PV Component Selection for Off-Grid Applications

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Abstract Although component selection is one of the major tasks of the PV system design and installation, it is often overlooked and poorly integrated within the thought process. This particular aspect needs to be given special attention and awareness ought to be created amongst the installer. This chapter deals with the guidelines, methodology and approaches that need to be adopted for the appropriate selection of the components used in the solar PV-based off-grid application. These approaches are developed based on the state-of-the art system design as well as field experience and extensive research work carried out by the authors in this sector. This chapter will help readers in understanding the importance of each component of the solar PV system which may significantly affect its performance. Further, it will guide the implementers and designers in proper selection of the solar PV components for off-grid applications.

1 Introduction

Appropriate selection of components for a typical battery-based off-grid solar PV system is extremely important as they affect the system performance, efficiency, reliability, maintenance cost and aesthetics in the long run. Component selection and its overall integration are very critical for proper functioning and the reliability of the overall PV system. There would be a drastic reduction in the energy yield if the operating characteristics of different components do not match (Mohanty 2008). For example, if *voltage and current limits of the solar PV do not match with the*

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inverter's voltage and current characteristics, the desired output will not be obtained.

Therefore, it is important to follow the guidelines for the selection of various components of a solar PV system for off-grid applications.

2 Guidelines for the Selection of Solar PV Components for Off-Grid Applications

A typical solar PV system for off-grid application consists of the following major components:

- PV Array;
- Charge controller;
- Inverter;
- Storage battery;
- PV source circuit combine box;
- PV fuse disconnect;
- Ground Fault protection circuit;
- Battery fuse disconnect;
- Inverter fuse disconnect and
- Cables, wires and other accessories.

The following sections discuss the critical points to be considered for selecting the above components of a PV system.

3 Guidelines for the Selection of PV Modules

Solar PV modules are subjected to various national and international standards; however, these only provide measures of safety of the devices and do not indicate field performance or reliability. Therefore, the following parameters should be considered for module procurement to ensure their reliable field level performance:

- Electrical characteristics and its specification;
- Temperature tolerance and hail impact resistance;
- Efficiency, dimensions and weight;
- System compatibility;
- Quality requirement, quality marks, standards and specifications and
- Warranties and guarantees.

Each of the above -mentioned parameters is explained below.

3.1 PV Module Electrical Characteristics

While buying a solar module, one should ask for the I–V characteristic curve (Current versus Voltage Graph) of the solar module. When buying multiple solar modules, I–V characteristic curve for each should be taken from the supplier. An I–V curve can be used to ascertain the following:

- Open-Circuit Voltage (V_{oc}) and Short-Circuit current (I_{sc});
- Maximum Power Point (MPP);
- Wattage at Maximum Power Point (W_p);
- Voltage at Maximum Power Point (V_m);
- Current at Maximum Power Point (I_m) and
- Fill Factor (FF).

For a solar power plant, modules with higher wattage, i.e. higher W_p, should be used because it will require less number of modules thus covering less roof area, fewer mounting structure and fewer inter-module electrical connections (Fig. 1).

The Fill Factor (FF) of the solar module is a critical parameter, although many people tend to ignore it. The FF is defined as the ratio of the maximum power (W_p) from the PV module to the product of the open-circuit voltage (V_{oc}) and short-circuit current (Isc). Graphically, FF is the measure of the squareness of the I–V characteristic curve of a PV module, and is given by the area of the largest rectangle which will fit in the I–V curve. FF ranges from 0.76 to 0.8, in case of a good solar PV module (Fig. 2a). So by knowing the FF of a solar PV module, the quality of a PV module can be found out [good quality (Fig. 2a) or bad quality (Fig. 2b)].

Power tolerances are also very critical and these need to be checked before the purchase of the module as the module's output varies significantly based on the tolerance range. Generally, power tolerance of a good quality PV module is ±3 % to ±5 %.

First Solar, LLC
28101 Cedar Park Blvd.
Perrysburg, OH 43551
www.FirstSolar.com

Made in USA

Nominal Power (+/-5 %)	60 W
Current at mpp	0.97 A
Voltage at mpp	62 V
Short Circuit Current	1.15 A
Open Circuit Voltage	90 V
Maximum System Voltage	(600V UL) 1000 V
Max Source Circuit Fuse	(2A UL) 10 A
Protection Class	Class II
Cell Type	CdTe

Warning - Electrical shock hazard
This solar module produces high voltages in sunlight. Read and observe all instructions before attempting installation or service. Do not disconnect under load.

