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# A Systematic Approach to the Optimal Sizing of 500 W Stand-Alone Photovoltaic System Using Multi-Port Converter

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**ABSTRACT**

This paper presents an appropriate design methodology to precisely size the configuration of a 500 W stand-alone photovoltaic (PV) system with a newly derived SEPIC/ZETA converter topology being used as an interfacing device. The standardization of PV system configuration and the sizing of co-efficients are considered very important, for the reliability analysis of stand-alone PV system. This analysis provides the complete design of a stand-alone PV system to supply electric power for a residential application. For analysis, direct current (DC) appliances (lighting, motor, compact fluorescent lamp) are considered. The sizing and the optimization of the PV/battery hybrid system co-efficients are obtained by considering the typical energy consumption of daily profiles. The array to load ratio is determined and the daily energy consumption is calculated to be 1.910 kWh. MatLab/Simulink environment is used for modelling the required PV array size. The results show that the sizing of PV stand-alone system mainly depends on the load data with an advantage of maintaining a clean environment. Simulation results and analyses are presented to validate the proposed system configuration.



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## INTRODUCTION

Nowadays PV/battery hybrid system is most widely used to power many house hold applications not only in villages but also in cities and industries. In order to provide backup power and fast dynamic response energy storage devices are required in a stand-alone system. Hence a power electronic converter interfaces the sources and the load along with energy storage device. In this study the multiport converter used as an interfacing device is the four-port SEPIC/ZETA bidirectional converter with three input ports and one output port. Out of these three input ports, two ports are connected to the PV source, third port to the battery, and the output port to the load (Tao, H., 2006).

The stand-alone system includes components such as PV array, a battery, a charge controller, and the load. When the generation of PV power is abundant, it supplies power to meet the required load and also charges the battery via charge controller. When the generation of PV power is less than the required load power, the power that is stored in the battery supplies the required power to meet the demand along with the source. The charging and the discharging mechanism with state of charge (SoC) and depth of discharge (DOD) are controlled by the control mechanism (Ibrahim, U.H., 2013).

To protect the battery from over charging and discharging regulator is used. The maximum power from the PV sources is also extracted using maximum power point (MPPT) algorithm. The DC output voltage to power the house hold appliances is also regulated. The proposed interfacing converter is capable of regulating all the individual components simultaneously and makes the provision of separate controller for each component unnecessary. The block diagram of the interfacing circuit is shown in Fig. 1.

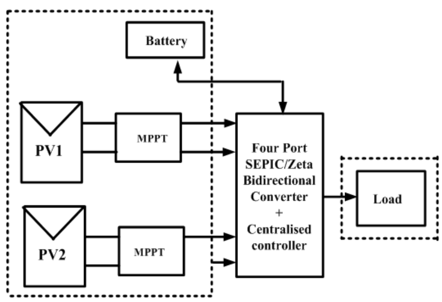


**Fig.1:** Stand-alone PV system.

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The efficiency of the system depends on the reliability and the compatibility of the individual components as they are interconnected to one another. This paper discusses the load requirement of the stand-alone PV system with proposed interfacing converter and the optimal sizing of the battery, charge controller, and PV system. The array size of the PV system and the battery depends upon the individual requirement. The size of a system depends on the quantity of the required power (in watts), the amount of time it is used (in hours) and the quantum of energy available from the sun in a particular area (in sun hours per day). Hence there exist two dependent variables and one independent variable. The step by step procedure of designing the system is presented in following section.

***II. Design and the sizing of stand-alone solar photovoltaic system:***

The major criterion in stand-alone PV system is the sizing of PV array, as oversizing leads to increased cost. It involves a number of steps to select the accurate size of the individual components for the proper functioning of the system (Industrial Electronics and Applications Conference, 2008; Industry Applications Conference, 1999). The steps involved in the design consideration of the stand-alone PV system are here.

1. Determine the amount of the total load requirement. Estimate the magnitude and the duration of the load requirement per day and on seasonal basis.
2. Determine the battery bank capacity (Ah) based on days of autonomy (DA), temperature
3. compensation (TC) factor, design margin (DM), SoC, and DOD.
4. Estimate the size of the PV array based on the load requirement, battery capacity, average solar insolation and the system losses.
5. Evaluate the control strategy to be used for the safe charging and discharging of the battery by the proper selection of the set points.

