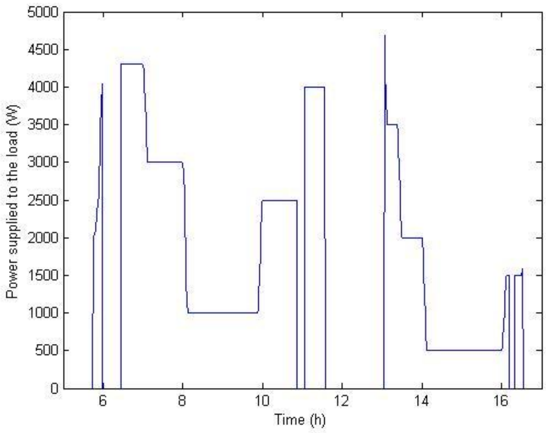
Figure 4: Simulation results for summer day of 2010/12/22



A1) Environmental data



B1) Load profile for simulation



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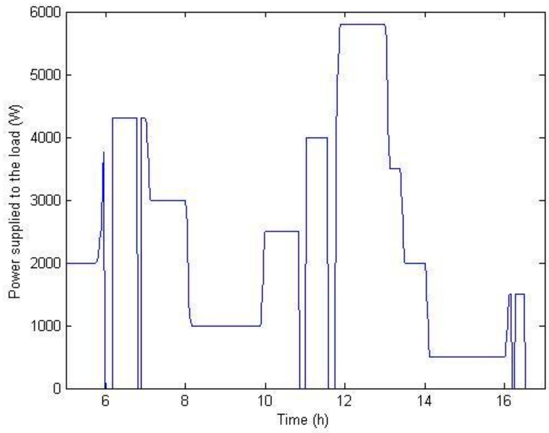
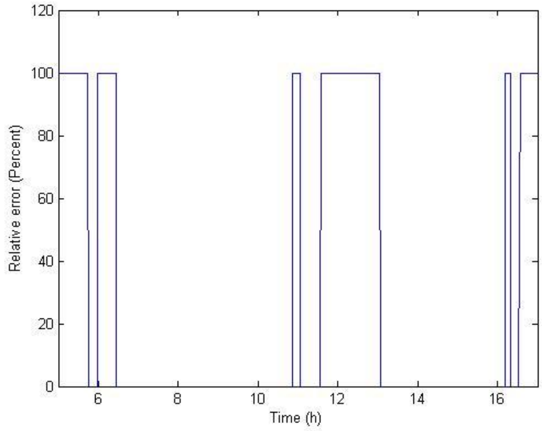
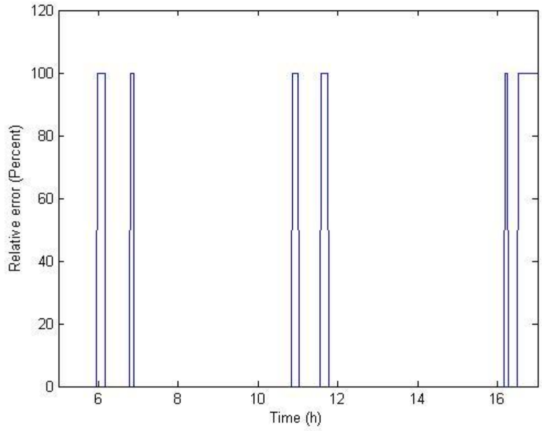


