Renewable Energy 34 (2009) 348–352

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Technical Note

# Optimally sizing of solar array and battery in a standalone photovoltaic system in Malaysia

W.X. Shen*

School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 46150 Bandar Sunway, Selangor Darul Ehsan, Malaysia

ARTICLE INFO

Article history:
Received 27 January 2007
Accepted 15 March 2008
Available online 16 June 2008

Keywords:
Optimal size
Solar array
Battery
Standalone photovoltaic system
Malaysia

ABSTRACT

Size optimization of solar array and battery in a standalone photovoltaic (SPV) system is investigated. Based on the energy efficiency model, the loss of power supply probability (LPSP) of the SPV system is calculated for different size combinations of solar array and battery. For the desired LPSP at the given load demand, the optimal size combination is obtained at the minimum system cost. One case study is given to show the application of the method in Malaysian weather conditions.



## 1. Introduction

Standalone photovoltaic (SPV) systems are becoming increasingly viable and cost-effective candidates for providing electricity to remote areas, especially to some areas of Sabah and Sarawak in East Malaysia, where higher solar radiation is received [1–3]. This SPV system typically consists of a solar array, a controller with maximum power point tracker (MPPT), a battery, an inverter and loads. The configuration of an SPV system is shown in Fig. 1. In the system, the solar array converts solar radiation falling on its surface into DC electricity. The controller with the MPPT helps to extract maximum power from the solar array regardless of the variation of solar radiation and temperature as well as protect the battery from overcharging and under-discharging. The battery stores energy when solar array generates more power than load demand or supplies power to load when the solar array generates less power than the load demand during cloudy or rainy days or at nights. The inverter converts DC into AC at a similar voltage level and frequency of the power grid for the convenient usage of normal AC loads (electric appliances). Since output power of a solar array varies with weather conditions, the successful operation of the SPV system is to find out the optimal size of a solar array and battery to meet load demand.

Many attempts have been made to optimize renewable energy systems. Among them, most studies emphasized on hybrid wind/solar array systems with a battery [4–8], where wind energy is another source besides a solar array. In these hybrid systems, solar energy and wind energy complement each other; thus the size of the battery is relatively small and the role of the battery is less important than that in the SPV system. There were some studies on sizing of the SPV system as well. In [9], a total of 18 configurations of solar array and battery is defined according to commercially available components, then the performances and costs of the systems were evaluated for the given load demand. The optimum size of solar array and battery is chosen based on the proper balance between the LPSP and the system cost in those limited configurations. However, the mixed use of batteries with two different capacities in one system is seldom adopted in real applications. In [10], the influence of tilt angle on sizes of the SPV system was investigated for the given load demand, the optimal size of solar array and battery was obtained when the tilt angle was adjusted in accordance with seasons, which complicates the installation of the solar array. Based on the spirit of Borowy's method [5], this paper investigates the optimum sizes of solar array and battery in the SPV system under the conditions of a fixed tilt angle and continuous size variations of solar array and battery. The loss of power supply probability (LPSP) is calculated for different size combinations of solar array and battery. For the desired LPSP at the given load demand, the optimal size combination is obtained at the minimum system cost. One case study shows the procedure of the size optimization of the SPV system in Malaysian weather conditions.

* Corresponding author. Tel.: +60 3 5514 6258; fax: +60 3 5514 6207.
E-mail address: shen.wei.xiang@eng.monash.edu.my