Serial Number
F01260301

Model Number
FS-260

SHARP
SOLAR MODULE
NT-S5E1U

034090273

Fig. 1 Electrical characteristic of the solar PV module

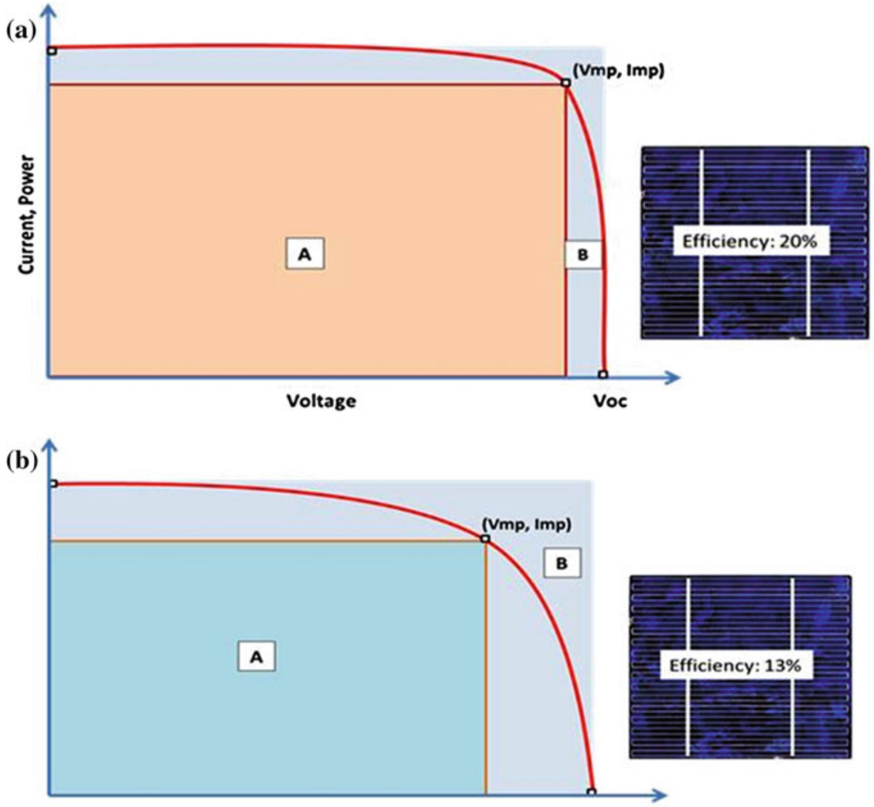

Fig. 2 **a** Fill factor of a good quality solar PV module with higher efficiency, **b** fill factor of a bad quality solar PV module with lower efficiency

3.2 PV Module Temperature Tolerance and Hail Impact Resistance

The open-circuit voltage (V_{oc}) of an individual silicon solar PV cell reduces by 2.3 mV per degree rise of cell temperature. Therefore, the temperature coefficient of the voltage is negative and expressed as shown in Eq. 1:

$$\frac{\mathrm{d}V_{\mathrm{OC}}}{\mathrm{d}T} = -2.3\mathrm{mV} \text{ per } {}^{\circ}\mathrm{C} \text{ for Si solar PV cell} \qquad (1)$$

As a PV module consists of large number of PV cells in series, the voltage drop increases proportionally as is shown in Eq. 2:

$$\frac{\mathrm{d}V_{\mathrm{OC}}}{\mathrm{d}T} = -2.3\mathrm{mV}\ \text{per}\ ^{\circ}\mathrm{C}\ \text{for}\ \ \mathrm{Si}\ \text{solar}\ \ \mathrm{PV}\ \text{module} \tag{2}$$

where n_{c} is the number of PV cells in series.

On the other hand, the temperature coefficient of the current is slightly higher and the current increases very slightly with an increase in the cell temperature (Eq. 3). However, this is a small effect and the temperature dependence of the short-circuit current from a silicon solar cell is

$$\frac{1}{I_{SC}}\frac{\mathrm{d}I_{\mathrm{SC}}}{\mathrm{d}T} \approx 0.0006\ \text{per}\ ^{\circ}\mathrm{C}\ \text{for Si} \tag{3}$$

However, the temperature coefficient of the power is negative for the silicon solar PV module. This means, with the rise of temperature, that the maximum power output of the silicon solar PV module decreases which can be calculated as per the following equation (Eq. 4):

$$\frac{1}{P_{\mathrm{Max}}}\frac{\mathrm{d}P_{\mathrm{Max}}}{\mathrm{d}T} \approx -(0.004\ \text{to}\ 0.005)\ \text{per}\ ^{\circ}\mathrm{C}\ \text{for Si} \tag{4}$$

This temperature coefficient effect needs to be taken care of in the system design and in estimating the yield of a PV array. If the power output of the silicon PV module is specified as 100 Wp at Standard Test Condition (STC), in real condition, its actual power output at 50 °C would be 90 Wp.

3.3 PV Module Efficiency, Dimensions and Weight

PV module efficiency has a practical relevance because a module with a low efficiency will simply cover a larger roof space to provide the same power output compared to an efficient module. So if the cost per Watt peak (Wp) of the solar PV module is substantially lower for the relatively lower efficiency module and there is a considerable free surface area already available without any future plan for utilizing that roof space, then it makes sense to install relatively inefficient modules. However, if the low-cost modules lead to reduced life and poor performance, then it is better to go for high efficiency PV modules even at a higher price. Therefore, modules with same Wp but different efficiencies can be compared with their cost and the available surface area. The most optimum PV module can thus be chosen.

3.4 PV Module with System Compatibility

PV module or array should be compatible with the rest of the electrical components in the system. Particularly, the PV module or array's electrical characteristics should be compatible with that of the inverter, charge controller and the batteries. For example, the voltage of the PV array should match with the battery voltage in order to be able to charge the battery appropriately and/or it should match with the input voltage required for the inverter in order to provide the desired AC output.

3.5 PV Module Quality Requirement, Quality Marks, Standards and Specifications

PV modules which comply with appropriate national and international standards developed by recognized institutions such as the International Electro-technical Commission (IEC), the American Society for Testing and Material (ASTM) and the Sandia National Laboratory can be considered as reliable and are likely to have longer life (Antony et al. 2007). The compliance with the standards will also take care of the minimum degradation of power output (%) from the solar PV module in a defined time period.