B2) Stand-alone hybrid PV-PEMFC generator power supplied to the load

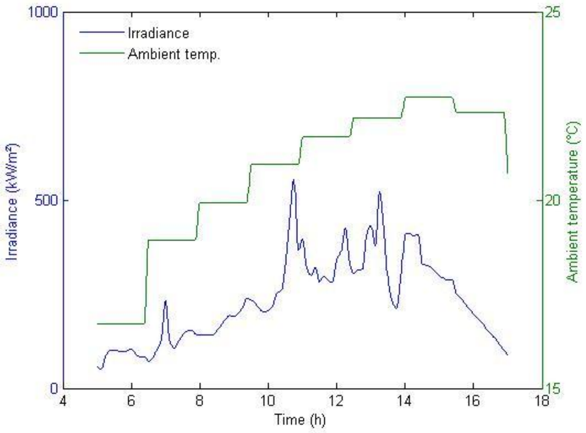


A3) Stand-alone PV generator power relative error



B3) Stand-alone hybrid PV-PEMFC generator power relative error

Figure 5: Simulation results for summer day of 2010/12/29



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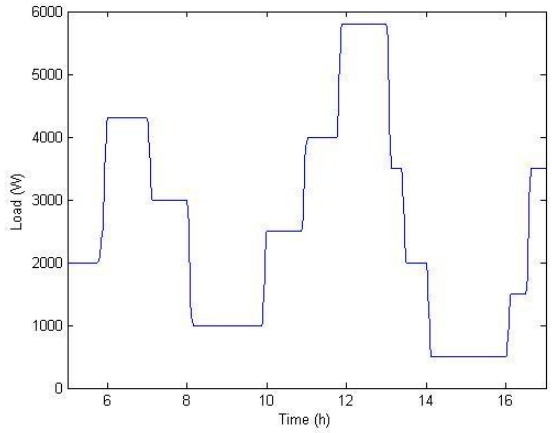
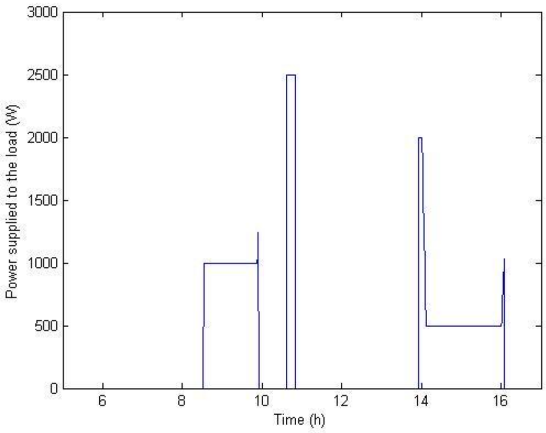
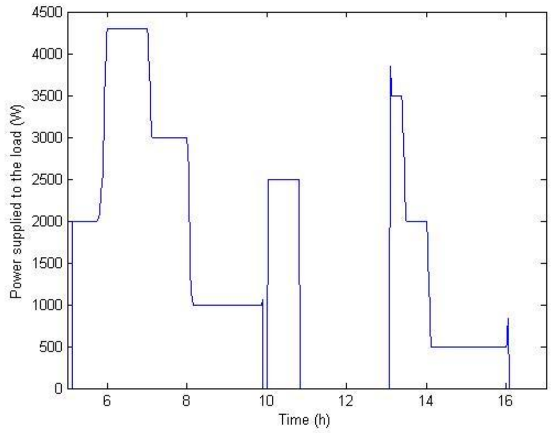


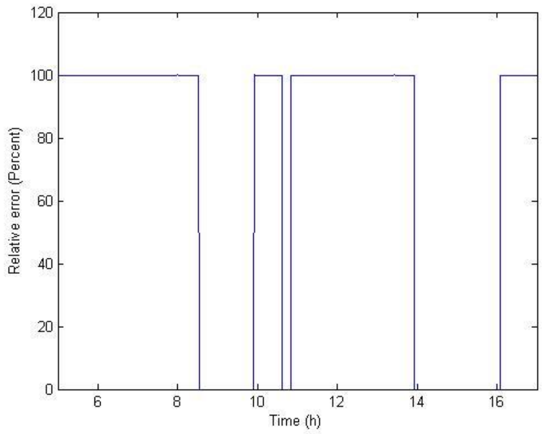
B1) Load profile for simulation



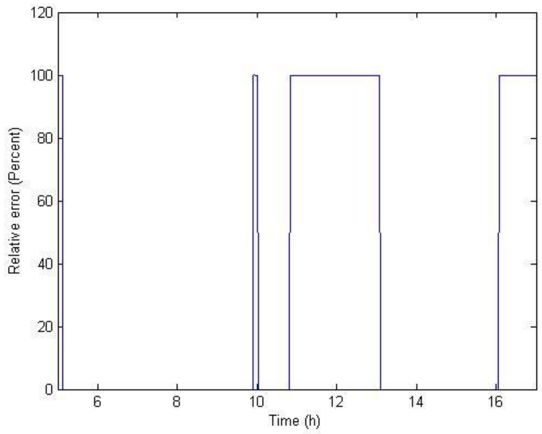
A2) Stand-alone PV generator power supplied to the load



