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RESEARCH ARTICLE

Modelling and Performance Optimization by Simulation of a Stand-alone Solar Photovoltaic system

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Abstract

Solar photovoltaics prove to be the best promise for use when global resources of fossil fuels are fast depleting. A stand alone PV system is considered to have a great potential in India in meeting the electrical energy requirement in remote villages having no grid connectivity. Here, a mathematical model is developed for all the components of a standalone PV system. Various parameters affecting the system are identified as the intensity of solar radiation, ambient temperature, cell and its characteristics, battery performance, type of load and other system parameters like days of autonomy, depth of discharge etc. The effect of these parameters on the system performance is studied in detail. To calculate the module and battery capacity for the expected load, a detailed sizing method is suggested. From the simulation it is seen that the sizing procedure adopted is able to meet the load and also works optimally year-round. The model developed here is a simpler and accurate one suitable for our local conditions but without compromising the effect of any parameter influencing the system performance.

Introduction

India is poorly placed in energy resources. Though 16% of world population lives in India, only 0.6% of world's oil, 0.6% of natural gas and 6% of coal are in India. It is evident that all energy resources based on fossil fuels has limitations in availability and will soon exhaust. Hence the long term option for energy supply lies only with renewable energy sources. These resources are in-exhaustible for the next hundreds of years. These sources include Solar Energy, Bio-Energy, Wind Energy, Geothermal Energy, Wave, Tidal and OTEC. *Photovoltaic* (PV) refers to the creation of voltage from light. A solar cell is a converter; it changes the light energy into electrical energy. A cell does not store any energy, so when the source of light (typically the sun) is removed, there is no electrical current from the cell. If electricity is needed at night, a battery must be included in the circuit. There are many materials that can be used to make solar cells, but the most common is the element silicon.

The two principle classifications of photovoltaic systems are:-

Grid-connected or utility-interactive systems: They are designed to operate in parallel and interconnected with the electric utility grid.

Stand-alone systems: They are designed to operate independent of the electric utility grid, and are generally designed and sized to meet DC and/or AC electrical loads.

For PV systems, the initial construction and equipment costs are high, and hence it is essential to simulate the system before connecting it so that the cost can be minimized. Long term performance analysis of a system can be carried out by modelling and simulation. Here an attempt is made to model a stand-alone PV system and to carry out performance simulation with various parameters affecting its performance. A sizing/design recommendations of a stand-alone system having 1KW load has been carried out.

1. MODELLING THE COMPONENTS OF A STAND-ALONE SYSTEM

Stand-alone system involves no interaction with the utility grid. A typical stand-alone system consists of a PV generator (cell, module or array), a charge-controller, a battery bank, an inverter and a load (DC or AC). Fig. 1 illustrates the components of a stand-alone PV system. Various parameters affecting the performance of a stand-alone PV system are identified as the intensity of solar radiation, ambient temperature, type of cell & its characteristics, battery performance, type of load and other system parameters like days of autonomy, depth of discharge, etc. The effect of these parameters on the system performance is studied in detail subsequently.

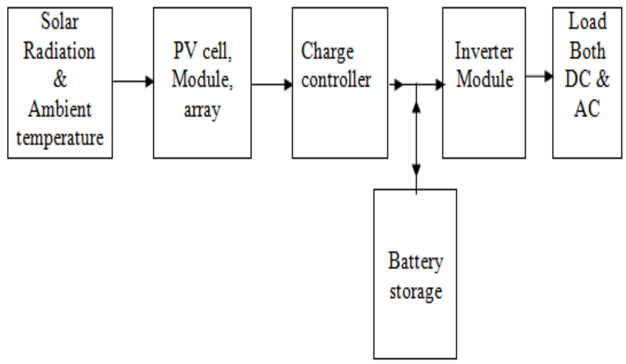

Fig. 1 Block diagram of a stand-alone PV system

1.1 SOLAR RADIATION MODEL

The solar radiation that penetrates the earth's atmosphere and reaches the surface differs in both amount and character from the radiation at the top of the atmosphere. The insolation at a given location on the earth's surface depends on the altitude of the sun in the sky. Since the sun's altitude changes with the date and time of the day and with the geographic latitude at which the observations are made, the rate of arrival of solar radiation on the ground is a variable quantity even in the time. The cell temperature depends exclusively on the irradiation and ambient temperature. The open-circuit voltage increases logarithmically with the ambient irradiation, while the short-circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cell`s temperature is the linear decrease of the open circuit voltage.

