An Optimum Control Strategy for Energy Management in a Remote Area Stand-Alone PV System

Abd El-Shafy A. Nafeh*

Electronics Research Institute, Cairo, Egypt

Abstract: A new modified configuration for the stand-alone photovoltaic (PV) system to electrify a remote area household load in Egypt is presented. The modeling, simulation, and operational control strategy for the system is developed. The developed control aims to optimize the energy flow within the system, such that the load is satisfied independent on the variations in insolation. Also, it aims to protect the battery against overcharging or excessive discharging. Moreover, it aims to protect the global system against the unpredictable excess or deficit of the available energy. The simulation results led to a good realization of the operational control strategy.

Keywords: Remote area electrification, PV array, Storage battery, ON-OFF control, Energy management.

1. INTRODUCTION

Renewable energy sources are considered as alternative energy sources to conventional fossil fuel energy sources due to environmental pollution and global warming problems [1]. One of these, most important, sources is the photovoltaic (PV) modules, which may be equipped with storage batteries to supply electrical power to remote locations worldwide [2-6].

The power supplied by a PV array depends upon the insolation level, cell temperature, and array voltage. Battery forms an important element of stand-alone PV systems, because of the fluctuating nature of the output delivered by the PV arrays. Both the battery voltage and the PV array voltage vary during operation due to the charging state of the battery and the atmospheric conditions [7,8,15].

In this paper a new modified configuration for the stand-alone PV system, which includes a storage battery, is presented; to electrify a remote area household load in Sinai Peninsula of Egypt. Also, the complete modeling and control of this system is developed and simulated; to indicate the capability of the developed control strategy in controlling and protecting the modified configuration of the stand-alone PV system.

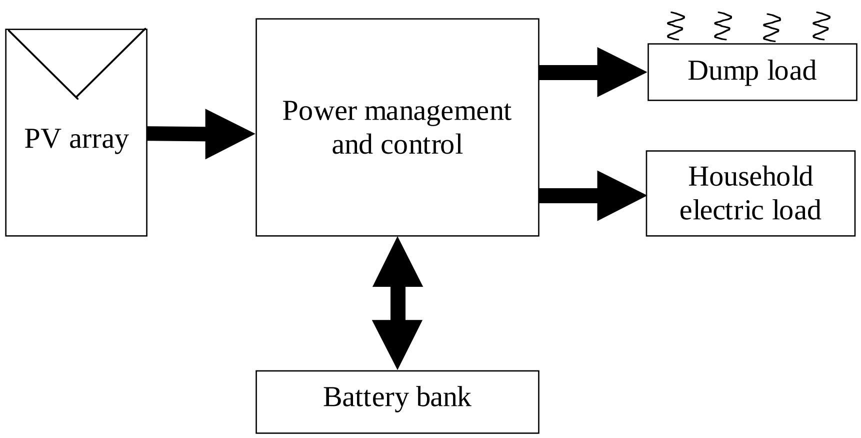


Fig. (1). Block diagram of the suggested PV system.

The provision of electricity to remote areas derives important social and economic benefits to remote communities throughout the world. The common configuration of PV systems that is usually used for this purpose is the stand-alone type [6,7]. Where, stand-alone PV systems can be considered as reliable and economical sources of electricity in remote areas, which are far from the grid power supply [5,8-14].

2. CONFIGURATION OF THE PV SYSTEM

The block diagram of the suggested PV system, in this work, is shown in Fig. (**1**). This system can be described as

*Address correspondence to this author at the Electronics Research Institute, Cairo, Egypt; E-mails: abdelshafyn@eri.sci.eg, abdelshafyn@yahoo.com

1876-3871/09

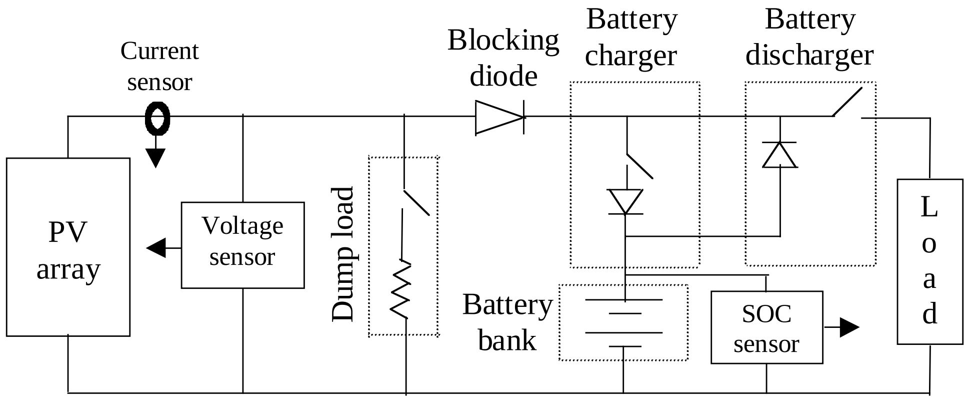


Fig. (2). Schematic diagram of the stand-alone PV system.

autonomous system, which can supply electricity to the remote area household load without being connected to the electric grid. The PV array is used to convert the incident solar energy into electrical energy, while the battery is used to store the excess power from the PV array; to supply the household load at night and during deficit times of solar energy.

