10

PHOTOVOLTAIC ENERGY—SOLAR CELLS AND SOLAR POWER SYSTEMS

10.1 PHOTOVOLTAIC ENERGY—HOW IT WORKS

When a photovoltaic (PV) cell is exposed to the sun's thermal radiation, it absorbs the thermal energy and converts it directly into DC electrical energy. The size of the PV cell and the DC voltage and energy it can deliver are small. A number of these cells are mounted on a plate and connected in series and parallel. These plates together form a solar array. These arrays require sizeable exposed area and reasonably clear skies to deliver useable quantities of electrical energy.

Exploiting solar energy and converting it into an electrical form has been under intense development for a long time. It has several advantages.

10.2 ADVANTAGES OF PHOTOVOLTAIC ENERGY

First of all, this energy is free. It consumes no fuel. No fuel means no pollution. It is easily and universally available. Increases in solar radiation leading to increases in solar array output coincide with the increase in the load demand during a day. One advantage of solar energy is that its availability, except for cloud formation, is precise and definite. Scheduling and delivery come on the dot.

Electric Power Generation. By Digambar M. Tagare

With countries all over the world getting pollution conscious, solar energy is becoming the primary renewable energy source to be developed to replace the present fossil-fuel-based thermal generation of electricity. To that extent, many economic incentives are offered in most of the countries in the world for developing solar energy. To begin with, there are direct subsidies and tax incentives to support the high capital costs. Second, there are carbon trading certificates which are issued for reduction of so many tons of carbon dioxide from emission into the air. Thermal plants have restrictions on how much carbon dioxide gas they can put into the atmosphere. When they exceed this limit, they have to buy carbon trading certificates. These certificates can be traded internationally and are a great attraction for solar energy producers.

Being dispersible is a big advantage for solar energy generators. Locations far from the generating stations suffer losses and voltage drops when they draw electric power from utility grids. Supporting PV generation at these locations can help both the utility and the customer greatly.

PV is a "must" at locations where a grid has not been able to reach.

10.3 DISADVANTAGES OF PV ENERGY

PV energy has some substantial disadvantages as well. First of all, the basic solar cell is still very costly. Collecting viable energy requires sizeable infrastructure support in panels and space. The capital costs are quite high. In spite of free energy and next-to-nothing labor costs, the energy costs with reference to servicing the capital costs are much too high.

Another big disadvantage is the uncertainty in energy supply due to cloud effects. This uncertainty could occur within the routines of a day. It could occur seasonally also. The uncertainty has to be supplemented through costly storage batteries or through other types of generations or through the increased reserves in the utility system. All these raise the overall costs. Solar energy also has problems in interfacing with regular utility grids.

10.4 SOLAR THERMAL DENSITY—INSOLATION

Insolation is a measure of solar thermal density in terms of W/m^2 of the colleting area. For comparing the output of various solar cells, the reference insolation level generally accepted is 1000 W/m^2. This solar density varies as the day proceeds, being low in the morning and evening hours and high during the day. Figure 9-1 gives this value in average terms. It shows how much insolation is available for how many hours of a day. The insolation varies seasonally also. Figure 9-2 gives the values for insolation and ambient temperature in one of the world's extreme climate places, Kuwait. In the figure, the area above 30% insolation denotes major availability of solar insolation. On the hottest day in summer, in July, it occurs between 7:15 AM and 16:45 PM. On the coldest day in winter, in January, it occurs between 8:45 AM and 15:15 PM. As we move geographically to the north, these time windows will narrow down, and expand as we move south toward the equator.

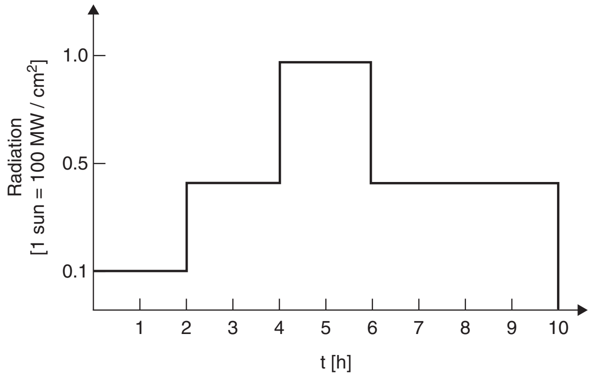

Figure 10-1. Daily insolation curve. (From [1], © IEEE 2001.)