B2) Stand-alone hybrid PV-PEMFC generator power supplied to the load

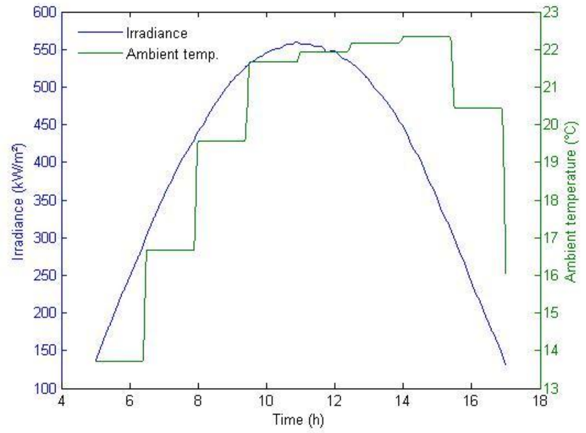


A3) Stand-alone PV generator power relative error



B3) Stand-alone hybrid PV-PEMFC generator power relative error

Figure 6: Simulation results for winter day of 2011/06/07



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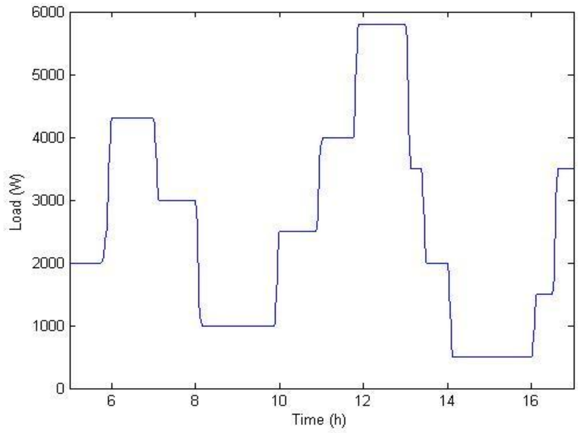
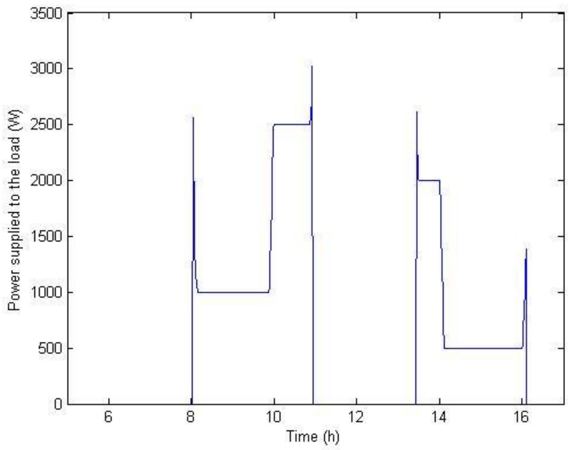
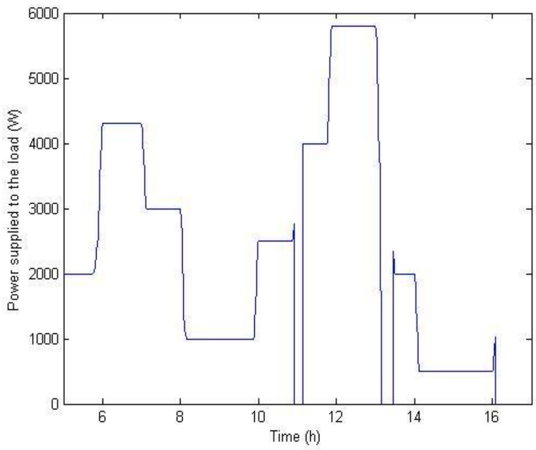