The power management and control unit is used to optimally control the management of the energy flow within the overall system, and to match and protect its components. The dump load is used, in this work, to guarantee the proper functioning of the suggested PV system, where it is used to consume the surplus energy generated by the system.

3. STAND-ALONE PV SYSTEM SIZING

The schematic diagram of the considered stand-alone PV system is shown in Fig. (**2**). Where, the PV array is considered to be the only source of the required electrical energy in the system, and the battery is the storage medium. Therefore, the considered stand-alone PV system must be carefully sized to continuously supply the required electrical power to the household electrical load. It is to be noted here that the author has accomplished the required complete sizing steps in another paper [5]. Where, the remote area household load, in this case, includes five lamps (each of 60 W), one washing machine (100 W), one water pump (120 W), and one television set (80 W). The monthly averaged daily radiation data of the remote site [16] together with the load data are used, in [5], to size the stand-alone PV system. Where, the sizing process is based on the energy balance between the radiation and the load. The results of the sizing process are: 1392 W_P PV array and 1500 Ah battery.

4. STAND-ALONE PV SYSTEM MODELING

4.1. The PV Array

The PV array has a nonlinear current-voltage (I-V) characteristic, which can be described as [17]:

$$I_{PV} = n_p I_{Ph} - n_p I_{os}\left[\exp\left(\frac{eV_{PV}/n_s}{nTK}\right)-1\right] \tag{1}$$

$$I_{Ph} = [I_{sc} + \alpha_{sc}(T_c - 28)] \times \frac{Rad}{1000} \tag{2}$$

$$I_{os} = I_{or}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{eE_{G\circ}}{nK}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right] \tag{3}$$

$$T_c = T_{air} + 0.3 \times Rad\% \tag{4}$$

4.2. The Battery

The battery can generally be modeled according to its state of charging or discharging in the system. Where, the relation between the battery voltage V_B and current I_B during the states of discharging and charging can, respectively, be described in terms of the battery ampere-hour rating AH and state of charge SOC of the battery by the following two equations [18].

$$V_B = n_{Bs} V_r - \frac{n_{Bs} I_B}{n_{Bp} AH}\left(\frac{0.189}{SOC} + R_i\right) \tag{5}$$

and

$$V_B = n_{Bs} V_r + \frac{n_{Bs} I_B}{n_{Bp} AH}\left(\frac{0.189}{1.142 - SOC} + R_i\right) + (SOC - 0.9)\ln\left(300\frac{I_B}{n_{Bp} AH} + 1\right) \tag{6}$$

Note that the last term of Eq. (6) is included only if the first two terms sum to more than 2.29 V/cell. Also, the other terms are given by:

$$V_r = V_{ro}\ [1 - 0.001(T_a - 25)] \tag{7}$$

$$R_i = R_o[1 - 0.02(T_a - 25)] \tag{8}$$

Note, also, that the factor 0.189 of Eqs. (5) & (6) represents the internal resistance due to polarization. Moreover, the battery typical open-circuit voltage can be indicated to be dependent on the battery SOC, as shown in Table **1** for a 12 V lead-acid battery [19].

Table 1. Typical Open-Circuit Voltage at Various Charge Levels

Charge Level (%)	Battery Open-Circuit Voltage (V)
100	12.7
75	12.6
50	12.45
25	12.2
Discharged	11.7

5. STAND-ALONE PV SYSTEM CONTROL

Stand-alone PV systems for remote area household electrification must be totally self-sufficient in generating, storing and supplying electricity to the household electrical load. These systems are subjected upstream to the unpredictable variations in solar insolation and/or ambient temperature and downstream to the household electrical load. Therefore, these systems must require certain control strategy to optimally manage the energy flow within them. Where, in this work, the designed control strategy can determine the current state of the system and subsequently can issue the appropriate orders or commands aimed at optimizing the energy transfer function within the system, to fulfill the technical requirements of the system. The main purposes of the designed control strategy are to satisfy the household electrical load and to discharge or charge the storage battery whenever possible. Moreover, the designed control strategy can protect the storage battery from excessive discharge and overcharge, and at the same time it can protect the global system from the unpredictable excess or deficit of the available energy. The designed control strategy, as shown in the flowchart of Fig. (**3**), is based on the IF-THEN rules; such that the IF-part of a rule represents the current state of the system, while the THEN-part represents the suitable-issued-control command of the system.