Similarly, the ISO 9001:2000 standard is the globally accepted system for quality management of the manufacturing processes as well as for distributors, system assemblers and installers. This is a generic standard, used by many industries. Several PV module manufacturers presently meet the ISO 9001:2000 standard and are certified. Further, the Global Approval Program for Photovoltaics (PV GAP) was established in 1998 under the auspices of an independent organization, PV GAP, to promote the use of international standards, quality management processes and organizational training in the manufacture, installation and sale of PV systems. It also defines the procedure for certification of photovoltaic products and the use of the PV quality mark and PV quality seal.

3.6 PV Module Warranties

PV module warranties are extremely critical and the modules with a minimum guaranteed output of 80 % of its original rating after 20–25 years of installation should be purchased.

3.7 Performance Comparison of Different PV Technologies

Table 1 compares the performance of different PV technologies which can be used for designing the various PV systems as well as for selecting the appropriate PV modules for specific site conditions and requirements.

4 Guidelines for Battery Selection

Solar PV modules can generate power only when it is exposed to the sunlight. Therefore, there is a need for storage batteries to store the energy that is being generated by the PV module during periods of high irradiance and make it available at night as well as during overcast periods. Unlike car batteries, solar PV applications demand for frequent charging and discharging of batteries. So the type of battery used here is not the same as that of an automobile battery. Figure 3 shows the different categories of batteries.

Out of the above-mentioned batteries, the following types of batteries are available and mostly used for PV application:

- Lead acid battery (most common);
- NiCd (Nickel Cadmium);
- NiMH (Nickel Magnesium Hydroxide) and
- Lithium-based battery.

A large numbers of batteries are available in the market and each of these is designed for a specific application. Lead acid batteries are most widely used in solar PV applications. Currently, lithium-ion based batteries are also being used in solar PV applications, particularly for small-scale applications. Other battery types, such as NiCd or NiMH, are used in portable devices. The life of typical solar system batteries spans from 3 to 5 years. However, a life of around 6–8 years can be achieved with proper battery management and regular preventive maintenance of the battery bank.

While selecting the batteries, utmost attention ought to be given to ensure that all the batteries used in a battery bank must be of same type, same manufacturer, same age and must be maintained at equal temperature. Further, the batteries should have the same charge and discharge properties under these circumstances. If the above characteristics do not match, there is a high probability of huge energy loss within the battery bank.

For product designers, an understanding of the factors affecting the capacity and life of the battery is very important in order to manage the product performance and its warranty. Following characteristics need to be ensured while selecting a battery used for solar applications:

- Battery capacity and discharge rate;
- Cycle life and temperature;

Table 1 Performance of different PV technologies

	Mono-crystalline	Poly- crystalline	Thin-film		
			Amorphous	Cadmium Telluride (CdTe)	Copper Indium Gallium di-selenide (CIGS
Typical module efficiency at the field	13–18 %	10–14 %	6–8 %	9–11 %	10–12 %
Lab scale Solar PV cell efficiency	25.0 %	20.4 %	13.4 %	18.7 %	20.4 %
Space required for installation of 1 kWp of solar PV array (in m^2)	6–9	8–9	13–20	11–13	9–11
Typical length of warranty	25 years	25 years	10–25 years		
Temperature resistance	Performance drops by 10–15 % from its value at standard test condition at high temperatures	Less temperature resistant than mono-crystalline	Tolerates extreme heat	Relatively low impact on performance	
Additional details	Oldest cell technology and most widely used	Less silicon waste in the production process	Tend to degrade faster than crystalline-based solar PV modules		
I–V Curve Fill Factor (Idealized PV cell is 100 %)	73–82 %		60–68 %		
Module construction	With Anodized Aluminium		Frameless, sandwiched between glass; Lower cost, lower weight		
Inverter Compatibility and Sizing	Lower temperature coefficient is beneficial		System designer has to consider factor such as temperature coefficients and $V_{oc} - V_{mp}$ difference		
Mounting systems	Industry standard		Special clips and structures may be needed		

Source Authors compilation, 2014

- Battery Ampere-hour (Ah) efficiency;
- High charging current capability;
- Good reliability under cyclic, deep discharge conditions

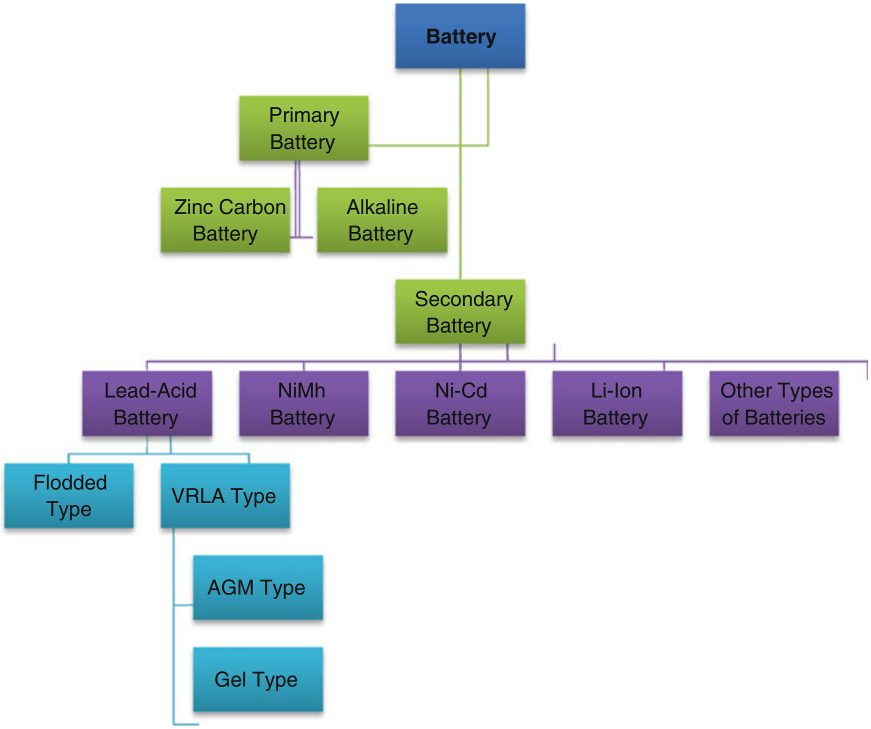

Fig. 3 Categorization of batteries (*Source* Author's compilation)

