Chapter 8
Solar Photovoltaic Power

8.1 Pollution Free Power Generation

In recent years global warming and associated climate changes have received steadily increasing attention and Greenhouse gas (GHG) pollution control has become an important issue in both industrialised and developing countries. In this regard environmentally benign power generation has been seriously counted upon to bridge the gap between demand and supply of power. Extensive efforts over the past 30 years aimed at research, development, testing and demonstration of several technologies have indicated that principal technologies are solar photovoltaics, solar thermal electric and wind power (Kaushika and Kaushik 2005; Winter et al. 1991). Solar photovoltaics has several positive attributes and scores over other technologies since it does not involve moving parts and there is now a growing optimism that incoming decades solar photovoltaic power supplies will be the solution for the crippling power shortage facing the world. It is now a global sunrise industry growing well over 30 % every year. It is fast becoming a major power resource, increasingly affordable and proving to be more reliable than utilities. Total global production of SPV modules in 1989 was 45 MW. It had increased to 62.5 MW in 1993 and to 1,36,697 MW (according to European Photovoltaic Industry Association (EPIA) data) in 2013. This awareness of PV technology is rising and there is an increasing number of systems beginning to appear as the concern for the need of 'clean' electricity is gaining importance. Some typical current applications of photovoltaic and their estimated share in the PV market are as illustrated in Table 8.1.

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Table 8.1 Applications of photovoltaic and their estimated share in the PV market

S. No	Application	Percentage %
1.	Lighting, security and other consumer products	28
2.	Rural electrification	10
3.	Remote refrigeration	1
4.	Electricity for individual buildings	22
5.	Water pumping and irrigation	2.6
6.	Grid connected	1
7.	Communications	20
8.	Remote monitoring equipment	1
9.	Aids to navigation	1
10.	Cathodic protection	4
11.	PV/diesel hybrid generators	8
12.	Military application	0.5
13.	Miscellaneous	2

8.2 Solar Cells

Solar photovoltaic involves the conversion of the sun's radiant energy into electricity using a semiconductor device known as solar cell. The most common material used for solar cells is silicon. Based on the state and quality of the silicon material there are three types of solar cells that have been produced and marketed.

8.2.1 Mono-crystalline Cells

These are made from pure mono-crystalline silicon with almost no defects or impurities. These cells have a solar conversion efficiency of about 15–17 %. They are expensive to produce. The most efficient and expensive single-junction silicon cells have been reported to have about 22 % efficiency.

8.2.2 Polycrystalline Cells

These cells are produced from slightly poorer grades of mono-crystalline silicon or semiconductor grade silicon. The cells have white speckles on the surface due to impurities. They are comparatively less expensive since simpler processes are involved in their production. They have a solar conversion efficiency of about 10–12 %.

8.2.3 Amorphous Silicon Cells/Thin Film Cells

These are often referred to as second generation solar cells and are made from amorphous silicon rather than silicon of crystal structure. They absorb light more effectively than crystalline cells and can, therefore, be thinner. Thin film technology has been successfully used on rigid, flexible, curved and foldable substrates. Thin film cells of other materials such as cadmium telluride (CdTe) and Copper Indium Gallium Diselenide (CIGS) have also been fabricated and tested. They have a lower cost than crystalline cells but have a lower conversion efficiency of 5–7 %. However, the reduced cost often overweighs the reduced efficiency, leading to a net increase in ratio of performance to cost.

More recent developments in solar cells physics include third generation solar cells which combine in themselves the advantages of the first generation and second generation devices. The proposed and tested cells include nano crystal solar cells, photoelectrochemical cells, polymer solar cells, dye sensitised solar cells and fourth generation solar cells such as hybrid inorganic cells with polymer matrix.

8.3 Solar Pv Modules and Arrays

Solar cell is the smallest unit of a solar PV system (Fig. 8.1). A typical crystalline silicon solar cell manufactured in India produces about 1Wp at 0.5 Volts and 2.3 Amp. Under full sun at Standard Test Conditions (STC) of 1000 W/m^2 and 25 °C cell temperature.