6. STAND-ALONE PV SYSTEM SIMULATION

MATLAB-SIMULINK is a general simulation software, that uses a graphical user interface (GUI) tools, which allows a model to be built up from a basic library of mathematical blocks. For example, to model a global system using the SIMULINK software, the complete mathematical models of the constituent subsystems must be available at first. Then, the complete SIMULINK model of the global system can be easily formed by linking the different constructed models together. Here, considering the designed stand-alone PV system to be a global system, that includes the subsystems: the PV array, the battery, the load, the dump load, and the controller, then the designed stand-alone PV system can be easily simulated by using MATLAB-SIMULINK, as shown in Fig. (**4**). Where, the complete mathematical models of the constituent subsystems together with the daily load profile of the household are utilized in this case, to model the system.

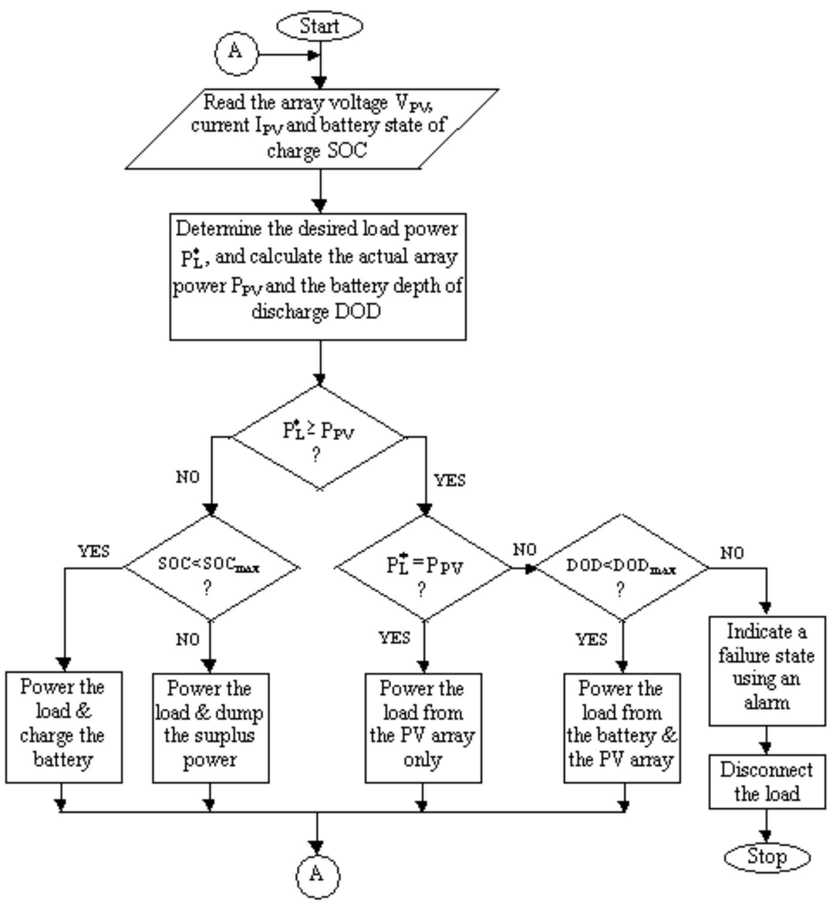


Fig. (3). Flowchart of the designed control strategy.