10.5 OUTPUT OF A PV CELL

Figure 10-3 illustrates curren-versus-voltage characteristics of a PV cell. The curve P denotes the locus of points for various degrees of insolation at which we can get the maximum PV cell output.

10.6 VARIATION WITH AMBIENT TEMPERATURE

Figure 10-4 shows the output of a PV cell at varying ambient temperatures. Note that the output falls drastically as the ambient or PV cell temperature rises.

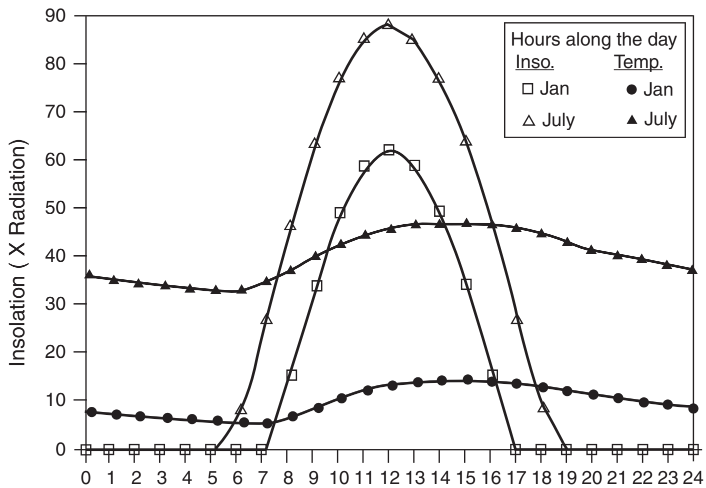

Figure 10-2. Hourly variation in solar insolation. (From [1], © IEEE 2001.)

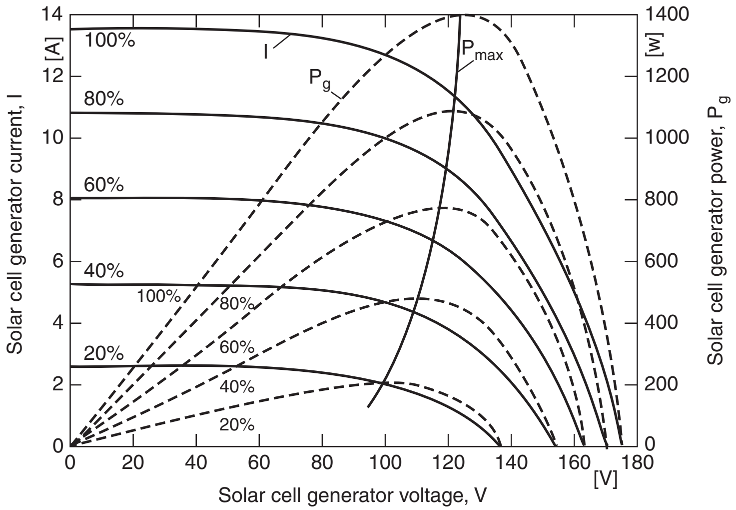

Figure 10-3. SCA voltage–current characteristics of a PV cell. (From [2], © IEEE 2001.)

10.7 VOLTAGE-VERSUS-CURRENT CHARACTERISTICS OF A SOLAR CELL

It may be seen that the power output of a PV cell is a complicated problem for analysis and control. The voltage created is a function of insolation. The current and power output depend on the properties of the silicon wafers commonly used in PV cells. Masoum [9] gives the following equation for the relation between voltage and the current:

$$v_{PV} = \frac{N}{\lambda}\ln\left(\frac{I_{sc} - i_{pv} + MI_0}{MI_0}\right) - \frac{N}{M}R_s i_{pv}$$

This is based on the basic diagram shown in Figure 10-5. Here,

v_{PV} = the output voltage of the PV cell at load terminals
i_{pv} = the output current of the PV cell at load terminals
i_{sc} = the cell short-circuit current, which is proportional to the insolation level
I_0 = the reverse saturation current
R_s = the series cell resistance
λ = a constant coefficient representing the cell material

Masoum gives the specifications shown in Table 10-1 for the solar panel he has experimented on. The voltage and power output with respect to current for two conditions of isolation as per computations based on the table and as per actual readings are given in Figure 10-6.

