OPTIMIZATION OF THE SIZE OF PHOTOVOLTAIC (PV) ARRAY AND BATTERY STORAGE CAPACITY FOR POWER SUPPLY SYSTEM IN REMOTE AREAS

MOHAMMAD JAVAD OKHRAWI
Department of Electrical Engineering, Faculty of Engineering
Azarbaijan University of Tarbiat Moallem, Tabriz, Iran

In this paper, a new model is developed for determination of the size of photovoltaic (PV) array and battery storage capacity for stand-alone power supply system. The optimum size of the PV array and battery bank is important factor for a cost effective and good performing system. Based on the energy concept, data of solar irradiance, temperature, manufactures specifications of a PV module and battery, this model enables us to optimize the number of PV modules and the size of battery bank for the best performance of the entire system.

1. Introduction

Photovoltaic energy can make a significant contribution to improving the quality of life of innumerable small communities especially in rural areas by helping to meet the basic needs such as health care, education, refrigeration, water pumping and communication [1].

The present work is to assess the economic feasibility of stand-alone PV power supply systems in sunny countries and to find hints on the most suitable plant concept [2].

Two different options were investigated in order to evaluate the most attractive photovoltaic stand-alone electricity supply concept for a remote area with an averaged daily demand of 30 kWh.

Polycrystalline (LA361K54S) was selected in both the fixed-mounted and sun-traced operational mode. This new model is developed to estimate the photovoltaic generator's area and battery storage capacity requirements. A chart recorder has recorded the annual amounts for global normal and global inclined $(30°)$ data of irradiance. The amount of electricity produced by the photovoltaic generators (rated peak power: 50-150 kW, depending on battery capacity) was calculated the model efficiency as a function of cell temperature, irradiation intensity and air mass. The battery store (Ni-Cd) was modeled in form of linear Model [3]. These equations were all then combined to carry out real-data simulations over one year for all two cases based on hourly mean values of irradiation and temperature data [4]. Therefore, this data is used as the basis for the design and sizing of a stand-alone photovoltaic (PV) [7].

2. Investigated Options

It was intended that the power plant should consist of a PV generator (consisting of modules and panels) and battery storage only. Plant reliability should be guaranteed for 24 hours per day throughout the whole year. The following PV module (Table 1) is selected for the present investigation.

Within the simulation performed, two options were considered: Sun-traced and fix-mounted PV generators. Table 2 shows the monthly global irradiation. Two typical profiles for the summer and winter consumption resp. were created for simulation purposes. They differ remarkably.

The annually averaged daily load curve is shown in Fig.1.

Table 1
Investigated module

Cell type	Polycrystallin
Module type	LA361K54S
Produced by	Kyocera
Efficiency (η_{PV})	11.7%
Cost US$/Wp 1998	5.3
Lifetime	25
Maximum power	45W
Open circuit voltage	20.5 V
Short circuit cell current	I_{ph} =2.98 A
Reverse saturation current	I_O =9.23 nA
Voltage (max. power point)	V_{MPP} = 16.3V
Current (max. power point)	I_{MPP} =2.76A
Number of cells in series	N_S =36

Table 2: Monthly global irradiation (kWh/m^2) on to a sun-traced and an inclined plane $30°$

Month	Sun-traced	Inclined plane 30°
Jan	225	148
Feb	234	165
Mar	275	227
Apr	264	215
May	350	234
Jun	365	228
Jul	374	230
Aug	346	247
Sep	325	246
Oct	284	225
Nov	233	175
Dec	230	170

3. Mathematical Model for the PV-Battery-Load System

The equivalent circuit of a solar cell can be best estimated by single diode in parallel with the cell [5]. The generation of current I_{ph} by light is represented by a current generator in parallel with a diode, which represents the p-n junction.

$$I = I_{ph} - I_0 (e^{\frac{V}{mkt/q}} - 1)$$

Where k is Boltzmann's constant, T is absolute cell temperature, I_o is the dark saturation current, m is an empirical non-ideality factor and I_{ph} is the light generated current.

The output power from a PV module is directly dependent on the irradiance level.

$$P_{out} = V_{out} \cdot I_{out}$$

$$I_{out} = I_{ph} - I_0 (e^{\frac{V_{out}/N_S}{mkt/q}} - 1)$$

N_S is the number of cells in a series which in this study N_S equals 36.

$$P_{out} = V_{out} (I_{ph} - I_0 (e^{\frac{V_{out}/N_S}{mkt/q}} - 1))$$

$$P_{out}(i) = V_{out}(i) \cdot (I_{ph}(i) - I_0 (e^{\frac{V_{out}(i)/N_S}{mkt/q}} - 1))$$

Where *i* represents the *i*-th typical day in month.