- Good power density, high recharge efficiency, rapid re-chargeability;
- Maintenance free, wide operating temperature range; and
- Low cost per Ah, low self-discharge rate.

4.1 Battery Capacity

The capacity of a battery is measured in Ampere-hour (Ah). It provides information on the number of hours a specific current can be delivered by a fully charged battery before it gets completely discharged.

Battery capacity depends on the following:

Discharging current: the higher the discharging current, the lower the capacity, and vice versa. For example, a battery delivering 1 Ampere current for 100 h has a capacity of 100 Ah. However, if the same battery is discharged (delivering a current) with 8 Amperes current, it may provide that current for 10 h. This means that the capacity is no more 100 Ah and instead reduces to 80Ah. *Therefore, from the designer's perspective, the selection of the battery based on its capacity is*

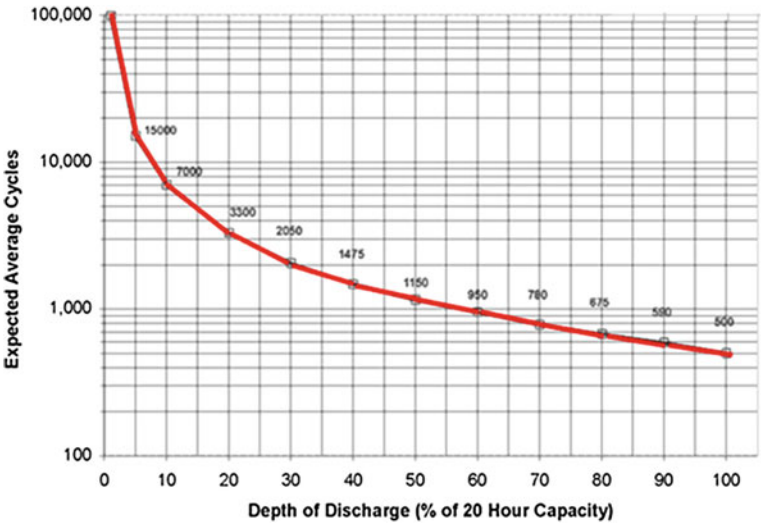

Fig. 4 Depth of discharge versus number of cycles of battery discharge (*Source* author's compilation)

important but more importantly at what rate (C/10 or C/20 or C/100) is most critical (Lasnier and Ang 1990). *Because that decides what would be the actual capacity of the battery if it is not discharged at the designed rate.*

To supply a given load of X Watt, a bigger battery will be drained by a lower percentage, and would last for more cycles. This means that, to supply a 50 Ah load, a 100 Ah battery would be drained by 50 %, whereas a 200 Ah battery would only be drained by 25 %. The bigger battery will last longer. From Fig. 4, it can be seen that if the depth of discharge (DoD) changes from 50 to 25 %, then the life cycle of the battery would be more than doubled. Thus a bigger battery is always recommended. But a bigger battery would also increase the cost. Thus a balance between the cost of the battery and its capacity can be made to select the most appropriate capacity and type of battery.

Temperature: The capacity of the battery available in the market is specified from 25 to 27 °C. When the temperature exceeds this range, the capacity of the battery increases with temperature, whereas the life of the battery decreases. The performance of all batteries drops drastically at low temperatures. At minus 20 °C (–4 °F), most nickel-, lead- and lithium-based batteries stop functioning. Specially built lithium ion brings the operating temperature down to minus 40 °C, but only on a reduced discharge. So for lower temperature, lithium-ion battery can be chosen.

Figure 5 shows the ideal working temperature of the battery in order to get the optimum life cycle. Operating above 55 °C damages the battery permanently. One of the main functions of the battery management system is to keep the battery cells operating temperature within their designed operating temperature window.

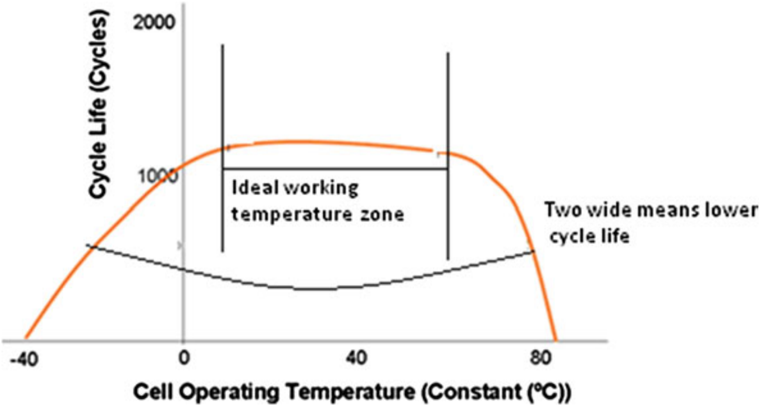

Fig. 5 Operating temperature of the battery versus cycle life

4.2 *Life of a Battery*

The life of lead acid batteries is quoted as 5 years, 10 years or 20 years. However, this is a *conditional statement,* and generally this condition is overlooked. The condition is that the life of the battery will be X years if the battery is "*kept in a specific temperature band*" and is "*kept at a specific float voltage*". If these conditions are not satisfied, the life of the battery will reduce and the rate of reduction of life depends upon how far its operation deviates from the designed values. Therefore, it is always advisable to operate the batteries near to its specified conditions, particularly in terms of its temperature band and float voltage.