***2.1 Estimation of the load requirement:***

While designing the stand-alone PV system, the amount of the total load required has to be fixed by specifying the number of individual appliances with their corresponding wattage (Hammad Abo-Zied Mohammed, 2013; Ahmad, G.E., 2002). In this work the terminal voltage is set as 100 V. The loads chosen are the light, motor, and the compact fluorescent lamp (CFL). The daily load consumption for the given load is shown in Table. 1. The total load of the proposed system is calculated to be 500 W and is obtained by taking the average over daily load consumption. As these loads do not work for all the 24 hours simultaneously, the duration of the usage of each load has been calculated separately. Finally the summative of total power consumption for each load is calculated to their corresponding time duration of usage as shown in Table. 1.

To achieve power balance, the control and the management of the storage system play a vital role in designing the stand-alone PV system, which includes the choice of the load profile, the calculation of the battery voltage (in charge and in discharge), battery current, and the SoC [8-10].

**Table 1:** Daily load energy consumption.

| Load type | Quantity | Rated Power (W) | Total Wattage | Hours Used/day | kWh/day |
|---|---|---|---|---|---|
| Lights | 6 | 15 | 90 | 3 | 720 |
| Universal motor | 5 | 60 | 300 | 4 | 1200 |
| Compact Fluorescent lamp(CFL) | 11 | 10 | 110 | 4 | 440 |
| Total Consumption Wh per 24-hr Day | | | | | 1910 |
| Total load demand = 500 W | | | | | |
| Battery bank voltage (12 x 6) = 72 V | | | | | |
| $\text{Total consumption Amp-hours per 24-Hr Day (Ahd)} = \frac{\text{Total consumption Wh per 24-hr Day}}{\text{Battery bank voltage}} = 26.52\ \text{Ah/day}$ | | | | | |

***2.2 Estimation of Energy storage capacity:***

As the excess power from PV generation is utilized for charging the battery, its status is indicated through a charge controller. In addition, a control is adopted through SEPIC/ZETA converter to direct the battery voltage to load in case of low PV array voltage generation (i.e., during night and/or shading effects). The size of the battery opted is designed based on the voltage capacity of battery, number of batteries, power converter capacity, and load. The battery type selected for this application is lead-acid battery which is promising from the viewpoints of low cost, wide availability, good deep cycle, high temperature performance and its capacity to replenish electrolyte.

While designing the battery capacity for the stand-alone PV system some of the parameters that are considered more precisely are the battery storage capacity, days of autonomy, SoC, DOD, temperature, etc (Koutroulis, E. and K. Kalaitzakis, 2004; Harrington, S. and J. Dunlop, 1992). In this study, a lead-acid battery having an efficiency of 85% is preferred, with the DOD ranging between 60% and 80%. The battery bank voltage is set at 72 V. It is derived by connecting 6 numbers of 12 V batteries in series.

The charge capacity required by each battery in terms of Ampere-hour (Ah) and the battery bank capacity ($B_c$) is expressed as

$$B_c = \frac{Ah_d \times TC \times DA \times DM}{DOD} \quad (1)$$

where it is defined as the capacity to run the daily load under normal condition (total consumption Ah per day). It also measures the current that is required to fully charge the battery within one hour under lossless condition.

The days of autonomy (DA) are chosen to be 2 days since a fully charged battery is capable of supplying the load for 2 days in the absence of the PV supply. Since the battery action at any instant depends on its own SoC and the relative magnitudes of the generation and the load, in this work the SoC is set as 50 % as it is referred to the amount of energy in the battery expressed as the percentage of the energy stored in the fully charged battery (Piller, S., 2001).

In this work the lower limit of SoC is taken as 50% of the rated capacity. This can also be called as depth of discharge (DOD) which deals about the percentage of capacity that is withdrawn from a battery to the fully charged capacity. The deficit generation when the battery SoC is less than 50% results in a loss of load at that instant.