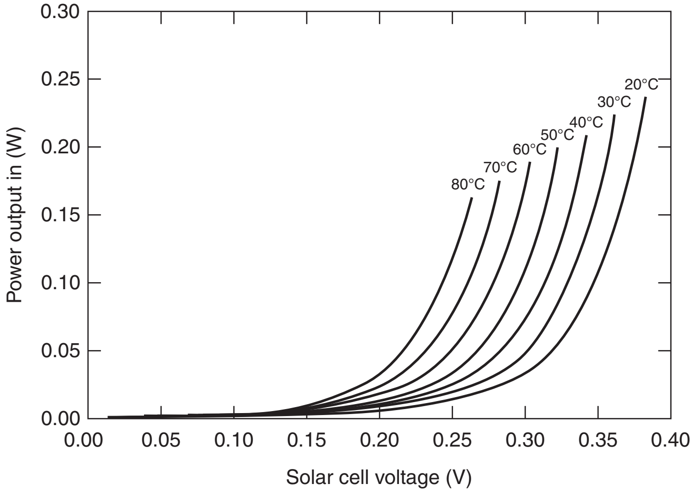

Figure 10-4. Effect of temperature on the maximum cell electrical power P_{emax} in terms of V_{max}. (From [2], © IEEE 2007.)

10.8 MATCHING THE PV WITH THE LOAD

10.8.1 Maximum Power Point Tracker (MPPT)

If we just connect a solar array and leave it at that, we might not get the best or maximum output from it. Output improves if we continuously correlate V and I. An MPPT enables us to do so. There are two important parameters for an MPPT. One is the i_{sc} or the short-circuit current of the cells. This is linearly proportional to the insolation. It varies per environmental conditions. It is periodically measured by an MPPT. The load is momentarily disconnected, the cell is shorted through a known resistance, and the i_{sc} value is read. Another important parameter is the V_{oc} or the open circuit voltage of the cell. It is logarithmically related to the insolation.

The actual cell voltage and currents are measured, referred to i_{sc}, and fed to the MPPT. The MPPT works out the maximum power point and gives switching signals to

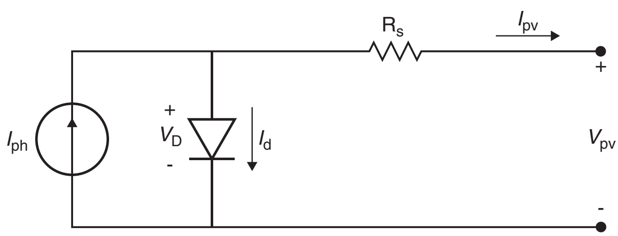

Figure 10-5. Equivalent circuit of PV solar cell. (From [3], © IEEE 2004.)

Table 10-1. Specifications of silicon solar panels manufactured by OFFC

Current temperature coefficient	α = 0.002086	[A/°C]
Voltage temperature coefficient	β = 0.0779	[V/°C]
Reverse saturation surrent	I_0 = 0.5 × 10^{-4}	[A]
Short-circuit cell current	$I_{ph} = I_{sc}$ = 2.926	[A]
Cell resistance	R_s = 0.0277	[Ω]
Cell material coefficient	λ = 0.049	[1/V]

Source: [3].

the PWM system in the inverter. The inverter switches by modulating the pulse width control, the power input in the load. Note that in a normal electricity power generator, one controls the generator output by controlling the field excitation, energy input, inlet air control, and so on. Here, we pick up the best points across a PV cell for the maximum energy it is producing. The control is relative to the load and MPPTs are said to characterize the load. We do not control the voltage induced by isolation but pick up the most favorable value. In a voltage-reference-based VMPPT, the reference is made to the open-circuit voltage of the cell. This arrangement is suitable for resistive loads. Typically, it has increased the power output by 20%.

