Design and Control of Standalone P-V System for Rural Residential Applications

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ABSTRACT

In this paper, the design of a standalone P-V system in terms of sizing of P-V units and battery storage will be discussed. The sizing of the system will be determinant based on the expected loads, characteristics of the used PV module and the meteorological data of the region of installation. The system consists of PV panels, a DC-DC converter interfacing PV panels, a bi-directional DC-DC battery charger and a single phase inverter interfacing the DC bus to the loads. The power conditioning unit needed to regulate the output voltage of the system across the terminals of the load and track the maximum power point (MPP) will be presented. The control of power electronic converter will be developed and investigated. An economic evaluation will be done to validate the applicability of the designed system.

Keywords: Energy storage, PV systems, renewable energy sources, residential applications and standalone systems.

1. INTRODUCTION

The global need to reduce pollutant gas emissions, rapid increase in the cost of energy and fossil fuels and inevitable energy shortage give rise to a worldwide trend to utilize renewable energy sources. Among the renewable energy sources Photo-Voltaic (PV) attracts a special focus. However, relying on renewable energy sources associated with some concerns, such as high uncertainty, unavailability during some day periods and rapid- out of control changes. The output power fluctuation of renewable energies may cause excess variations of the system's voltage and frequency. In recent years, storage systems have been combined to photovoltaic systems, which are able to provide an energy reserve with less fluctuating output power.

In this study, a P-V system will be used to feed a typical house in rural area. The system operation in standalone mode will be addressed, since there's no connection to the grid and in order to guarantee continuous power supply an energy storage system will be connected to the system. This paper is organized as the following; general description of the system and study of the expected loads in the house will be provided in section 2. Section 3 presents the design of the P-V system, design of the DC- DC converter interfacing the P-V system and maximum power point tracking (MPPT) algorithm. Design of the battery system along with design of the bi-directional battery charger will be provided in section 4. An economic evaluation for the designed system is given in section 5, finally the derived conclusions are given in section 6.

2. System General Description and Load Study

The system under study is standalone system, lack of grid connectivity imposes more complexity to the system design since reliability and supply continuity become a crucial issues. Load curve should be analyzed carefully and the P-V system should be sized and combined with the battery system in such a way to cover all the points of the load curve. On the other hand the economical aspects should be considered, it can be seen in some systems that PV modules and batteries are oversized to avoid power interruptions. Designs of these systems are not optimum and involve more –useless costs. A trade off has to be done between over-sizing the system to guarantee more power continuity and system costs.

In this system, PV modules are connected to a DC bus through DC-DC converter to control the output power from the PV system and to achieve maximum power point tracking (MPPT). Energy storage system consists of 12V lead acid batteries will be connected to the same DC bus through a bi-directional battery charger. During the day time when there's an excess power available from the PV system, battery controls the excess amount of power to charge the batteries. During the night time when the solar radiation equals zero and consequently, there's no power available from the PV modules, the battery charger reverses the power flow to feed the load from the energy stored in the batteries. Most of the used devices in typical homes are operated with AC power, hence all house loads are connected to single phase AC bus. The interfacing between AC bus and DC bus will be done using a single phase- voltage source inverter (VSI). Figure 1 shows a schematic diagram for the aforementioned system.