Similarly the effects of the temperature are also taken into account while designing the battery capacity, since it includes the temperature compensation factor. The temperature compensation or temperature correction (TC) factor is set at 1.42 at the room temperature of 25°C. Below this temperature the effective capacity decreases as the rate of chemical reaction reduces and the value of design margin (DM) is set to be 1 (Ross, J. N., 2000; Dianguina Diarisso, 2013).

By substituting all the factors in equation (1) the required battery bank capacity (Bc) of the system becomes

$$B_c = \frac{26.52 \times 1.42 \times 2 \times 1}{0.8} = 94.14 \approx 100Ah \quad (2)$$

The discharge rate is expressed as Bc/t where‘t’ corresponds to the discharge time in hours. Then the discharge duration is given by

$$\text{Discharge } hours = \frac{Rated\ capacity\ of\ the\ battery}{load\ current} \quad (3)$$

Hence the discharge duration = 100/5 =20 hours or approximately $B_c$/20 discharge rate. The voltage $V_B$ and the current $I_B$ during discharge are given as

$$V_B = V_R - \frac{I_B}{B_c}\left(\frac{0.189}{1.142 - SOC} + R_i\right) \quad (4)$$

Where

$$V_R = 2.094\left\{1 - 0.001\left(T_{amb} - 25^\circ C\right)\right\} \quad (5)$$

$V_R$= rest voltage

$T_{amb}$ = ambient temperature = 23°C

After substituting the ambient temperature value in equation (5), the rest voltage ($V_R$) is calculated to be 2.098 V. The current $I_B$ is equated to the source current.

$I_B$ = 5 A

$R_i$ is the internal resistance of the cell and it comes to

$$R_i = 0.15\{1 - 0.02[T - 25]\} = 0.156\ \Omega$$

By the substitution of the above parameter values in equation (4) the rate of battery voltage during discharging process is obtained as 2.0823 V.

Similarly during charging period the current-voltage relation is given as follows

$$V_B = V_R + \frac{I_B}{B_c}\left\{\frac{0.189}{1.142 - SOC} + R_i\right\} \quad (6)$$

Hence the rate of battery voltage during discharging process stands at 2.113 V. But under idle condition, when the power generated by the PV source is equal to the load power, neither charging nor discharging takes place. Therefore, the corresponding SoC is given as

$$SoC = SoC_O \times \exp(-k \times t) \quad (7)$$

Where $k = 300 \times \exp(-4400/T)$

T = ambient temperature (in kelvin) =23+273=296 K

t=hours (15 hours for 2 days of Autonomy)

By substituting the value of k = $1.05\times10^{-4}$ in equation (7) SoC is obtained to be 0.5 i.e., 50 % is maintained under idle condition, hence the chosen limit is also verified.

The control strategy of the proposed system works in such way that under any circumstances the power balance is maintained in the system. Battery supplies power when the SoC > Smin and PV array current is less than the load current. Similarly when SoC < Smin battery does not possess enough energy to supply the load and hence it has to be recharged (Massimo cerolo, 2000). The minimum and the maximum SoC limits are set at 50 % and 100 %.

### *2.3 Estimation and the sizing of the PV array:*

PV output voltage varies depending on the intensity of solar radiation. The abrupt variation in the PV output voltage may be due to the shading effect by the clouds on the PV panel and is one of the critical areas of research that has a direct influence on the transient in power sources. After designing the battery capacity the optimal size of the PV array is determined. The size of the PV array is based on several parameters such as load, power converter capacity, battery size and system voltage. The exact panel rating is calculated from the available panel rating of 37.08 Wp under the assumption that the sun light is available for 8 hours per day with 2 sunless days in a week.

Maximum power point tracking algorithm (MPPT) is used to track maximum power from the PV array for various insolation level and temperature condition. Simple MPPT algorithms called perturb and observe method is used to track maximum power from the PV array. This allows the array to continuously operate at its maximum efficiency except when charging is reduced or suspended to protect the battery. Owing to accuracy and simplicity, a single diode model of PV panel is used and the same has been simulated in MatLab/Simulink model. The performance charteristics of a single PV panel is given in Fig. 2 in which the I-V curve and the P-V curve is illustrated under standard test condition (STC) of 1000 W/m$^2$ at the temperature of 25$^0$C.