0960-1481/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2008.03.015

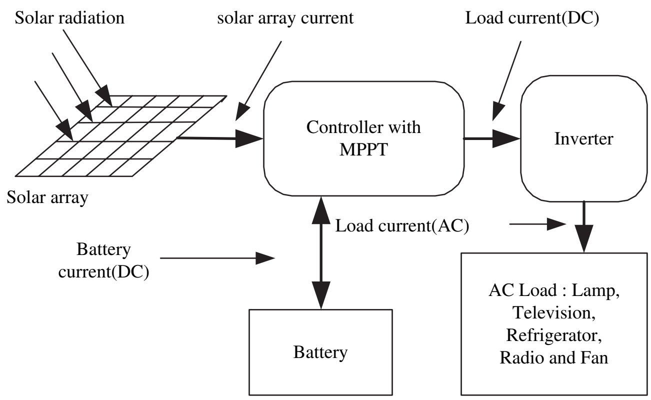


**Fig. 1.** Standalone photovoltaic system.

## 2. Methodology

### 2.1. Calculation of the daily output of a solar array

The solar array is the only energy source in the SPV system. The daily output of a solar array depends on solar irradiation, solar cell temperature and the operating point of the system. Solar irradiation is the integration of solar radiation over time. Normally, the time frame for this integration is one day. Since solar arrays are rated at a solar radiation level of 1000 W/m$^2$ and a solar cell temperature of 25 °C, the peak sun hours (PSHs) are often used to represent solar irradiation so that the daily output of the solar array is easily calculated by using the peak watt ($W_p$) of solar array times the PSHs, where the PSHs is equivalent to the length of time in hours at a solar radiation level of 1000 W/m$^2$ [11].

The solar cell temperature affects the output power of a solar array significantly. The relationship between solar cell temperature ($T_{cell}$) and ambient temperatures ($T_{ambient}$) is established to take solar cell temperature into account. According to the measured solar module temperature ($T_{module}$) and the measured ambient temperature at the given location as well as the relationship between solar cell temperature and solar module temperature [12], the solar cell temperature can be approximately estimated by using ambient temperature and solar radiation [13].

$$T_{cell} = T_{ambient}{}^*(1 + 1.25{}^*H) \quad (1)$$

where $H$ is the average solar radiation over a day in the units of kW/m$^2$.

For the operating point of a solar array, the MPPT is included in this SPV system; thus the solar array always operates at the maximum power point regardless of the variation of solar radiation and temperature. As a result, the daily energy output of a solar array can be calculated by

$$E_{pv} = P_{pv\ max}{}^*[1 + \rho^*(T_{cell} - 25)]^*\mathrm{PSHs}^*\eta_c{}^*\eta_o \quad (2)$$

where $P_{pv\,max}$ is the maximum power output of the solar array under a solar radiation of 1000 W/m$^2$; $\rho$ is the negative temperature coefficient of power with respect to solar cell temperature provided by the manufacturers. $\eta_c$ and $\eta_o$ are the factors representing connection losses and other losses such as those caused by accumulative dust, etc.

### 2.2. Estimation of daily battery status

The operating conditions of the battery in the SPV system are very different from those in conventional systems because the SPV system is neither a constant current source nor a constant voltage source. The output power of a solar array, which is used to charge the battery, varies with solar radiation and temperature. Under such uncontrolled charge/discharge cycles, the estimation of the battery state of charge (SOC) is complicated [14]. In this study, battery charge/discharge efficiency is adopted to estimate daily battery SOC. Since the battery discharge efficiency is normally assumed to be 100%, the battery charge efficiency is considered to be the round-trip efficiency which can normally be found in the battery specifications. As a result, the energy stored in the battery on day $n$ during the charging period is calculated by

$$E_B(n) = E_B(n-1)^*(1-\eta_s) + \left(E_{pv}(n) - E_L(n)/\eta_{inv}\right)^*\eta_{batt} \quad (3)$$

and the energy stored in the battery on day $n$ during the discharging period is calculated by

$$E_B(n) = E_B(n-1)^*(1-\eta_s) + \left(E_{pv}(n) - E_L(n)/\eta_{inv}\right) \quad (4)$$

where $E_B(n)$ and $E_B(n-1)$ are the energy stored in the battery on day $n$ and $n-1$, respectively. $\eta_s$ is the daily battery self-discharge rate; $E_{pv}(n)$ is the energy generated by the solar array on day $n$; $E_L(n)$ is the load demand on day $n$; $\eta_{inv}$ is the efficiency of the inverter and $\eta_{batt}$ is the charge efficiency of the battery. On any day $n$, the energy stored in the battery is subject to the following constraints:

