PV System Design for Off-Grid Applications

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PV System Design for Off-Grid Applications

Parimita Mohanty, K. Rahul Sharma, Mukesh Gujar, Mohan Kolhe and Aimie Nazmin Azmi

Abstract Solar photovoltaic (PV) technology has the versatility and flexibility for developing off-grid electricity system for different regions, especially in remote rural areas. While conventionally straight forward designs were used to set up off-grid PV-based system in many areas for wide range of applications, it is now possible to adapt a smart design approach for the off-grid solar PV hybrid system. A range of off-grid system configurations are possible, depending upon load requirements and their electrical properties as well as on site-specific available energy resources. The overall goal of the off-gird system design should be such that it should provide maximum efficiency, reliability and flexibility at an affordable price. In this chapter, three basic PV systems, i.e. stand-alone, grid-connected and hybrid systems, are briefly described. These systems consider different load profiles and available solar radiations. A systematic approach has then been presented regarding sizing and designing of these systems. Guidelines for selection of PV components and system sizing are provided. Battery energy storage is the important component in the off-grid solar PV system. Due to load and PV output variations, battery energy storage is going to have frequent charging and discharging. So the type of battery used in a PV system is not the same as in an automobile application. Detailed guidelines for selection of battery are therefore also provided. At present, most of the world-wide PV systems are operating at maximum power points and not contributing effectively towards the energy management in the network. Unless properly managed and controlled, large-scale deployment of PV generators in off-grid system may create problems such as voltage fluctuations, frequency deviations, power quality problems

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in the network, changes in fault currents and protections settings, and congestion in the network. A possible solution to these problems is the concept of active generator. The active generator will be very flexible and able to manage the power delivery as in a conventional generator system. This active generator includes the PV array with combination of energy storage technologies with proper power conditioning devices. The PV array output is weather dependent, and therefore the PV power output predictability is important for operational planning of the off-grid system. Many manufacturers of PV system power condition devices are designing and developing new type of inverters, which can work for delivering the power from PV system in coordination with energy storage batteries as conventional power plant.

1 Introduction

This chapter is an introduction to guidelines and approaches followed for sizing and design of the off-grid stand-alone solar PV system. Generally, a range of off-grid system configurations are possible, from the more straightforward design to the relatively complex, depending upon its power requirements and load properties as well as site-specific available energy resources. However, the overall goal of the off-gird system design should be such that it can give maximum efficiency, reliability and flexibility of the system at an affordable price. While considering the above-mentioned points, the following sections cover the designing of solar PV system for off-grid electrification projects.

1.1 Types of Solar PV Systems

PV systems are broadly classified into three distinct types:

1. **Stand-alone systems** where the energy is generated and consumed in the same place and which does not interact with the main grid. Normally, the electricity consuming/utilizing device is part of the system, i.e. solar home systems, solar street lighting system, solar lanterns and solar power plants.
2. **Grid-connected systems** where the solar PV system is connected to the grid. The grid-connected system can either be a grid-tied system, which can only feed power into the grid and such system cannot deliver power locally during blackouts and emergencies because these systems have to be completely disconnected from the grid and have to be shut down as per national and international electrical safety standards. Some grid-connected PV systems with energy storage can also provide power locally in an islanding mode.
3. **Solar PV hybrid system**: In a hybrid system, another source(s) of energy, such as wind, biomass or diesel, can be hybridized with the solar PV system to

provide the required demand. In such type of system, main objective is to bring more reliability into the overall system at an affordable way by adding one or more energy source(s).

2 Guidelines for Designing of Stand-Alone Solar PV Systems

A systematic approach is important and required when sizing and designing stand-alone solar PV systems. The following procedures are generally followed:

A. *Planning and site survey;*
B. *Assessment of energy requirement;*
C. *Assessment of solar resource availability;*
D. *System concept development;*
E. *Sizing of main component of the PV systems; and*
F. *Selection of main components of the PV system.*

2.1 Planning and Site Survey

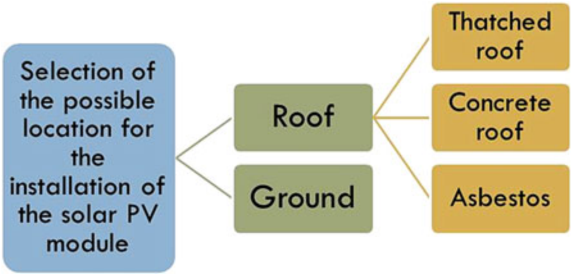
The PV array output depends on the geographical locations and timing. It is very important to select proper site based on solar resources. Therefore, in planning a PV system installation, appropriate selection of site with consideration of nearby high rise objects is necessary. The following points need to be covered during the site survey to check the suitability of the site (*Antony, Durschner, Remmers 2007*):

- site orientation, total land area/surface area of roof available;
- structure and type of roof; and
- possible routes for cables, battery and inverter location;

In order to identify the possible location for the installation of a solar PV module, probable options need to be assessed, such as “where exactly should the module be installed?” and “Can it be installed on the roof or on the ground?” (Fig. 1). If it is going to be installed on the roof, then whether the roof would be a thatched or a concrete or an asbestos one. And if it is going to be installed on the ground, then again the exact location needs to be identified.

The most critical parameter is the identification of a shadow-free location. It is to ensure that the solar PV array is installed in an area where no object casts a shadow on the array. For example, if there is a tall tree or a huge building in the vicinity of the selected location, then probably this is not a good location for the installation of the solar PV array. The required space needs to be identified appropriately, keeping in mind the capacity of the solar PV array, which is going to be installed in a particular location.

Fig. 1 PV system installation



Hence, in order to address the above-mentioned points, the proposed site for installation can be surveyed with a solar path finder to check whether there is any possibility of seasonal shading problem. In addition to this, the most essential input parameters like incident solar radiation, the ambient temperature and wind velocity, which are likely to vary widely from site to site, need to be collected for a specific site. The air temperature and wind speed significantly affect the cell's operating temperature, and hence the output energy. So it is necessary to have access to necessary information on all these parameters in order to carry out an optimum PV system design exercise.

Box 1 Guidelines for PV system installation

Eliminating module shading by relocating the mounting system does not cost any additional money and can increase the system's efficiency by a large percentage. Inefficiency caused by excessive voltage drop in the system's wiring can also be inexpensively eliminated. Intelligent advance planning does not have high incremental cost, but can drastically reduce system's initial cost. In general, the designer should consider some important points while trying to optimize the system:

✓ Siting a system correctly so that it is not shaded;
✓ Orientation of the system is a critical element in maximizing annual PV output based on local meteorological conditions;
✓ Mounting options can maximize insolation gain;
✓ Modules should be selected according to a system's parameter;
✓ Wiring should be designed to minimize voltage drop;
✓ Controllers must operate system efficiently while meeting the needs of the system;
✓ Battery storage must be sized to a specific installation; and
✓ Loads determine the size of the system and should be scheduled by intelligent planning.

2.2 Assessment of Energy Requirement

In a stand-alone solar PV system, estimating the energy requirement and assessing the realistic solar resource availability are the most important tasks which have to be done properly. This is also critical from the point of view by adding smart load and resource management features. Following steps need to be considered for carrying out this exercise.

2.3 Load Assessment

In planning, seasonal and daily load variations are needed. It is important to assess the types and utilization of loads with their load profiles. An energy assessment should be undertaken for different types of appliances. A system designer needs to consider the energy requirements with load profiles in consultation with the consumers (Table 1). In process of load calculations, system designer should also discuss all the potential energy resources that can meet the energy needs of the consumer and also educate to the customers on energy efficiency.

Steps for load assessment

1. List all of the electrical appliances to be powered by the PV system.
2. Separate types of loads and enter them in the appropriate table.
3. Record the operating wattage of each item.
4. Specify the number of hours per day each item will be used.
5. Multiply step 2, 3 and 4 to calculate the daily energy requirement.

2.4 Load Profiling and Load Categorization

Once the load details are collected, the profiling of the load is done in order to find out the maximum load, average daily daytime energy requirement and average daily night time energy requirement. Loads can be categorized based on their priority and load profiles such as peak loads, off-peak loads and intermediate loads. In order to design a configuration and proper capacity of the energy storage system as well as the entire off-grid system, the loads should be considered based on their timing of operations. Furthermore, in order to give preference to certain loads over others in case of limited availability of energy, the loads can also be categorized based on their priorities, i.e. (i) critical or essential load and (ii) non-essential load. From the tariff payment point of view, the loads can also be categorized as based on operational requirements.

