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Technical Note

Autonomy considerations for a standalone photovoltaic system

Nikhil Pattath Gopi *, Subhakar Devendran

Energy Division, School of Mechanical and Building Sciences, VIT University, Vellore 632014, India

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ABSTRACT

The standard procedures for photovoltaic (PV) system sizing consider a representative value for autonomy based on the solar irradiation of the given location and the load consumption. However the post charging and discharging events that occur after the defined autonomy period were seldom considered in the earlier studies. This technical note appraise the application of a proposed simulation model of a standalone PV system, evolved from an hourly performance model, system which can simulate the module output along with battery charging and discharging cycles during the post autonomy hours of system operation. Based on the yearly irradiation input, the simulation model can predict the minimum time duration (hold time) required for the PV system to prepare for the load between two consecutive low irradiation cycles. All the simulation codes were developed in Matlab (r2010a).

The result shows that the success of any stand alone PV system with autonomy $d > 1$ strongly depends on the irradiation cycles of the location, and autonomy considerations would help save the system requirements up to 15% .The applicability of the proposed autonomy model is described and validated using a real time example of a refrigeration system.

Introduction

The switch over to PV option is becoming popular and it is expected to take an exponential leap with a growth rate of 56% in the upcoming years, as reported by International energy agency [1]. To keep up with this projected growth of PV sector, there is a demand for control algorithms which can effectively predict the PV system behavior as well as provides an option to design the system based on user requirements. A critical load application is often characterized by the most reliable PV system configurations and this presumable high reliability is often reflected on their high storage capacity and hence higher investment. Low irradiation cycles can influence the loss of load hours (LOLH) in critical applications, and hence these systems are designed with high values of autonomy [2]. World meteorological organization [3] defines a low irradiation cycle as the number of continuous days on which the daily average of global solar radiation is below 120 W/m^2. By definition, loss of load hours is the total hours in a year during which the PV system fails to meet the required load. The autonomy d represents the number of additional days of storage required by the system to meet the load during the days of cloud cover, and generally this value is a user input considering the fluctuation in the yearly solar radiation of the given location. The large variations in solar irradiation make the system sizing a challenging task and over the past years many studies were carried out in the field of PV system sizing [4–8]. Clearly, most of the prominent works [9–15] in this field recommends the application of stochastic and iterative methods for optimization since it could take into account the uncertainties in the load demand and solar input. A systematic approach for the design of a standalone PV system is presented in IEEE standard sizing procedures [16]. An autonomy span (AS) is defined as the number of continuous days of low radiation (or no radiation) and it can take a range from zero to d days. Likewise there can be a number of AS occurring in a given location in a given year. An autonomy span can evidently influence the LOLH, if more cloudy days occur after the actual autonomy. This is usually witnessed during the days between summer winter transitions. Certainly, majority of the studies in the past have included autonomy as one of the design parameter [17], however none of them investigates the effect of charging and discharging cycles in the post autonomy period.

Hence, the main objective of this study is to investigate the response of PV system in between two consecutive autonomy spans – ASI and ASII, which can be further extended to other autonomy spans. For this, a simulation model is developed in MATLAB platform for predicting the hourly behavior of a PV stand alone system with storage, and hence to understand the effect of consecutive low irradiation cycles on the system performance. The

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* Corresponding author at: National Institute of Solar Energy, Gurgaon, India. Tel.: +91 9962074466.

E-mail address: nikhilpg_mnre@hotmail.com (N. Pattath Gopi).

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Nomenclature

AH_d	daily ampere hour consumed by the load
A_h	ampere hour rating of the individual battery
C	battery capacity (Ah)
d	number of days of autonomy
E_b	$ø_{ch}$ if battery is charging, $ø_{dch}$ if battery is discharging
D_r	dust rate factor on the PV module
h	time interval used in simulation
H	monthly average daily radiation on horizontal surface in MJ/m^2
I_{bat}	battery charging/discharging current (A)
I_{mpp}	current at maximum power point in Amps.
N_{bp}	number of batteries in parallel
P_{inv}	capacity of the inverter (Watts).
R	rate factor for the battery.
SOC	state of charge of the battery
t_r	temperature de rate factor for the battery
V_{bat}	voltage across battery terminal
V_m	nominal voltage of the system in Volts
V_{dc}	system voltage at DC terminal in Volts
W_{ac}	total wattage capacity of the AC load
σ	self discharge coefficient of the battery

simulation model is validated using a real time example, from IEEE standard sizing procedures, of a refrigeration system at a Brazilian village [16].

