An Efficient Technique for Power Management in Hybrid Solar PV and Fuel Cell System

Krishan Kumar, M.A. Ansari, Shreshth Kumar Varshney, Vinay Rana and Arjun Tyagi

ABSTRACT

In this paper, a hybrid system with solar PV, fuel cell (FC), and battery energy storage system (BESS) for the efficient power-management scheme have been proposed. The combined system is designed for the load of 1.2 kW consist of 0.9 kW AC and 0.3 kW of DC load. A power-management scheme is implemented and the modeling of the PV array with maximum power point tracking technique is used here. This hybrid system is providing power to a mutual DC bus from where the AC and DC type of loads are taking the supply. The power-management scheme used in this paper depends on power sharing and regulation of voltage at DC bus. The hybrid system provides the advantage of the reduction in capacity of battery banks to be used as it is integrated with a fuel cell system.

1. Introduction

The rise in the standards of living and the increase in demand of electricity have led to the exploitation of conventional sources of energy, especially in the depletion of fossil fuels, which is in form of a major part of conventional sources. Also, the generation of power from the fossil fuels adversely affects the environment. So, it is necessary to move toward new sources of energy and ways of integrating them with the existing system [1]. The renewable sources of energy like wind, solar, hydro, biomass, etc. provide a very promising scope from the above problem. Also, the generation of power from these sources do not affect the environment.

Among all the renewable sources of energy, the solar energy is very abundantly available. The extraction of power from solar energy can be done in various ways like solar energy to thermal energy, conversion of solar...
energy directly to electricity using PV technology or indirect conversion of solar energy to electricity using concentrators. The solar cells which work on the photovoltaic technology can convert solar irradiation directly to electricity and also the cost of fabrication of these cells is less. Therefore, solar PV systems are widely used on small scale as well as large scale for the production of power. One of the main drawbacks of solar PV system is that it is not available in the night. Therefore, we cannot completely rely on solar PV systems to obtain a continuous 24-hour power supply. Therefore, solar PV systems are used with alternate sources of energy that provide power when the solar power is unavailable. Certain other sources like wind, diesel, fuel cell, and BESS are generally used with solar PV systems [2].

Wind energy conversion systems (WECS) can be integrated with solar PV systems to provide large power demands. WECS cannot be used with solar PV systems for providing power on a small scale like residential applications [3–5]. Sometimes, diesel is also used as a backup with solar PV systems. The operating efficiency of a diesel generator is very high but operating diesel generator for large durations is not economical and environment-friendly. So, we use fuel cell (FC), FC technology work on the principle of conversion of chemical energy of fuels into electrical energy. They provide a very high energy density. A fuel cell stack can be used as an independent power source or it can be integrated into a system with a separate electrolyzer.

The fuel cell stack is considered as an independent source of power due to the presence of various pipes and valves to facilitate the flow of fuel. The fuel cell has slow dynamics. So, it takes some time to initially build up the voltage, when it is switched on. Therefore, some other source of power is needed for a fuel cell that has fast response to overcome its shortcoming. The secondary storage system also called as BESS can be used for this purpose. Batteries can provide a very high-power density but they cannot provide power for a very long duration. Also, BESS of large capacity are bulky, increase cost, and require maintenance [6]. The solar PV array with fuel cell and BESS have been used to make a hybrid system to overcome the shortage of power. To operate these sources efficiently power-management scheme is employed in this work.

Study of renewable energy sources (RESs) has been discussed earlier with hybrid system. Power-management schemes play a very important role when we discuss the hybrid system or microgrids with RESs [7]. It is very important to supply uninterrupted power for various applications [8]. So, the power-management schemes are needed to apply for any hybrid system for maximum utilization of sources used in the hybrid system and to supply continuously. An efficient power-management schemes for the proposed hybrid system is discussed in this work. The advantage of power-management scheme used here is that it manages the supply power of individually subsystems hybrid system with the modified algorithm and combined hybrid system efficiently meeting the load demand [9].

This paper contains five parts: in the first part, the structure of the hybrid system is explained with its components; in next section, the individual systems of the proposed hybrid system are shown with mathematical modeling and ratings. In the third section, the hybrid system is explained with efficient power-management scheme as compared to other power-management techniques. In the fourth part, the results and discussion are shown in detail of this work and the last section concludes the work.

