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Case Study

Precise sizing of stand-alone photovoltaic system for residential use in Nagpur, India

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Abstract

The aim of this paper is to present precise sizing of a stand-alone PV system for a typical residence in Nagpur Maharashtra. A PV system design can be either approximate or precise. The approximate design is useful as it allows one to size the PV system without going much into the details of each component. But the efficiency of large PV systems can only be improved by precise sizing. There are various factors that should be incorporated in precise sizing of a PV system some of them are precise estimation of solar radiation data, information about battery Dod and PV array losses. All these factors have been considered in this paper for a precise sizing of stand-alone PV system for a residence in Nagpur (Maharashtra).

Keywords: Dod, critical design month, system sizing, Nagpur residence.

Introduction

While designing the stand alone PV system it is always required to meet the load in the best possible manner. The design of PV system for converting solar irradiance directly into electricity includes the choice of components e.g. PV panels, batteries, inverter, charge controller etc. and their usage[1]. The design and configuration of the stand-alone PV system also depends on many factors such as type of load, topography of the location etc[2,3].

There are numerous papers that discuss stand-alone PV systems, their modelling and applications[4-7]. A simple solar PV system will have only two components PV panel and the load whereas a PV system can be sophisticated having several power sources and many other multiple units to meet the load requirement. In this paper the sizing of a standalone PV system is done more precisely by taking into account for critical design month. Thereafter a residence in Nagpur (Maharashtra) is considered as a practical case study for which the detailed sizing steps are provided.

Photovoltaic power system components

A standalone PV system consists of various components connected together to generate electricity directly from sun light. Figure-1[8] shows the typical connection of the PV system components and the description of each component is hereunder.

Photovoltaic array: A solar PV module is a collection of series connected solar cells. A single solar cell would generate power in range of 2 to 3 watt. For fulfilling high power requirements the cells are connected together to make a PV Module. The PV modules are available in wattage rating of 3 W_p to 300 W_p . Series connection of many PV modules is referred as PV module string. To increase the voltage in PV system, series connection of PV module is used. To increase the current in PV system, parallel connection of individual PV module or PV module strings are used. The series and parallel combination of PV module is used to increase the power[1].

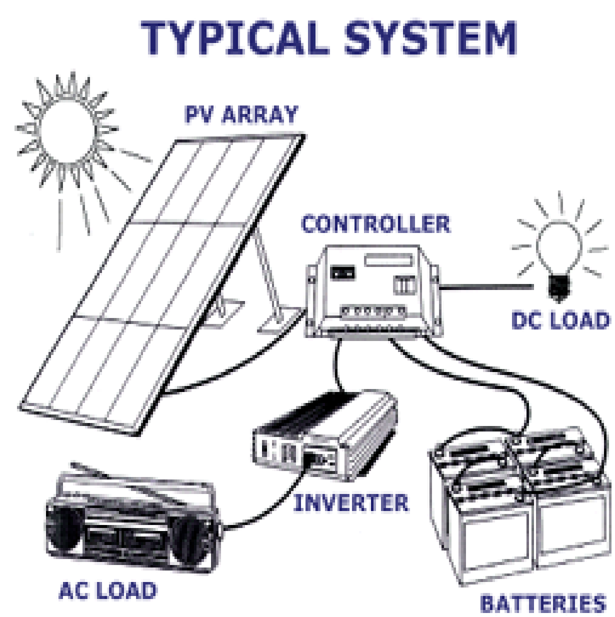

Figure-1: Stand-Alone Photovoltaic Power System Components[8].

Batteries: Batteries are used as an electrical energy storage medium in a standalone PV system. The energy storage is important to deliver the energy to the load when sunlight is not present. In PV system it is required that the batteries should be rechargable. There are various commonly available rechargeable batteries but in general the battery with high depth of discharge are used in solar PV systems[1].