The sinusoidal distribution of irradiance can be obtained from

$$G_{a} = P\sin\left(\frac{\pi}{2} + \alpha\right) \qquad (1)$$

G_a can be calculated for a given location from H_{av}[12].

$$H_{av} = H_o\left[a + b\left[\frac{S}{S_{max}}\right]\right] \qquad (2)$$

From the radiation data of a given location, say Trivandrum,on a typical day(say March 15) for S=8.2h, P can be calculated. Here averaging is done for a day(march 15) and this area is divided by 12 hours of daytime and is integrated over S to find the peak value of radiation.This is found to be 1035.86W/m^2.

1.2 CELL MODEL

A solar cell can be represented by a one-diode electrical equivalent model as shown in Fig. 2.

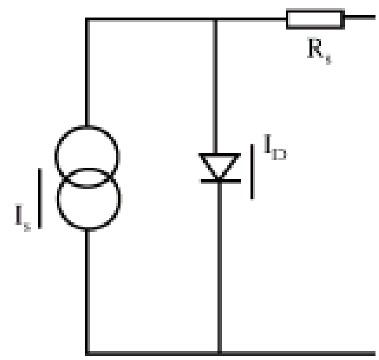

Fig. 2 *Model* for a single solar cell

The model contains a current source $I_{ph,}$ a diode and a series resistance Rs, which represents the resistance inside each cell and in the connection between the cells.
The operating current of a solar cell is given by [3]

$$I = I_{ph} - I_D$$
$$= I_{ph} - I_0 \left[e^{\frac{e[V+IR_S]}{mKT_c}-1} \right] \quad (3)$$

1.3 MODULE MODEL

Cells are normally grouped into modules, which are encapsulated with various materials to protect the cells and the electrical connectors from the environment. Modules consists of N_{PM} parallel branches, each with N_{SM} solar cells in series

The PV module current I^M under arbitrary operating conditions can be described as [13]

$$I^M = I_{SC}^M \left[1 - e^{\left(V^M - V_{OC}^M + I^M R_S^M / N_{SM} \, V^{C_t} \right)} \right] \quad (4)$$

Successive approximation technique is used to solve this equation. A program is written in C language to find the module current and is tested for a solar module SP36.

1.4 ARRAY MODEL

The modules in a PV system are connected in arrays. If modules are assumed to be identical and the ambient irradiation is the same on all the modules, then the array current will be

$$I^A = M_P I^M \quad (5)$$

1.5 BATTERY MODEL

Most stand-alone PV systems have a storage battery as a daytime load to be charged from the PV array during the day. The equivalent circuit of such a system is shown in Fig. 3, where the PV cell/module/array is represented by the single-exponential lumped-constant parameters model [7].

When charged, the storage battery is represented by its open-circuit voltage E_b in series with its internal resistance R_b and has an I-V characteristic described by

$$V = E_b + IR_b \quad (6)$$

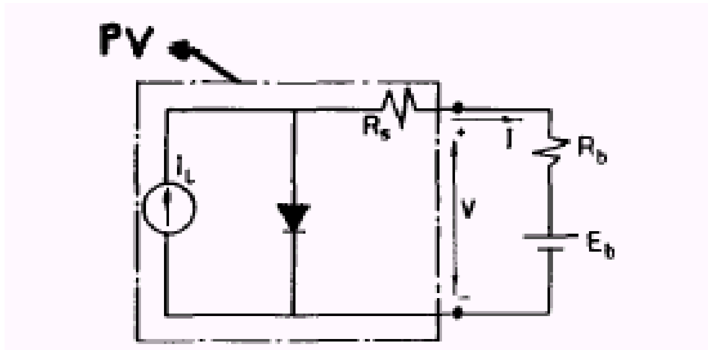

Fig. 3 Equivalent circuit of a battery charging from a PV array

The following equations are used to describe the battery open-circuit voltage/cell as a function of its SOC under both charging and discharging conditions [7].