2. Structure of the System

A hybrid power system has been developed which consists of a PV array, a proton exchange membrane fuel cell (PEMFC) stack, and battery for a load of 1.2 kW. The power of these sources has been controlled through proper converters for making DC bus. The basic structure of the power system is explained in Figure 1 [10]. The PV array works as the main source of energy and fuel cell works as an alternate source of energy. Since the battery is an energy storage device, it is used to supply power to the load when required. This is required when the PV array and fuel cell are insufficient to supply power to the load [11].

During the day when the radiation reduces and the PV array is not capable of delivering power the battery supports, and during the night when the radiation is not present, that is, the PV power output is zero the fuel cell delivers to the load. But since the fuel cell is a device that converts chemical energy to electrical energy, it is a slow acting device and takes some time initially to reach its defined voltage, current, and power levels. Until the fuel cell reaches this value, the battery supports the fuel cell. In addition to this, the battery also absorbs the excess of power generated by the PV array during the day [12,13].

The load comprises both AC and DC types of load. The power-management scheme takes its input as the power available from the PV array, the voltage of the DC bus, the state of charge (SOC) of battery, and the power supplied by the fuel cell, and accordingly, generates signals for the switching of all the three power sources [14].
3. PV Array with MPPT Control

In general, we can use the solar PV without Maximum Power Point Tracking (MPPT) technique but here we are using solar PV with MPPT so that we can use it with maximum output.

3.1. Solar PV Array

The basic unit of a solar PV array is a solar cell. It is a semiconductor device that converts sunlight into electricity directly by the photovoltaic effect. A large number of solar cells connected in series form a solar PV module and a solar PV array is a combination of series or parallels connected PV modules. An equivalent electrical circuit of the solar cell is shown in Figure 2 [15].

Some certain nominal conditions are considered for a solar cell, by which the cell can give the maximum output power. Therefore, nominal irradiation is taken to be 1000 W/m$^2$ and the nominal temperature is 25°C. In the equivalent circuit, the solar cell is considered to be a current source. The equations used for modeling have been modified for a PV array of $N_s$ modules in series and $N_p$ modules in parallel. From Figure 2, it can be seen that:

$$I = I_{pv} - I_d - I_{sh}$$  \hspace{1cm} (1)

Where, $I$ is the current that is being supplied to the load, $I_{pv}$ is the current generated by the solar cell (A), $I_d$ is the reverse saturation/leakage current of the diode (A), and $I_{sh}$ (A) can be said as the current flowing through $R_{sh}$. The current $I_{pv}$ can be further written as:

$$I_{pv} = N_p \frac{G}{G_n} [I_{scn} + K_i(T - T_n)]$$  \hspace{1cm} (2)

Where, $G$ is the irradiation on the cell surface at any point in time (W/m$^2$), $G_n$ is the nominal irradiation, that is, 1000 W/m$^2$, $I_{scn}$ is the short circuit current at nominal conditions (A), $K_i$ is the temperature coefficient (mA/°C), $T$ is the temperature of the cell surface at any point in time (°K), $T_n$ is the nominal temperature, that is, 298°K. The current $I_{sh}$ can be expressed as:

$$I_{sh} = \frac{V + IR_s}{R_{sh}}$$  \hspace{1cm} (3)

Where, $V$ is the terminal voltage available at the load and $I$ is the current available to the load, $R_s$ represents the resistance due to the metal contacts between the metal terminals and the diode (Ω), $R_{sh}$ represent the resistive losses due to recombination of electrons of holes inside the diode (Ω).

The leakage current of the diode can be expressed as:

$$I_d = I_0 \left[ \exp \left( \frac{V + IR_s}{aV_i} \right) - 1 \right]$$  \hspace{1cm} (4)

Where, $a$ is the diode ideality factor whose value is in between 1 and 2, in this modeling its value is taken to be 1.3, $V_i$ is the thermal voltage and is given by:

$$V_i = \frac{CkT}{q}$$  \hspace{1cm} (5)
C is the number of cells in series in a module, k is the Boltzmann constant whose value is given by $1.38065 \times 10^{-23}$, and $I_0$ can be written as:

$$I_0 = I_{0n} \left( \frac{T}{T_n} \right)^3 \exp \left( \frac{E_g}{kT_n} \left( \frac{1}{T} - \frac{1}{T_n} \right) \right)$$  \hspace{1cm} (6)