For each typical day in a month, the necessary energy (E_{out}) to cover the energy of the load demand (E_{load}) is calculated.

While $(N_{PV} \cdot E_{out}(i) \cdot \eta_{PV} \le E_{load}(i))$ for any typical day, is increased the number of modules N_{PV} in the PV array by one. This process continues and the final value of N_{PV} is the optimum number of PV module in the array. η_{PV} is the efficiency of a PV system due to conversion losses.

This load is to be fitted with a linear combination of two other function of time. These functions are the average power output of the PV module and the power available from battery bank. In a design of a solar-battery system, it is desirable to cover the load demand by PV module as much as possible. First step in determination of the performance of the solar-battery system is to determine the number of PV modules that meet the load for a PV system only.

$$N_{PV} = \frac{P_{load}}{P_{out} \cdot \eta_{PV}}$$

The amount of power generated by PV array can be greater than the load,

$$(N_{PV} \cdot P_{out}(i) \cdot \eta_{PV} \ge P_{load}(i))$$

or less than the load,

$$(N_{PV} \cdot P_{out}(i) \cdot \eta_{PV} \le P_{load}(i))$$

The battery current (in-flow or flow-out) is calculated by:

$$I_{bat}(i) = \frac{N_{PV} \cdot P_{out}(i) \cdot \eta_{PV} - P_{load}(i)}{V_{bat}}$$

If $(N_{PV} \cdot P_{out}(i) \cdot \eta_{PV} \le P_{load}(i))$, then $I_{bat}(i) \le 0$, battery is discharging, (out-flow).

If $(N_{PV} \cdot P_{out}(i) \cdot \eta_{PV} \ge P_{load}(i))$, then $I_{bat}(i) \ge 0$, battery is charging, (in-flow).

The battery's state of charge (*SOC*) is computed as [6][3]:

$$SOC(i+1) = SOC(i) - SOC(i) \cdot \sigma_{SDR} \pm I_{bat}(i) \cdot \Delta t \cdot \eta_{BCE}$$

Where $SOC(t)$ is the state of charge, σ_{SDR} is the discharge rate, $\pm I_{bat}(t)$ is the battery charge (+) and discharge (-) current, Δt is time in hours, η_{BCE} is battery charging efficiency.

During discharge, η_{BCE} is assumed to be one. When charging, η_{BCE} is 0.65 to 0.85, depending on the charging current. When gassing starts at critical state of charge, η_{BCE} drops to 0.3

The demand for 100% power reliability means that the loss-of-load probability *LoLP* [2] has to be zero during the observed period of time *T*:

$$LoLP = \frac{\sum_{t=1}^{T} k_t \cdot \Delta t}{T}$$

where

$$k_t = \begin{cases} 1 \rightarrow when: P_{load,t} > (P_{out \rightarrow load} + P_{bat \rightarrow load}) \\ 0 \rightarrow else \end{cases}$$

Battery storage lifetime is highly dependent on the number of cycles, being determined by the storage capacity and the permitted minimum state of charge $SOC_{\min}$.

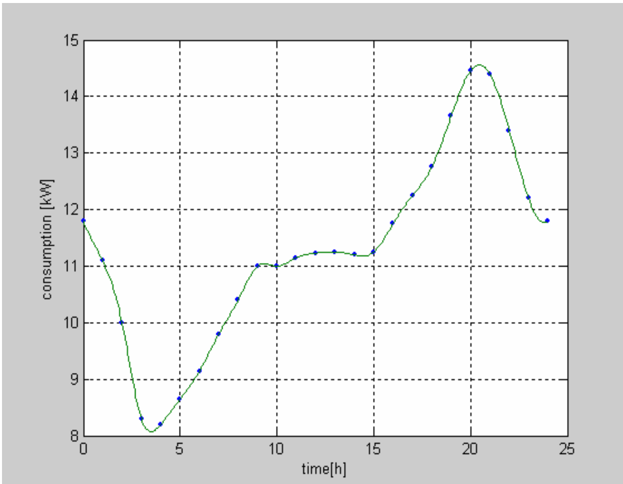

Fig. 1: Daily consumption profile of electricity

4. Simulation Model

The amount of electricity produced was calculated using correlations expressing the solar cell efficiency η_{PV} as a function of the irradiance intensity *G*, cell temperature υ and air mass *AM* [7]. For the Polycrystalline modules in equation they are given bellow.

$$\eta = P1*\left[\left(\frac{G}{G_O}\right)^{P2} + P3*\left(\frac{G}{G_O}\right)\right]*\left[1+P4*\left(\frac{\upsilon}{\upsilon_O}\right)+P5*\left(\frac{AM}{AM_O}\right)\right]$$

P1=0.28204 P2=0.39668 P3=-0.44730
P4=-0.092864 P5=0.016010

$$G_O = 1000W/m^2 \quad \upsilon_O = 25°C \quad AM_O = 1.5$$

$$50 \le G/Wm^{-2} \le 1100 \qquad 25 \le \upsilon/°C \le 50$$

$$1.3 \le AM \le 3$$

The parameters P_i in these semi-empirical correlation were found by non-linear least squares fitting techniques using hundred of tests under actual operating conditions. Measuring results and correlated values agree well in the covered ranges of independent variables [8].