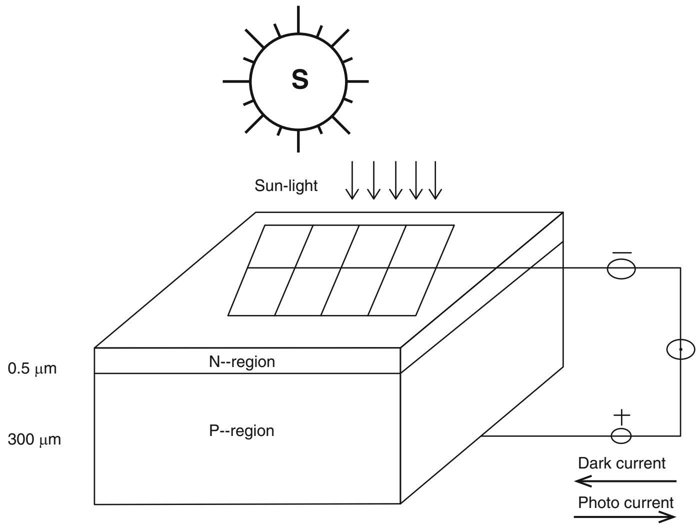

Fig. 8.1 Solar PV system

In a solar PV power unit, solar cells are connected in series to obtain the desired voltage and in parallel to obtain the desired current. A string of solar cells connected in a series arrangement is referred to as a series string or a sub-string. A group of series string or sub-strings connected in parallel forms an array. The array is constructed in the field and transported from the factory in the form of small units called modules. The modules can be used to construct mW to MW size PV arrays. The number of cells determines a module's size and power. Modules are typically available in ratings from 30 Wp to 300 Wp. Two basic types of PV modules are commercially available today:

(i) Those made from poly/single crystalline silicon and crystalline silicon, are presently the dominant (90 %) commercial product and deliver approximately 100–130 W/m^2 at STC.
(ii) Those made from amorphous silicon (A-Si). These are thin-film modules, and are beginning to enter the market. They require less material to produce than the thick crystalline products and so can be made inexpensively. Today's commercial A-Si modules deliver 40–50 W/m^2 under full sun at STC. The modules are connected electrically in series and parallel and mounted on structural support for exposure to sun to build arrays. Owing to cost considerations the fixed tilt arrays are often used.

Several options are possible for the mounting of module/array as follows:

(a) It may be placed at a fixed tilt angle to maximize the generation of yearly average energy.
(b) The tilt may be seasonally adjusted in accordance with the energy requirement in summer, equinoxes and winter respectively.
(c) The module/array may be mounted on a tracking unit that follows the sun. Single axis trackers follow the sun daily from east to west and two axis trackers further include elevation control to correct for seasonal north–south sun movement.

8.4 Balance of System

The array is the energy generating subsystem. It's output is variable direct current (DC) which is not available during off sunshine hours. It is stored in batteries if the power is to be supplied on continuous basis. The battery bank serves the load either directly or after conversion into alternating current (AC). The battery power produced tends to be at a low voltage (12 V) and, since general applications require 240 V, an inverter is needed to convert DC into AC. The charge controller is yet another component of PV systems. It protects batteries from excessive charge when the array produces more electricity than the batteries can store. Also, it prevents deep discharge of batteries. Sometimes, during over-charging, gassing from the acid of a battery may take place which in turn may become a fire hazard. Maximum power point tracker (MPPT) is also an important component to ensure maximum