Where, $q$ is the charge of an electron given by $1.602 \times 10^{-19}$ C, $E_g$ is the band gap of silicon at 25°C, and $I_{0n}$ can be expressed as:

$$I_{0n} = \frac{i_{scn}}{\exp(V_{ocn}/aV_n) - 1}$$  \hspace{1cm} (7)

$V_{tn}$ is the thermal voltage at nominal conditions and it can be further expanded as:

$$V_{tn} = \frac{CkT_n}{q}$$  \hspace{1cm} (8)

With the help of these equations, the modeling of a solar PV array is done in MATLAB that comprises of $2 \times 2$ PV solar panel of 0.3 kW each. Therefore, the combined power output of the array is 1200 W.

### 3.2. MPPT Control

As discussed above the output of the PV array varies significantly with the variation in weather conditions. This is because the operating characteristic of the PV module changes with changes in the environment. The I-V and P-V curves of the solar PV array are given below in Figure 3.

Due to a reduction in irradiation falling on the panel surface the short circuit current ($I_{sc}$) reduces, while there is a slight change in voltage, keeping the temperature constant. But with the increase in operating temperature, the open circuit voltage ($V_{oc}$) reduces while there is a slight change in current, keeping the irradiation constant. Therefore, since the I-V and P-V graph of PV module is not linear for all values of voltage and current and the maximum power ($P_m$) that can be obtained from an array for a given value of irradiation and temperature is obtained at a voltage and current less than $V_{oc}$ and $I_{sc}$ which is $V_m$ and $I_m$, respectively [16].

Therefore, an MPPT device is needed to make the PV array operate at its $V_m$ and $I_m$ so that maximum power can be extracted from it at any point of time. There are various kinds of MPPT techniques like perturb and observe method, incremental conductance method, fuzzy controller, and ANN controller etc. to track the MPPT [17].

#### 3.3. Incremental Conductance MPPT

In this work, modified incremental conductance is used to track the maximum power point of the PV array. This technique works on the principle of obtaining the maximum power point on the P-V curve with the help of voltage and current, and thus, operates the PV array at $V_m$ and $I_m$ by adjusting the duty cycle of the converter. Here is modified incremental conductance, two sensors are considered to sense the voltage and current of solar PV system. In this technique, the terminal voltage of array is always attuned according to the output voltage that depends upon the incremental and instant conductance of solar PV module. Figure 4 shows the concept of incremental conductance, here we can see that the solar PV system power curve is zero at the maximum power point. Figure 5 shows the flowchart of incremental conductance technique. The basic equations for this technique are given as:

$$P = VI$$  \hspace{1cm} (9)

On differentiating this with respect to $V$ we get:

$$\frac{dP}{dV} = I + V \frac{dI}{dV}$$  \hspace{1cm} (10)
Figure 4. Basics idea of incremental conductance method for MPPT.

Figure 5. The modified algorithm of incremental conductance method for MPPT.
Dividing both sides by \( V \), we obtain
\[
\frac{1}{V} \frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV}
\] (11)

Here, \( I/V = G \), conductance and \( -dI/dV = \Delta G \), incremental conductance. Therefore, the maximum power point can be obtained from the P-V curve when \( dP/dV = 0 \), that is, \( G + \Delta G = 0 \).

The algorithm of MPPT reads the voltage and current that the PV array is supplying and initially some duty cycle is provided to the converter. The condition for conductance and incremental conductance is checked and the duty cycle is adjusted accordingly to obtain the maximum power output from the PV array by operating it at \( V_m \) and \( I_m \).

4. Fuel Cell System

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent. Figure 6 shows the basic structure of a proton conducting fuel cell [18].

There are various types of fuel cells mainly classified on the basis of electrolyte used like proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), alkaline fuel cell (AFC), etc. In this work, PEMC fuel cell stack is chosen because of its low operating temperature and high power to weight ratio. In order to understand and improve the performance of PEMFC systems, several different mathematical models have been proposed to estimate the behavior of voltage variation with a discharge current of a PEMFC. The expression of the voltage of a single fuel cell is [19]:
\[
V_{cell} = E_{\text{Nernst}} + V_{\text{act}} + V_{\text{ohmic}} + V_{\text{conc}}
\] (12)

In this equation, \( E_{\text{Nernst}} \) is the thermodynamic potential of the cell and it represents its reversible voltage; \( V_{\text{act}} \) is the voltage drop due to the activation of the anode and cathode (also known as activation over potential), a measure of the voltage drop associated with the electrodes; \( V_{\text{ohmic}} \) (also known as ohmic over potential), a measure of the ohmic voltage drop resulting from the resistances of the conduction of protons through the solid electrolyte and the electrons through its path; and \( V_{\text{conc}} \) represents the voltage drop resulting from the reduction in concentration of the reactant gases (also known as concentration over potential). Mathematical expressions for all the terms are given and explain in [20].