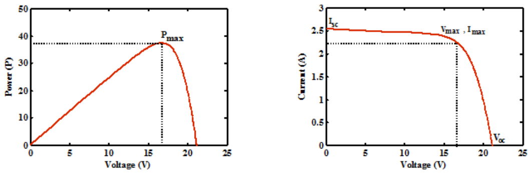



**Fig. 2:** Performance characteristics of the PV module.

When PV system is used as the source the incident solar radiation and the temperature are the two main parameters which affect the performance of the PV system. The controlling parameter plays a vital role in characterizing the performance curve of the solar cell. Fig. 2 depicts the control parameter values like the short circuit current ($I_{sc}$) to be 2.55 A and the open circuit voltage ($V_{oc}$) is about 21.24 V. The value of maximum peak current ($I_{max}$) and the maximum peak voltage ($V_{max}$) to be 2.25 A and 16.54 V with the corresponding maximum power ($P_{max}$) value of 37.2 W. Therefore, from the above parameters it was inferred that the maximum peak current and the maximum power are directly related to the incident solar radiation. When the irradiation goes below the 200 W/m2 the peak voltage becomes unstable. Similarly when the temperature increases the peak voltage and the peak power degrades. To overcome such incompatibility and to increase the reliability of the stand-alone PV system, standard condition for the PV module is specified. To supply the maximum load current of 5 A the current from the source is designed to be more than 1.5 times of the load current. Hence the input current becomes 9 A and the input voltage in the port 1 is set at 50 V. As the equivalent circuit between the PV ports and the battery is step-up mode the input voltage in the two PV ports were chosen to have lesser value than the battery port. Therefore to generate the maximum peak wattage of 450 $W_p$, panel array size becomes 3 × 4. The panels of the specified size were connected in series to provide the required voltage of 50 V and the four panels were connected in parallel to provide the required current rating of 9 A. The properly sized solar PV array can be connected to the port 1 which is capable of varying the power from (0-450) W with the corresponding voltage and the current varying from (45-50) V and (1.6 - 9) A . Similar type of array is also connected to the other input port say port 2 of the converter, such that the two input ports are powered by the renewable energy sources.

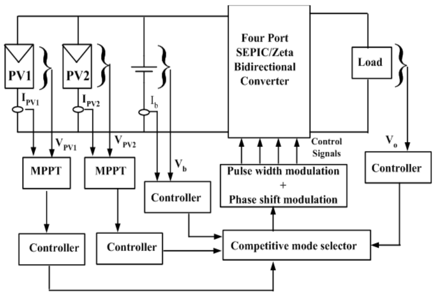
### *2.4 Centralised Controller of the stand-alone PV system:*

The charge controller being the main component of the stand-alone PV system to achieve power balance, proper design is essential. It enables safe charging and discharging of the battery under various changes in the input voltage and the load current. It also ensures that the battery to maintains maximum possible state of charge. The selection of the charge controller for the PV system depends on several considerations such as maximum PV array current, required load current, nominal system operating voltage, battery charging and the discharging characteristics, system line regulation, load regulation, and the control strategies incorporated in the output load side. In this study, centralised controller is realized for the proposed four-port SEPIC/ZETA bidirectional converter which is capable of obtaining the characteristics of the charge controller for the battery side; also it is tracks the maximum power on the two input port side besides regulating the output voltage on the load port to the desired value. The control strategy shown in Fig. 3 (a) behaves in such a way that when excess PV power is available than supplying the load, then the excessive power is used for charging the battery, under this condition the charging current is compared with the PV array current or the bulk current ($I_b^*$) of 5 A; if they are not equal, the controller generates a positive signal such that MPPT is enabled in the PV source.