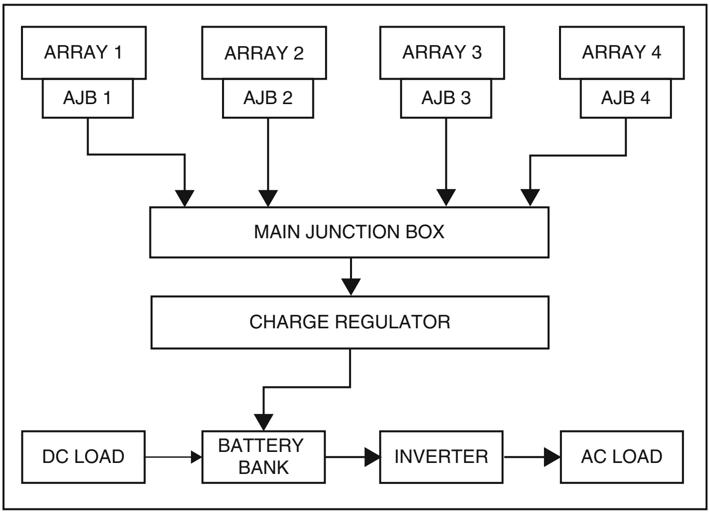

Fig. 8.2 Schematic diagram of a photovoltaic power supply system

power transfer from array to the battery bank. The photovoltaic system, in practice, therefore requires several other components in addition to the PV modules. Often called the balance of system, it includes system wiring, support structures, inverters, batteries, charge regulators, string combiners, lightning protection, over current protection, disconnect switches, and ground-fault protection. The components of the balance of systems may be classified in three categories.

(a) **Mechanical:** Panel structures, battery racks, poles, cables etc. designed to withstand wind-loading and adverse weather conditions.
(b) **Electrical:** Master control panel, circuit breakers, switchgear, connectors, cables, lightning arrestor, earthing for safety.
(c) **Electronics:** DC-AC inverter, DC-DC converter, power conditioner, charge controller, timer, load switching, monitoring, data-logging etc. control and management etc.

Schematic diagram of a photovoltaic power supply is shown in Fig. 8.2.

8.5 Systems and Applications

Solar PV plants are basically decentralised power units. They have several major differences with fossil fuel based power plants as shown in Table 8.2. Extensive efforts over the past 25 years aimed at testing and demonstration of solar photovoltaic technologies have been made throughout the world. SPV power system have been operated in various modes which can be classified into following three categories (Fig. 8.3).

Table 8.2 Major differences between SPV power plant and fossil fuel-based power plant

S. no	Item	Power plant configuration	
		Solar PV	Fossil fuel based
1.	Operation	Decentralised	Centralised
2.	Dependency on external fuel source	Very low	Completely
3.	Design	Load specific	Capacity-specific
4.	Suitability	Lower capacity	higher capacity
5.	Gestation period	Short	Long
6.	Transmission losses	Low	High
7.	O&M costs	Low	High
8.	Capital costs	High	Low
9.	Running costs	Low	High
10.	Environmental pollution	None	Adds gaseous and particulate toxins which causes pollution and ecological imbalance

(i) *Stand alone system:* The entire power is generated by an SPV array and stored in a battery to be provided in response to demand.
(ii) *Hybrid system:* In addition to an SPV array, other means such as AC mains, wind and diesel generators are also used to supply power.
(iii) *Grid-connected system:* In such systems the output of SPV plants is connected to the grid and there is no storage battery; Metering is used to keep account of imported and exported power by the user.

8.5.1 SPV System Design Considerations

Solar PV power system is designed in accordance with the load in distinction to the conventional power system which is designed in accordance with its capacity. The design involves the sizing of the array and battery bank to serve a given load. The array needs the use of an optimum load offered by the battery into which it can deliver maximum power. This requirement varies with insolation and solar cell temperature in a module as well as with the state of charge of the battery. This requirement is difficult to be realized in all field conditions and the resultant mismatch offers problem in optimum sizing of system components. A rationale for optimum utilization of variable solar radiation in terms of diurnal and seasonal variations is that the stand alone solar photovoltaic system should be sized in such a way that it can deliver power to the load without failure during diurnal and seasonal variations of solar irradiance. An undersized array will cause total discharge of the battery