Charge controller: Charge controller protects the battery from over charging as well as deep discharging. In case of overcharging of battery, it disconnects it from the PV module, whereas in case of deep discharge of the battery it disconnects it from the load[1].

Inverter: The output of a PV array is DC and it is required to convert it into AC to meet the load requirements. DC to AC inverter is used for this purpose[1].

Balance of system component: The components necessary to protect the PV system such as protective devices, blocking & bypass diodes, lightning-protection system and cable wiring constitute the balance of system components. Particularly cables of correct size are an important component to enhance the performance of the system.

Loads: The loads connected to PV system are power consuming units, and they may be either DC loads or AC loads[1].

PV system sizing procedure

Sizing of a PV system is the process of calculating the capacity of different components required to make the complete PV system capable of supplying the required load demand.Sizing involves four steps[3]: i. Determine monthly average daily load. ii. Determine load and insolation for critical design month, iii. Sizing the battery bank, iv. Sizing PV array.

Estimating daily energy consumption: Off-grid load analysis begins with an inventory of all energy consuming devices. Power rating is determined for each device along with its usage time. Energy consumption is calculated of each load is calculated by Energy = Power x Time. If usage significantly varies monthly, load analysis must be conducted for each month. DC and AC loads are to be listed separately as AC loads go through the inverter and need to account for inverter losses and DC loads must be accounted for cable losses.

Determining critical design month: Critical design month is the month with the worst sun light to energy-use ratio. By designing the system to meet the requirements of the 'worst' month, it will be able to deliver energy requirements year-round.

The daily energy load is divided by the available solar insolation for different tilt angles. The highest ratio of load to solar insolation will give the critical design month. The best tilt angle is the one with the highest PSH value in the worst month. For constant loads during the year, the lowest irradiation month is the design month. Since lowest irradiation usually falls in winter when the sun is lower in the sky, the best tilt angle for constant loads is Latitude + 15° as this angle is pointed more directly at the lower-sun[3].

Battery bank sizing: Batteries store energy generated by the solar array and deliver energy to supply the load (light, TV, etc). Batteries are specified in Voltage and Amp-hour capacity. Total amount of rated battery capacity requirements are based on[3]: i. Desired days of storage also known as days of autonomy. ii. Days of autonomy are the number of days that a fully charged battery bank can supply the load without any recharge. Greater autonomy periods increase the size of the battery bank and the amount of energy storage. To keep the PV system cost low the autonomy can be kept bare minimum but this can cause discomfort in cloudy weather. iii. Maximum allowable depth-of-discharge (DOD). iv. The Depth of Discharge is the maximum level that the system is able to discharge the batteries. It is controlled by the Cut Off Voltage (LVD), which is set by the charge controller. Depth of discharge should not be lower than 75%. It is commonly between 50% and 75%. v. System losses and efficiencies, vi. The final consideration when sizing batteries is selecting the system voltage. System voltage determines the number of batteries that are connected together in series to form the battery bank. Smaller stand-alone systems used for residential and small off-grid application Inns typically use 12 V or 24 V. The higher the system voltage, the lower the current & the power loss.

PV Array Sizing: The size of PV array is calculated for the critical design month to meet the load demand. To do this, the final sizing must account for the following losses[3]: i. Soiling losses, ii. Charge controller and battery charging efficiency, iii. Losses due to higher operating temperatures, iv. Cable losses

Losses such as battery charging, PV panel manufacturer's tolerance and charge controller efficiency can be read from the equipment technical sheets. Soiling losses vary depending on the tilt angle, cleaning regime and general dustiness of the installation site. Cable losses can be calculated based on cable distances and thickness. Losses are multiplied together to arrive at a final de-rating factor. Battery charge equalization is also taken into account to provide boost charging to the batteries.