4.3 *Self-discharge of a Battery*

This parameter is typically critical for a remote electrification project, where the transportation of the materials including batteries takes more time due to the remote and inaccessible nature of the site. If the self-discharge rate of the battery is high, it needs regular charging, even in unused and no load conditions, in order to extract the desired energy output and life of the battery. Therefore, based on the type of batteries selected and their self-discharge rate, the frequency of charging the battery in no load condition can be decided. The typical self-discharge rates for common rechargeable batteries are as follows:

- Lead Acid batteries—4 to 6 % per month;
- Nickel Cadmium batteries—15 to 20 % per month;
- Nickel Metal Hydride batteries—30 % per month and
- Lithium-Ion batteries—2 to 3 % per month,

It shows that if a new fully charged, unused lead acid battery gets fully discharged in 15–20 days, the new fully charged, unused Nickel Metal Hydride battery will get fully discharged in only 3–4 days.

4.4 Comparison of Batteries Available in the Market

Table 2 compares the characteristics of four commonly used rechargeable batteries used for solar applications.

Based on the above-mentioned parameters, the appropriate battery for a particular application can be selected. For example, if the battery is to be used for a location which is remote with very difficult terrain and road connectivity, then in such a case, lithium-ion battery can be used because of its quite high cycle life as compared to other types of batteries and thus requiring less frequent replacements. At the same time, it requires very less maintenance. Further, unlike a lead acid battery, a lithium-ion battery can be discharged up to 98–99 %, without shortening the life of the battery and thus reducing the size of the battery by half compared to that of a lead acid battery for a specific application. However, the charge controller

Table 2 Comparison of characteristics of different batteries

Specification	Lead Acid	NiCd	NiMH	Lithium based		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–80	150–190	100–135	90–120
Cycle life (number of cycles)	200–300	1000	300–500	500–1000	500–1000	1000–2000
Duration of charging	8–16 h	1 h	2–4 h	2–4 h	1 h or less	1 h or less
Overcharge tolerance	High	Moderate	Low	Cannot tolerate		
Self-discharge rate per month	5 %	20 %	30 %	<5 %		
Frequency of maintenance requirement	In every 3–6 months (topping)	In every 30–60 days – recharging	In every 60–90 days - recharging	Normally not required		
Cell voltage	2 V	1.2 V	1.2 V	3.6 V	3.6 V	3.3 V
Temperature range during charging	–20 to 50 °C	0–45 °C				
Safety requirement	Thermally stable	Thermal protection mandatory				

of such a battery needs to be designed properly with proper temperature control and thermal protection circuits as well as overcharge protection as the safety measure.

On the other hand, if the battery is to be used for very large rugged applications under varying operating temperatures and without proper sophisticated electronic charge controllers, a lead acid battery can be preferred over other batteries.

5 Guidelines for the Selection of Inverters

The following sections describe the selection of inverters based on different characteristics.

5.1 Selection of Inverters Based on Its Configurations

5.1.1 Single-Stage/Central Inverter

The single-stage inverter (central inverter) is widely used for large-scale power applications. Here, the single power processing stage takes care of all the tasks of Maximum Power Point Tracking (MPPT), voltage amplification and grid side current control. In this configuration, the solar modules are connected in series to create strings with output voltage high enough to avoid an additional voltage boost stage (Tang and Zhao 2010). In order to obtain the desired power level, the strings are connected in parallel through interconnection diodes (string diodes) as shown in Fig. 6.

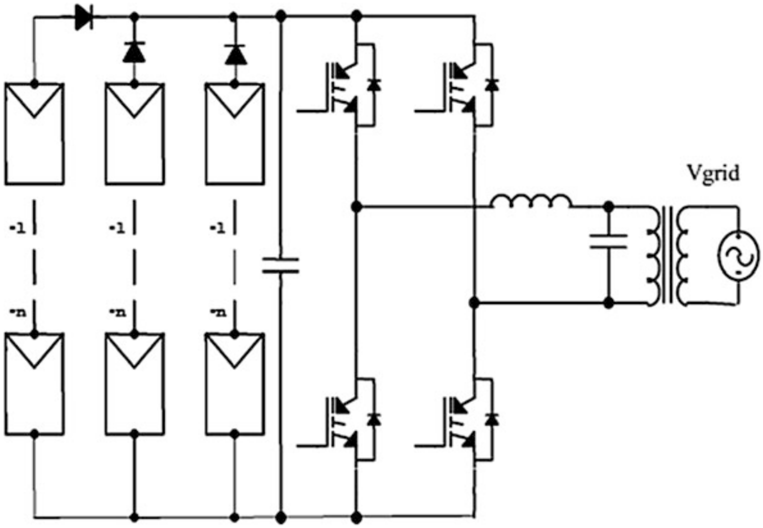

Fig. 6 Connections of solar PV strings

5.1.2 Double- or Multistage Inverter

Here, each string is connected to a double- or a single-stage inverter. If a large number of modules are connected in series to obtain an open-circuit voltage higher than 360 V, the DC/DC converter can be eliminated. On the other hand, if a few number of PV modules are connected in series; a DC/DC boost converter is used. The DC–DC converter is responsible for the MPPT and the DC–AC inverter controls the grid current.