$$E_{B\ min} \le E_B(n) \le E_{B\ max} \quad (5)$$

where $E_{B\,max}$ is the maximum allowable energy level which is equal to the rated capacity of the battery $C_{batt}$ times the rated voltage $V_{rated}$ and $E_{B\,min}$ is the minimum allowable energy level which must be remain in the battery for each cycle to have the battery life as stated in the battery specifications. It is determined by the maximum depth of discharge (DOD) or minimum SOC, namely $E_{B\,min} = (1 - \mathrm{DOD}_{max})^*C_{batt}$ or $\mathrm{SOC}_{min}{}^*C_{batt}$, where SOC = 1 − DOD. In general, the lower the battery DOD needs to be maintained, the lower the cost of the systems, the shorter the battery life, and vice versa. The selection of the maximum allowable DOD is actually a compromise between system life and cost. Thus, the calculation of the battery SOC is

$$\mathrm{SOC}(n) = E_B(n)/(C_{batt}{}^*V_{rated}) \quad (6)$$

where SOC($n$) is the SOC when the systems stay on the $n$th day.

### 2.3. Match method

The SPV system does not include any other auxiliary energy sources, such as diesel generators or wind generators. The battery in the system only stores energy. When the solar power is higher than load demand, excess power is used to charge the battery. When the solar power is lower than the load demand during cloudy or rainy days or at nights, the battery provides the deficient part of power or full power to the load. The loss of power supply probability (LPSP) is adopted to describe the reliability of power supply to load. Its definition is the ratio of the number of hours that the system fails to supply a load to the total number of hours required by the load. An LPSP of 0 means that the power can fully meet load demand, whereas an LPSP of 1 means that the power can never meet load demand. An LPSP from 0 to 1 means the power cannot fully supply to the load when the solar power is not enough while the battery has been in the allowable maximum DOD or the allowable minimum SOC. The purpose of the size optimization of solar array and battery is to match the load demand at the desired LPSP with the preset allowable minimum battery SOC at the minimum cost of the system.

The battery SOC on any day $n$ depends on the SOC on the previous day ($n-1$), the solar power for a charging battery and the

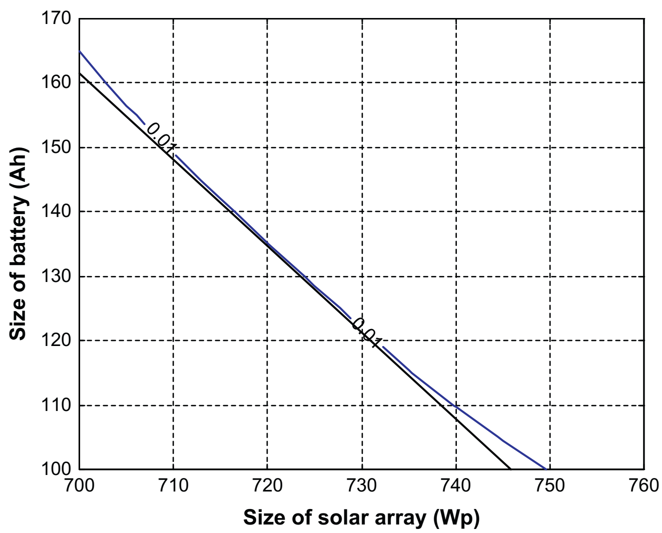


**Fig. 2.** Size of battery versus size of solar array at an LPSP of 0.01.

load demand for discharging a battery on day $n$. This indicates the battery status and the system status as well. The system controller monitors the battery SOC. When the SOC is 0 (fully discharged) or the preset allowable minimum value is reached, the system controller will stop discharging the battery and protect the battery from over-discharging. When the SOC is 1 (fully charged), the system controller will stop charging and prevent the battery from overcharging. In terms of the allowable minimum battery SOC, the LPSP can be mathematically defined as