Table 1 Form for assessing the load and energy requirements

a	b	c	d	$e = c/d$	f	g	$h = e*g$	$i = c*f$
AC/DC Appliances/Load	Number	Power consumption (Wattage of each load) (W_{AC})	Power factor	Max Power demand (VA)	Daily usage hours (h/day)	Surge factor	Maximum surge demand (VA)	Daily energy requires (Wh_{AC}/day)
TV	–	–	–	–	–	–	–	–
Refrigerator	–	–	–	–	–	–	–	–
Lights	–	–	–	–	–	–	–	–
….	–	—-	–	–	—-	–	–	–
Total Wattage (of appliances) Sum of column c								
Maximum demand Sum of column e								
Surge demand Sum of column h								
Total Daily AC energy required ($E_{AC\text{-}Daily}$) Sum of column i								

The information about the maximum demand and surge demand is collected in order to appropriately size and select an inverter for the solar PV system

2.5 Assessment of Solar Energy Resources

The assessment of solar energy resources is very important from the sizing point of view because it helps in estimating the output of the solar PV array. Incident solar radiation on PV array consists of direct radiation, diffuse radiation and ground reflected radiation. Solar radiation information is available through NASA by giving location latitude and longitude. While assessing the solar energy resource, the following information is important: average annual global solar radiation, average daily global solar radiation (direct and diffuse) on horizontal surface and no of sunshine hours in a year. A typical monthly averaged daily global and diffuse solar radiation on a horizontal surface is given in Fig. 2. However, since the power output of the PV array depends upon the incident solar radiation, the solar radiation falling on a horizontal surface needs to be adjusted with a tilt factor for calculating incident solar radiation on a tilted PV array.

2.6 System Configuration

An overall system configuration needs to be decided at stage of the design process. Several possible configurations need to be examined and the appropriate option should be selected at design stage considering energy demand, type of applications, spread of the community, willingness of the community, etc. In several cases, if the community has only lighting load requirement and the households are scattered,

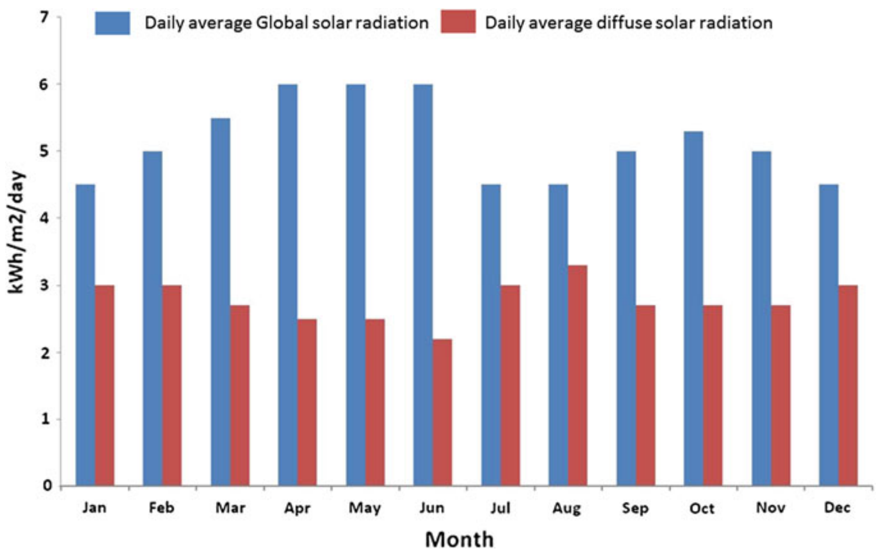


Fig. 2 Monthly averaged daily global and diffuse solar radiations on a horizontal surface

then probably Solar Home lighting System (SHS) or Solar Charging Station (SCS) will be preferred over solar mini-grid system. However, if the households are situated very closely and there is a demand for heavy motorized load, the centralized solar mini-grid may be preferred over SHS. Another thing that needs to be decided at this stage is the system voltage, especially in case of solar charging station, i.e. 12/24/48 V DC. A typical load variation with voltage is shown in Fig. 3.

- **Length of cable from solar PV module to battery**: Long DC distribution circuit may require higher system voltage in order to avoid heavy power loss or large cable diameter (if to keep the power loss under recommended limit).
- **Capacity or rating of the inverter** (if it is a large AC system): Generally, inverters over 2000 W are actually 24 V DC and inverters over 5000 W are often 48 V or above.

2.7 Sizing of Main Components of the PV System

The actual sizing of the PV system including its different components takes place, once the system configuration is decided. In general, a stand-alone solar PV system for off-grid applications majorly consists of (a) solar PV modules, (b) solar charge controller, (c) inverter, (d) storage batteries, (e) load and (f) other accessories such as cables, connectors, etc. Possible components, which are needed to consider in PV system design process, are given in Fig. 4.

The subsequent section explains the steps followed for sizing and designing of stand-alone solar PV power plant (without distribution network). The steps are based on a standard design procedures adopted universally. These steps can be customized further for designing of different configurations of PV system. For example, the steps associated with inverter in the standard sizing and design procedures can be omitted for a DC-based system without distribution network, whereas sizing of distribution network can be added to the standard procedures for AC-based mini-grid system.

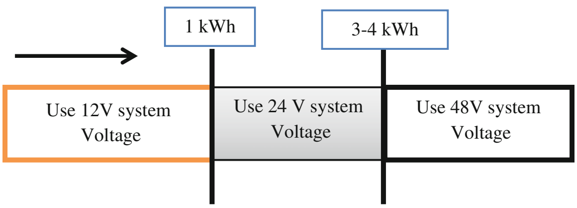


Fig. 3 A typical load variation with voltage

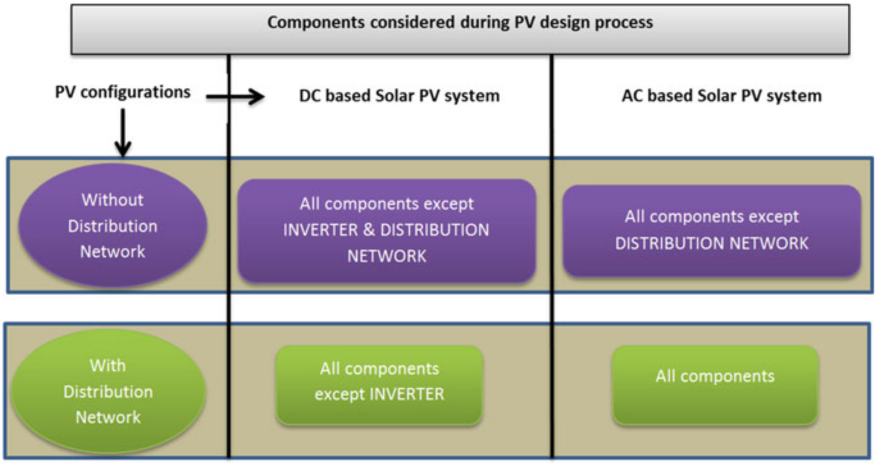


Fig. 4 PV system design process

2.8 *Standard Sizing and Design Steps for Components of PV System*

Step I: Assessment on energy requirement

The assessment on energy requirement (as explained in Sect. 3.2.2) is the first step of solar PV system sizing. Once this is carried out, the following steps are followed.

Step II: Specifying the inverter rating

An inverter is used in the system where AC power output is needed. The inverter must have the same nominal input voltage as the battery voltage. For stand-alone systems, the inverter must be large enough to handle the total amount of power that will be used at one time. The inverter size should be 20–25 % bigger than total power of appliances (as obtained from Table 1). Again the selected inverter should be capable of supplying continuous power to all AC loads and providing sufficient surge capability (Maximum demand and Surge demand as obtained from Table 1) to start any loads that may surge when turned on and particularly if they turn on at the same time.

Steps for determining inverter rating

1. Obtain "*Total power of AC appliances*", "*Maximum demand* "*and* "*Surge demand*" from Table 1.
2. Capacity or rating of the inverter should be 20–25 % bigger than "*Total power of AC appliances*".

Capacity or rating of inverter ≥ 1. 2 X *Total power of AC appliances.*

More details on selection of inverter are provided in Chapter 4.

Step III: Specifying the battery and PV capacities

The first decision that needs to make for battery sizing is 'how much storage you would like your battery bank to provide'. Often this is expressed as 'days of autonomy', because it is based on the number of days you expect your system to provide power without receiving an input charge from the solar PV array. In addition to the days of autonomy, load usage pattern and the criticality of the application should be considered.

While considering the battery sizing, the following parameters need to be considered:

i. **Daily Ampere-hour requirement:** The following steps can be adopted for calculating the daily Ampere-hour requirement from the battery.