Charging: $E_b = 1.95 + 0.43 \times SOC$ (7)

Discharging: $E_b = 2.22 - 0.32 \times DOD$ (8)

Because of the complexity involved in determining the battery charging trajectory and in order to simplify the analysis, the following assumptions have been adopted .

(i) The battery internal resistance R_b is considered constant.
(ii) Temperature influence on battery performance is neglected.
(iii) Self-discharging effects of battery are neglected.
(iv) The battery is characterized by an overall Ah conversion efficiency.

The overall efficiency of the battery will then be,

$$\eta = \eta_c \times \eta_d \quad (9)$$

The initial battery capacity and the corresponding SOC are found from the discharging process which is assumed to take place in a prescribed constant load for a certain period of time during the night, previous to the charging day. Knowing the discharge load current in A and the duration in h, the Ah going to the load, $(Ah)_L$, is determined. The charging current during the first morning hour of operation I(1) is determined from Eqn. (4) corresponding to 12V of module voltage.

Assuming the charging current to remain constant during the entire hour, the amount of charge (in Ah) actually stored in the battery during the first hour is calculated taking the charging efficiency into consideration (I(1) *1 h * η_c)**.**This stored charge represents the increment with which the capacity of the battery increases denoted by $\Delta c_b(l)$. The new battery capacity at the end of the first hour of operation $CC_b(l)$ is then found by adding this increment to the initial starting battery capacity $C_b(O)$. Once the new battery capacity is found, the new SOC is determined by simply dividing the above battery capacity by the rated value. The calculated SOC represents the battery state at the beginning of the next hour SOC(2).The above procedure is repeated until we reach the full charge condition (100% SOC).The open-circuit voltage of the battery is assumed to vary between a minimum cut-off voltage of 11.4 V (1.9 V/cell) and a maximum acceptable value of 14.3 V (2.38 V/cell) from Eqn. (7) & (8) respectively. In such case, the charge-controller should disconnect the battery from the PV module/array to prevent it from excessive overcharging.

The above procedure is mathematically expressed by the following equations:

$C_b(k) = CC_b[k-1]$ (10)

$SOC(k) = CSOC[k-1]$ (11)

$\Delta C_b(k) = I(k) \times \Delta_t \times \eta_c$ (12)

$CC_b(k) = C_b(k) + \Delta C_b(k)$ (13)

$CSOC(O) = CC_b(O)/C_0$ (14)

3 SYSTEM SIZING

The operation of a stand-alone photovoltaic (PV) system depends, among other factors, on the energy input on the panel surface and on the energy demand or load. Incident solar radiation has a random component which makes it impossible to accurately know how much energy the system will receive during a given period. So, before building a stand-alone photovoltaic system, it is necessary to calculate the size of the generator and the storage system for the expected load via a sizing method. There are several such methods available and the use of one or the other will depend on the initial data available [10,11]. A simple sizing procedure is outlined here.

A stand-alone PV system sizing involves three stages. They are

- Load estimation
- Battery sizing
- Module sizing

3.1 LOAD ESTIMATION

The AC and DC loads are estimated separately. They may vary from day-to-day and hence in such cases, weekly averaged load estimation will be prepared.