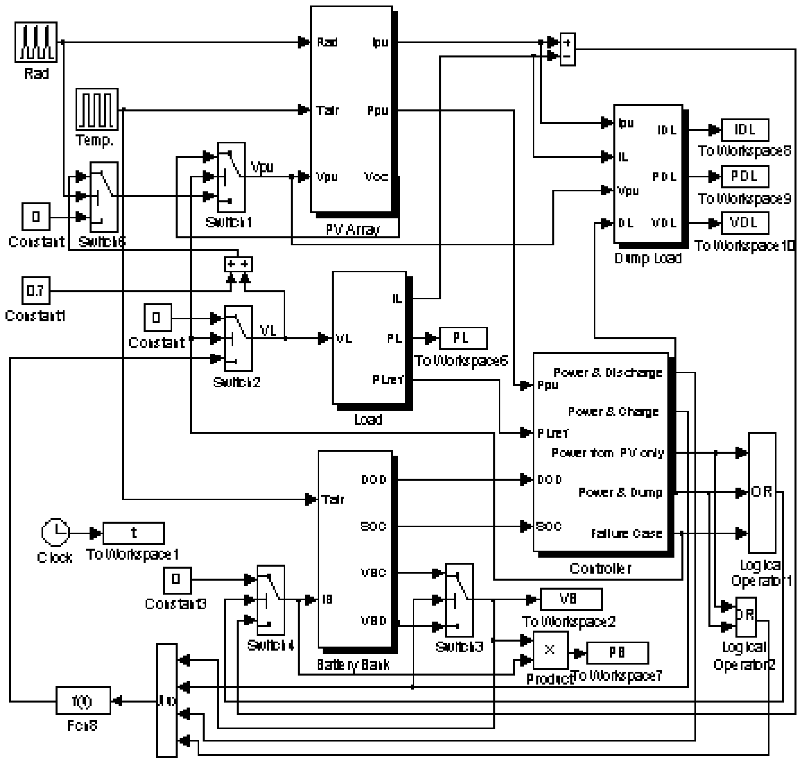
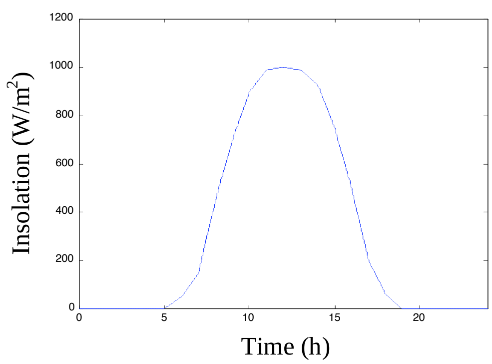
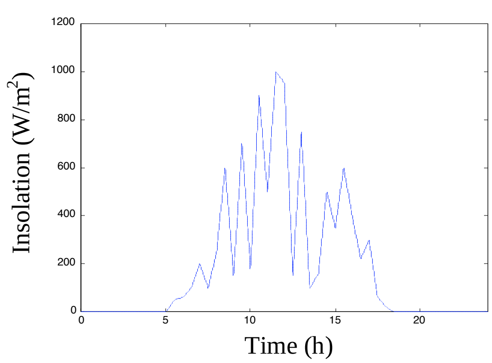


Fig. (4). SIMULINK block diagram of the stand-alone PV system.



(**a**) During sunny day



(**b**) During cloudy day

Fig. (5). Variations in solar insolation.

Also, the system's controller is mainly constructed, here, depending completely on using the flowchart of Fig. (**3**).