   1. Enter the 'daily AC energy requirement ($E_{\text{AC-daily}}$)' and 'daily DC energy requirement ($E_{\text{DC-daily}}$)' from the load assessment sheet (Table 1).
   2. Enter the 'inverter efficiency' (η_{inv}) from the manufacturer's specification sheet.
   3. Divide the 'daily AC energy requirement ($E_{\text{AC-daily}}$)' with inverter efficiency (η_{inv}) and add that to 'daily DC energy requirement ($E_{\text{DC-Daily}}$)' to get the 'total daily DC energy requirement'.
   4. Enter the 'voltage of battery bank' (12 V/24 V/48 V or above).
   5. Divide the 'total daily DC energy requirement' with 'voltage of battery bank' to get the 'daily Ampere-hour requirement'.

ii. **Temperature effect**: Batteries are sensitive to temperature extremes, and you cannot take as much energy out of a cold battery as a warm one. Although you can get more than rated capacity from a hot battery, operation at hot temperatures will shorten battery life. Try to keep the batteries near room temperature. While sizing the battery, the winter ambient temperature multiplier (as shown in Table 2) should be considered in order to take care of the battery capacity in winter season.

iii. **Depth of Discharge**: The maximum depth of discharge value used for sizing should be the worst-case discharge that the battery will experience. The system control should be set to prevent discharge below this level.

iv. **Days of Autonomy**: to find out the days of autonomy, you need to take a decision on the following:

   (a) whether to increase the capacity of the solar PV array in such a way that there would not be any situation when load requirement is more than the generated PV energy and thus there is no extra day for storing energy in battery,
   or
   (b) certain number of extra days (generally 2–3 days) is considered for storing energy in battery,
   or

Table 2 Ambient temperature multiplier

Winter ambient temperature	Multiplier
80 °F (26.7 °C)	1.00
70 °F (21.2 °C)	1.04
60 °F (15.6 °C)	1.11
50 °F (10.0 °C)	1.19
40 °F (4.4 °C)	1.30
30 °F (−1.1 °C)	1.40
20 °F (−6.7 °C)	1.59

(c) solar PV array is sized in such a way that it can cater the required energy in most of the months in a year, and in the remaining month, battery can be charged through another energy resource (such as diesel and/or wind generator) and thus there is no extra day (or maximum one day) for storing energy in battery.

The following worksheet (Table 3) is followed to carry out the sizing of the storage battery.

Table 3 Battery sizing worksheet

1. Enter your daily amp-hour (Ah) requirement	Ah/Day
2. Enter the maximum number of consecutive cloudy weather days expected in your area, or the number of days of autonomy you would like your system to support	________
3. Multiply the amp-hour requirement by the number of days. This is the amount of amp-hours your system will need to store	Ah ________
4. Enter the depth of discharge[a] for the battery you have chosen. This provides a safety factor so that you can avoid over-draining your battery bank. (Generally minimum discharge limit is 20 % i.e. 0.2. and this should not exceed 0.8)	________
5. Divide line 3 by line 4	Ah
6. Select the multiplier that corresponds to the average wintertime ambient temperature your battery bank will experience	________
7. Multiply line 5 by line 6. This calculation ensures that your battery bank will have enough capacity to overcome cold weather effects. This number represents the total battery capacity you will need	Ah ________
8. Enter the amp-hour rating for the battery you have chosen (use the 20 or 24 h rate from the battery manufacturer)	________
9. Divide the total battery capacity by the battery amp-hour rating and round off to the next highest number. This is the number of batteries wired in parallel required	________
10. Divide the nominal system voltage (12 V/24 V/48 V) by the battery voltage and round off to the next highest number. This is the number of batteries wired in series	________
11. Multiply line 9 by line 10. This is the total number of batteries required	________

[a]The maximum allowable DoD of the battery depends upon the type as well as characteristic of the battery (*whether lead acid battery—flooded type, Sealed Maintenance Free* (*SMF*), *Valve Regulated Lead Acid* (*VRLA*) *or gel type; lithium* (*Li*) *based—lithium ion, lithium phosphate* etc.). More details about the selection of the batteries are given in Chap. 4

$$\text{Battery capacity (Ah)} = \frac{\text{Total Daily energy (Wh per day) required by appliances} \times \text{Days of autonomy}}{0.85 \times 0.6 \times \text{nominal battery voltage}} \tag{1}$$

Note (Box 2):
In a standard design, the battery capacity is done based on the total daily energy requirement, whereas in a smart design concept, the battery sizing is done based on the total nocturnal energy requirement and 5–8 % of the daytime energy requirement. In a standard design, the capacity of the battery is decided based on the total daily energy requirement. It does not segregate between the daytime energy requirement and nighttime energy requirement. However, the difference between these design approaches does not seem substantial if there is no or little daytime load and daytime energy requirement. But it makes considerable difference if there is considerable daytime energy requirement.

For a daytime load, there is no need of storing a large proportion of solar PV-generated DC electricity in battery. Rather, the DC electricity can be directly converted to AC electricity through the inverter. This would result not only improve the efficiency of the entire system (by around 5–7 %), but would also lead to smaller capacity of the battery and thus reduce the capital as well as replacement cost of the battery. However, the battery capacity should be selected that it can take care of the sudden fluctuation in the solar radiation (such as swift movement of clouds would result in a sudden drop of solar irradiation). So, in order to cater to the above points, on an average, 5–8 % of the daytime energy requirement can be added to the nocturnal energy requirement to find out the ideal daily energy requirement which is used to design the battery capacity:

$$\begin{aligned}&\text{Daily energy requirement (for battery sizing) E}\\&\quad = \text{nocturnal energy requirement} + 0.08\ \text{X day} - \text{time energy requirement}\end{aligned} \tag{2}$$

Once the above-mentioned information is collected, all other steps mentioned above are followed to calculate the battery capacity. In order to determine the energy required from the PV array, it is necessary to increase the energy from the battery bank to account for battery efficiency. The average round-trip energy efficiency of a new battery is 80–85 % (variations in battery voltage are not considered). Therefore, the energy required, which needs to be provided by the solar PV array, is

$$\text{Energy(Wh) to be provided by the solar PV array} = \text{Daily energy requirement expressed in Wh} \div 0.85 \quad (3)$$

Oversize factor—If the system does not include a diesel generator which can provide extra charging to the battery bank, then the solar PV array should be oversized to provide the equalization charging of the battery bank. This is recommended as 10 %.

De-rating of module performance—Several factors (such as when you will be using your system—summer, winter, or year-round, location and angle of PV array, fixed mountings vs. trackers, etc.) influence how much solar insolation falls on the solar modules. Again, whatever solar insolation is falling on the solar module is not fully converted into useful electricity and there exist a power loss from solar PV module.

The PV array is de-rated due to various factors:

(a) Dirt and dust: Over a period of time, dirt or salt (if located near the coast) can build up on the array and reduce the output. The output of the module should therefore be de-rated to reflect this soiling. The actual value will be dependent on the site but this can vary from 0.9 to 1 (i.e. up to 10 % loss due to dirt).
(b) Temperature: Modules' output power decreases with temperature above 25 °C and increases with temperatures below 25 °C. The output power and/or current of the module must be based on the effective temperature of the cell.

The following worksheet (Table 4) is followed to carry out the sizing of the solar PV array.

Step IV : System wiring sizing

Cable or Conductor of working zone critical to the safe, long-term operation of any electrical system. This is particularly critical for PV applications, where the outdoor environment can be extreme and the PV modules will be sourcing current for 40 years or more. Cable sizes are particularly important for low voltage battery cables, solar panels and load cables. Voltage drops through incorrectly sized cables are one of the most common reasons for low voltage (12 V/24 V/48 V) system faults. If the cable is far too small, it can be very dangerous as the cable will heat up and potentially cause a fire. Undersized cables also waste energy.