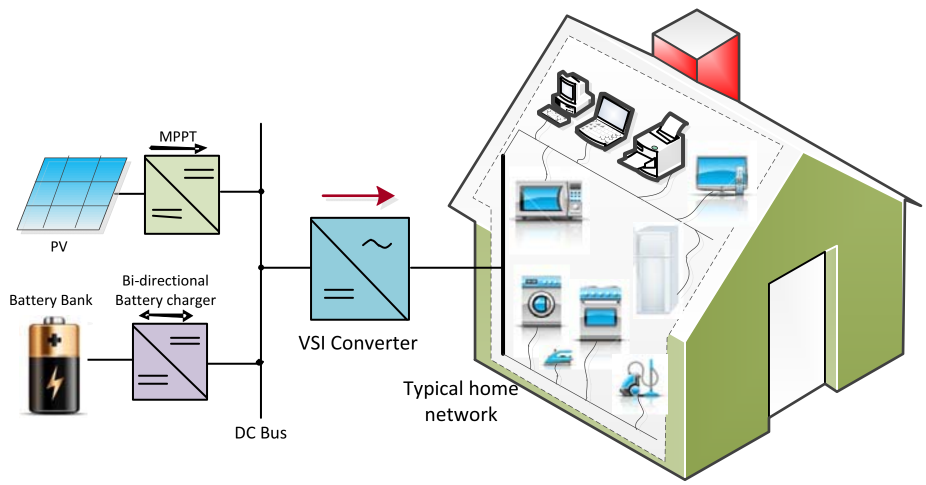


Figure 1: System schematic diagram.

The first step in design process is the load investigation,Typical home appliances with its power ratings and estimated operating time per day are listed in Table 1.Its shown that the total energy consumption of the home is 19050 Wh per day, by dividing over 24 (no of hours per day), it yields ≈ 794 W as an average load. Designing the system to supply the average load (794 W) assumes that the load curve is uniform,which is not valid assumption especially in residential appliactions.

3. Design of PV Array

In order to satisfy load requirements, all the components of the system (PV array can be excluded) should be rated to the maximum demand. The load profile for a typical house was investigated and its shown in Figure2. The maximum demans is 5100 W, this is due to the operation of the clothes drayer which a bulky load. Since the refrigrator is connected and disconnected automatically, it was taken into account that the refrigrator is operating all the day when calculation the maximum demand. The area under the curve shown in Figure 2 should equal the total energy consumption over the day calculated in Table 1.

Table 1: Typical home appliances, power ratings and estimated operating time per day.

Appliance	Power(W)	Hours/Day	Wh/Day
Fans	100	7	700
Coffee maker	600	0.2	120
Clothes Drayer	4500	0.5	2250
Computer +Monitor	160	4	640
Laptop	75	6	450
Dishwasher	1200	0.5	600
Light	80	7	560
Microwave	1100	0.5	550
Radio	50	2	100
Refrigerator	600	12	7200
LCD Television	200	8	1600
Vacuum Cleaner	1400	0.2	280
Stove	2000	1.5	3000
Washing machine	1000	1	1000
Total			19050

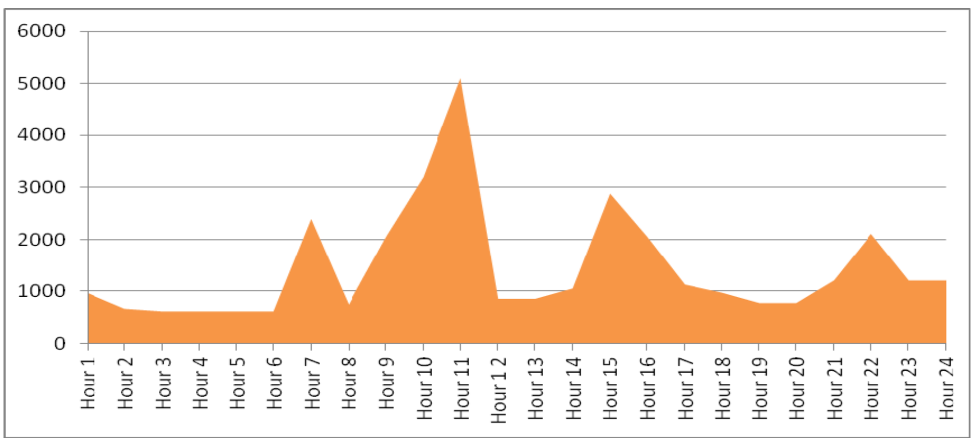


Figure 2: Investigated load profile for a typical house.