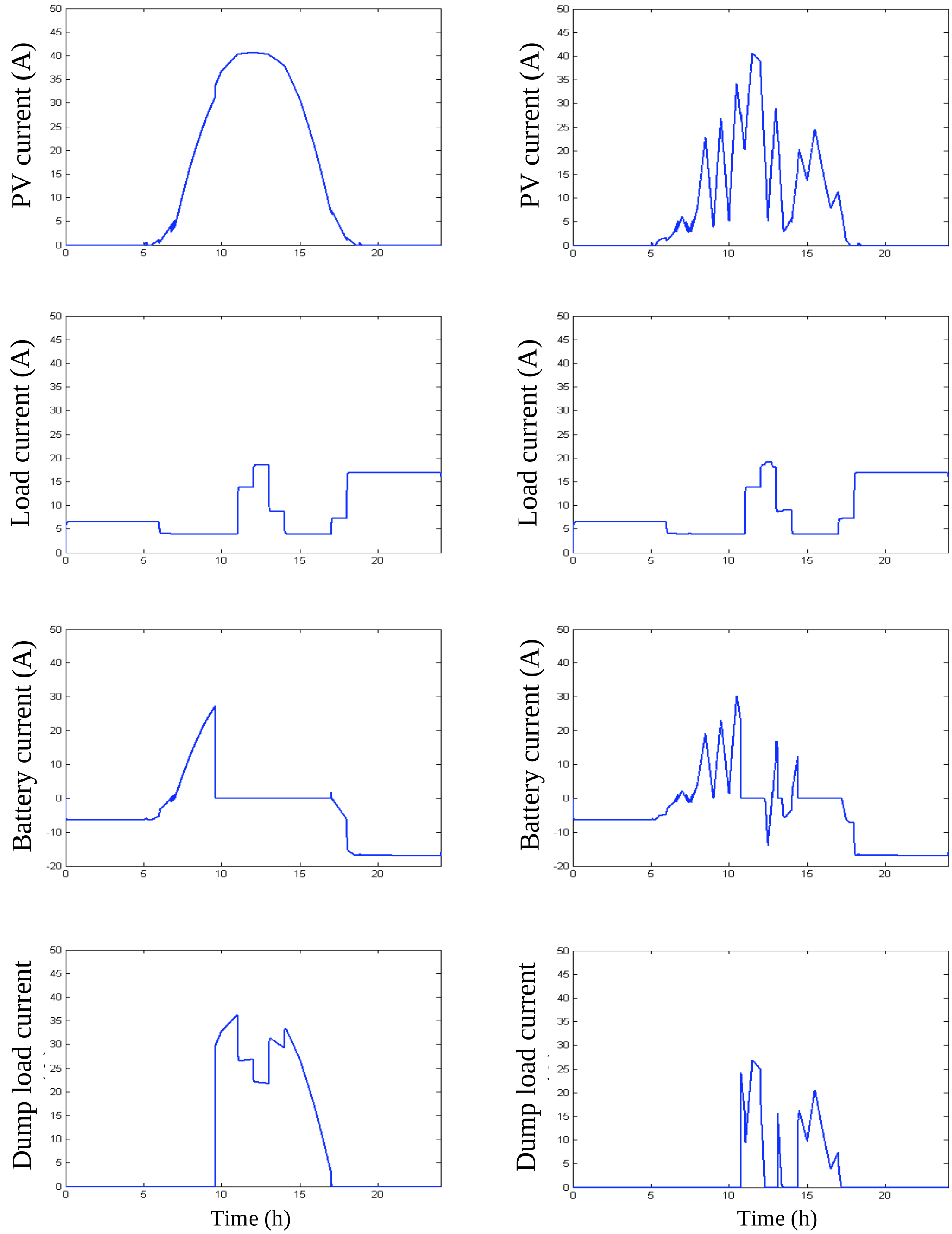
7. SIMULATION RESULTS

Due to the unavailability of the measured hourly solar radiation data for the studied site, the results of the stand-alone PV system are best evaluated by comparing the performance of the system during a hypothetical sunny day with that obtained during a hypothetical cloudy day. Where, Figs. **5**(**a**) & (**b**) show the variations in the hypothetical solar insolation, for a sunny day and for a cloudy day, respectively.

The performance of the system currents during the sunny and cloudy days is shown in Figs. **6**(**a**) & (**b**), respectively. Thus, it is illustrated from Fig. (**6**) that the PV current is proportional to the corresponding insolation level only. While, the battery current and the dump load current depend on the insolation level, the state of charge of battery, and on the load demand. Also, it is indicated from Fig. (**6**) that the load is satisfied with the required current, whatever the value of the corresponding insolation level is.

Fig. **7**(**a**) & (**b**) illustrates the performance of the system voltages, during the sunny and cloudy days, respectively. Thus, Fig. (**7**) indicates that the voltage difference at the terminals of the dump load is the same as that of the PV array; and this is true since the dump load is connected in parallel with the PV array. Also, the figure indicates that the PV voltage exists only during the daylight time and its value is nearly independent on the variations in solar insolation. While, the load and battery voltages exist all over the 24 hours of the day and have nearly constant value (i.e., independent on the insolation variations).

The Performance of the system powers during the sunny and cloudy days is indicated in Figs. **8**(**a**) & (**b**), respec-