$$\mathrm{LPSP} = P\{E_{\mathrm{B}}(n) \leq E_{\mathrm{B\ min}}; n \leq N\} \tag{7}$$

which means the LPSP is the probability of the SOC at any accumulative day $n$, within a period of $N$ days, to be less than or equal to the minimum allowable energy level $E_{\mathrm{B\ min}}$. According to this definition, the LPSP can be calculated by

$$\mathrm{LPSP} = \frac{\sum_{n=1}^{N} \mathrm{LPS}(n)}{\sum_{n=1}^{N} E_{\mathrm{L}}(n)} \tag{8}$$

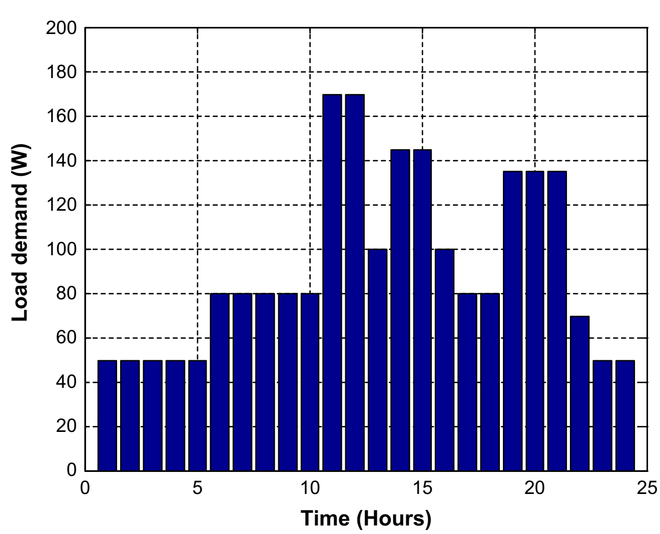


**Fig. 3.** Load profile for a typical house in rural areas of Malaysia.

**Table 1**
Load demand

| Loads | Total usage in a day (h) | Power (W) | Total energy (W h) |
|---|---|---|---|
| Fluorescent lamp 1 | 10 | * 20 | = 200 |
| Fluorescent lamp 2 | 4 | * 40 | = 160 |
| Television | 5 | * 60 | = 300 |
| Refrigerator | 24 | * 50 | = 1200 |
| Radio cassette | 11 | * 10 | = 110 |
| Ceiling fan | 2 | * 60 | = 120 |
| Desk fan | 5 | * 25 | = 125 |
| Total | | | = 2215 |

where LPS($n$) is the loss of energy supply on day $n$ which can be expressed as

$$\mathrm{LPS}(n) = E_{\mathrm{L}}(n) - (E_{\mathrm{pv}}(n) + E_{\mathrm{B}}(n-1) - E_{\mathrm{B\,min}})^{*}\eta_{\mathrm{inv}} \tag{9}$$

From (8), the LPSP of the SPV system is calculated. It is found that different size combinations of solar array and battery can meet the given load demand for the desired LPSP.

To determine the optimal size combination, the cost function of the SPV system is defined as

$$C_{\mathrm{sys}} = C_{\mathrm{pv}}{}^{*}\alpha + C_{\mathrm{batt}}{}^{*}\beta + C_{\mathrm{other}} \tag{10}$$

where $C_{\mathrm{sys}}$ is the total costs of the systems; $C_{\mathrm{pv}}$ is the capacity of the solar array; $C_{\mathrm{batt}}$ is the capacity of the battery; $C_{\mathrm{other}}$ is the other total costs except the solar array and the battery, which is considered to be constant, including the costs of the controller with MPPT, inverter, etc. $\alpha$ is the unit cost of the battery (\$/A h), $\beta$ is the unit cost of the solar array (\$/W$_\mathrm{p}$). From (10), the condition to minimize $C_{\mathrm{sys}}$ is

$$\frac{\partial C_{\mathrm{batt}}}{\partial C} = -\frac{\alpha}{\beta} \tag{11}$$

The solution of (11) can be solved graphically in the way that the two curves will be drawn in the $C_{\mathrm{batt}} - C_{\mathrm{pv}}$ coordinate system (see Fig. 2). One curve represents different size combinations of the solar array and battery for the desired LPSP. The other curve is the line with a slope of ($-\alpha/\beta$). The tangent point of the two curves corresponds to the optimum sizes of solar array and battery.