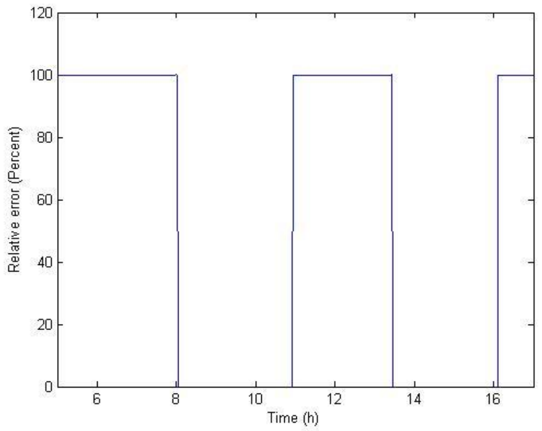
B1) Load profile for simulation



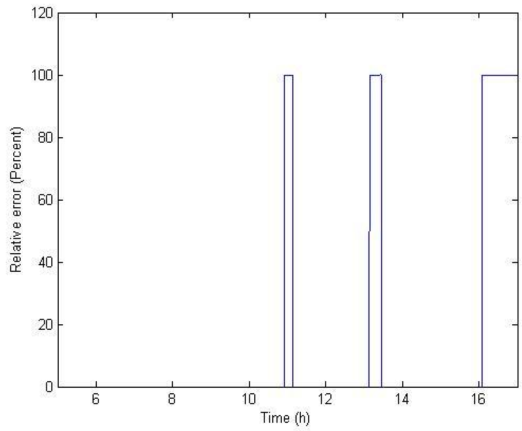
A2) Stand-alone PV generator power supplied to the load



B2) Stand-alone hybrid PV-PEMFC generator power supplied to the load



A3) Stand-alone PV generator power relative error



B3) Stand-alone hybrid PV-PEMFC generator power relative error

Figure 7: Simulation results for winter day of 2011/06/28

Simulation results are summarised in Tables 3 and 4. It can be seen that PV-PEMFC hybrid system present better performance compared to conventional stand-alone PV system.

Table 3: Simulation results for stand-alone PV generator

Date	Day type	Power supplied to the load (W)		Relative error (%)	
		Mean value	Rms value	Mean value	Rms value
2010/12/22	Regular summer insolation	1579.2	2072.9	38.4%	32.0%
2010/12/29	Irregular summer insolation	1390.6	1972.7	45.7%	35.3%
2011/06/07	Irregular winter insolation	269.61	563.17	89.5%	81.5%
2011/06/28	Regular winter insolation	570.14	982.05	77.7%	67.8%

The performance of the PV-PEMFC system is observed in winter regular insolation day follows by summer irregular insolation day and then by summer regular insolation day. This is justified by the regular insolation and low temperature below $25^{o}C$ in regular winter insolation, while summer irregular insolation day present high insolation than summer regular insolation day with peaks of about 1300 W/m^2, the system operating at temperatures sometimes above $32^{o}C$ in both summer days.

Table 4: Simulation results for stand-alone hybrid PV-PEMFC generator

Date	Day type	Power supplied to the load (W)		Relative error (%)	
		Mean value	Rms value	Mean value	Rms value
2010/12/22	Regular summer insolation	2137.8	2676.1	16.6%	12.2%
2010/12/29	Irregular summer insolation	2196.4	2818.8	14.3%	7.6%
2011/06/07	Irregular winter insolation	1402.8	1984.8	45.3%	34.9%
2011/06/28	Regular winter insolation	2213	2861	13.6%	6.2%

CONCLUSION

There is a lot of disturbances in power supplied to the load in summer as well as in winter with irregular insulations, but the PV-PEMFC performs much better in this situation than conventional stand-alone PV generator as shown. The better performance of the system to handle the load with variations in solar insolation is observes more particularly in summer then winter as expressed by power supplied relative errors as the PV generator produced enough power to supply the load and more efficiently to store energy. This is achieved with a better energy management as provided in this paper.

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