With the help of the equations given above and the parameters given in Table 1, the 1.26 kW fuel cell stack is modeled and simulated with a load of 1.2 kW to verify its output. A PEMFC stack of 1.26 kW working at a voltage of 24 V DC is chosen for this work. The output of this stack is fed to a 1.2 kW load working at a voltage of 72 V DC with the help of boost converter during simulation. Thus, the simulation of the fuel cell system with the load showed that fuel cell voltage was fixed at 24 V DC and it provided a continuous power of 1.2 kW while the load voltage was fixed at 72 V DC and the power delivered to the load was about 1.1 kW. Also, from the simulation, it was evident that since the fuel cell is a slow acting device, it takes some time to attain its value of voltage, current, and power at the time of start. But after attaining the defined power it remains constant until the end of time.

4.1. PWM Converter Operation

A pulse width modulated (PWM) inverters which are considered here as it is the most popular and convenient device used to convert DC voltage to AC voltage. This inverter is proficient to produce variable magnitude AC voltages and frequency. The parametric values of PWM inverter used in this work are given in Table 2.

![Figure 6. Scheme of a proton conducting fuel cell.](image-url)

**Table 1.** Parameter set for a 1.26 kW PEMFC stack.

| Parameters                      | Value   |
|--------------------------------|---------|
| No. of cells in the stack      | 42      |
| Working temperature            | 328 K   |
| Nernst voltage of one cell (\( E_{\text{Nernst}} \)) | 1.115 V |
| The partial pressure of hydrogen | 1.5 bar |
| The partial pressure of oxygen  | 1 bar   |
| The power output of the stack  | 1.26 kW |
| Stack efficiency               | 46%     |
Now using solar PV system, FC system and PWM inverter the hybrid system is designed to do the power-management analysis on it.

5. Hybrid Solar PV and Fuel System

After the modeling and simulation of both the energy sources, that is, solar PV array and fuel cell and then combined together for making a hybrid system. In addition to these two sources of power, the battery is also employed with them to maintain the steadiness power when they both are absent or to store power whenever the excess power is generated by the PV array. Therefore, the hybrid system is modeled and simulated for a total load of 1.2 kW which comprises of 0.9 kW AC and 0.3 kW DC.

Since the total load is of 1.2 kW, and four solar panels are connected, each having the capacity of 0.3 kW. Also, since the PV array is connected to the DC bus which is at a voltage of 72V the \( V_{mpp} \) of the solar array has to be in this range. Therefore, an array of 2 \( \times \) 2 modules is formed which is capable of delivering 1.2 kW at 72 V under nominal conditions. The PV array is simulated with irradiation and temperature as its inputs. The power from the PV array is then fed to the DC bus through a boost converter that is controlled by an MPPT tracker, which works on the principle of Incremental conductance.

The fuel stack taken must also be capable of delivering complete 1.2 kW to the load in the absence of solar and storage power. Therefore, a fuel cell stack of 1.26 kW is chosen. But this power provided by the fuel cell is at 24 V DC, therefore it must be passed through a boost converter as shown in the model. The power is transferred from the fuel cell to the bus through an ideal switch. This switch is controlled by the power-management controller.

A battery is used as a secondary storage device for this system to supply power in the absence of irradiation or when the load demand increases. Since the fuel cell is a slow acting device, the battery also supports in maintaining the power requirement until the fuel cell attains its specified power. BESS is also helping in absorbing excess power generated by the PV array by shifting into charging mode. Here, a battery bank of six batteries, each having a terminal voltage of 12 V, connected in series is considered. Hence, the total output voltage of the battery is 72 V. The battery is charged and discharged through separate paths, which consist of ideal switches in them. These switches are also controlled depending upon the voltage of the bus and the SOC of the battery. Initial SOC of the battery is taken to be 90%. The battery is discharged if the bus voltage falls below 70 V and charges in case the bus voltage exceeds 74 V.