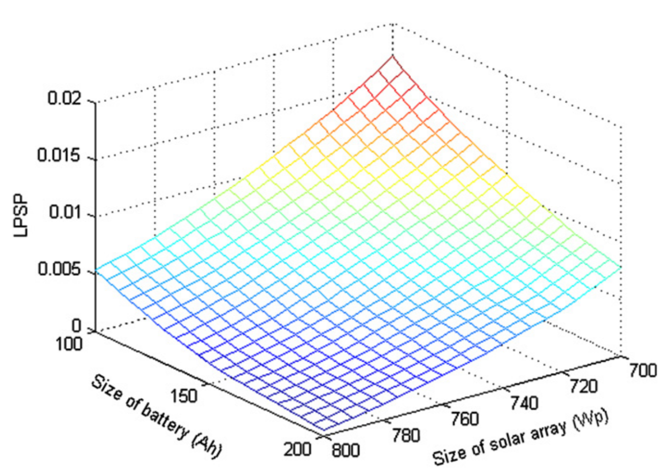


**Fig. 4.** 3D plot of different size combinations of solar array and battery at different LPSP values.

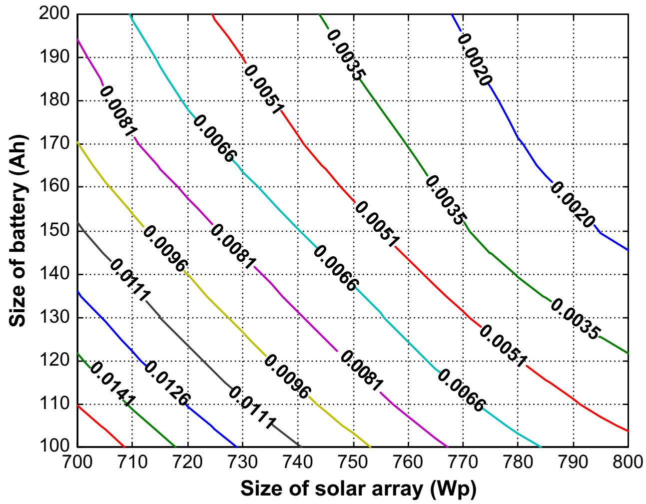


**Fig. 5.** Contour plot for different size combinations of solar array and battery at different LPSP values.

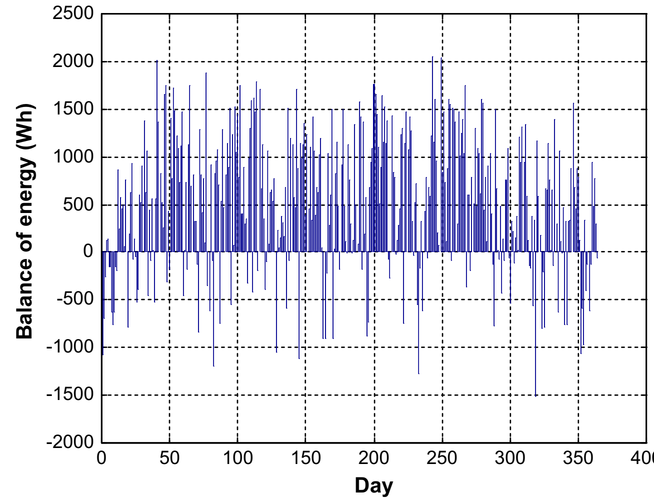


**Fig. 7.** Energy balance.

## 3. Case study based on Malaysian weather conditions and discussions

The size optimization of an SPV system based on Malaysian weather conditions is given to show the application of the above-introduced method. The solar radiation data of the year 1999 in Kuala Lumpur obtained from the Malaysian Meteorological Services Department is used in the optimization process. The load profile of a typical house in remote areas in Malaysia [1] is shown in Fig. 3, and it is assumed that this load profile remains the same over the year. The details of the corresponding load profile are shown in Table 1. It is further assumed that the battery DOD cannot be higher than 0.8 or the SOC cannot be lower than 0.2; the desired LPSP of the system is set to 0.01 which means there is 14.4 min power-off within one day or 3.65 days power-off within one year. With the help of the program developed by using the MATLAB, the LPSPs for different size combinations of solar array and battery are calculated. Figs. 4 and 5 show the calculated results in 3D and contour plots, respectively. Fig. 2 shows the size combinations of solar array and battery at an LPSP of 0.01 by adding the line with a slope of $-\alpha/\beta$, where $\alpha = 1.08$ (US\$/A h) and $\beta = 5$ (US\$/W$_p$). The tangent point of the two curves corresponds to the optimal size combination of solar array and battery which are approximately equal to 135 A h and 720 $W_p$, respectively. If the commercial availability of solar array and battery is taken into account, two battery units with 68 A h and 12 solar modules with 60 $W_p$ are selected. With this optimum configuration, daily energy generation, energy balance, and battery SOC over the year are evaluated and the corresponding results are shown in Figs. 6–8, respectively.

For the LPSP of 0.01, the size ratio of battery to solar array in this case study is about 0.18 A h/$W_p$ (135 A h/720 $W_p$) while the size ratio of battery to solar array in [6] is about 0.84 A h/$W_p$. Two factors cause this difference. Firstly, the conditions in this study are based on the Malaysian context while the conditions in [6] are based on the Hong Kong context. For both places, weather conditions, load profiles and unit costs of the system components are very different. Secondly, the system in this study is an SPV system while the system in [6] is a hybrid wind/solar array system. Thus, it is understandable that only one source (solar array) in the SPV system leads to a relatively larger size of the solar array than the multi-sources (solar array and wind generator) in the hybrid wind/solar array system.