The battery storage was modeled in the form of linear equation using the following recursive relationship [6][3]:

$$SOC(t+1) = SOC(t) - SOC(t)\cdot\sigma_{SDR} \pm \frac{I_{bat}.\Delta t}{C_{bat}} * \eta_{BCE}$$

where *SOC* is the state of charge, C_{bat} is the nominal capacity of the battery store, σ_{SDR} is the discharge rate, $\pm I_{bat}$ is the battery charge (+) and discharge (-) current and η_{BCE} is battery charging efficiency.

Fig. 2 shows the simulation process. Total module or panel area *A*, battery capacity C_{bat}, state of charge SOC and starting time t_O are all initialized at the beginning of the simulation process. Load demand P_{load} , irradiation *G* and temperature υ are extracted from a previously prepared data sheet. The module's efficiency η_{PV} and the air mass *AM* are then calculated. This information subsequently is used to determine the power P_{out} of the photovoltaic generator and the loss-of-load probability *LoLP*. Finally, a new *SOC* is found from the battery store model. This procedure is repeated over the time period *T* (one month). As long as *LoLP* is not equal to zero at the end of this time period, either the battery storage or the generator area will have to be increased. The cost of electricity production was calculated when the generator area *A* and battery capacity C_{bat} satisfied the demand for 100% reliability.

5. Results

As shown in Fig. 3, the minimum permitted state of charge, $SOC_{\min}$, has a powerful effect on the battery store capacity (at constant panel area), and therefore has a strong influence on the size of the whole battery store. High $SOC_{\min}$ values lead to very long store. As expected, small storage capacities lead to a large panel area. Conversely, large storage capacities lead to small panel area. However, the simulations also show that the panel area *A* must not fall bellow a certain minimum value. Due to the self discharge of the battery store this holds even in the case of continues no-load operation. The analysis of the electricity generation cost shows a strong dependence on the battery store capacity and on the minimum permitted state of charge $SOC_{\min}$ (Fig. 4). In Fig. 4 the results of the most attractive case, i.e. sun-traced Polycrystalline modules is shown. Minimum cost are found at a $SOC_{\min}$ value of 0.8. From Fig. 4 it is concluded that undersizing of the battery store leads to a significant increase of the generation cost, while oversizing has less consequences.