5.1.3 Multi-string Multistage Inverters with High-Frequency Transformer

Another topology adopted is multi-string, multistage inverter. The multi-string inverter has been developed to combine the advantage of higher energy yield of a string inverter with the lower costs of a central inverter. Lower power DC/DC converters are connected to individual PV strings. Each PV string has its own MPPT, which independently optimizes the energy output from each PV string. All DC/DC converters are connected via a DC bus through a central inverter to the grid. Depending on the size of the string the input voltage ranges between 125 and 750 V, here, the system efficiency is higher due to the application of MPPT control on each string and higher flexibility comes from the ease of extensions for the photovoltaic field. This topology is more convenient for power levels below 10 kW. The multi-string inverters provide a very wide input voltage range (due to the additional DC/DC stage) which gives the user better freedom in the design of the PV system. However, the disadvantages are that it requires two power conversion stages to allow individual tracking of the inputs.

5.2 Selection of Inverters Based on Switching Devices

To effectively perform Pulse Width Modulation (PWM) control for the inverter, Insulated Gate Bipolar Transistor (IGBT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET) are mainly used as switching devices. *IGBT is used in more than 70 % of the surveyed inverter products and MOSFET is used in around remaining 30 % of the inverter*. As far as differences in characteristics between IGBT and MOSFET are concerned, the switching frequency of IGBT is around 20 kHz and it can be used for large power capacity inverters exceeding 100 kW (Kjaer et al. 2005). On the other hand, although the switching frequency of MOSFET can go up to 800 kHz, its power capacity is reduced at higher frequencies and MOSFET are used for output power range between 1 and 10 kW. So in a nutshell, both IGBT and MOSFETs are used for small to medium range PV system with power capacity of 1–10 kW, whereas IGBTs are used for large-scale power plants with power rating of 100 kW or more. High-frequency switching can reduce the harmonics in the output current, the size and the weight of an inverter and thus nowadays High-Frequency (HF) inverters with a compact size are available and widely used.

5.3 Selection of Inverters Based on Operational Perspectives

In order to assess the inverter's performance in terms of its operational perspective, a literature review and collection of secondary information were carried out by the authors. For this analysis, information of about 200 models of different inverters with different capacities and types were collected. The subsequent sections (Sect. 4.5.5–4.5.13) bring the findings from that survey.

5.4 Features of Grid Connectivity

The distributed or off-grid inverter should have the grid connectivity feature (both incoming and outgoing) so that these solar PV systems would not be completely obsolete when the grid extension takes place. As there are massive plans for conventional rural electrification, it is always wise to select an inverter having grid connectivity features from the beginning with some incremental cost. It is cheaper than completely changing the inverters later on.

5.5 AC Voltage and Frequency Range

An inverter can be operated without any problems within the tolerance of +10 and –15 % of the standard voltage, and ±0.4 to 1 % of the normal frequency specified by the grid standards of any country. For example, in India, where the single-phase AC line is specified as 230 V, 50 Hz, the inverter should work at any voltage value between 253 and 198 V and at any frequency value between 49.5 and 50.5 Hz without any problem. Any inverter which does not have this wide range might not be considered, particularly for distributed power systems which are installed in relatively remote and rural locations, where wide fluctuations of voltage and frequency are prevalent (Kim et al. 2009)

5.6 Operational DC Voltage Range

The operable range of the DC voltage differs according to the rated power of the inverter, the rated voltage of the AC utility grid system and the design policy. In this survey, the operable range of the DC voltage for a capacity in the range of

180–500 W includes 14–35 V, 30–60 V. Similarly, the operable DC voltage range for a capacity of 10 kW or over includes 330–1000 V. Hence, depending on the operational range of the voltage range of the inverter, the capacity and configuration of the solar PV modules should be decided. While designing the capacity of the solar PV system, this is one criterion that decides how many modules need to be connected in series or parallel to get the required DC operating voltage.

5.7 AC Harmonic Current from the Inverter

Minimization of harmonic current production is required as the harmonic current adversely affects load appliances connected to the distribution system and can impair load appliances when the harmonic current is increased (Farahat et al. 2012). The results of this survey show that the Total Harmonic Distortion (THD)[1] is 3–5 %. However, there are certain inverters in the power rating of 10–100 kW that have THD in the range of 1–5 %.

5.8 Inverter Conversion Efficiency

Figure 7 presents the performance of a range of inverters.

Figure 7 shows that the euro efficiency range for all the inverters varies from 94.5 to 98.7 % (Photon International 2012). In the medium-scale range (10–20 kW), there are several inverters available with the euro efficiency range of 97–98 % and the incremental cost of these inverters is not much different from that of the low efficiency inverters (generally USD 50/kW). Thus the project designer can evaluate the cost versus benefit of the inverter in terms of the enhanced efficiency.

5.9 Operational Environment

The installation conditions of the inverter (the indoor installation specification or the outdoor installation specification), the ambient temperature, the requirements for water and dust proofing, actual audible noise level of the inverter and applicable regulations for EMC (electro-magnetic compatibility), need to be examined carefully. As per the survey (Fig. 8), the maximum acceptable ambient temperature at nominal AC power is in the range of 40–75 °C. Whereas this range is relatively wider for 10–40 kW inverter, it is narrower in the operational range of 40–50 °C for larger inverters.