10.8.2 VMPPT and CMPPT

In a current-based MPPT (CMPPT), the reference is made to i_{sc}. This arrangement is suitable for a pump load. Here, the losses are slightly higher and the reported increase in pow-

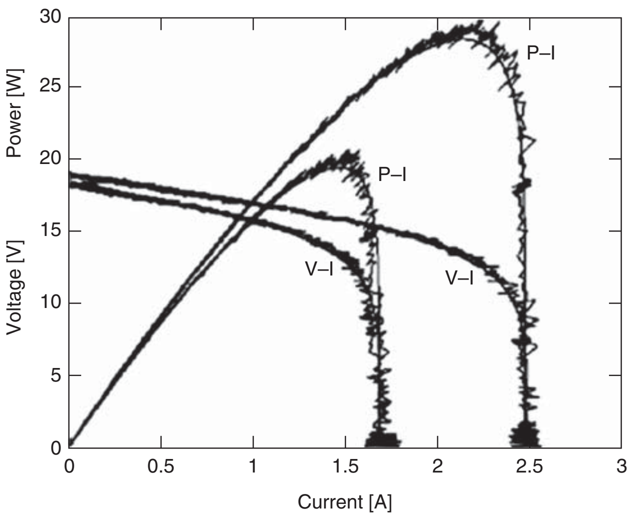

Figure 10-6. Computed (two conditions) and measured nonlinear V–I and P–I characteristics of one OFFC silicon solar panel (see Table 10-1). (From [3], © IEEE 2004.)

er output stands at 10%. The overall efficiency of an MPPT-based control system is fairly high—over 97%. The increase in output is not diminished by the losses in the MPPT.

A voltage-based MPPT (VMPPT) is more suitable for low-voltage, high-current loads such as battery chargers and low resistance levels. A CMPPT is more suitable for high-voltage, low-current loads such as DC motors on agricultural pumps.

10.9 OLD WORKING MODEL OF AN MPPT

A simple old-time MPPT based on saturating a transformer and controlling the current output is shown in Figure 10-7. In the figure, TVT is a time-variable transformer, for which the transformation ratio k is controlled and changed corresponding to the operating point of the load. As the name suggests, it is also time variable to enable it to keep in step with the insolation time variation. Thus, it gives maximum possible power-point operation.

Use of an MPPT depends on a variety of factors. If the seasonal temperature variation is high, it is preferable to have an MPPT. A load requiring constant current is bad for a PV system whose I–V and temperature characteristics make it difficult to comply with the requirements of constant current. An MPPT helps here. A solar array costs \$5000 to \$10,000 per watt. Corresponding MPPT costs will vary between \$150 and \$200 per watt. Its efficiency will be as high as 90%.

10.10 MAXIMIZING THE OUTPUT OF A SOLAR PANEL

10.10.1 By Orienting the Solar Panel

A low available solar input may be maximized by orienting the PV cells in the direction of the sun's rays. This is accomplished by rotating the panel around its axis during the day and rotating the axis itself as per season.

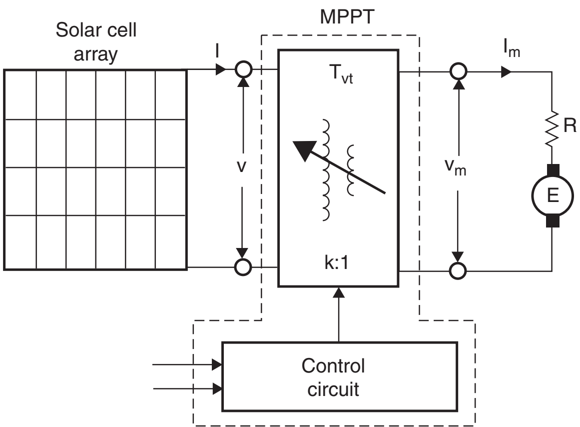

Figure 10-7. A solar cell system with an MPPT. (From [4], © IEEE 1993.)

The Carissa solar power plant rated at 6.5 MW installed by Pacific Gas and Electric Co. in the United States is reported to have incorporated both the above movements. It has also incorporated reflecting plates around the solar arrays, thus increasing the radiation collection. This plant is tied directly into a 110 kV electricity grid system.