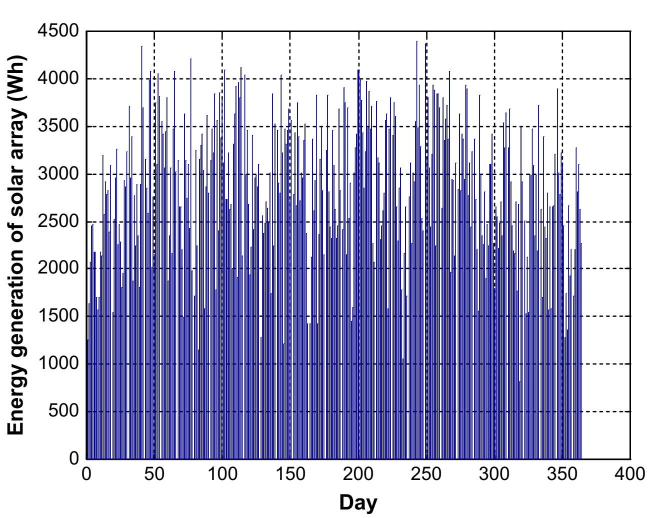


**Fig. 6.** Energy generation of a solar array.

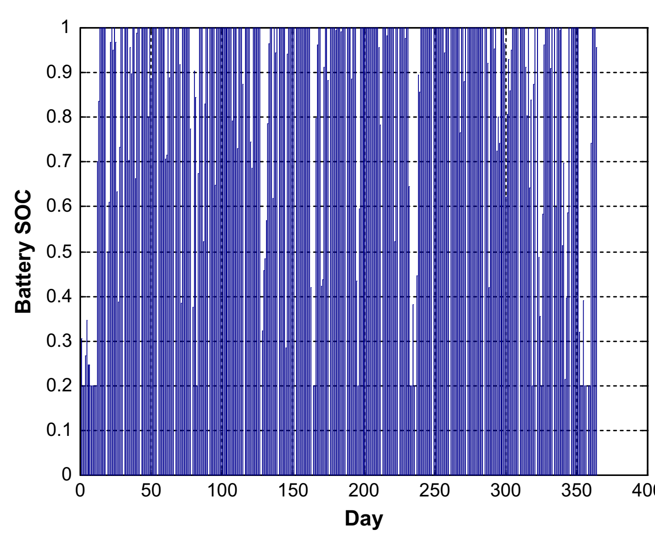


**Fig. 8.** Battery SOC.

## 4. Conclusions

Size optimization of solar array and battery in the SPV system is presented. Under the given load demand and the desired LPSP, the optimum sizes of solar array and battery are found at the minimum cost of the system. The method is applied in a case study based on Malaysian weather conditions. This shows that the places of the system used and the types of the systems adopted will affect the optimization results significantly.

Further research work will be considered on the accuracy of the energy efficiency model and the detailed cost analysis of system components as well as the program with a user-friendly interface.

## Acknowledgement

This work was supported by the Monash University Malaysia under Project No. 2004-ES-7-04. Thanks are also extended to the Malaysian Meteorological Services Department for making the meteorological data available for this work.

## References

[1] Noh Dalimin Mohd. Renewable energy update: Malaysia. Renewable Energy 1994;6:435–9.
[2] Zamzam Jaafar Mohd, Kheng Wong Hwee, Kamaruddin Norhayati. Greener energy solutions for a sustainable future: issues and challenges for Malaysia. Energy Policy 2003;31:1061–72.
[3] Ajan Christopher W, Shahnawaz Ahmed S, Ahmad Hussien B, Taha Faridah, Mohd Zin Abdullah Asuhaimi B. On the policy of photovoltaic and diesel generation mix for an off-grid sit: East Malaysian perspectives. Solar Energy 2003;74:453–7.