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[1] the total distortion factor of the current normalized by the rated fundamental current of many of the inverters.

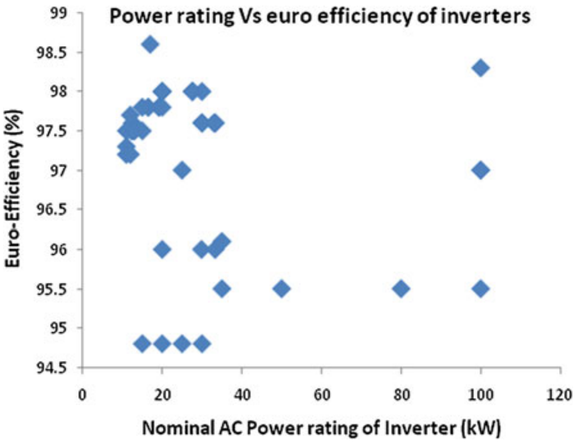


Fig. 7 Power rating versus euro efficiency of inverters

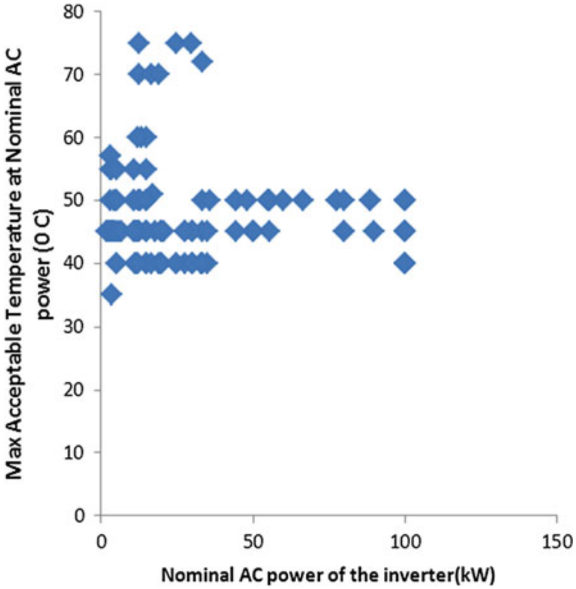


Fig. 8 Maximum acceptable temperature at nominal AC power

5.10 Required Protection Devices or Functions

Protective functions include protection for the DC and the AC sides. The protective functions for the DC side include those for DC over power, DC over voltage, DC under voltage, DC over current and detection of DC grounding faults. Protective functions for the AC side include AC over voltage, AC under voltage, AC over current, frequency increase, frequency drop and detection of AC grounding. Most of the inverters include these basic protections.

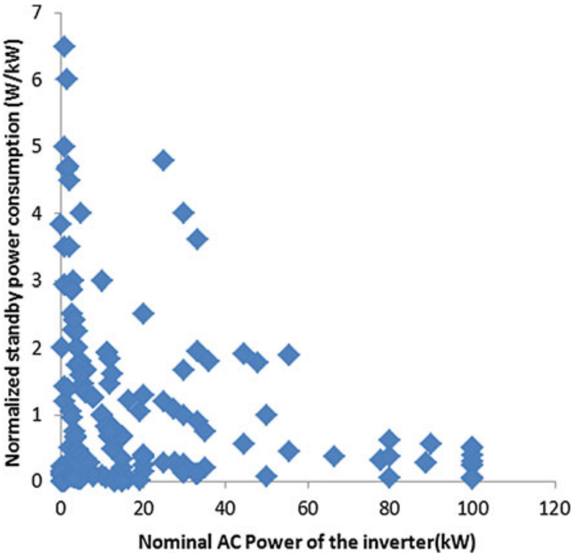
5.11 Standby Power Consumption

The standby power consumption of the inverter is a very important parameter that needs to be checked, particularly for off-grid PV applications where the only source for providing power is the PV. So, by practice the lesser the standby power consumption is, the better it is for distributed PV applications. As per Fig. 9, it is observed that there is a wide range of products that are available with normalized standby power consumption for inverter capacity of less than 20 kW. So the inverter can be judiciously selected so that self-consumption of these devices would not be significant.

5.12 Inverter System Cost, Size and Weight

The cost of the inverter system is very crucial when considering the economy of a photovoltaic power system. Although the cost of the inverter varies from country to country as well as with the make and model, the average cost range of the inverter is found to be USD 600–1000 per kW (Photon International 2012). The weight of the inverter system differs considerably according to the presence/absence of the isolating transformer (shown in Fig. 10). However, from the project developer's point of view, it is a very critical parameter to judge as the weight of the system affects the total transportation cost, handling and installation cost. For an inverter for a household PV power system, the weight reduction is important when the inverter is installed indoors or it is to be mounted and thus an appropriate inverter with lower weight should be preferred.

Fig. 9 Normalized standby power consumption of a selection of inverters



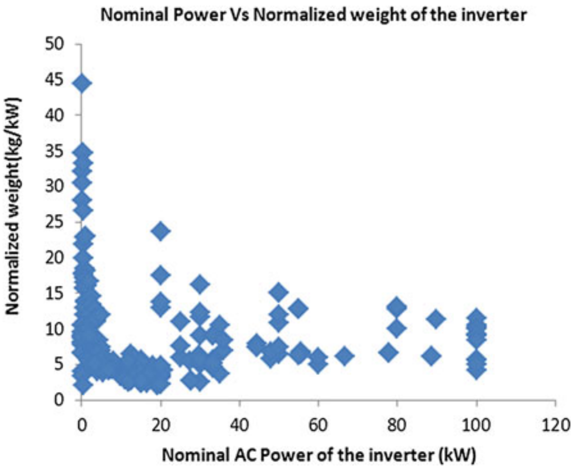


Fig. 10 Normalized weight of different inverters

5.13 System Guarantee

System guarantee plays a crucial role as it influences the entire system economics. Although the cost data for each of the inverters is not available, it is noted that there are some inverters that are available with an extended guarantee of 25 years.