Case Study - a typical residence in Nagpur Chhattisgarh

Nagpur city in Maharashtra, India, receives good amount of solar radiation as the average annual solar radiation for Nagpur is 5.09 kWh/m2 /day. The geographical location of Nagpur (Latitude 21.1 N, Longitude 79.1 E) implies that the optimal tilt angle for solar array is about 36^0 facing southward is best to harvest the maximum solar energy all over the year. Table-1 given below shows the daily load profile for a typical residence in Nagpur. The load profile is assumed to be constant all over the year.

Table-1: Load Profile of a Typical Residence in Nagpur.

Load Discription	No. of Items	Wattage (W)	Total Wattage	Daily Run Time (Hours)	DC Energy Usage (Watt-Hour)	AC Energy Usage (Watt-Hour)
LED Lights (Bedrooms)	4	12	18	4	4×12×4= 192	0
LED Lights (Bathrooms)	1	12	6	1	1×12×1= 12	0
LED Lights(Living Area)	4	12	12	6	4×12×6=288	0
LED Lights (Kitchen)	2	12	12	6	2×12×6= 144	0
Fan	4	36	144	8	4×36×8=1152	
Television(AC)	1	125	125	5	0	1×125×5=625
Refrigerator	1	250	250	6	0	1×250×6=1500
	Total	459 W			1788Wh	2125Wh

We include a small buffer for growth of 10% to this calculation. This gives the system some protection. We also adjust the DC load for cabling losses and the AC load for inverter efficiency.

Table-2: DC and AC Load Adjustment.

DC Load Adjusted for Wiring Loss of 5% = 1788/0.95		
DC Load Adjusted for Wiring	1882 Wh	
	DC	AC
Total Design Load	1882 Wh	2125Wh
Buffer for Growth (10%)	2070Wh	2337Wh
Inverter Efficiency (90%)	AC-DC Load	2337/0.9
		2596Wh
Final Design Load	2070+2596	
Final Design Load	4666Wh	

Determining Critical Design Month: The performance of the solar collectors depends on the amount of solar radiation falling at a given location and time. The global solar radiation on tilted collector surface (tilted at latitude angle, latitude +15^0 and latitude -15^0) for Nagpur city is given in following Table-3[2].

Monthly daily load is listed and these are divided by the available solar insolation for different tilt angle as given in Table-4. Since lowest irradiation usually falls in winter when the sun is lower in the sky, the best tilt angle for constant loads is Latitude + 15° as this angle is pointed more directly at the lower-sun.

Table-3: Estimated Solar Radiation Data for Nagpur.

City: Nagpur Latitude: 21.15			
Month	Latitude – 15^0 (6^0)	Latitude (21^0)	Latitude + 15^0 (36^0)
Jan	5.41	6.31	6.87
Feb	6.18	6.88	7.18
March	6.43	6.65	6.53
April	6.91	6.72	6.19
May	7.09	6.56	5.71
June	5.69	4.85	5.16
July	4.52	4.11	4.15
Aug	4.47	4.16	4.17
Sept	5.05	4.92	4.92
Oct	5.83	6.26	6.36
Nov	5.63	6.51	7.01
Dec	5.22	6.19	6.81

Table-4: Determination of Critical Design Moth and Optimal Tilt Angle.

Month	Design Load (Whs)	PSH at tilt of 6^0		PSH at tilt of 21^0		PSH at tilt of 36^0	
		Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio	Insolation (PSH/day)	Design Ratio
Jan	4666	5.41	847	6.31	739	6.87	679
Feb	4666	6.18	735	6.88	678	7.18	649
Mar	4666	6.43	689	6.65	701	6.53	714
Apr	4666	6.91	696	6.72	694	6.19	753
May	4666	7.09	748	6.56	711	5.71	817
June	4666	5.69	884	4.85	962	5.16	904
July	4666	4.52	988	4.11	1135	4.15	1124
Aug	4666	4.47	988	4.16	1121	4.17	1118
Sep	4666	5.05	909	4.92	948	4.92	948
Oct	4666	5.83	990	6.26	745	6.36	733
Nov	4666	5.63	1025	6.51	716	7.01	665
Dec	4666	5.22	980	6.19	753	6.81	685
Design Month		July					
Design Tilt		36^0					
Average Consumption		4666	Wh/day				
Solar Insolation		4.15	PSH/day				

From the table critical design month is July as this has the highest ratio of load to solar insolation. The optimal Tilt is 36^0 Degrees as this tilt gives the best sunshine in the worst month.