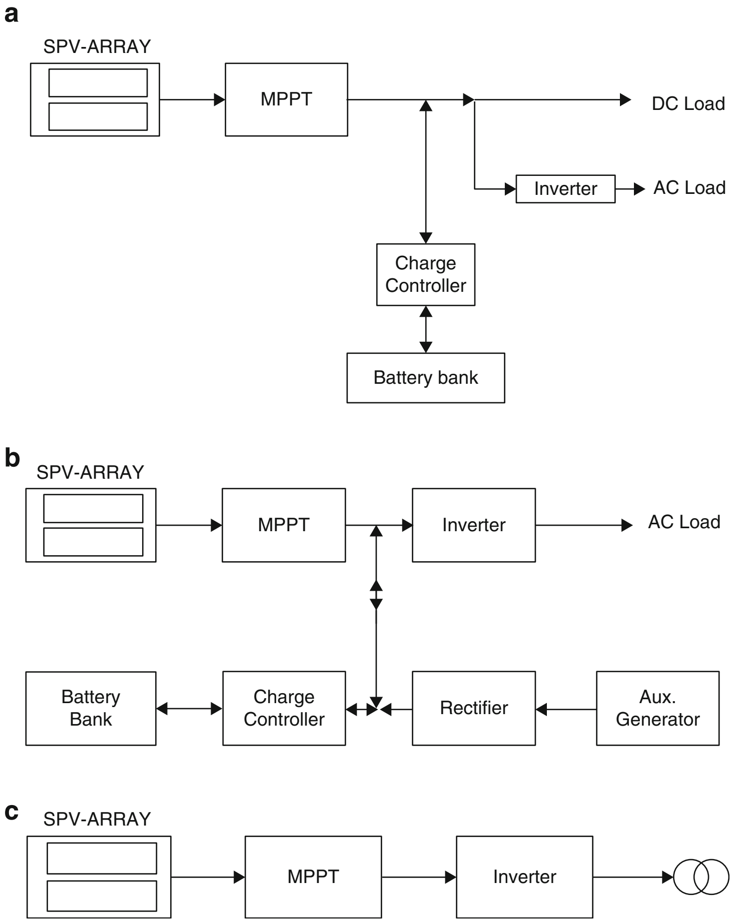

Fig. 8.3 Classification of solar PV power systems (**a**) Stand alone PV System (**b**) Hybrid PV System (**c**) Grid-connected PV System

and an oversized array involves waste of capital. The idea of solar PV system is therefore to have a reasonable size of the array and battery bank to meet the demand of particular load round the cycle allowing the battery to be discharged upto a minimum acceptable level during low/off sunshine period (Bandyopadhyay et al. 1995).

The array size in terms of peak array of current of (A) at 1 kW/m^2 is calculated from the following relationship

$$A_p = \frac{L_d}{R_d K} \tag{8.1}$$

where L_d is average daily load in Ah. R_d is the average daily radiation in kWh/m^2 in low/off sunshine period during which the soc of the battery is ensured to remain greater than 50 %; where K is battery efficiency.

8.5.2 SPV Plant Operating Experiences

Several demonstrations units of large size (upto 500 MW) SPV power plants have been operated around the world. These units are located mainly in USA, Europe, India and China. In USA both the utility industry and the government have participated in detailed performance evaluation of grid connected SPV power plants. Utility interest in SPV has grown steadily since the early 1980s; SPV has now received their greatest attention among all the renewable energy and power technologies. Extensive reviews of these experiences have been reported. The largest Solar Park built in India is on a 2000-ha plot of land near Charanka village in Patan district, Gujarat with a total installed capacity of 214 MW. As of 31 August 2015, the installed grid connected solar power capacity in India is 4230 MW (Ministry of New and Renewable Energy Annual Report 2014-15). Monitoring of these power plants is in progress for further development. The total number of SPV power systems in India are tabulated as below (Table 8.3).

Experience has proved that SPV technology and associated power conditioning equipments are technically viable. Specific global experiences may be outlined as follows (Winter et al. 1991).