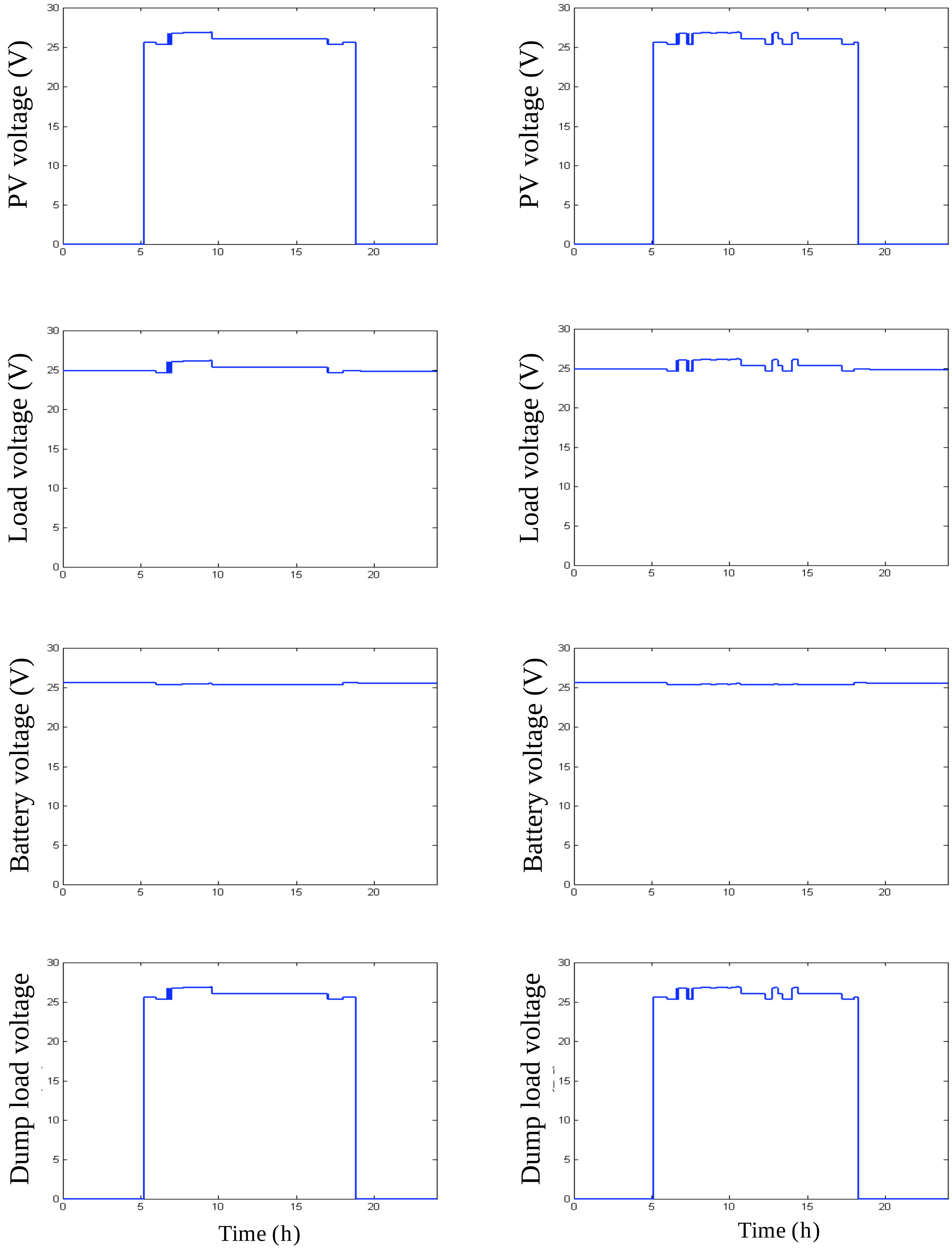


(**a**) During sunny day (**b**) During cloudy day

Fig. (6). Performance of the system currents.

tively. Hence, it is shown from Fig. (**8**) that the generated PV power is proportional to the corresponding variations in solar insolation only. While, the battery power and the dumped power depend on the corresponding insolation level, the battery state of charge, and on the load demand. Also, it is illustrated from Fig. (**8**) that the load is satisfied with the required power, whatever the value of the corresponding insolation level is.

Figs. **9**(**a**) & (**b**) indicate the state of charge of the system battery during the sunny and cloudy days, respectively. Thus, it is cleared from Fig. (**9**) that whatever the value of



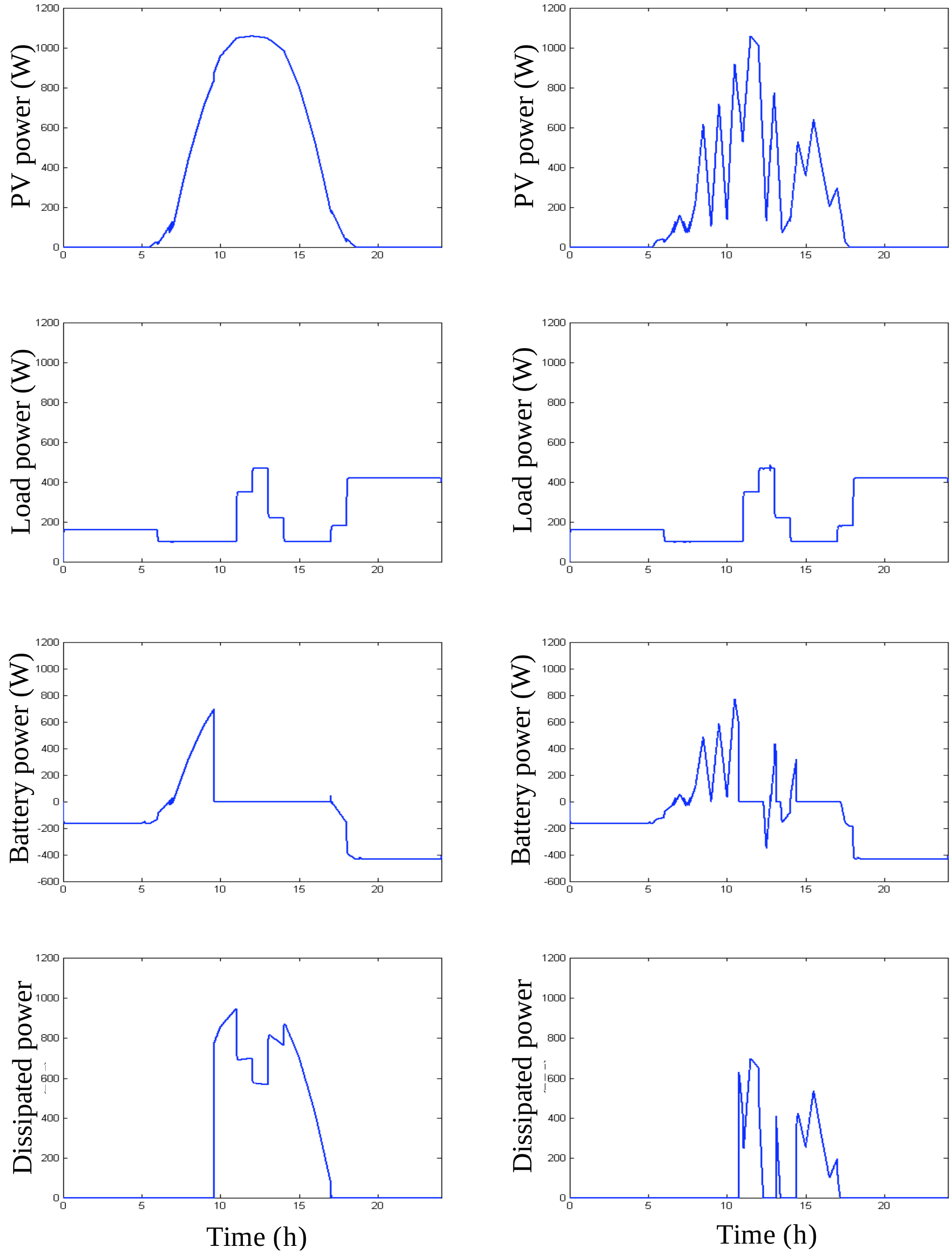
(**a**) During sunny day (**b**) During cloudy day