A. Cable size between solar PV array and battery

The following steps can be followed to calculate the conductor size:

Step-1: Determine the maximum DC system voltage

In the DC side of the circuit, i.e. from the PV module side to the combiner box or to the inverter, calculate the maximum DC system voltage (shall not exceed the inverter maximum DC input voltage):

$$\text{Maximum DC system voltage (volt)} = \text{Maximum number of modules per string} \times V_{oc} \times \text{temperature correction factor} \quad (4)$$

Table 4 Solar PV array sizing worksheet

1. Daily energy requirement	——Wh
2. Battery round-trip efficiency	80–85 %
3. Dividing the total energy demand per day (Line 1) by the battery round-trip efficiency (Line 2) determines the required PV array output per day	——Wh
4. Enter selected PV module maximum power voltage at standard test conditions (STC) (module specifications)	——V
5. Multiply 0.85 PV module maximum power voltage at STC to establish a design operating voltage for the solar module	—-Vop
6. Enter nominal power output at 1000 watts/m^2 and 25^0 C (module specifications)	——W
7. Module de-rating factor	0.9
8. Multiply Line 6 with Line 7 to obtain the guaranteed power output	———W
9. Enter peak sun shine hour (Equivalent hours of Sun Shine—EHSS)	——h
10. Multiply Line 8 with Line 9 to get the average energy output from one module.	——Wh
11. Divide Line 3 with Line 10 to get the number of modules required to meet energy requirements	——Nos
12. Enter nominal power output of PV module	—-W
13. Multiplying the number of modules to be purchased (Line 11) by the nominal rated module output (Line 12) determines the nominal rated array output	——
14. Enter the battery bus voltage	——V
15. Dividing the battery bus voltage (Line 14) by the module design operating voltage (line 5), and then rounding this figure to the next higher integer determines the number of modules required per string	—— Nos of module per string
16. Dividing the number of modules required to meet energy requirements (Line 11) by the number of modules required per string (Line 15) and then rounding this figure to the next higher integer determines the number of string in parallel	—— Nos of string in parallel

Step-2: Calculate the Maximum DC current

As per standard 690.8(A), in the DC PV array circuits, the maximum DC current is defined as 1.25 times the rated short-circuit current I_{sc} (module specification). For example, if a module had an I_{sc} of 7.5 amps, the maximum current would be $1.25 \times 7.5 = 9.4$ amps. If three strings of modules are connected in parallel, the PV output circuit of the combiner would have an I_{sc} of $3 \times 8.1 = 24.3$ amps. So the maximum current in this circuit would be $1.25 \times 24.3 = 30.4$ amps.

Step-3: Calculate the Maximum DC current to be carried by the conductor

For code calculations, PV currents are considered continuous and are based on worst-case outputs and based on safety factors applied to rated outputs. Because PV system currents are considered continuous, the maximum currents calculated as per standard 690.8(A) must be multiplied by 125 % to calculate the maximum continuous current or minimum conductor size/minimum ampacity:

$$\text{Maximum continuous current to be carried by the conductor} \\ = 1.25 \times \text{Maximum DC current} \quad (5)$$

Hence,

$$\text{Maximum continuous current to be carried by the conductor (ampacity)} \\ = 1.25 \times 1.25 \times \text{rated short circuit current (Isc)} \quad (6)$$

This calculation is done before applying any adjustment and correction factors, commonly referred to as 'conditions of use', which include corrections for conductors exposed to temperatures in excess of 30 °C or more than three current-carrying conductors within a conduit. The ampacity of the conductor, at a minimum, needs to be greater than or equal to the maximum current in given in standard 690.8(A) × 1.25.

Step-4: Enter percentage cable loss acceptable

Generally, the cable length and the cross-sectional area are chosen in a way that voltage drop between any two sections is within the permissible voltage level. Normally, 2–3 % voltage drop is allowed to calculate the cable length and the cross-sectional area.

Step-5: Calculate the cable length and the cross-sectional area

Once ampacity of the circuit is known, the maximum distance a cable can run in a 12-V DC system with expected maximum DC current, where 2 % voltage drop is allowed from PV array to charge controller or power converter can be found out using the chart as shown in Table 5 (source—http://www.affordable-solar.com/Learning-Center/Solar-Tools/wire-sizing).

The above chart gives the nominal ampacity, when ambient temperature is 30 °C. However, the ambient temperature and the cable operating temperature need not always be kept at 30 °C and thus the correction factor with respect to change in operating temperature needs to be considered to calculate the actual ampacity. The ambient temperature correction factor will depend upon

i. hottest outdoor temperature (expected) and
ii. the number of current-carrying conductors, running inside the conduit.

Table 6 (source—http://www.thesolarplanner.com/steps_page9b.html) shows the ambient temperature correction factor, whereas Table 7 (source—http://www.thesolarplanner.com/steps_page9b.html) shows adjustment factor with respect to the current-carrying conductors, running inside the conduit.

The actual ampacity after factoring the ambient temperature correction factor and adjustment factor with respect to the current-carrying conductors, running inside the conduit, will be

$$\text{Actual ampacity} = \text{Nominal ampacity} \div \text{ambient temperature correction factor} \\ \div \text{adjustment factor with respect to the current carrying conductors} \quad (7)$$

Table 5 Voltage drop in cables

2 % Voltage drop chart										
	In sq mm									
	2.5	4	6	10	16	25	35	55	70	
	AWG									
Nominal Ampacity (Amps)	#14	#12	#10	#8	#6	#4	#2	#1/0	#2/0	#4/0
1	45	70	115	180	290	456	720	–	–	–
2	22.5	35	57.5	90	145	228	360	580	720	1060
4	10	17.5	27.5	45	72.5	114	180	290	360	580
6	7.5	12	17.5	30	47.5	75	120	193	243	380
8	5.5	8.5	11.5	22.5	35.5	57	90	145	180	290
10	4.5	7	11.5	18	28.5	45.5	72.5	115	145	230
15	3	4.5	7	12	19	30	48	76.5	96	150
20	2	3.5	5.5	9	14.5	22.5	36	57.5	72.5	116
25	1.8	2.8	4.5	7	11.5	18	29	46	58	92
30	1.5	2.4	3.5	6	9.5	15	24	38.5	48.5	77
40	–	–	2.8	4.5	7	11.5	18	29	36	56
50	–	–	2.3	3.6	5.5	9	14.5	23	29	46
100	–	–	–	–	2.9	4.6	7.2	11.5	14.5	23
150	–	–	–	–	–	–	4.8	7.7	9.7	15
200	–	–	–	–	–	–	3.6	5.8	7.3	11

Source http://www.affordable-solar.com/Learning-Center/Solar-Tools/wire-sizing

Table 6 Ambient temperature correction

Ambient temperature (°F)	Ambient temperature (°C)	Correction factor 75 °C conductors	Correction factor 90 °C conductors
70–77	21–25	1.05	1.04
78–86	26–30	1.00	1.00
87–95	31–35	0.94	0.96
96–104	36–40	0.88	0.91
105–113	41–45	0.82	0.87
114–122	46–50	0.75	0.82
123–131	51–55	0.67	0.76
132–140	56–60	0.58	0.71
141–158	61–70	0.33	0.58
159–176	71–80	0.00	0.41

Source http://www.thesolarplanner.com/steps_page9b.html

Table 7 Adjustment factor with respect to the current-carrying conductors

Number of current-carrying	Adjustment factor
1–3 conductors	1.00
4–6 conductors	0.80
7–9 conductors	0.70
10–20 conductors	0.50

Source http://www.thesolarplanner.com/steps_page9b.html

Once the actual ampacity is found out, it is used to find out the length and size of the cable which is to be used.

Alternatively, the cross-sectional area (A) of the cable is given by the equation

$$A = \frac{\rho l I}{Vd} \times 2 \tag{8}$$

where ρ is the resistivity of copper wire which is 1.724×10^{-8} Ωm,

Vd is the maximum allowable voltage drop,

l is the length of the cable and

I is the maximum current that can be carried by the cable or the conductor.

Based on the above formula, the cross-sectional area (A) of the cable between PV module to charge controller, battery to the inverter or to the load, and between the inverter to the load can be calculated.

Determine the cable size between battery to load and inverter:

Let us consider the length of the cable (l) as 5 m and the allowable voltage drop is 4 %. In such scenario, the cross-sectional area is determined as follows.

The maximum current from battery at full load supply is given by

$$I = \frac{\text{Inverter } kVA}{\eta_{\text{inverter}} \times V_{\text{system}}} \tag{9}$$

Here, V_{system} is the minimum possible voltage of the battery.

Since 4 % voltage drop is allowed, allowable maximum voltage drop (Vd) will be

$Vd = 0.04 \times 48\,\text{V} = 1.92\,\text{V}$ (Assuming that the system voltage is 48 V).

Applying the value of l, Vd, I and ρ in Eq. (8), the cross-sectional area of the cable can be calculated.

Determine the cable size between inverter and load:

Let us assume that the maximum length of the cable for powering the load from the inverter is 20 m and the allowable voltage drop is 4 %. So the maximum current on the phase is

$$I\text{max} = \frac{\text{Inverter } kVA}{\sqrt{3} \times V_{\text{output}}} \text{ (in case of 3 phase inverter)} \tag{10}$$

Table 8 PV system component sizing

Component	Description of component	Result
Load	Total estimated load (kW) Total estimated energy(kWh)	
PV Array	Capacity of PV array	
Number of modules in series		
Number of modules in parallels		
Total number of modules		
Battery Bank	Battery bank capacity (Ah)	
Number of batteries in series		
Number of batteries in parallel		
Total number of batteries required		
Voltage Regulator	Capacity of voltage regulator	
Number of voltage regulators required		
Inverter	Capacity of the inverter (kW)	
Wire	Between PV modules and batteries through voltage regulators	
	Between battery bank and inverter	
	Between inverter and load	

$$I\text{max} = \frac{\text{Inverter}kVA}{V_{\text{output}}} \text{ (in case of single phase inverter)} \tag{11}$$

The maximum continuous current will be $I = 1.25 \times I\text{max}$ and maximum allowable voltage drop (Vd) will be $Vd = 0.04 \times 220\,\text{V} = 8.8\,\text{V}$. Applying the values of l, Vd, I and ρ in Eq. 8, the cross-sectional area of the cable between inverter and load can be calculated. Once the sizing for different components of the PV system are done by following the above-mentioned steps, a summary table (Table 8) can be prepared.