Array Ratings Manufacturer-supplied DC power ratings were universally higher than those observed in field conditions even when the operating conditions were close to standard test conditions.

Array Efficiency In earlier power plants at Lugo or Phoenix the temperature induced decrease in efficiency was observed at higher insolation levels. However, the array operating efficiencies in subsequent plants were observed to be higher at insolation levels above 600 W/m^2. In crystalline cell modules the efficiency degraded with time at a rate less than 1 % per year.

Array Reliability An important fault which often results in the failure of SPV modules is known as 'hot-spot effect'; it is an excessive heating of the cell and may be caused by following factors:

(i) Initial Mismatch of photovoltaic cell characteristics
(ii) Stress induced by environment or otherwise

Table 8.3 SPV power systems in India

Item	Number of installations
Solar lanterns	9,10,504
Water pumps	7771
Domestic lights	8,61,654

(*Source:* Press Information Bureau, MNRE 2012)

8.6 Building Integrated Photovoltaics (Bipv)

The cost of solar photovoltaic electricity has gradually decreased during the past decade from Rs. 25 per kWh to Rs. 15 per kWh in 2013. This decline in cost significantly owes to distributed PV systems on buildings which is an attractive application to compete commercially with the utility grid. In particular SPV could be a preferred power source for buildings in remote areas not served by the utility grid. The PV systems on buildings do not involve the cost of land required for ground-mounted systems, as well as the cost of site development, foundations, structural support systems, underground electrical distribution and the utility connection. In practice, PV modules often become an integral part of the building, serving as the exterior weathering skin of improved aesthetics. The building should provide sufficient solar exposure area to array and support structures and the building's utility service should become the consumer of PV electricity. The resultant systems are known as building-integrated PV systems (BIPV). The effectiveness in electricity generation of BIPV systems depends on several variables as follows:

(a) Location of building.
(b) Orientation of BIPV with respect to sun. For example in northern hemisphere a south-facing façade will collect the maximum solar energy throughout the year and produce the maximum electricity.
(c) Tilting solar panels towards the sun can increase the levels of solar irradiance on the array surface and therefore cause an increase in electricity output. The appropriate angle of inclination will depend upon the latitude of the proposed site.

These parameters can be easily optimized in the design of a building as shown in Fig. 8.4. The inclination of the roof of a building or a wall may be chosen to maximize electricity production.

Photovoltaic systems for building can be either stand-alone hybrid or grid-connected. In a stand-alone system, the building has no connection to the utility

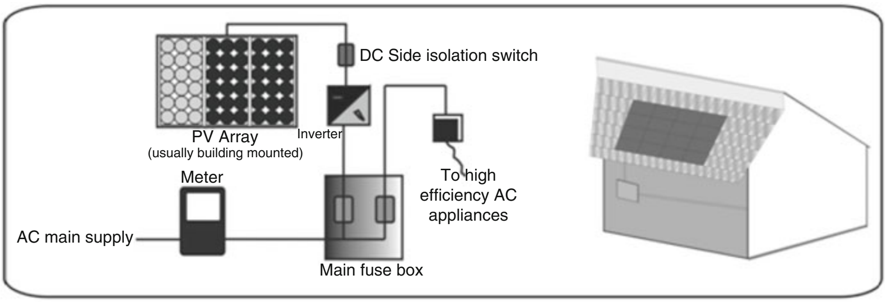

Fig. 8.4 Schematic of a building integrated photovoltaic system. (*Courtesy:* www.solarcentury.co.uk)

grid and often relies on a bank of batteries to store power for supply at night and during limited sun shine periods. In India, hybrid systems have been considered to avoid excessive cost of solar panels and the battery bank. In a grid connected or utility-interactive (UI) system, the building receives electricity from both the PV array and the utility grid. Some PV systems based on both stand-alone and utility-interactive modes of operation have also been reported.