When designing a PV system,the location of the system should be considerded to determine the availabilty of solar radiation. Its assumed that the system is in a rural area in the southern area of Florida state, USA. The solar irradiances in this area for typical winter and summer weeks of year 2010 are shown in Figure 3.Obviously there's a npticable difference between solar radiation in winter and summer,so as a common practice the design will be carried out based on the worst month.In order to add reality and plausibilty to the system,the design will be based on commercially available equipments only. The parameters of the chosen PV module are given in Table 2. During daylight time, PV array should do two functions; supply the reguired power to loads and recharge the batteries. During nigth time, the batteries should have the capability of supplying the loads continously. To calaculte the number of required modules,we can project the solar radiation values to the irradiadiance-output curve

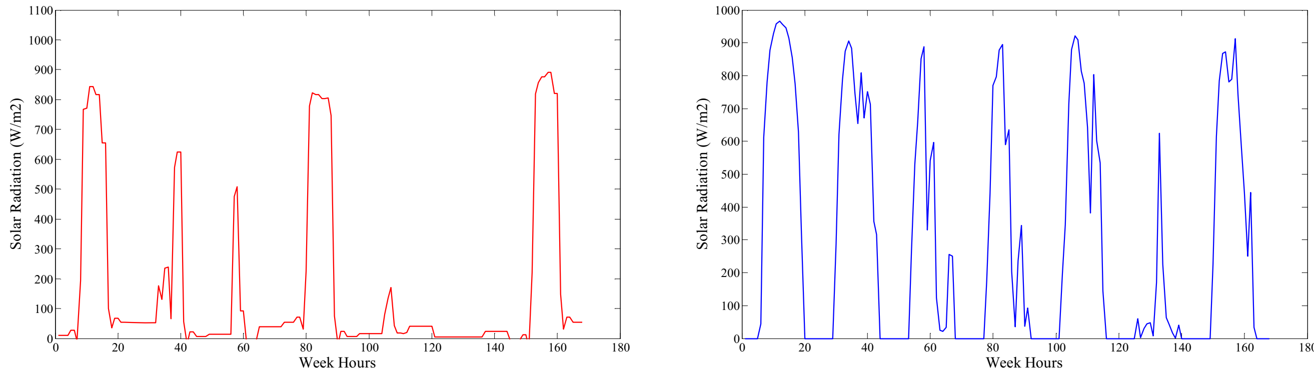


Figure 3: Solar Irradiance for one week in south Florida, left side: winter, right side: summer.

Table 2: Parameters of the chosen PV module.

Power	175 Watt
Area	1658mm*835mm
V(Maximum Power Point)	23.9V
V(Open Circuit)	30.02V
I (Maximum Power Point)	7.32Amp
I (Short Circuit)	7.963Amp
α	-0.0821
β	0.00318
K	-0.005
Efficiency	15%

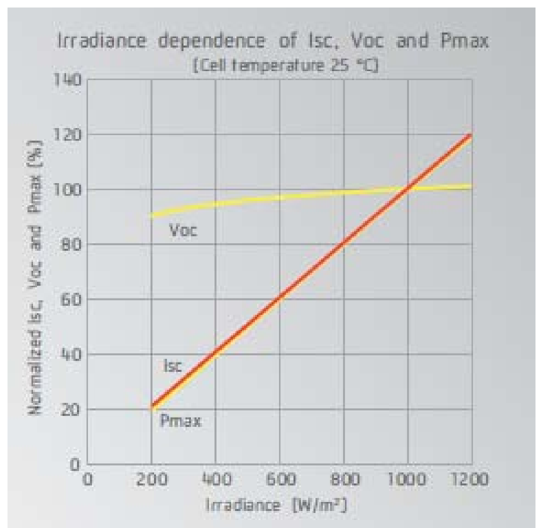


Figure 4: PV module characteristics.