3 Design and Actual Implementation of Solar PV System for Lighting and Livelihood Applications

In this section, design of various off-grid solar PV systems for lighting and livelihood generation activities will be described along with few examples of actual implementation of such systems.

3.1 Design and Actual Implementation of Solar PV System for Lighting Applications

Traditionally, solar lighting was provided through stand-alone individual systems such as solar lantern, Solar Home lighting System (SHS). However, in the recent years, in addition to the individual solar lighting systems, centralized solar systems too have come into use are also used for providing lighting options. Such centralized systems are available in the form of solar charging stations or small micro-grids or nano-grids. This entire configuration has its own advantages as well as limitations, depending on the requirement and applications. Whereas the sizing and design of the stand-alone solar lantern is very common and widely known, the authors exclude it in this book and focuses only on the sizing and actual implementation of solar charging station and solar micro-/nano-grid.

3.2 Design and Actual Implementation of Solar Charging Station for Lanterns

A Solar Charging Station (SCS) for lantern (Fig. 5) is a charging station where a number of lanterns charge simultaneously through a junction box (JB) using one or more solar PV modules that are centrally located. A solar lantern charging station facilitates the use of large capacity PV modules, which offer better efficiency and lowers unit costs as compared to the small capacity PV modules that are used individually and dedicatedly with a single solar lantern.

Following are its major components of the solar charging station to be used for charging lanterns or task lights.

PV modules—A set of PV modules is installed on the shadow-free area of the charging station. The voltage and current of each PV module are chosen in a way that it is capable of charging a particular pre-determined number of lanterns.

Lantern—A lantern is a portable lighting system consisting of lighting device (lamp), a maintenance-free storage battery and electronics that are all placed in a case made of plastic or fibreglass. During the day, the storage battery of the lanterns is charged through the JB ports by the electricity generated from the PV module. When the lantern is fully charged, it is disconnected from the JB and then can be used as an independent portable lighting source. Lantern is suitable for both indoor and outdoor lighting applications. The specifications of the lanterns are generally based on their light output and typical power rating.

Junction boxes—A JB basically contains the electronic interface circuitry that is required between the PV module and the lanterns. It houses the necessary protections such as short-circuit and reverse-polarity protections for effective charging of the lanterns. For proper distribution of current and the protection of the lanterns, the JB in SCS contains current limiting circuits for each individual port.

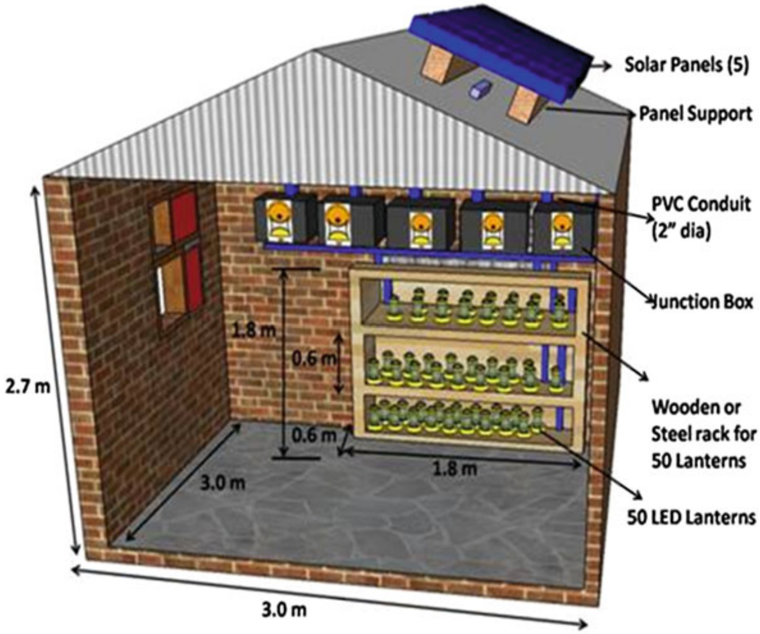


Fig. 5 A Solar Charging Station (SCS) for lantern. Source: TERI

Design of Solar Charging Station (SCS)—The concept of SCS has been tried out in many countries including India, Indonesia, Nepal and Myanmar as well as in many African countries. In those countries, SCS is implemented in order to charge lantern or task lights. The 'Lighting a Billion Lives (LaBL)' initiative taken by TERI had used this concept and so far implementing the largest number of SCS for charging lanterns (Fig. 6).

Step-1: Determine your power consumption and daily energy demand

Here, there is no AC loads and only have LED lights which are DC load. So the designer only has to use the format as per Table 9 to calculate the power consumption and daily energy demand. A typical example is shown in Table 9.

Step-2 Assess solar energy resources

In order to carry out this exercise, the location, where the SCS is going to be installed, has to be identified and the solar resource assessment needs to be carried out for that particular location. Let us assume that this particular sizing exercise is carried out for a SCS which is to be installed at New Delhi. The average daily insolation (sometimes referred to as "peak sun hours) for New Delhi is found out to be 4.8 kWh/m^2/day, which is used in the sizing purposes in subsequent steps.

Fig. 6 A solar charging station implemented in India and Africa. *Source: TERI*

Table 9 Daily energy consumption of LED lighting

a	*b*	*c*	*d*	*e*	*f* = *b***c***e*
DC Appliances/Load	Number	Power consumption (Wattage of each load) (W_{DC})	Max Power (W max)	Daily usage hours (h/day)	Daily energy required (Wh $_{DC}$/day)
LED light	10	1.25	12.5	5	62.5
Maximum DC demand 15 W					
Total daily DC energy required ($E_{DC\text{-}Daily}$) 62.5 Wh					

Step-3 Specifying the inverter capacity

Since there is no AC load, there is no requirement of inverter.

Step-4: Specifying the battery

Here, the storage battery is with each lantern and thus the sizing of battery is carried out for each lantern. Here, it is assumed that small sealed maintenance-free (SMF) lead acid batteries are used in the lantern. The battery sizing worksheet (Table 10) is used to find out the battery capacity which is to be used for each lantern.

Step-5: Sizing of solar PV array

Although individual battery is used for each lantern, the sizing of solar module/array will be for simultaneously charging 10 numbers of lanterns. The solar module/array sizing worksheet (as mentioned in Table 11) is used to find out the solar PV capacity to be used for charging 10 lanterns.

Table 10 Battery sizing worksheet

1. Enter your daily amp-hour requirement for an individual lantern (Daily DC energy requirement/system voltage) (assuming that the driver efficiency is 0.95)	= 6.25 Wh/0.95/6 V = 1.1 Ah/Day
2. Enter the maximum number of consecutive cloudy weather days expected in your area, or the number of days of autonomy you would like your system to support (Days of Autonomy)	3 days
3. Multiply the amp-hour requirement by the number of days. This is the amount of amp-hours your system will need to store	= (1.1* 3)Ah = 3.3 Ah
4. Enter the depth of discharge for the battery you have chosen. This provides a safety factor so that you can avoid over-draining your battery bank	0.8
5. Divide line 3 by line 4	= (3.3/0.8) Ah = 4.1 Ah
6. Select the multiplier that corresponds to the average wintertime ambient temperature your battery bank will experience	1.1
7. Multiply line 5 by line 6. This calculation ensures that your battery bank will have enough capacity to overcome cold weather effects. This number represents the total battery capacity you will need	4.5 Ah
8. Enter the voltage and amp-hour rating for the battery you have chosen (use the 20 or 24 h rate from the battery manufacturer)	6 V, 4.5 Ah
9. Divide the total battery capacity by the battery amp-hour rating and round off to the next highest number. This is the number of batteries wired in parallel required	One
10. Divide the nominal system voltage (12, 24 or 48 V) by the battery voltage and round off to the next highest number. This is the number of batteries wired in series	One
11. Multiply line 9 by line 10. This is the total number of batteries required.	One 6 V, 4.5 Ah
Battery capacity (SMF lead acid battery) to be used for each lantern	6 V, 4.5 Ah