Incorporating array orientation towards the sun's rays involves additional capital costs as well as some energy loss due to use of collected electrical energy for rotation. Both of these have to be balanced against the benefits in increased PV output and its value.

Rahman [5] has calculated that incorporating daily axis rotation is not viable on the basis of a cost-to-benefit ratio. Instead, axis orientation once a month is just as productive, with minimum costs involved.

An ingenious method reportedly uses air cylinders to rotate the panels [5]. These air cylinders develop air pressures as they get hot under sun's radiation and do not require external energy input for rotation.

10.10.2 By Water Cooling the Solar Panel Backs

Another installation has reported water cooling of the plates from the underside of array plates to keep the PV cell temperatures low [5]. This gives increased electrical outputs.

10.11 INTERFACE WITH A POWER SYSTEM

Figure 10-8 gives the workings of a complete system. The PV panel feeds into an MPPT. Output of the MPPT is supported by a paralleling device, in this case, an EDLC (electric double layer capacitor). This output goes to a power conditioning system, PCS. The PCS gets its control signals from a control system. There are a number of storage devices to complement the output from the PV panel, the EDLC or ECaSS being one of them. Table 10-2 compares the properties of an ECaSS with two different batteries.

10.12 POWER CONDITIONING SYSTEMS

The DC output of a PV system has limited direct uses, including residential panels for water heating and directly coupled agricultural pumps in a standalone system, for which the driving motors are rated at DC voltages.

In residential complexes, PV systems are used to substitute for grid energy when the sun's energy is available. PV supply parameters must be identical with the grid supply parameters for the same customer's appliances to work. In this case, a utility might use a PV system owned by it to reduce the power peak demand by air conditioners during the noon and afternoon periods of hot summer months. The utility might

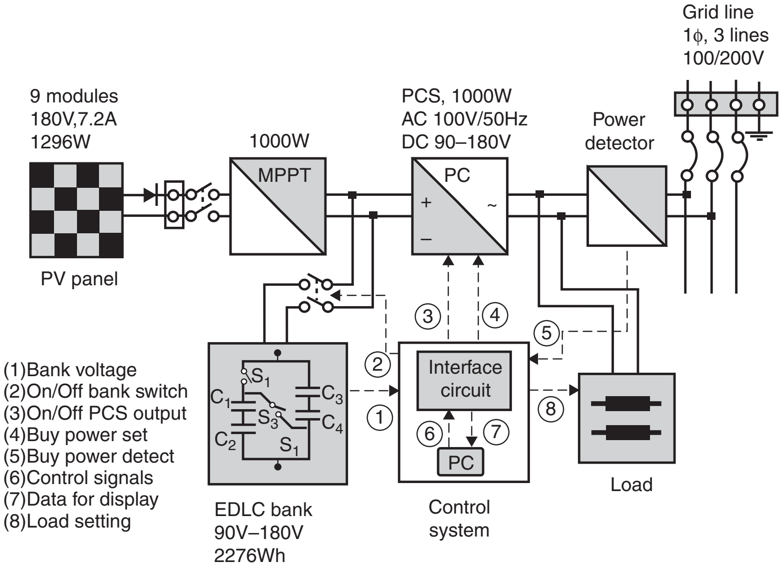

Figure 10-8. Block diagram of a solar power system. (From [6], © IEEE 1998.)

also want to use the PV system to support its distribution at far off points, both with active as well as with reactive power.

All these require an interface or a power conditioning system (PCS) that will match and tie up with the grid system in voltage, frequency, transient behavior, and so on.

The PCS converts DC into AC with parameters required at the utility connection point.

The PCS has three basic functions to perform:

1. It has to monitor and adjust so as to receive maximum power from the PV source and match its output with an MPPT. For this, the load characteristic represented by the PCS has to suit the output characteristic of the PV–MPPT system so that there is optimum power under all conditions of insolation.
2. It must transform DC into AC and hold on to the quality of power on the AC side.
3. It must monitor the utility system and maintain the steady-state compatibility, as well as respond appropriately to utility-side dynamics.

In this way, it forms an interface with the utility. It is an important and critical link.

10.12.1 Quality Requirements of a PCS

- It must have as perfect a reliability as possible.
- It must have a high efficiency.