Owing to various above mentioned advantages, and continued cost reductions, the potential for PV-powered buildings have escalated. In a best-case scenario, Arthur D.Little, Inc., has projected that the annual U.S. market for PV on buildings could exceed $2.5 billion in the next 10 years.

8.6.1 BIPV as Glazing Material

BIPV means that the solar features become part of the building. Initially, building cladding with solar photovoltaic panels was carried out as a retrofit. The PV modules were manufactured with aluminium frames. These modules were designed for grouping on racks placed on or around buildings or on the ground, to provide a reduction of building electrical load. The installation was often carried out in the post-construction phase of the building. This type of installation posed problems in building maintenance. In some cases PV installation had to be removed. In recent years the demand for solar PV modules as building elements has been recognized; the modules that become part of the weather proof skin of a building and can mimic windows or skylights or become part of the actual roofing material. In this approach, an array takes over the normal function of the roof and is not just placed on top of an existing structure. It serves both as a room covering and as an electricity-producing device. Based on this concept several BIPV demonstration units have been set up at a number of global locations. It has been experienced that the PV cell patterns can create interesting effects for instance in corridors, where you can experience the patterns in motion, as you pass by. Similarly, window-integrated photovoltaics' patterns can sometimes be architectural attachments. Hundreds of projects in Europe, USA and Asia are the glaring examples.

8.6.2 BIPV Projects in India

Several BIPV projects have been commissioned in India, the most notable of which are as follows:

(a) A 10 kWp PV Gasifier Hybrid Power Plant for the residential training facility at the Energy and Resources Institute (TERI), Delhi, and ten (type PL-11) stand-alone dusk to-dawn street lights.

(b) A building -integrated solar PV system plant at Mamata Machinery, Hyderabad.
(c) A 36.3 kWp hybrid PV power plant at Matrimandir, Auroville, Pondicherry.

In India, BIPV systems have used three types of modules:

(i) Solar PV modules,
(ii) Solar PV metal roofing modules and
(iii) Dummy modules.

The salient feature of dummy modules is that they have no solar cells. Instead of cells, the backing Tedlar is screen printed with solar cell images so that they look similar to actual solar cells.

The research and development activities in the field of building-integrated photovoltaic systems are concentrated on the development of constituent products in three principal areas: (i) integral roof modules, (ii) roofing tiles and shingles, and (iii) integral modules for vertical facades and sloped glazing.

8.6.3 Environmental Aspects

Solar photovoltaic systems in general, and building integrated photovoltaic systems in particular, offer a number of environmental benefits and hazards as listed below:

(i) Cutting edge design and technology that offsets the cost of traditional building materials.
(ii) Operation is noiseless.
(iii) No transportable fuels required.
(iv) No moving parts involved. The system requires minimum maintenance during its life span of 20 years.
(v) Clean Development Mechanism (CDM) benefits. For example 1kWp of solar cells displaces 1000 kg of carbon dioxide.
(vi) Decentralized generation at the point of use. Thus avoiding transmission and distribution cost.

8.7 Concentrating Solar Photovoltaic

Third generation SPV systems are characterized mainly by the fact that they offer substantial improvement in the efficiency of solar conversion or a large reduction in their cost of production as compared to previous generation of system. For cost reduction, concentrating module is an important approach to overcome the problem

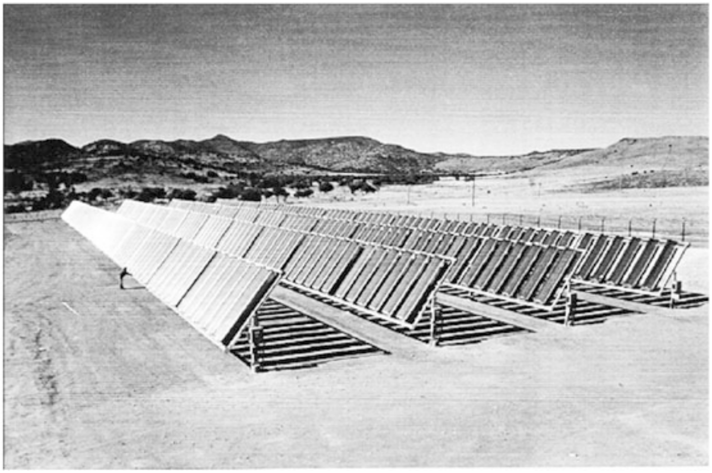

Fig. 8.5 Solar concentrating PV array (*Courtesy:* ENTECH-USA)