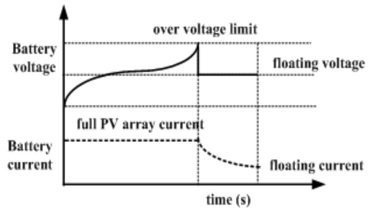
When MPPT is enabled, the battery gets charged during which the battery voltage is compared with the overcharging limit ($V_b^*$) or the overvoltage of 84 V. If these voltages are not equal, then the bulk current is maintained constant and it is referred to constant current stage. If, however they are equal, then the bulk current decreases. As the bulk current decreases, there is a limitation that it should get decreased below the floating point current value. Under this condition the battery voltage is maintained at the constant value termed as the floating point voltage value which is referred to as constant voltage stage. The floating point current value is given by BC/100 which becomes 1 A. Therefore care should be taken to avoid the bulk current decreasing below the floating point value. If it goes below the floating point current value, then the charging process is terminated.When the PV power is surplus, it charges the battery. In this case the charging current is equal to the bulk current ($I_b^*$). The signal generated by the controller will go negative which in turn disables the MPPT thus achieving the power balance in the system. The characteristics of the battery charging control scheme (Power Electronics Specialists Conference, 2008; Mehdi Ouada, M.S., 2013) are shown in Fig. 3 (b) and the corresponding charging and the discharging curve are shown in Fig. 4. Table 2 illustrates the various design parameters and their corresponding values involved in designing the stand-alone PV system.

## *III. Conclusion:*

The design of the stand-alone PV system for the required load power of 500 W was made on the basis of the calculation of various parameters. The step by step procedure of the proper selection and the sizing of the various components like battery, charge controller and the PV array was presented in detail with the algorithm and verified by the theoretical calculation. A novel power management control strategy for proper charging and discharging of the battery was proposed. It ensures the operation of the system with high efficiency and the provision of good dynamic response. The procedure presented in this study can be used as a general procedure to design the stand-alone PV system of any rating.




(a)




(b)

**Fig. 3:** (a) Schematic diagram of centralised controller (b) Battery constant current and constant voltage charging profile.

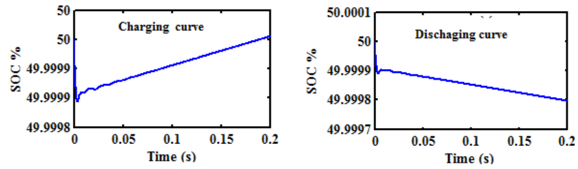



**Fig. 4:** Battery charging and the discharging curve.

**Table 2:** Sizing parameters of stand-alone PV system.

| Component | Parameter | Symbol | Value |
|---|---|---|---|
| Load | Total load current (A) | $I_L$ | 0-9A |
| | Total load power (W) | $P_L$ | 0-500 |
| | Total Consumption Wh Per 24-hr Day | $W_{hd}$ | 1910 |
| | Nominal load voltage (V) | $V_L$ | 100 |
| Battery | Day of Autonomy | DA | 2 |
| | Maximum allowable depth of discharge | DOD | 0.5 |
| | Temperature correction factor | TC | 1.42 |
| | Design margin | DM | 1 |
| | Battery capacity in (Ah) | $B_c$ | 100 |
| | Nominal battery voltage(V) | $V_b$ | 12 |
| | Number of batteries connected in series | n | 6 |
| | Overcharging limit (V) | $V_{max}^*$ | 84.8 |
| | Floating point voltage | $V_f$ | 77.5 |
| | Battery lower limit (V) | $V_{min}$* | 64.8 |
| | Floating point current | $I_f$ | 1 A |
| | Bulk current (A) | $I_b$* | 4.5 |
| Solar PV array | Short circuit current (A) | $I_{sc}$ | 2.55 |
| | Open circuit voltage (V) | $V_{oc}$ | 21.24 |
| | Maximum power (W) | $P_{max}$ | 37.08 |
| | Total number of cells connected in series | $N_s$ | 36 |
| | Total number of cells connected in parallel | $N_p$ | 1 |
| | Array size | $N_{ss} \times N_{pp}$ | 3 x 4 |
| | Maximum Voltage (V) | $V_{max}$ | 16.54 |
| | Maximum Current (A) | $I_{max}$ | 2.25 |
| | Temperature ($^oC$) | T | 25 |
| | Insolation ($W/m^2$) | $I_n$ | 1000 |

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