Fig. (7). Performance of the system voltages.

the insolation level be during the day, the maximum depth of discharge of the battery will not exceed the designed maximum permissible value which is 80 %.

8. CONCLUSION

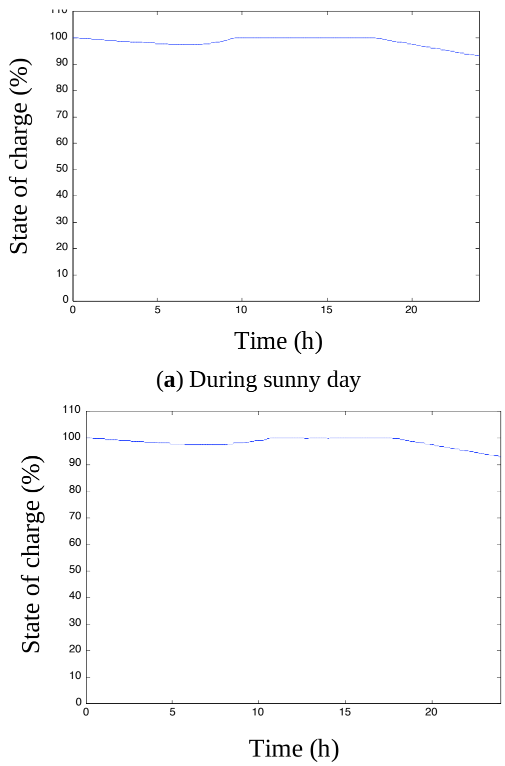
Remote and isolated areas usually need a stand-alone PV system to electrify their electrical loads. The configuration of



(**a**) During sunny day (**b**) During cloudy day

Fig. (8). Performance of the system powers.

the designed stand-alone PV system consists, mainly, of a PV array and a storage battery. The complete mathematical model of the designed system is developed and simulated by using MATLAB-SIMULINK. Also, the control of the system is optimally designed to issue the suitable control commands, which are based upon the current state of the system. Simulation results indicate that the overall performance of the system depends on the insolation level, state of charge of the battery, and on the load demand. The results indicate, also, the priority of the designed system to satisfy the load with the required power, whatever the value of the insolation level is. Moreover, they indicate the high capability of the designed control strategy in protecting the global stand-alone PV system against the hazards caused by the unexpected excess or deficit of the available energy. At the same time the results exhibit, also, the high capability of the control strategy in safely charging and discharging of the system battery.



(**a**) During sunny day

(**b**) During cloudy day

Fig. (9). State of charge of the system battery.