Hourly simulation model

This study is essentially a continuation of the earlier research carried out by the authors [21], where in the authors presented a methodology for the optimization of a PV system which considers effect of module and battery aging and effect of h_i and h_e. The methodologies adopted for developing a simulation model to investigate the autonomy effect is described in this section. The ideal behavior of a standalone PV system is given by Eq. (1), where the rate of charging and discharging of a battery is a function of load power (P_L) and the PV module power (P_M). The load demand is primarily met by P_M, and the deficit energy is supplied by battery.

$$\frac{\partial C}{\partial t} = \alpha(P_M - P_L) \tag{1}$$

$$\begin{aligned} \alpha &= ø_{ch} \text{ if } \Delta P > 0 \text{ and } C < C_{max} \text{ and } V_{bat} < V_{vr} \\ \alpha &= ø_{dch} \text{ if } \Delta P < 0 \text{ and } C > C_{min} \text{ and } V_{bat} > V_{vld} \\ \alpha &= 0 \text{ if otherwise} \end{aligned}$$

where $\Delta P = (P_M - P_L)$; C is the battery capacity with maximum value of C_{max} and minimum value of C_{min}, $ø_{ch}$ and $ø_{dch}$ are the charging and discharging constants, V_{bat} is the battery voltage, V_{vr} is the voltage regulation set point of the battery and V_{vld} is the low voltage disconnect of the battery.

The proposed simulation model comprises of following steps.

1. First and foremost hourly values of global solar radiation and ambient temperature were collected for a specific location. Proposed simulation model was designed for simulating the system performance for each hour as recommended by Notton et. al [11]. Hence, it is desirable to use the hourly global solar radiation data for a complete year. However, for those locations with scarce available hourly data, an average radiation equivalent to the peak sunshine hours of the given location may be used. Based on the irradiation data and user demand, the autonomy d is defined which is normally in the range of 1–14 days [4].
2. The load demand was estimated for the specific application, along with the load duration profile. If the load profile is not known (or not repeating), a daily average value of the load may be used. However, inclusion of load duration profile will give a more realistic result.
3. Next, the system coefficients which represent the losses associated with inverter, battery, cables and PV modules were estimated using the models from [18]. Using these input data in 1 and 2 above, a preliminary sizing was carried out using the models as given in Eqs. (2)–(6):

The inverter is designed to meet unreasonable high surge demands caused by inductive loads. Higher the inverter input voltage lesser the current rating and hence smaller the conductor size. The total inverter capacity is fixed to a maximum value of,

$$P_{inv} = 1.1 \times W_{ac} \tag{2}$$

Accordingly an inverter of next higher capacity available in the market is selected.

The battery size is a function of the daily ampere hour demand of the load, number of days of autonomy, system voltage, rate factor and temperature de rate factor. While temperature de rate factor compensate for the battery capacity for different temperature values, the rate factor takes care of the variation in the battery capacity for various charging rates. First the total number of batteries connected in series and parallel combinations is determined using the following equation. The battery specification must be chosen in such a way that there is no more than 4 batteries in a string.

$$\text{Number of batteries in parallel} = \frac{d \times AH_d}{t_r \times R \times A_h} \tag{3}$$

$$\text{Number of batteries in series} = \frac{V_{dc}}{V_{bat}} \tag{4}$$

The modules are determined to meet daily ampere hour of the load. The number of modules thus required will be,

$$\text{Number of modules in parallel(No. of strings)} = \frac{AH_d}{d_r \times E_b \times I_{mpp} \times H} \tag{5}$$

$$\text{Number of modules in series} = \frac{V_{dc}}{V_m} \tag{6}$$

4. The results of preliminary sizing serve as an input to estimate the hourly performance of the PV module and battery using the model [19,20] given in Eq. (7). The simulation was carried out for 8760 h, and corresponding values of state of charge (SOC) at each hour was quantified, and based on the predefined permissible battery SOC limits, loss of load hours (LOLH) were calculated. In the equation, I_{bat} is the battery current, σ is the battery self discharge, E_b is the battery efficiency, N_{bp} is the number of batteries in parallel, C is the battery capacity and h is the simulation step time.

$$SOC(t+h) = SOC(t) \times (1 - \sigma \times h) + \frac{I_{bat}(t) \times E_b \times h}{N_{bp} \times C} \tag{7}$$