to the selected module and calculate the output power for each module,this can be done by MATLAB lookup tables.This step yeilds an average solar radiation of 530W/m^2 ,and output power of 55% of the maximum output power (97 W) . Then after calculating the output power, it's multiplied by number of hours when the solar radiatio is available to calculate the daily available energy from the module . The average number of shinning hours is 6-7 h per day.

$$E_{out} = P_{out} * N_h = 679Wh$$

Since it's assumed that the load profile is the same over the whole year, we can make calculations over one day. Then the total number of modules is given by:

$$N_{\text{mod}} = E_{required} * S.f / E_{out}$$

Where *s.f* is a safety factor accounts for tsystem losses (such as losses in the DC-DC converter and DC-AC inverter) and the expexted degrading of the PV mosule output power due to dust and environmental conditions,usually this factor is selected to be 1.1-1.2, it will be selected here as 1.15. This step gives the number of required modules as 32 PV module. It can be approximated to 34 as it will be connected in pairs to get the rerquired voltage level. A chech has to be done here , we have to check the ability to this system to meet the maximum load, so by multiplying 34 by 97, we get 3298 W as a maximum power which enough for the most loading conditions but it is less than 5100W. In this case some designers go to the solution of increasing the number of PV modules in order to cover the peak load, the other solution is to account on the batteries to cover this energy deficit. For economical aspects and not to introduce additional costs to the system, the second solution appears more reasonable especially when the peak load duration is short.

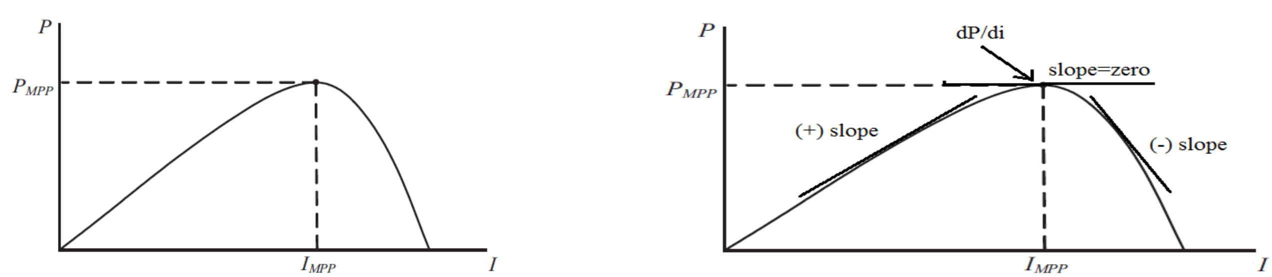
PV array will consist of 34 modules, to determine how many modules will be selected in series we have to select the voltage of the DC bus. Many researched have investeigated the the DC bus voltage selection, based on theses studies the DC voltage will be 48 V to reduce the susyem losses. Since the maximum power point voltage of the PV module is 23.9V,we can connect two in series to get a total voltage of 47.8V and use the DC-DC converter to adjust the output voltage to 48 V. Finally the array will be 2*17 modules.

The DC-DC converter interfacing the PV system should be rated 5%-10% higher than the maximum power rating of the PV array.

$$P_{conv}=175*34*1.05= 6247.5 \text{ W}$$

The DC-DC converter interfacing the PV system should be capable of tracking the maximum power point. Nowadays,there are many inverters available in the market with the feature of the maximum power tracking (MPPT). However, these inverters are grid-tied inverters which are not suitable for our standalone case. Generally, (MPPT) mechanismm is essential in the PV system to extract the expected power and to increase the efficiency. The relation between output voltage and current in PV panles is nonlinear. Figure 5(a) shows the relation betweent the output current and output power of PV module. The maximum power point tracking algorithm monitors the PV panles output and set the output voltage and current to the point that produce maximum power under given irradiance and temperature conditions by controlling the output impedance. Several techniques for implementing MPPT were presented such as perurbation and observation techniques, incremental conductance method, dP/dV or dP/di feedback control and intelligent techniques. Chosing the suitable MPPT techniques should take into account the climate and weather change for example perurbation and observation technique fails under rapidly changing weather which is the case in Florida. Faliure of MPPT techniuqe not only reduces the generated power from the PV system but also cause output power and DC bus voltage oscillations.