4 Role of Photovoltaic System in Future Smart Micro-Grid

4.1 What Is Future PV-Based Smart Micro-Grid Will Look Like?

Future electrical grid will be face numbers of physical changes with introduction of new technologies for integrating PV system. According to the report from MIT entitles ‘the future of electrical grid’, the challenge will be massive as large penetrations of intermittent resources into the grid system will change a lot of things in the grid system. This will significantly change the policy initiatives as well as design of the grid. A lot of countries around the world have put a renewable initiatives as part of their policy initiatives in order to face this huge challenge towards the conventional grid system which has been exist since early 1900. There

Table 11 PV module/array sizing worksheet

Daily energy requirement (for 10 lanterns)	62.5 Wh
Battery round-trip efficiency	80–85 %
Charging efficiency of the junction box	0.9
Dividing the total energy demand per day (Line 1) by the battery round-trip efficiency (Line 2) and charging efficiency of the junction box to determines the required array output per day	= (62.5/0.8/0.9) = 87 Wh
Enter selected PV module max power voltage at STC Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltaic module	8.3 V
Multiply 0.85 PV module max power voltage at STC to establish a design operating voltage for the solar module	= 8.3*0.85 Vop = 7 Vop
Enter nominal power output at 1000 W/m^2 and 25 °C	25 Wp
Module de-rating factor (including mismatch, soiling and other losses	0.9 (90 %)
Multiply line 6 with 7 to obtain the guaranteed power output at operating temperature	= 25*0.9 W = 22.5 Wp
Enter peak sun shine hour (Equivalent hours of Sun Shine (EHSS)	4.8 h
Multiply line 8 with 9 to get the average energy output from one module	= 108 Wh
Divide line 3 with 10 to get the number of modules required to meet energy requirements (No of modules purchased)	One
Enter nominal power output of PV module	25 Wp
Multiplying the number of modules to be purchased (line 11) by the nominal rated module output (line 12) determines the nominal rated array output	One 6 V, 25 Wp solar module

are needs to introduce a new type of smart grid system that really can plug and play rather than replacing all the conventional grids as it is not financial beneficial.

'Smart grid' is being publicized by most of the utility providers throughout the world. This can be seen as a future grid system. However, there are much more things that the power system needs to face to maintain it reliability and security. This is going to be one of the major engineering challenges ever. The transition from conventional to smart grid system can be represented in three stages.

The smart grid includes several crucial components (Fig. 7) and it will define a future grid system. As such system will turn into maturity after sometimes, it needs to be evolved according to the rapid technology growth. It is expected that the future grid will be a two-way flow of energy and information compared to current grid system which is unidirectional. Future grid is expected to be more resilient and capable of self-healing to any fault. Basic ingredients in intelligent grid can be seen in Table 12.

The modernization of power generation by utilization of technological advancement is to make sure a better efficiency, more reliable grid system and environmental friendly.

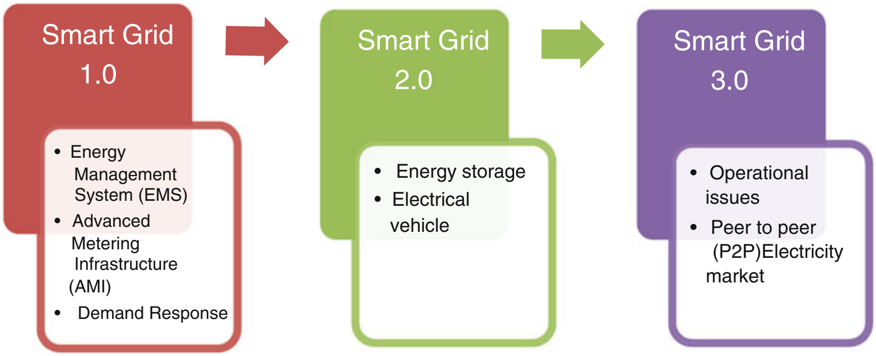


Fig. 7 Evolution of smart grid transition (Carvallo and Cooper 2011)

Table 12 Smart grid compared with existing grid (Farhangi 2010)

Existing grid	Intelligent grid
Electro-mechanical System	Digital system
One-way communication	Two-way communication
Centralized generation	Distributed generation
Hierarchical	Distributed network
Few sensors	Sensors throughout
Blind	Self-monitoring
Manual restorations	Self-healing
Failures and blackouts	Adaptive and islanding
Manual check/test	Remote check/test
Limited control	Pervasive control
Few customer choices	Many customer choices

4.2 Future Grid Interconnection Option for Solar PV Systems

This subsection will provide a future grid connection to the PV system with energy storage and it is going to be called an active generator. At present, most of the world-wide grid-connected PV systems are operating at maximum power points and not contributing effectively towards the energy management in the power system network. Unless properly managed and controlled, large-scale deployment of grid-connected PV generators may create problems: voltage fluctuations, frequency deviations and power quality problems in the power system network, changes in fault currents and protections settings and congestion in distributed network. These problems are becoming critical for maintaining the power system stability and control. A solution to these problems is the concept of active generator. The active generators will be very flexible and able to manage the power delivery as used to be in conventional generator system in micro-grid. This active generator includes the PV array with combination of energy storage technologies and proper power conditioning devices. Many manufacturers of PV system power condition devices are designing and developing new type of inverters, which can work for delivering the power from PV system in coordination with energy storage/batteries as conventional power plant.

The higher penetrations of distributed generators are going to create different possibilities of the faults not only in the micro-grid network but also at higher voltage power system network. Fault detection and isolation mechanism is compulsory for power system operation. It is needed to analyse the fault protection system, for instance: fault current levels, relay settings and fault clearing time in the micro-grid environment by considering the existence of PV-based active generators (Najy et al. 2013). During fault or any unwanted events and abnormal conditions at the micro-grid network, the grid may be disconnected, and islanding effect may occur in micro-grid. It will create many problems towards the grid operation and safety issues. In such situations, micro-grid EMS has to be intelligent for effectively managing the power flows within the micro-grid by considering not only voltage and frequency fluctuations but also taking into accounts the safety using different protection standards (Kunsman; Teodorescu and Liserre 2011). These standards are used to make sure that the PV-based active generator and grid connections are safe and not going to harm either equipment or personnel. Using these protection standards, the utilities company can envisage the impact of the control strategies of the connection, which includes the performance of voltage deviations, power quality and harmonics.

4.3 Overview of PV-Based Active Generator

PV-based active generator is a system that comprises PV array with a battery storage system with a capacity of storing energy for a long and short term for local usage (Kanchev et al. 2010). From this definition, it can be concluded that this system will be able to generate, store and release energy as long as the electricity is needed. This can be done with a proper hierarchical monitoring and energy management system. Figure 8 shows systematic of PV-based active generator.

Power management is crucial to control the whole energy flow in the PV-based active generator with the emphasis on the power management algorithm on the active PV station with a battery storage (Di Lu et al. 2008). Four hierarchical positions have been introduced and each level has its own task, as shown in Fig. 9. This PV-based active generator is expected to offer a new flexibility to the consumer and operator and will be a new dimension of generating electricity through clean energy. The system will be operated in a micro-grid environment and will have a lot more parameters that need to be considered.

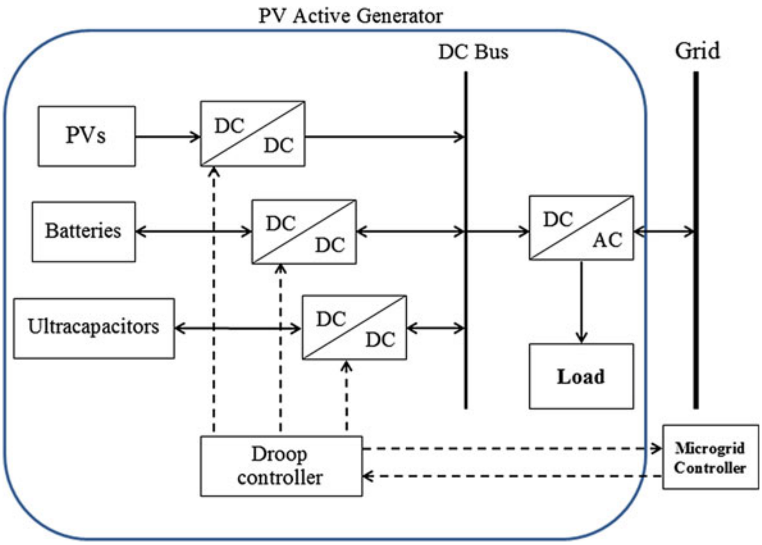
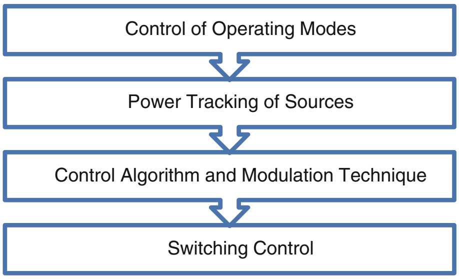


Fig. 8 PV-based active generator systematic

Fig. 9 PV generator control level (Kanchev et al. 2011)



The system is connected to the battery storage and or ultra-capacitors and which is then coupled with choppers and connected to the existing grid (micro-grid). With the combination of battery and ultra-capacitors, it will increase the system efficiency as the battery will be able to store and release energy gradually, while ultra-capacitor effectively acts as storage device with very high power density. For a complete PV active-based generator, a set of battery bank is connected in a combination series–parallel in order to provide desired power to the system. The additional ultra-capacitor will provide a fast response energy storage device that can reduce the effect of short-term fluctuations of PV output and will enhance the whole system (Shah and Mithulananthan 2011).