Battery Bank Sizing: For the proposed residential stand alone PV system choosing a 12V system voltage along with 2 days of autonomy and 75% DoD will decide the capacity of the battery bank.

Table-5: Battery Bank Sizing.

Estimated energy consumption	4666 Wh/day
Energy consumption for 2 Days of autonomy period	4666 × 2 days = 9332Wh
Ah of battery bank for 12V system voltage	9332 ÷ 12=778Ah
Ah of battery bank for 75% DoD	778÷ 0.75 =1037Ah
Final Ah of battery bank	1037Ah

PV Array Sizing: The first step in deciding the size of the PV array is to determine the de-rating factor due to various losses. Table-6 shows the various losses from PV array and their de-rating value. All the losses are multiplied together to obtain a final de-rating factor.

Table-6: Calculation of De-rating Factor.

Losses from PV array	Typical Derating Value	Range of acceptable value
Battery charging efficiency	85%	80%-90%
Soiling Factor	95%	90%-98%
Temperature Derating	85%	85%
Cable Losses	97%	95%-99%
Charge Controller Losses	95%	93%-97%
Tolerance of Solar Panels	95%	95%105%
Final Derating Factor	0.60	0.55-0.75

The energy consumption is divided by the final de-rating factor and then by the PSH of critical month to get the final energy consumption in critical month. The resulting power rating is multiplied again by 1.1 to ensure that power generated by PV array is enough to provide boost charging to the batteries to ensure they stay fully charged. The calculations are shown in Table-7.

Table-7: PV Array Sizing Calculation.

Energy Consumption in worst month	4666 Wh/day
Final Derating Factor	0.6
Critical Design month Insolation	4.15 PSH/day
Required power rating of array	Design load ÷ derating factor ÷ PSH
Required power rating of array	1873 Watts
Battery charge equalization	1.1
Final size of PV array	1873×1.1= 2060 Watts

The final PV array sizing calculation is 2060 Watts.

Summary of PV system component sizing: The PV system have been sized for the proposed residence in Nagpur, Maharashtra. The summary of the size of standalone PV system is given in the Table-8.

Table-8: Summary of PV system Component Sizing.

Size of connected Load	4666Whs/day
Critical Solar insolation	4.15PSH/day
Optimal tilt	36^0
Battery Bank Size	1037Ah
PV Array Size	2060 Watt

Selection of Charge Controller and Inverters: The next step is to calculate the no. of PV modules to be connected in series and parallel and the rating of panels to get the required size of the whole PV array. Depending upon the short circuit current rating of the panel the charge controller minimum power current with a factor of safety of 1.25 for continuous operation is calculated as follows:

Charge controller minimum power current = Short circuit current rating of PV module × No. of parallel connected modules × 1.25

Appropriate rating of charge controller is selected for the above calculated charge controller current. As inverter is used for all AC appliances, hence to calculate the inverter rating following formula is used:

Inverter minimum power size = power of all AC appliances × 1.25

Appropriate inverter rating is selected for the above calculated inverter power.

Conclusion

The PV system sizing may be either approximate or precise, but for large PV system the sizing should be based on the real facts. The methodology used in this paper for precise sizing of stand-alone PV system for a residence in Nagpur, can be used for other locations also, if the solar radiation data is available for that place. Though the cost of the overall system gets increased but the energy supplied by the system can be as high as 30%. Some other factors such as seasonal variation in load, sun-tracking, ambient temperature in which modules and batteries are working, type of PV technology used in the system can also be incorporated to make the system more precise.

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