DC load Demand= DC load current (amps) x Hours of operation (15)

AC load demand= AC load Power (watts) x Hours of operation (16)

Daily load (Ah) = DC load + (AC total / efficiency / input DC voltage) (17)

Inverter Selection

The inverter should meet all continuous loads at a given time and meet surge demands also. To avoid unreasonably high surge demands, typically 4-6 times of inductive load currents is assumed to be surge currents. The other features need to be considered during inverter selection include – efficiency, output waveform, voltage or frequency regulation, etc. An inverter with a higher DC input voltage is preferred since this reduces the size of other components like wires, fuses, connectors, etc. Hence, DC Amp Hours input to inverter is calculated as follows.

$$AC\ Load(Ah) = \frac{AC\ subtotal\ [Wh]}{(Efficiency\ \times Input\ \ DC\ voltage\ )} \quad (18)$$

$$DC\ watt\ hours\ into\ inverter = \frac{AC\ subtotal\ (Wh)}{Efficiency} \quad (19)$$

$$DC\ Amp\ hours\ into\ inverter = \frac{DC\ Watt\ \ hours\ \ into\ \ inverter}{DC\ Input\ \ voltage\ \ of\ \ inverter} \quad (20)$$

3.2 BATTERY SIZING

An average of 5 and 10 days can be used as autonomy for non-critical and critical applications respectively. 50% and 80% loads can be discharged from a shallow and deep discharge battery respectively. The battery capacity need to be corrected for rate of discharge. If no correction factor is available, a default value of 1.3 as rate factor for converting from C/120 discharge to C/10 rate. To correct for temperature, a temperature derate factor of .97 can be used. Hence,

$$Battery\ capacity = \left(\frac{autono\ my \times daily\ \ load}{Max\ \%\ uasable\ \times Temp\ .derate\ \times Rate\ \ factor}\right) \quad (21)$$

$$No.of\ parallel\ batteries = \frac{Battery\ \ capacity\ \ required}{Capacity\ \ of\ selected\ \ battery} \quad (22)$$

$$No.of\ series\ batteries = \frac{Load\ \ nominal\ \ voltage}{Battery\ \ nomonalvoltage} \quad (23)$$

3.3 ARRAY SIZING

The effect of temperature on cell can be offset by using I_{mp} values rather than I_{Sc} values in sizing. The modules may be derated by 10% to account for dust. Further an increase in capacity of 5-10 % is also needed to accommodate the battery Coulombic efficiency.

Hence,

$$No.of\ parallel\ modules = \frac{Daily\ \ load\ \ demand\ \ (Ah)}{(0.95 \times module\ \ input\ \times 0.9)} \quad (24)$$

$$No.of\ series\ modules = \frac{Nominal\ \ system\ \ voltage}{Nominal\ \ module\ \ voltage} \quad (25)$$

A battery sizing recheck can be carried out to make sure that the final battery size arrived is within the manufacture's specifications as detailed below.

$$Daily\ discharge\ of\ battery = \frac{Daily\ \ load\ \ (Ah)}{(No.of\ \ parallel\ \ batteries\ \times Battery\ \ capacity\ )} \quad (26)$$

$$Max\ rate\ of\ charge = \frac{(No.of\ \ parallel\ \ batteries\ \times Battery\ \ capacity\ )}{(No.of\ \ parallel\ \ modules\ \times I_{mp})} \quad (27)$$

For an assumed load of 1000W, the above sizing procedure is applied assuming 80% inverter efficiency, 90% charging and discharging efficiency for the battery and an autonomy of 3 days. The following values have been obtained.

M_P =6, M_S =2 and C_0=200Ah

4 PERFORMANCE SIMULATION

To determine the performance of the stand-alone system over a long period of time, a component based system simulation has been carried out. Parameters like solar radiation, ambient temperature, type and duration of load, depth of discharge (DOD) of battery, efficiencies of charge-controller and inverter, system autonomy, etc have been considered. The module current is calculated for different values of irradiation and temperature for a solar module SP36 having the following electrical parameters: $P_{max,}$ 36W, $I_{sc,}$ 2.4A, $V_{oc,}$ 21.7V, N_{SM}=9, N_{PM}=4 and the following plots are obtained.