[4] Gavanidou ES, Bakirtzis AG. Design of a standalone system with renewable energy sources using trade off methods. IEEE Transactions on Energy Conversion 1992;7(1):42–8.
[5] Salameh Ziyad M, Borowy Bogdan S. Methodology for optimally sizing of the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Transactions on Energy Conversion 1996;11(2):367–75.
[6] Ai B, Yang H, Shen H, Liao X. Computer-aided design of PV/wind hybrid system. Renewable Energy 2003;28:1491–512.
[7] Chedid Riad, Rahman Saifur. Unit sizing and control of hybrid wind-solar power systems. IEEE Transactions on Energy Conversion 1997;12(1):79–85.
[8] Kellogg WD, Nehrir MH, Venkataramanan G, Gerez V. Generation unit size and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems. IEEE Transactions on Energy Conversion 1998;13(1):70–5.
[9] Shrestha GB, Goel L. A study of optimal sizing of standalone photovoltaic stations. IEEE Transactions on Energy Conversion 1998;13(4):373–8.
[10] Bhuiyan MMH, Ali Asgar M. Sizing of a standalone photovoltaic power system at Dhaka. Renewable Energy 2003;28:929–38.
[11] Markvart Tomas. Solar electricity. 2nd ed. John Wiley & Sons Inc; 2000. pp. 95–8.
[12] Messenger Roger A, Ventre Jerry. Photovoltaic systems engineering. 2nd ed. CRC Press LLC; 2004. pp. 76–9.
[13] Shen Weixiang, Tan Wei Kuang, Kok Bin Alex See, Kok Seng Ong. Sizing of standalone photovoltaic system using Matlab/Simulink, Proceedings of the international conference on robotics, vision, information and signal processing, Penang, Malaysia; 2005. pp. 288–93.
[14] Piller Sabine, Perrin Marion, Jossen Andreas. Methods for state of charge determination and their applications. Journal of Power Sources 2001;96:113–20.