6 Selection of Protective Devices

Besides the major component selection, safety measures are equally important for the solar PV system for which the protective devices to be used need to be selected properly. Failure to do so may not only lead to system efficiency but also may pose severe safety hazards. Typical protection devices which are to be selected carefully are as follows:

1. PV source circuit combine box and PV fuse disconnect;
2. Battery fuse disconnect;
3. Inverter fuse disconnect;
4. Ground Fault protection circuit;
5. Lighting arrestor;
6. Grounding/Earthing;
7. Surge protector and
8. Cables, wires and other accessories.

Each of the components is described briefly in subsequent sections.

6.1 PV Source Circuit Combine Box and PV Fuse Disconnect

These fuses or circuit breakers [both known as over current protective devices (OCPD)] are installed to protect the PV modules *and* wiring from excessive reverse current flow that can damage PV cell interconnects and the wiring between the individual PV modules.

The rating of the fuse is specified by the PV module manufacturer. As per the NEC requirement for over current protection, the fuse rating marked on the back of the PV module must be at least 156 % of short-circuit current (Isc) of the PV module at STC. The fuse will generally be a *dc-rated cartridge-type fuse* that is installed in a finger-safe pull out-type fuse holder.

6.2 Battery Fuse Disconnect

The battery disconnect is a switch or a circuit breaker used for overcurrent protection and must be able to interrupt any battery short-circuit current. The dc voltage ratings of all components should be based upon the maximum system voltage, which is the PV system open-circuit voltage multiplied by the appropriate correction factor from NEC 690.7.

Since the battery is a dc circuit, dc-rated components should be used. It is important to remember that dc circuits require dc-rated components. It is not acceptable to substitute ac fuses, disconnects or circuit breakers for dc applications unless and until these are rated for both ac and dc circuits.

6.3 Grounding

Grounding is one of the most critical tasks in the entire installation of a solar PV system. Grounding means connecting a part of the system's structure and/or wiring electrically to the earth. Grounding of a system does four things:

- It discharges accumulated charges so that lightning is not highly accumulated in the system.
- If lightning does strike, or if a high charge does build up, the ground connection provides a safe path for discharge directly to the earth rather than through the wiring.
- It reduces shock hazard from the higher voltage (AC) parts of the system and
- It reduces electrical hum and radio caused by inverters, motors, fluorescent lights and other devices.

Grounding is required by the national electrical code (NEC). If the maximum system voltage of a PV system is greater than 50 V, then one conductor must normally be grounded. As per *NEC* 690.43, all exposed non-current-carrying metal parts of the components are to be grounded in accordance with *NEC* 250.134 or 250.136(A), regardless of the system voltage. This means that even if the current-carrying conductors of the PV array do not need to be grounded, all non-current-carrying metal equipment parts and cases must still be grounded with equipment-grounding conductors.

Where the ground is moist (electrically conductive), grounding can be provided by a copper-plated rod, usually 8 ft long, which is dug inside the earth. Where the ground is dry, especially sandy or where lightning may be particularly severe, more rods can be tied together through bare copper wire and installed.

If the PV array is at a distance from the house, ground rods can be dug near the house and a bare wire can be buried in the trench with the power lines.

6.4 Lightning Arrestor

In locations susceptible to lightning strikes, a lightning protection system must be provided, and all the exposed metallic structures of the solar PV system must be bound to the earthing system, and structures and PV module frames must be properly grounded. In certain geographical locations, solar PV systems might be exposed to the threat of lightning strikes. As lightning can cause damage to the PV modules and inverters, extra care must be required to ensure that proper lightning protection is provided for the solar PV system and the entire structure. The inverters should be protected by appropriately rated surge arrestors on the DC as well as AC side.

6.5 Surge Protector

Surge protection devices bypass the high voltages induced by lightning. They are recommended for additional protection in lightning-prone areas or where good grounding is not feasible (such as on a dry rocky mountain top), especially if long lines are being run to an array, pump, antenna, or between buildings. To reduce the possibility of a fire and to protect the system from a damage caused by lightings, it is recommended to have a voltage-clamping device across the DC bus bar. A metal oxide varistor (MOV) is commonly used in such applications.

6.6 Cables and Wires

PV array wiring should be done with minimum lengths of wire and tied into the metal framework and then run through a metal conduit. A rule of thumb is to limit the voltage drop from the array to power inverter to 2.5 % or less.

Positive and negative wires should be run together wherever possible, rather than being kept some distance apart. This will minimize induction of lightning surges.

7 Conclusion

Appropriate selection of each component of solar PV system is equally important and admittedly one of the most significant parts in implementation of such system for off-grid applications. The chapter has assisted the readers in understanding the importance of each component of the solar PV system, i.e. solar PV module to battery to inverter and to cable and wiring to other protection devices, which may significantly affect the overall performance. The chapter has also demonstrated the steps to be followed for proper selection of various components which would guide the implementers and designers to take a well-informed decision while designing and formulating the solar PV-based off-grid projects.

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