- It should not add substantially to the overall costs of a PV-energy system, which already has the handicap of high-cost solar cells.
- It should take care of harmonic distortion and improve power factors where feasible and necessary.
- The high-frequency switching of the inverter, especially at higher power handling, tends to create electromagnetic interference on the output side. This has to be checked and guarded against.
- Safety to utility personnel and equipment has to be the topmost priority.

10.12.2 Converting DC into AC

There are two basic methods of converting DC into AC: the line commutation method and the forced switching system, also known as pulse width modulation (PWM).

10.13 SUPER CAPACITORS AND STORAGE BATTERIES

Table 10-2 compares the performance of supercapacitors to two types of batteries.

10.14 NERC GUIDELINES FOR CONNECTING A PV SYSTEM TO A GRID

NERC guidelines require the PV system to be isolated from the utility at the instant the utility supply is switched off for any reason. Should this not happen, the PV system will enliven the utility system and endanger personnel and equipment on the utility side. This protection is dealt with in detail in a later chapter. One of the most secure methods to ensure that the interface is not alive is to deenergize the inverter control grids.

Another NERC guideline requires the system reserves to be adequate enough to hold the supply parameters within limits when the largest single contributing member goes out. This is where the irregularity of PV supplies clashes with NERC rules.

Table 10-2. Comparison between ECaSS and popular storage batteries

Parameters	EcaSS	Lead–Acid	NiCd
Power density	400	10–300	100–160
Energy density	6.5	40–45	45–53
Depth of discharge	95	50–70	80–100
Efficiency (%)	–97	–80	–75
Charging time	1 min	5–10 h	15 min–8 h
Life cycle	–3,000,000	300–1000	300–500
Oruce ($/kW-hr)	4	0.2–0.8	0.8–1.5

Source: [6].

10.15 PROBLEMS OF INTERFACING PV SYSTEMS WITH THE GRID

Effect on grid:

1. An ad hoc PV connection into a utility grid system can overload the distribution lines. The distribution lines normally keep on adding loads, but are not frequently replaced or strengthened. If a PV output also flows along these lines to a consumer, the lines will get overloaded. This has to be particularly watched on residential PV systems.
2. Single-phase residential PV systems can cause phase imbalance and shift the neutral to unsafe values.
3. Line commutation, usually on low-voltage systems, degrades the overall power factor and hurts the supply voltages. It also increases harmonic distortion.
4. If there is a fault, it will be doubly fed, both by the utility as well as by the PV systems. This could be dangerous.
5. Similarly, protective relays, voltage regulation with load tap changes, and so on can be affected by a newly connected PV system.

Overcoming all the above problems requires careful study, including load flows, before connecting to a PV system. However, there are more serious problems to be thought of when we think of switching over to 10% of the total supply under a PV energy system, as envisaged under the Kyoto proposal on renewable energies. These are:

1. Cloud effects. Fast ramping rates from the grid are required. Whenever a dark cloud passes over a PV array its output dips substantially. Let us assume that an array supplying 1 MW of power is blanked out by a cloud in 10 seconds. Then the utility should be able to pump in extra power at the rate of 1 MW/10 seconds. Instances have been reported where clouds have covered arrays at the rate of 15 clouds per minute. Conversely, when the cloud disappears, let us say in just 10 seconds, the utility will have to absorb power at the ratio of 1 MW/10 seconds. This reverse flow could raise bus voltages and result in uncontrolled and undesirable inter tie flow of current between adjacent feeders.
2. Loss-of-load possibility (LOLP). Suppose that the ramping up or down rate of energy flow is too high for the system capacity to absorb. The voltage dips momentarily to, say, 70% of the rated system voltage. Many of the magnetizing coils on switches and contactors will not be able to hold on the contactors, thus disconnecting the connected load. This loss-of-load possibility is strictly forbidden. On the other hand, if the lowest voltage limit is, say, 5% of the rated voltage and this is permitted to go down to, say, 7% then one can correspondingly raise the percentage penetration of the grid by a PV system (415 V tolerance of ± 5% is brought down to ± 7%).