The DC load comprises 0.3 kW at a voltage of 24 V. Since the DC bus is at 72 V and the load is at 24 V, it is connected to the bus with the help of a buck converter. The AC load is considered to be 3-phase, 0.9 kW at a voltage of 415 V, 50 Hz. This voltage is considered because this is the 3-phase voltage level used generally in India for power systems of such low size. AC load is also connected to the DC bus similar to the DC load. But in this, it is connected through a voltage source inverter. The removal of harmonics from the AC power is achieved by using PWM technique of inversion and filters. A transformer is also needed to step up 72 V AC, converted from 72 V DC into 415 V AC.

6. Power-Management Technique

The main motive of the power-management technique is to maintain the continuity of power with minimal fluctuations. This can be achieved by monitoring some of the system parameters and taking action accordingly. Since PV array is the main source of power, the emphasis is laid on extracting maximum power from it. The power is managed based on the algorithm given in Figure 7.

The fuel cell is switched on only if the battery and PV array is unable to provide power. This ensures that the fuel cell stack provides power only at night or when the power output from the PV array is very less. The minimum and maximum levels of the SOC of the battery are kept very close for the simulation purpose. Thus, this technique helps in utilizing as less fuel as possible without compromising the continuity of power on load [21,22].

7. Results and Discussion

The hybrid solar PV system, of capacity 1.2 kW, is modeled and simulated in MATLAB with both AC and DC load. The PV array was subjected to a variable irradiation, as shown in Figure 8 to observe the performance of the system.

The simulation was done for 2.7 sec. The distribution of power among the results obtained is as shown
in Figure 9. Therefore, it can be clearly seen from Figure 9 below that the power to be delivered to the load is shared between the sources appropriately. There is an initial fluctuation in load power even when the radiation is 1000 W/m², because when the system starts it takes some time to build up the voltage.

After that initial time when the irradiation is constant at 1000 W/m² till 0.5 sec only the PV array delivers the power and the fuel cell is switched off. It may also be seen that during the time interval 2–2.5 sec the irradiation is completely zero and only the fuel cell is supplying power. This time interval explains the working of the system at night when no radiation is present.

It may also be noted that during the period of 0.5 sec–1.25 sec and 1.5 sec–2 sec when the irradiation is not maximum, the output power of PV array is not sufficient to provide for the load. Therefore, during these time intervals, the battery supports the PV array and fulfills the requirement of the load. Moreover, the requirement of total power to the load is fulfilled at all times as can be seen in Figure 10. It can also be seen from Figure 10, that the AC load power and the DC load power are maintained at 0.9 kW and 0.3 kW, respectively.

In addition to the proper distribution of power and fulfillment of load requirement, we must also see the voltage profiles of the DC bus, DC, and the AC loads.
Figure 9. The distribution of power among the sources.

Figure 10. Total power; AC load power; DC load power.

Figure 11. DC bus and DC load voltage.

Figure 11 shows that the voltage of DC bus is maintained at 72 V and DC load voltage is at 24 V.

It can also be seen from Figure 12 that the peak value of the sinusoidal AC load voltage waveform is
around 530 V and has an equivalent RMS voltage of 415 V.

The secondary storage, that is, battery, as discussed earlier, supports the PV array by supplying power during partial radiation. Moreover, it absorbs excess power out of the PV array and helps in maintaining the voltage of the DC bus. There is an increase in SOC of the battery during the time interval 1.25 sec–1.5 sec, but this increase is not so significant because the battery is almost completely charged and there is not too much of excess power generated by the PV array.

8. Conclusion

As discussed earlier, a solar PV hybrid power system is modeled and simulated for a capacity of 1.2 kW, comprising of 0.9 kW AC loads and 0.3 kW DC loads. The results obtained for the distribution of power among the sources show that all the sources of power complement each other adequately. The waveforms of the load power delivered and the voltage waveforms of AC and DC also show that the requirements of the load have been fulfilled satisfactorily with some variations. The proposed hybrid system can be implemented for small-scale power generating systems using solar PV array like residential applications. The given system provides the advantage of the reduction in capacity of battery banks to be used as it is integrated with a fuel cell stack. This can be further improvised by completely eliminating the use of batteries with the interconnection to the grid and/or using a separate electrolyzer for the fuel cell stack, but for the interconnection with the grid, the synchronization of the Voltage Source Inverter (VSI) used for converting DC to AC with the grid would be challenging.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Krishan Kumar  http://orcid.org/0000-0002-3045-0788

Arjun Tyagi  http://orcid.org/0000-0002-2476-2769

References

[1] Cingoz F, Elrayyah A, Sozer Y. Optimized resource management for PV--fuel-cell-based microgrids using load characterizations. IEEE Trans Ind Appl. 2016;52:1723–1735.