of high cost of solar cell. The low-cost optical concentrator focuses solar radiation onto the cell array of area much smaller than the concentrator aperture (Fig. 8.5).

The concentration of radiation also leads to an increase in photon generation current and hence cell efficiencies. The operation of solar cells under high illumination requires the removal of heat from the cells to combat the drop (0.45 % of power per degree Kelvin) in efficiencies of cells. The outstanding problems of this technology are the development of:

(i) Efficient low cost concentrators
(ii) Cost-effective tracking systems
(iii) Concentrator cells
(iv) Efficient low cost heat sink

Furthermore, research on photovoltaic devices based on organic materials has received serious attention. Organic solar cells based on heterojunction and nanocrystalline dye sensitized interface have been considered (Mikroyannidis et al. 2009). The solar conversion efficiency achieved to this date in 12 % and it may be improved to 22 % through optimisation of parameter. It is inexpensive to produce these cells. In the category of ultra high efficiency solar cells, nanostructured solar cells have been reported which include several advanced concepts of quantum dot solar cells (Nozik 2001). Quantum dot is a special type of nanocrystal. It enables several advanced concepts of Solar Cell design to be implemented which includes intermediate band and multiple exiton devices, hot carrier and up/down conversion devices etc. In these devices the ultimate conversion efficiency at one sun intensity can increase to about 66 %.

8.8 System Reliability

Solar PV system reliability means the ability of the system to serve the variable load and to continue functioning without failure. In this regard the study of factors related to array operational faults and electrical mismatches resulting from environmental stresses and shadow problems are of most concern. For example, in the field solar cell arrays are subject to shadows from both predictable sources as well as from such unpredictable sources as bird droppings or fallen leaves. The percentage power loss is much greater than the percentage of array area which is shadowed; for smaller arrays with few or no parallel connections, one leaf could cause the system output to drop to a fraction of rated power, eventually resulting in system failure. There could also occur a partial; or full opening of a string due to cell cracking provoked by hail impact or other environmental stresses. The shadowed/cracked cells in series with illuminated cells block the current flow in entire series connection and tend to become reverse biased. This not only gives rise to a mismatch loss but also could result in excessive heating of the regions of power dissipation which in turn can lead to solder melting and damage the encapsulant. The region of excessive heating are referred to as hot spots. The hot spots may also be developed in concentrating solar PV systems wherein reflecting or refracting optical concentrator nonuniformly illuminates the costly solar cell arrays. It may sometimes offset the gain due to concentrating configurations (Winter et al. 1991).

In practical situations, the above faults exhibit themselves with varying degree of complexities and influence the system reliability. The strategies to increase the fault tolerance and improve the reliability of the array have been investigated amongst others by Kaushika and Kaushik (2005). Fault tolerance by redundancy at subsystem level is found to be cost-intensive and is not considered as an attractive option. Fault tolerance at component level by proper arrangement of cell interconnections will function as an active redundancy and hold promise of cost effectiveness. In this regard several configurations such as series-parallel configuration, series-parallel with bypass diode, bridge-linked configuration and total cross-ties configuration have been considered. Kaushika and Rai (2007) have carried out experimental and theoretical investigations on performance and trade-off characteristics of these configurations and have shown that total cross-ties and bride-linked configuration excel over others in the minimization of mismatch loses in the cell network. However the total cross-ties configuration which is the highest cell interconnection redundancy performs slightly better than the BL array under mismatch and shadowing conditions, but under short circuit conditions it is inferior to BL array.

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