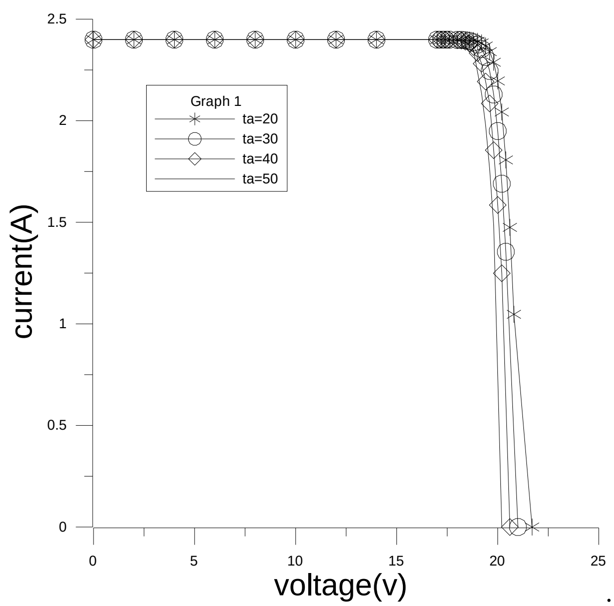

Fig. 4 V-I curves at various cell temperatures for an irradiation of 1000W/m^2.

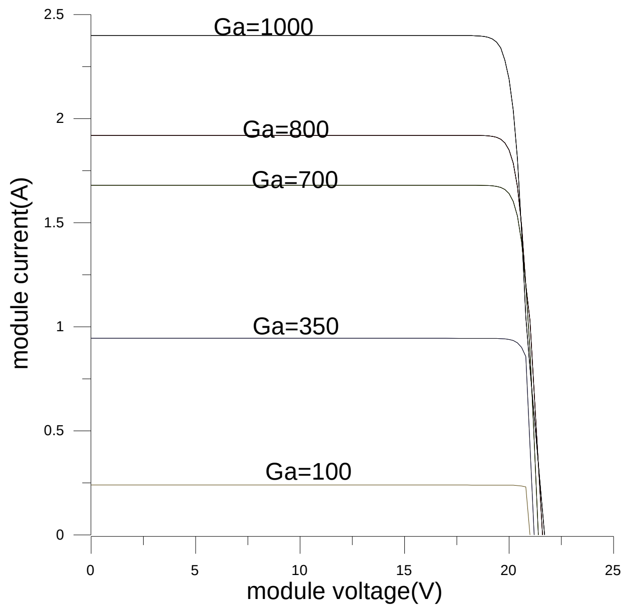

Fig. 5 V-I curves for various irradiation levels of ambient temperature of 20^{0}c

Fig. 4 shows that the open-circuit voltage increases logarithmically with the ambient irradiation, while the short-circuit current is a linear function of the ambient irradiation. The influence of the cell temperature on the I-V characteristics is illustrated in Fig. 5.The dominant effect with increasing cell temperature is the linear decrease of the open-circuit voltage, the cell being thus efficient. The number of days of autonomy is the main factor that determines the size of the battery and therefore the magnitude of the daily battery depth of discharge. Fig.6 shows the variation of autonomy with depth of discharge. Fig. 6 illustrates that for a given load of 1000W, the optimum occurs at an autonomy of 3 days since the change of slope occurs at that point.

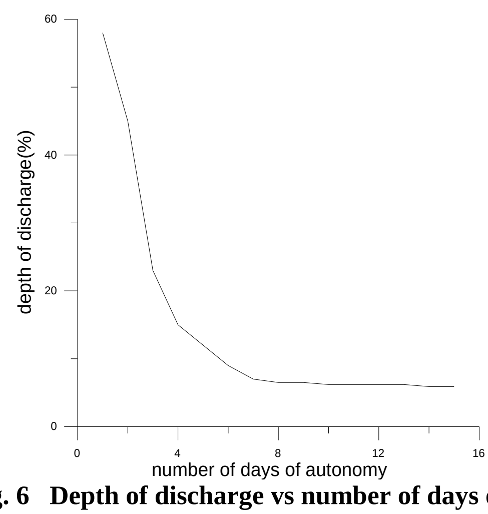

Fig. 6 Depth of discharge vs number of days of autonomy

Fig. 7 shows the performance of the system with parameters like solar radiation, array current, daily load, battery capacity at the end of charging and discharging and open-circuit voltage. From fig. 7 it is clear that the array current is charging the battery for 5 hours during the day time and the battery will remain in full charge till discharge occurs at night time through the load. In the second cycle, it is seen that only 4 hours of charging is required to bring the battery to full capacity. At this moment, cut-off voltage is obtained and the charge-controller will disconnect the array from the battery from further charging and the battery capacity is maintained till the next discharge occurs. From this it is seen that the designed system is able to meet the load.