4.4 Battery Storage and Ultra-Capacitor (Energy Storage System)

Battery storage sizing is very important. There are three main parameters that need to be considered for every installation of battery storage system: the depth of discharge (DOD), state of charge (SOC) and state of health (SOH), as well as battery capacity, maximum battery charge and discharge power and the utility rating type (Aichhorn et al. 2012). Battery storage systems are being progressively used in distributed renewable energy generation nowadays. With the existence of ultra-capacitors, the effectiveness of the storage system will be much more reliable to be used in the near future. With the combination of battery and ultra-capacitors, it will increase the system efficiency as the battery will be able to store and release energy gradually, while ultra-capacitor effectively acts as storage device with very high power density. For a complete PV active-based generator, a set of battery bank is connected in a combination series–parallel in order to provide desired power to the system. The additional ultra-capacitor will provide a fast response energy storage device that can reduce the effect of short-term fluctuations of PV output and will enhance the whole system. Basically, the total produced power from the system is a total power generated from the PV, battery and ultra-capacitor (Fig. 10).

A lot of research has been done for the battery storage system for PV generator. The battery dynamic equation can be represented as

$$\frac{\mathrm{d}E_B}{\mathrm{d}t} = P_B(t), \tag{12}$$

where E_B represents the amount of electricity stored at t time and P_B is the charging or discharging rate. This should be integrating with the ultra-capacitor to make sure that both of this storage system can be used and compatible to each other. There are several relevant resources regarding the optimization of batteries for PV. There are following levels of working zone and conditions for a stand-alone PV application, and they are

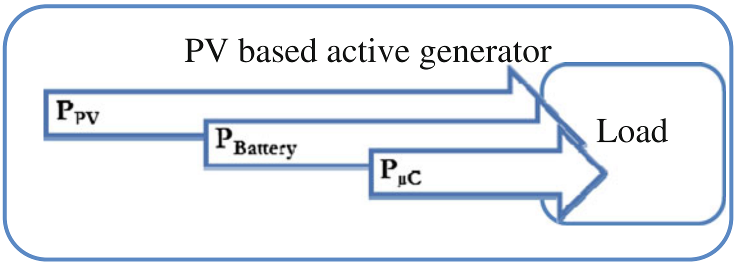


Fig. 10 Power flow in PV-based active generator

(i) Saturation zone;
(ii) Overcharge zone;
(iii) Charge zone;
(iv) Changing from charge to discharge or vice versa;
(v) Discharge zone; and
(vi) Over discharge and
(vii) Exhaustion.

As can be seen in Fig. 11, the working condition depends on the voltage and current that went through the battery. This is a sample of a 2-V battery.

For basic facts on installation of storage system to a grid-connected PV system, there are three different facts (Vallvé et al. 2007). First, argument is the storage system that can undoubtedly improve the security of supply to the whole system; however, the grid quality is the main issue. The existing grid is ageing and the possibilities of interruption are high. Second, the addition of storage function might increase the performance ratio of PV generator. The third fact is that large penetration of PV will definitely not be able to cover the whole load consumptions. PV source can be able to supply at least some part of overall energy consumed by specific load. These facts may lead the utility company or customer to consider on the battery and ultra-capacitor as a main storage structure for future housing development. The Fraunhofer Institute for Solar Energy Systems has developed a battery-management system for renewable energy system. For a conventional renewable energy system, the battery often operated at the low state of charge that

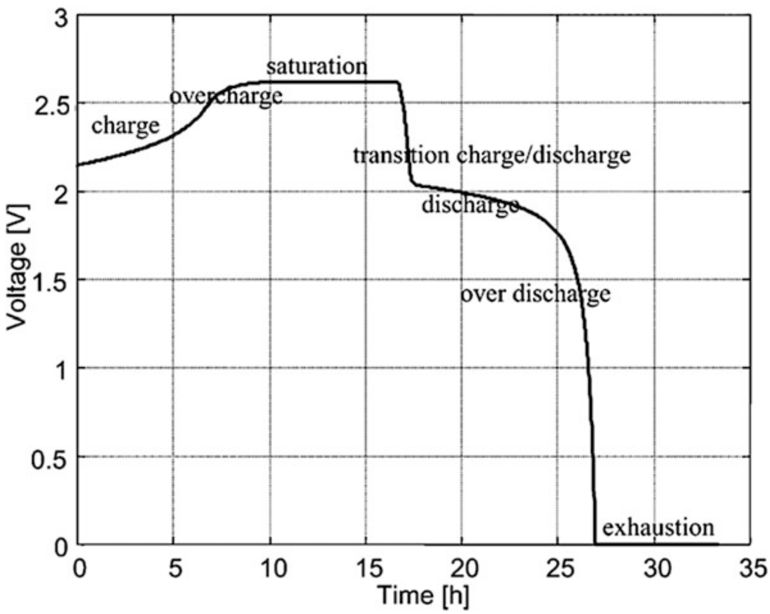


Fig. 11 Battery working zone conditions (Guasch and Silvestre 2003)

resulting the decreasing lifetime of the battery. By implementing a battery-management system on the renewable energy system, it improves the storage lifetime and reliability of batteries in the system and thus reduces maintenance and lifetime costs considerably.

The battery storage system for PV integration is also discussed further in (Le Dinh and Hayashi 2013), (Li et al. 2013), (Yoo et al. 2012). The authors in these papers discuss on the main topic related to connection of PV system to the micro-grid: frequency control, voltage stability and energy storage smoothing control. These parameters are significant for a PV-based active generator, since it is compulsory to get a very efficient system to make sure that it can be implemented in the real system. A smoothing control method for reducing output power fluctuations and regulating battery state of charge (SOC) under typical condition is proposed. Voltage control and active power control algorithm for centralized battery storage system is already proposed in (Le Dinh and Hayashi 2013).

There are a lot of new inventions on the energy storage system to fit in the new grid system or micro-grid with PV system going on. One of the discoveries is the utilization of Vanadium Redox Battery (VRB) in PV system. As discussed in (Wang et al. 2012b) and based on the evidence in (Nguyen et al. 2011) and (Wang et al. 2012a), the utilization of VRB in micro-grid has abundance of chance. Based on Table 13, the comparison between conventional Lithium ion (Li-ion), Sodium Sulphur Battery (NaS), Lead Acid battery, VRB and flow battery can be seen.

Table 13 Comparison between different types of batteries

Parameter/Technology	Li-ion	Na S	Lead acid	VRB	Flow battery
Energy density	Average	High	Low	Low	Varies (lower than Li-ion)
Efficiency	High (near 100 %)	High (~92 %)	85 %	~85 %	60–85 %
Lifecycle	500–1000		200–300	High	
Toxicity	Non-toxic (electrolyte may be harmful)	Highly Corrosive	Sulphuric acids in the lead is highly corrosive	No fire hazard	Low toxicity
				No highly reactive or toxic substances	
Cost	High (above ~ $600)	High (up scaling)	Low	High	Low on average (depends on type of chemical)
Other		High operation temperature (heating process needed)	Requires regular maintenance	Independent energy and power rating more complicated technology	High power and capacity for load levelling in grid system

For a PV system application, the battery storage system will be operated under the partial state of charge duty (Hill et al. 2012). In this condition, the battery or ultra-capacitors will be partially discharge at all time, in order to make sure that the system will be able to absorb or discharging power to the grid as it is needed (Guerrero et al. 2011). To charge the ultra-capacitor, a few methods can be done, and hence using a constant power charging mode will be better in PV environment; however, it is not proven that it will be suit to the micro-grid environment yet (Zhang et al. 2012). The charging efficiency using constant power charging mode is a ratio between energy in the ultra-capacitor (E_{μ}) and energy transmitted by the chargers (E_T):

$$\eta = \frac{E_{\mu}}{E_t} \tag{13}$$

And further it can be expressed by

$$\eta = \frac{\frac{1}{2}C_e(V_{cT}^2 - V_{c0}^2)}{PT} \tag{14}$$

where

C_e is the deal ultracapacitor value,
Vc_T is the ultracapacitor voltage as T time,
Vc_o is the ultracapacitor initial voltage and
P is the charging power.