[2] Badwawi RA, Abusara M, Mallick T. A review of hybrid solar PV and wind energy system. Smart Sci. 2016;3(3):127–138.

[3] Iqbal F, Siddiqui AS, Deb T. Study of xEV charging infrastructure and the role of microgrid and smart grid in its development. Smart Sci. 2017;5(2):61–74.

[4] Patterson M, Macia NF, Kannan AM. Hybrid microgrid model based on solar photovoltaic battery fuel cell system for intermittent load applications. IEEE Trans on Energy Conversion. 2015;30:359–366.

[5] Tyagi A, Verma A, Bijwe PR. Reconfiguration for loadability limit enhancement of distribution systems. IET Gener Transm Dis. 2018;12(1):88–93.

[6] Ko SH. Review of the multi-scale nano-structure approach to the development of high efficiency solar cells. Smart Sci. 2016;2(2):54–62.

[7] Kumar K, Ansari MA. Mathematical modeling and simulation of renewable energy based microgrid system. Indian J Ind Appl Math. 2017;8(2):155–166.

[8] Ahmad F, Alam MS. Optimal sizing and analysis of solar PV, wind, and energy storage hybrid system for campus microgrid. Smart Sci. 2017;6(2):150–157.

[9] Shemami MS, Alam MS, Jamil Asghar MS. Fuzzy control assisted Vehicle-to-Home (V2H) energy management system. Smart Sci. 2017;6(2):173–187.
[10] Rana V, Ansari MA. Wind farm integration effect on electricity market price. Energy Efficient Technologies for Sustainability (ICEETS). IEEE Int Conf. 2013;349–354.

[11] Navid E, Ebrahim F. Distributed charge/discharge control of energy storages in a renewable-energy-based DC micro-grid. IET Renew Power Gener. 2014;8:45–57.

[12] Shi W, Li N, Chu C-C, et al. Real-time energy management in microgrids. IEEE Trans smart grid. 2017;8:228–238.

[13] Natsheh EM, Natsheh AR, Albarbar A. Intelligent controller for managing power flow within standalone hybrid power systems. IET Science, Meas Technol. 2013;7:191–200.

[14] Cheknane A, Hilal HS, Djeffal F, et al. An equivalent circuit approach to organic solar cell modelling. Microelectronics J. 2008;39:1173–1180.

[15] Verma D, Nema S, Shandilya AM, et al. Maximum power point tracking (MPPT) techniques: recapitulation in solar photovoltaic systems. Renew Sust Energ Rev. 2016;54:1018–1034.

[16] Kumar B, Chauhan YK, Shrivastava V. A comparative study of maximum power point tracking methods for a photovoltaic-based water pumping system. Int J Sustainable Energy. 2014;33:797–810.

[17] Correa J, Farret F, Canha L, et al. An electrochemical-based fuel-cell model suitable for electrical engineering automation approach. IEEE Trans Ind. Electron. 2004;51:1103–1112.

[18] Kumar TP, Subrahmanyam N, Sydulu M. Fuzzy controlled power management strategies for a grid-connected hybrid energy system, IEEE PES T&D Conference and Exposition, Chicago, IL, USA, 2014; 1–5.

[19] Al-Baghdadi M. Modelling of proton exchange membrane fuel cell performance based on semi-empirical equations. Renewable Energy. 2005;30:1587–1599.

[20] Jiang Z, Power management of hybrid photovoltaic fuel cell power systems, IEEE Power Engineering Society General Meeting, Montreal, Que. 2006: 6.

[21] Bogaraj T, Kanakaraj J. Development of MATLAB/SIMULINK models for PV and wind systems and review on control strategies for hybrid energy systems. Int Rev Modelling Simulations. 2012;5:1701–1709.

[22] Faisal P, Mohd Fauzi O, Nazar HM, et al. Energy-efficient and environmentally friendly power dispatch by trigeneration with renewable energy and energy storage. Turk J Elec Eng & Comp Sci. 2016;24:5150–5161.