10.16 PENETRATION PERCENTAGE BY A PV ENERGY SYSTEM INTO A UTILITY GRID

Load following involves taking care of short-term or long-term dips and highs by the load and maintaining the power quality. For this, the supply system must have adequate capacity. When we add the cloud effect problems created by a PV system, the load following becomes more demanding. It requires more of the system capacity to handle this than before. Alternatively, we hold down these extra capacity requirements to manage the power quality control by limiting the percentage penetration by a PV of the utility capacity at that point. Thus, percentage penetration by a PV system is limited by the reliability of its energy supply when viewed against the potential capacity of the grid to absorb the cloud-effect shocks. This reliability increases as we increase the area under a PV system. Average cloud effect will fall as the coverage area increases and PV arrays are dispersed widely. Jewell [7] gives the following typical figures:

$$
\begin{aligned}
A_{H0} &= 10 \text{ km}^2 \\
&= 100 \text{ km}^2 \\
&= 1000 \text{ km}^2 \\
\text{penetration} &= 6.3\% \text{ by PV} \\
&= 18.1\% \\
&= 35.8\%
\end{aligned}
$$

10.17 PROGRESS IN APPLICATION OF PV ENERGY

As detailed earlier, capital costs for utilizing solar energy are high. Besides, solar energy is dispersed widely. It does not come in a concentrated form like wind energy and all other types of energies. There is a universal reckoning that solar energy could be one of our saviors in the long run. The progress in solar energy utilization may be attributed to necessity, institutional encouragement, and market forces.

Growth due to necessity is exemplified by agricultural water pumps—growers need not wait for the arrival of electricity distribution systems—and local electrification schemes for far off hamlets. Residential complexes have been encouraged to install PV panels, generally for home water heating, through inducements offered by local and government agencies. Multistory buildings with many computers, residential complexes, large commercial marketing installations, hospitals, and so on are increasingly taking a look at the financial advantages that can be gained particularly under the new electricity marketing systems. Other uses of PV systems are PV packages for power factor improvement and PV panels on the tops of automobiles. We will examine these in detail.

10.17.1 PV Cells and Agricultural Pumps

Selection of a DC Motor. Kolhe [8], in a series of experiments, has calculated that the solar panel and the DC motor must be selected with due consideration for matching. Morning solar intensities are low. The starting torque speed characteristics of the pump motor are generally steep. At noon when the solar intensities are high, the torque and speed could both be high (Figure 10-9). With normal tracking, the performance has been improved by over 20% (Figure 10-10).

An agricultural water pump has three components whose characteristics must match one another:

1. PV cells, output characteristics of which were given in Figures 10-1 and 10-2
2. A DC electric motor
3. A mechanical load driven by the motor

The types of DC motors available are series connected, separately excited, shunt connected, and permanent-magnet excited. The connections refer to the field winding, which produces the air gap flux.

The mechanical load is normally a centrifugal pump that requires fairly low starting torques. The starting torque has an important bearing in the Indian context.

The water pump population per hectare has gone up. With each pump trying to pump out maximum water, the subsoil water levels fall quickly to lower and lower levels. The starting torques and, consequently, the power used, goes up. If a larger than normal pump is used, which is often the case, then the supporting PV array system must also be large enough.

With a large population of water pumps, the subsoil water level recedes to lower strata in the summer season and the running and starting torque requirements increase. Here again, more often than not, larger pump sizes are used than otherwise required. The PV array sizes will have to match accordingly.

The starting current and starting torque with relation to their running values have important effects:

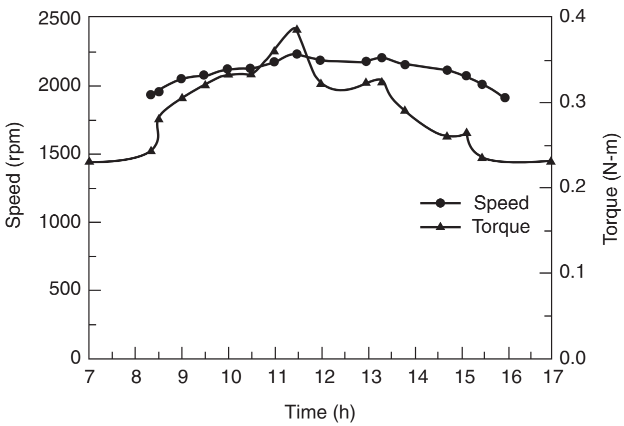

Figure 10-9. Speed and shaft torque with time for 5 m water head. (From [8], © IEEE 2004.)