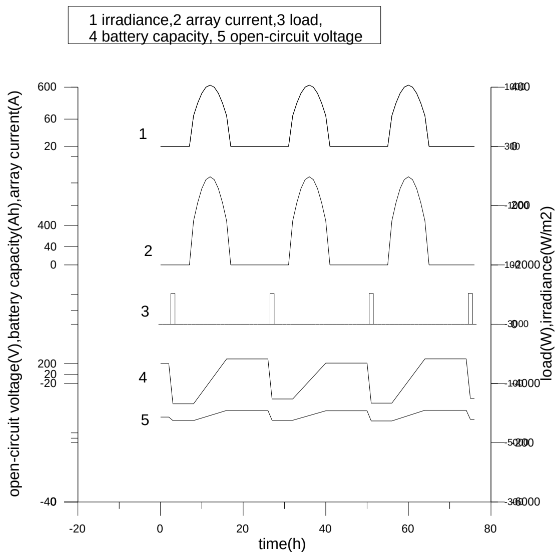

Fig. 7 performance simulation of irradiance, array current, load, battery capacity and open-circuit voltage over a period of time.

5 CONCLUSION

Modelling and performance simulation of a solar stand-alone system is essential since the initial system component costs are high. Hence overdesigning the system is uneconomical and under designing will lead to failure of the system by not meeting the load always. In this paper, a mathematical model is developed for all the components of a stand-alone PV system. Various components of the system are expressed in a mathematical model and the long term performance of the system has been simulated to find optimum values for its components. From the simulation, it is shown that the sizing procedure adopted is able to meet the load and also works optimally.

Nomenclature

Symbols	**Description**
C_0	Rated battery capacity, Ah
Cb(k)	battery capacity at the beginning of the k^{th} hour, Ah
$CC_b(k)$	the battery capacity at the end of the same hour, Ah
$\Delta c_b(k)$	charge stored in the battery during the k^{th} hour, Ah
e	electronic charge,1.602*10^{-19},C
E_b	open circuit voltage of the battery, V
G_a	irradiation, W/m^2
H_{av}	monthly average of the daily global radiation on a horizontal surface at a location, kJ/ m^2-day
H_0	monthly average of the daily global radiation on a horizontal surface at the same location on a clear day kJ/ m^2-day
I^A	array current, A
I_0	dark saturation current, A
I_D	diode current, A
I^M	module current, A
I^M_{SC}	short-circuit current of the module, A
I_{ph}	current source, A
I(k)	the charging current during the k^{th} hour, A
k	Boltzmann constant, k=1.38*10^{-23} J/K
m	idealising factor
M_P	number of parallel branches in an array
M_S	number of series branches in an array
N	day length, h

N_{PM}	number of parallel branches of solar cells
N_{SM}	number of solar cells in series
P	peak value of irradiation, W/m^2
R_b	internal resistance of the battery, Ω
R_S^M	series resistance of the module, Ω
S	monthly average of the sunshine hours per day at the location,h
S_{max}	monthly average of the maximum possible sunshine hours per day at the location,h
T_a	ambient temperature, ˚C
T_c	cell temperature, ˚C
V	voltage imposed across the cell, V
V^C_t	thermal voltage of a single solar cell, V
V_{OC}	open-circuit voltage, V
V^M	module voltage, V
V^M_{OC}	open-circuit voltage of the module, V

Abbreviations

DOD	depth of discharge
PV	photovoltaic
SOC	state of charge

Greek Symbols

α	hour angle
η_c	charging efficiency
η_d	discharging efficiency

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