For a dynamic equation of ultracapacitor, it can be seen as

$$\frac{C_e}{\omega}\frac{\partial V_c}{\partial t} = \frac{1}{R_e}\left[\left(\frac{1-d}{d}\right)V_{dc} - V_c\right] \tag{15}$$

where

C_e is the capacitance value,
R_e is the series resistance of ultracapacitor,
V_c is the ultracapacitor voltage and
d is the duty cycle.

The duty cycle implemented in the system is proportional and integration controller (PI).

4.5 PV-Based Active Generator in Future Micro-Grid Environment

Micro-grid is a system that operates at low voltage and has a few distributed energy resources (PV, wind, geothermal, etc.). With proper energy management and

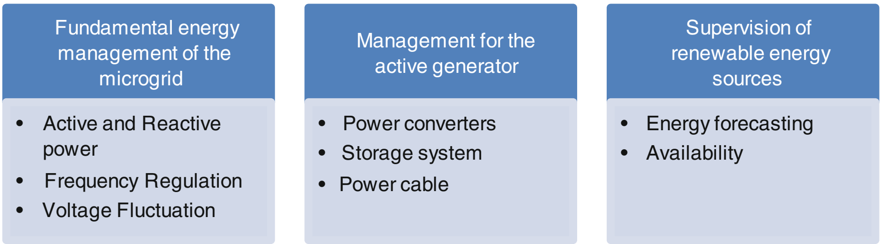


Fig. 12 Parameters that need to be considered in PV-based active generator energy management

systematic supervision, micro-grid can be a new dimension of generating and transmitting energy to the load. PV-based active generator can be integrated into micro-grid and it has been done in Kytnos Island in Greece, Tokoname city in Japan, Bronsbergen Holiday Park in The Netherlands and Mannheim-Wallstadt in Germany. It needs a good supervision from the utility operator to make sure that it will well operate. Energy supervision and optimization for the whole PV-based active generator system is compulsory and it can be separated into three major parts as shown in Fig. 12.

On the micro-grid side, the operator needs to manage the energy between source and load. This will includes the active and reactive power, frequency regulation, voltage fluctuations, etc. The implementation of PV-based active generator in a micro-grid environment has a high significant towards the energy management in the electrical grid. A strategic framework needs to be developed once it is executed in the system and it should be focused on a long-term and short-term energy management.

Figure 13 shows the micro-grid that integrates together three energy sources (PV, wind and micro-gas turbine). This is a representation of a micro-grid system with multiple sources that can be used in future micro-grid system.

4.6 *Energy Management in Micro-Grid*

For a better power delivery, the most crucial part is on the energy management side. Theoretically, it might look simple, yet it is tough. In micro-grid connection, other than findings, a new alternative optimization criteria and exploration of the fluctuations effect, energy management options, is important to be modelled so that a reliable energy with better efficiency can be delivered without any failure to customer (Quiggin et al. 2012). A deterministic energy management algorithm for a PV-based active generator in micro-grid environment needs to be set up for proper supervision.

Based on Fig. 8, the PV-based active generator will be coupled via a DC bus and will be connected to the micro-grid through a three-phase inverter. This will be connected and controlled by a micro-grid controller through a droop controller for

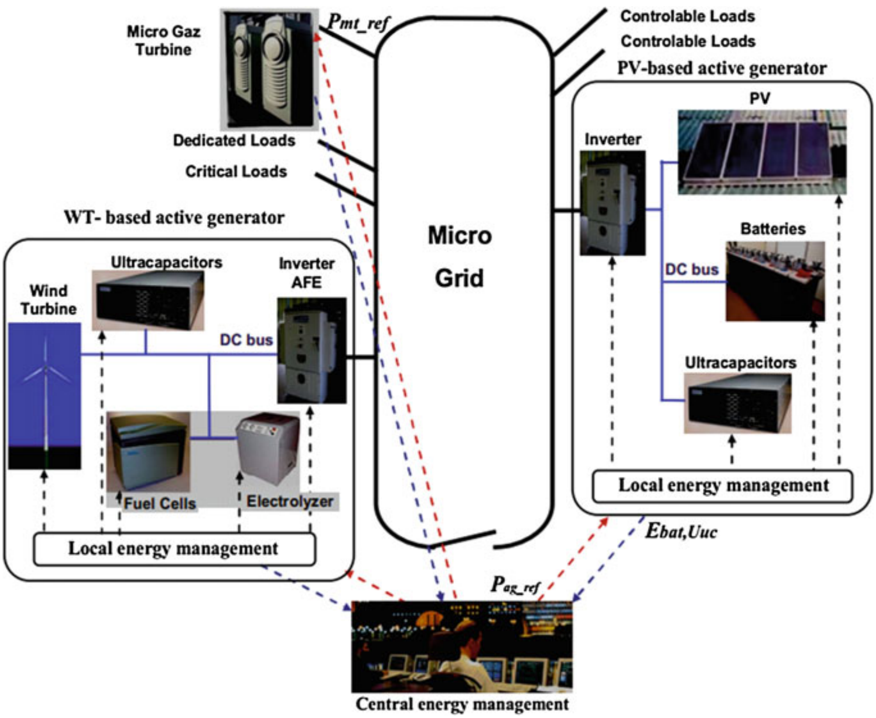


Fig. 13 Micro-grid with PV-based active generator and other sources (wind turbine and micro-gas turbine). Source: (D Lu and Francois 2009)

primary frequency control. A basic requirement for satisfactory operation of power system is the PV-based active generator which needs to maintain the nominal frequency of the grid (50 or 60 Hz). The rules of thumb for frequency control depend on active power (P), while voltage is based on reactive power (Q). Thus, for better energy management for PV-based active generator, a proper droop controller that will manage the voltage and frequency variation is a must.

For PV-based active generator, it will not engage any inertia of the mechanical system since there will be no kinetic energy involved during generating electricity from PV array. Then we can expect that there will be no abrupt changes on the frequency. However, load changes might lead to significant frequency changes that might affect the whole system. It is vital to manage this kind of problems to make sure that PV-based active generator in the micro-grid can operate efficiently (Table 14).

These are the things that need to be monitored and analysed. For a micro-grid-connected PV-based active generator, the network operators need reliable and robust PV energy output forecasting system in operational planning. PV array output depends not only on the incident solar radiation but also on the operating cell temperature as well as shading effect and its operating points. Therefore, a proper

Table 14 Timing classification for energy management system in Micro-grid (Kanchev et al. 2011)

Long term	Short term
• Electricity market • Load forecasting • Renewable energy production • Load management • Energy storage availability	• Voltage control • Frequency control • Dynamic storage availability • Power capability

forecasting methodology is required for predicting the PV array output. It is important to identify the pattern of the historical data set for predicting the output (Matallanas et al. 2012). There are a lot of work which have been done in this matter. This can be very helpful to generate enough power for PV-based active generator.

4.7 Conclusion

The utilization of PV as a source of electricity is something that needs to be emphasized now. The dependencies on the conventional way of generating energy via 'unclean' source and method need to be minimized. PV-based active generator can be a new way of generating energy in the future. It will be clean and very promising. Since this type of generator needs a good energy storage system, battery system with ultra-capacitor will be a great combination. Battery storage with the appearance of ultra-capacitor will increase the system efficiency as the battery will be able to store and release energy gradually, while ultra-capacitor effectively acts as storage device with very high power density. The new type of battery known as the VRB can be used in the near future for this type of generator.

For a better management in the micro-grid level, a new method of managing the energy needs to be implemented. The crucial part is to maintain the frequency and for this, a droop controller that will be connected with the micro-grid and the PV-based active generator needs to be developed. On the energy management side, the PV forecasting, power quality concern and fault issues need to be foreseen. Forecasting the PV energy needs to be done to make sure that there will be no shortage of power during operation, and if there is a power shortage, there should be a plan to overcome this problem.

In order to provide reliable energy, the micro-grid operator should monitor the power quality (harmonics, voltage variations). This is to avoid any deficiency to the consumer and this may lead to fault. Since in micro-grid environment there are probabilities on the islanding effect and this might as well affect the PV-based active generator, avoiding fault is something that the operator needs to be considered. Since the PV-based generator has a promising future, there should be more research on the energy storage side and on the PV cells. The impact of higher efficiency on PV cells and minimizing cost for a battery will have a significant impact to this new type of PV-based generator.

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