9. NOMENCLATURE

I_{PV}	=	PV array output current
V_{PV}	=	PV array voltage
n_s	=	number of series-connected cells
n_p	=	number of parallel strings
I_{Ph}	=	photo-current
I_{os}	=	PV cell reverse saturation current
I_{sc}	=	PV cell short-circuit current at standard conditions
I_{or}	=	reverse saturation current at reference temperature
n	=	ideality factor
K	=	Boltzmann's constant
e	=	charge of electron
T_r	=	reference temperature
T_c	=	PV cell temperature in °C
T	=	PV cell temperature in K
α_{sc}	=	short-circuit current temperature coefficient
Rad	=	PV cell illumination
$E_{G\circ}$	=	band gap for silicon
T_{air}	=	ambient temperature in°C
V_r	=	battery cell rest voltage
V_{ro}	=	battery cell rest voltage at 25°C
R_i	=	battery internal resistance per cell
R_o	=	battery internal resistance per cell at 25°C
n_{Bs}	=	number of series-connected battery cells
n_{Bp}	=	number of parallel strings of batteries

REFERENCES

[1] Islam, S.; Belmans, R. *Grid Independent Fuel-Cell Hybrid System: Optimal Design and Control Strategy*, Proceeding of the 19th European Photovoltaic Solar Energy Conference, Paris, France, **2004**, Vol. *3*, pp. 3311-3314.

[2] Sanidad, L.; Parsons, R.; Baghzouz, Y. Boehm, R. *Effect of ON/OFF Charge Controller on Stand-Alone PV System Performance*, American Institute of Aeronautics and Astronautics, Inc., **2000**.

[3] Taylor, R.; Abulfotuh, F. *Photovoltaic Electricity in Egypt*, Project Brief. http://www.rsvp.nrel.gov (accessed 2005).

[4] Vankeleom, J.; Dufourd, F.; Saleh, L.A. *ELVIRA: A Software for Rural Electrification in Developing Countries - Application for the Use of Photovoltaic Energy in Egypt*, Proceedings of the 19th European Photovoltaic Solar Energy Conference, Paris, France, June **2004**, Vol. *3*, pp. 3452-3455.

[5] Nafeh, A.A. Design and economic analysis of a stand-alone pv system to electrify a remote area household in Egypt. *Open Renewable Energy J.*, **2009**, *2*, 33-37.

[6] Moseley, P.T. Energy storage in Remote Area Power Supply (RAPS) systems. *J. Power Sources*, **2006**, *155*, 83-87.

[7] Markvart, T. *Solar Electricity*. John Wiley & Sons: New York, **1994**.

[8] Ishengoma F.M.; Norum, L.E. Design and *Implementation of a Digitally Controlled Stand-Alone Photovoltaic Power Supply, Proc. of the Nordic Workshop on Power and Industrial Electronics* (NORPIE/2002), Stockholm, Sweden, **2002,** pp. 1-5.

[9] Ashok, S. Optimized model for community-based hybrid energy system. *Renewable Energy*, **2007**, *32*, 1155-1164.

[10] Al-Alawi, A.; Al-Alawi, S.M.; Islam, S.M. Predictive control of an integrated pv-diesel water and power supply system using an artificial neural network. *Renewable Energy*, **2007**, *32*, 1426-1439.

[11] Shaahid, S.M.; I. El-Amin, I. Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—a way forward for sustainable development. *Renewable Sustainable Energy Rev*., **2009**, *13*, 625-633.

[12] Kaldellis, J.K.; Zafirakis, D.; Kaldelli, E.L.; Kavadias, K. Cost benefit analysis of a photovoltaic-energy storage electrification solution for remote Islands. *Renewable Energy*, **2009**, *34*, 1299-1311.

[13] Benghanem, M. Low cost management for photovoltaic systems in isolated site with new iv characterization model proposed. *Energy Convers. Manage*., **2009**, *50*, 748-755.

[14] Moharil, R.M.; Kulkarni, P.S. A case study of solar photovoltaic power system at sagardeep Island, India. *Renewable Sustainable Energy Rev*., **2009**, *13*, 673-681.

[15] Prasad, A.R.; Natarajan, E. Optimization of integrated photovoltaic-wind power generation systems with battery storage. *Energy*, **2006**, *31*, 1943-1954.

[16] New and Renewable Energy Authority. *Egyptian Solar Radiation Atlas, Ministry of Electricity and Energy*, Cairo, Egypt, **1998.**

[17] Jaboori, M.G.; Saied, M.M.; Hanafy, A.A.R. A contribution to the simulation and design optimization of photovoltaic systems. *IEEE Trans. Energy Convers.*, **1991**, *6*(3), 401-406.

[18] Lasnier, F.; Ang, T.G. Photovoltaic engineering handbook; IOP Publishing Ltd: Bristol, England, **1990**.

[19] Messenger, R.; Ventre, J. Photovoltaic systems engineering, CRC Press LLC: Boca Raton, Florida, USA, **2000**.

Received: December 17, 2008 Revised: February 27, 2009 Accepted: March 03, 2009