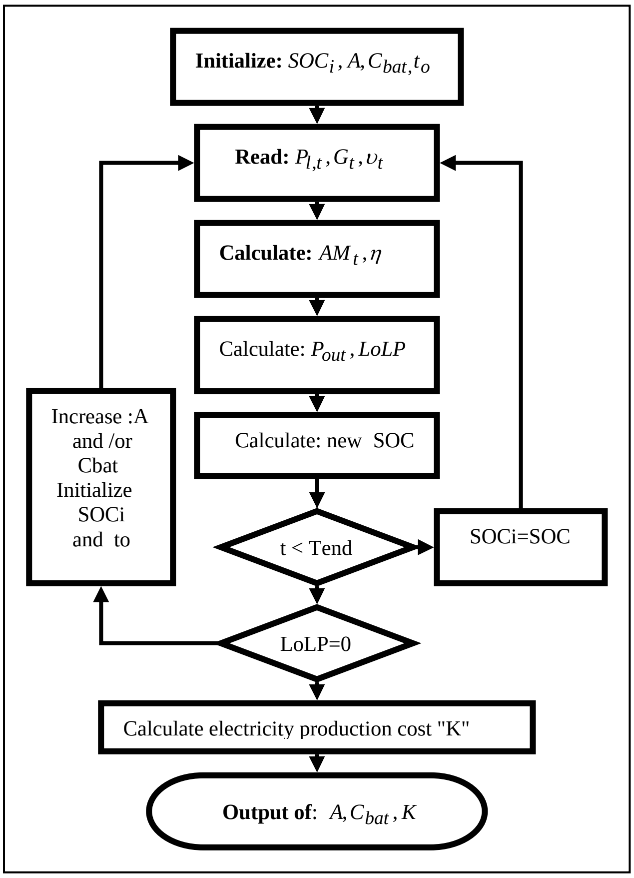

Fig. 2: Simulation process flow chart

6. Conclusions

The present investigation demonstrated that the minimum permitted state of charge $SOC_{\min}$ had a strong influence on the battery storage size and with that on the cost of the plant. Low values for $SOC_{\min}$ lead to small storage size and low storage costs, while high $SOC_{\min}$ values lead to very large and expensive battery stores. On the other hand, smaller stores have to be replaced more frequently, leading to increased electricity production cost too. In the cases examined, the optimum value of $SOC_{\min}$ was 0.8. The performed simulations show that one hour resolution for irradiation and temperature data is sufficient. Higher resolution leads to unnecessarily long computing time.

Furthermore, it has been shown for sunny countries that with stand-alone photovoltaic power plants, Polycrystalline modules in sun-traced operational mode lead to the lowest electrically production cost because of their longer lifetime and better efficiency. In some cases, the cost of the battery store exceeds 60% of the cost of the whole plant. When planning a stand-alone PV power plant, it may be better to include a reduced battery store capacity, i.e. to replace part of the store by the use of a fossil-fueled generator, to guarantee the reliability of the plant during periods of low irradiation. It would thus be possible to reduce the costs to about 70%.

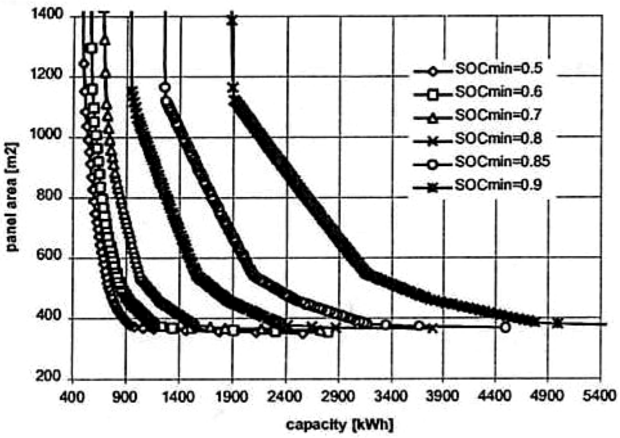

Fig. 3: Dependency of total panel area on battery store capacity

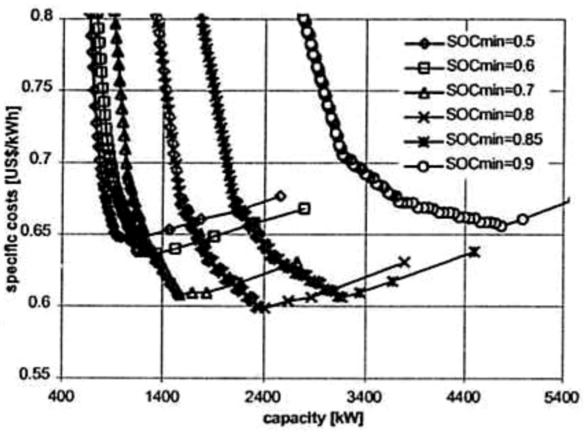

Fig. 4: Dependence of electricity cost on the battery store capacity

[1] Häberlin: "Photovoltaic", *AT Verlag*, Aarau/Schwize, 1991.

[2] *J. Badran*: "A Sizing Methodology for Stand-Alone Photovoltaic Power Systems", Dissertation, Techinsche Universität Wien, 1995.

[3] *Y.H. Kim, H.D. Ha*, "Design of Interface Circuit with Electrical Battery Models", IEEE Trans. on Industrial Electronics, Vol. 44, No. 1, Feb 1997, pp. 81-86.

[4] *J.A. Gow, and C.D. Manning*, "Development of a Photovoltaic Array Model for use in Power Electronic Simulation Studies", IEEE Proceedings of electric Power Applications, 146(2), March 1999, pp. 193-200, ISSN: 13502352.

[5] *F. Nakanishe, T. Ikegami, K. Ebihara*; "Modeling and operating of a 10 kW Photovoltaic Power Generator using Equivalent circuit Method", 28th IEEE PVSC, Kumamoto university, September 2000.

[6] *Z.M. Salameh, M.A. Casacca and W.A Lynch*, "A Mathematical Model for Lead-Acid Battery", IEEE Trans. on Energy Conversion, Vol. 7, No. 1, March 1992, pp. 93-97

[7] *W. Durisch et al.:* "Characterization of Photovoltaic Generators. Appl. Energy" 65(2000), pp. 273-284

[8] *W. Durisch*: "Internal Technical Report", Arge Solar 91,Waltenburg, Nov.1997