The dP/dV or dP/di feedback control has fast response with rapidly changing weather, the advantage of this technique that it is not dependent on the PV array parameters and could be easily implemented using micro-processors and micro-controllers.



(a) (b)

Fig.5. (a) Maximum power point on P-I curve for PV module. (b) dP/dV or dP/di MPPT technique based on zero slope to detect MPP.

The dP/dV or dP/di MPPT technique uses the fact the the slope of the dP/dV or dP/di is equla to zero at the point of maximum power and the slope sign is positive at the left side of MPP and negative at the right side of MPP. The controller calculates the dP/dV or dP/di and uses the slope as feedback to the DC-DC converter controller to control the duty cycle. The block diagram of the control porocess is given in Figure 6.

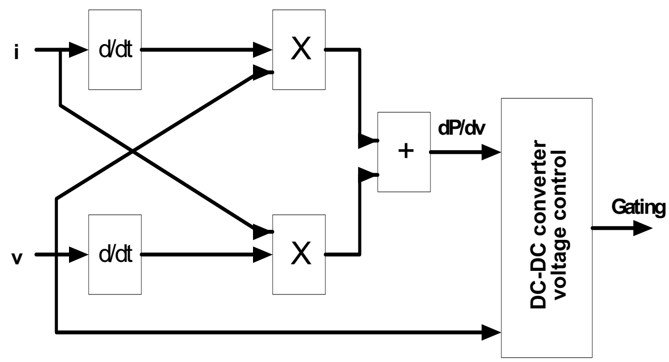


Figure 6: Block diagram of MPPT controller

4. DESIGN OF BATTERY SYSTEM

In this section the size of the battery block will be selected and the design of the battery charger will be provided. The battery block will be built with the commercially available lead-acid 12V batteries. For battery sizing there's a procedure which was suggested in literature,with the necessary modifications, it can be adopted to suit the system understudy. The first step is to choose the minimum and maximum voltage for the proper operation if the loads, for most of the home appliances the voltage range is ±10%. The second step is to calculate the voltage drop between the battery and the load,which Can be given as:

In DC side:

$$\Delta V_{DC} = I_{DC} * R$$

In AC side:

$$\Delta V_{AC} = VDF * I_{AC} * D$$

Where ΔV_{DC} is the voltage drop in the DC side, I_{DC} is the DC current, R is the cable resistance, ΔV_{AC} is the voltage drop in the AC side, VDF is a drop voltage factor which is given by the cable manufacturer, I_{AC} is the AC current and D is the distance between the battery and load (cable length).

$$\Delta V = \Delta V_{DC} + \Delta V_{AC}$$

This step yields a total voltage drop of 0.87 V. The number of the cells connected in series:

$$n = \frac{V_{\max} + \Delta V}{V_Z}$$

Where V_{max} is the maximum permitted continous (110% here), ΔV is the voltage drop, V_Z maximum trickle-charge voltage per cell. Trickle charging voltage means the voltage required to chare a fully charged battery under no-load at rate equal to its self discharging rate. This value ranges from 2.15-2.23 V per cell.By subsitituting with 2.23V as a trickle-charge voltage, we get the number of cells to be connected in series equals 24, given that each battery has 6 cells, so the number of batteries connected in series is 4 batteries.

The choice of the battery type depends on the discharge time and cutoff voltage, the chosen battery chould be capable of providing current -at the the discharge time and cutoff voltage- higher than than the total load current. The battery chosen here has 12 V and capacity of 17Ah. The discharge characteristics of the chosen battery are given in Figure 7.

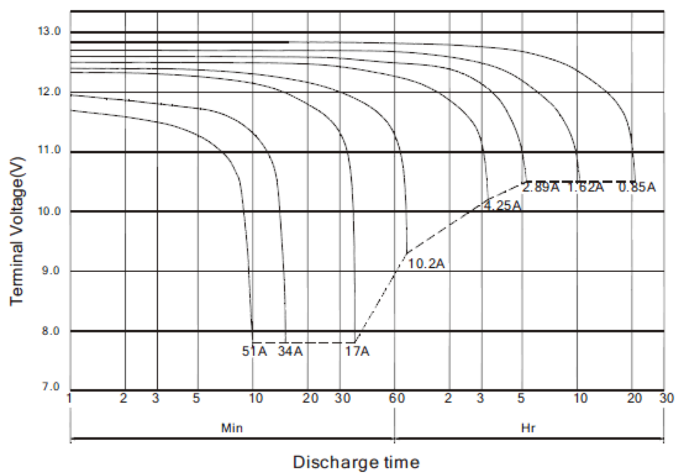


Figure 7: Battery discharge characteristics

It can be seen from figure 5 that the battery can provide current of 0.85A continously for 20 hours with final voltage drop 1 Volt. Then number of batteries connected in parallel can be given by:

$$N_P = \frac{S.f * L_{avg}}{V_n * I_{Batt}}$$

Where *S.f* is a safety factor which is selected here as 1.1, L_{avg} is the average demand, V_n is the nominal voltage, I_{Batt} is the battery discharging current.This gives 22 batteries, the total number of batteries is 88 battery. For the battery charger, it was selected form the available chargers in the marker (data sheets and websites are listed in reference section). The charger is capable of chraging lead-acid battery banks with 48 V and current up to 30 Amps and it's DC-DC, so it's suitable for this application.

5. Economic Evaluation

In order to make the solution more comprehenesive the costs of system have to be evaluated. Building and designing the system were based on the commercially available equipemnts in the market. Therefore, additional costs of designing or producing customized components have been eleminated.The costs of the system can be calculated as the following:

Cost of PV array= no of modules * price of each module= 34*515=17510 USD

Cost of battery bank= no of batteries * price of each battery= 88*34=2992 USD

The price of the battery charger is 950 USD approx.

The price of the single phase off grid inverter is 4000 USD approx.

For costs of DC-DC converter for MPPT, the prices can vary widely.Rough estimation with accceptable tolerance can be prepared. DC-DC converter can be available with 0.75 $ for each Watt of the output power.

Cost pf the DC-DC converter= 6247.5 *.75 = 4685 USD

Besides PV modules and batteries, complete PV system also uses wire, switches, fuses, connectors and other miscellaneous parts. We use a factor of 10% to cover balance of system installation costs.

Total cost for ths system = (17510+2992+950+4000+4685)*1.10= 33150 USD

For the first glance this system may appear vary costly, but if it's compared to the connection to the grid which involves expensive installation costs for extending cables especially for long distances. Electricity bills may represent another factor, typically the PV system has a life time of 25 years. On the other hand there's an interesting study prepared byer researches from (LBNL), this research has used a dataset of approximately 72,000 California homes to prepare a comprehensive economical model. One of the outcomes of this research that portion of the initial investment into a PV system will be recouped if the home is sold, as the research finds strong evidence that homes with PV systems in California have sold for a premium over comparable homes without PV systems.

6. Conclusion

In this paper, a comprhensiva and simple procedure for designing a standalone PV system for rural residential applications is provided. The design was based on commercially available equipments.The consumption of typical house was estimated, the number of required PV modules was calculated. There is a battery bank to supply the load at night,number of batteries connected in series and in parallel were determeined. The design was carried out with taking into consideration the minimization of the total cost. An economic evaluation for the system was prepared based on the market prices of the used equipments.

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