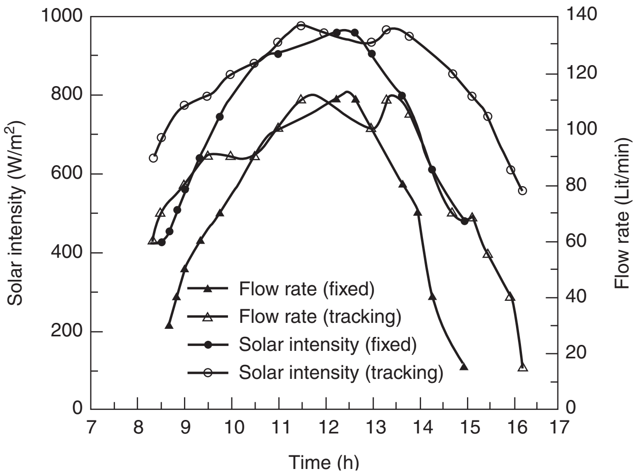

Figure 10-10. Solar intensity and flow rate for fixed and manual tracking modes. (From [8], © IEEE 2004.)

1. At the starting instant of a DC motor, the motor terminal voltage is equal to the voltage drop across the armature (and the field windings, in a series-type motor). As the armature picks up speed, it develops a back EMF. This reduces the current. With a PV cell, the starting current is limited to its short-circuit current at a given insolation. This implies two requirements. First, output from the PV cell should be drawn at the maximum power output point corresponding to the insolation level. An MPPT helps to achieve this. Second, the duration of these high starting currents, until the pump develops full speed, should be as low as possible. This requires as high a starting torque as possible. Long starting durations damage the armature windings.
2. The torque developed by a DC motor is proportional to the product of the air gap flux and the armature current. The starting torque should be high.

An MPPT Helps. Singer [4] has developed equations for the ratios of starting current to starting torques and starting currents to rated currents, with and without the use of an MPPT for various types of motors. These are given in Table 10-3.

Suitable DC Motor. Series and separately excited motors show better characteristics and are preferable. Shunt motors have the worst characteristics, followed by permanent-magnet motors. Again, performance with an MPPT is better than without it, justifying its additional costs and losses.

Operation of Solar Water Pumps. Solar water pumps cannot be switched on randomly. Starting a PV cell operated DC water pumps takes relatively longer time if started early in the morning, when insolation levels are low. It will develop an undesir-

Table 10-3. Starting torques and current ratios of DC motors rated at design insolation

	Permanent magnet	Series	Shunt	Separately excited (split)	Separately excited (unsplit)
			Starting to rated torque ratio		
Without MPPT	1.2	1.44	0.14	1.2	1.2
With MPPT	3.17	9.99	.97	8.33	26.35
Magnification m_T	2.64	6.94	6.94	6.94	21.96
			Starting to rated current ratio		
Without MPPT	1.2	1.2	1.2	1.2	1.2
With MPPT	3.17	3.17	3.17	3.17	3.17
Magnification m_T	2.64	2.64	2.64	2.64	2.64

Source: [4].

ably high starting torque if started at noon, when the insolation levels are high. High torques are also undesirable. They result in higher RPM and higher power output, leading to cavitations and formation of air bubbles in a pump. In such cases, the MPPT setting should be lowered.

Stand-alone Hybrid Power Stations for Remote Hamlets. These are covered in detail in Chapter 16.

Residential Complexes. The increasing cost of electricity and the increasing sizes of residential colonies and complexes are leading toward more solar energy than before, especially in Germany and Japan. First, technical problems due to the fluctuating nature of solar energy have to be overcome. This is dealt with extensively in Chapter 16 of this book, where detailed calculations for the storage needed to smooth out fluctuations are given.

There are financial advantages to solar systems under the new marketing schemes. Rahman [9] gives a detailed look into the possible financial gains in a Japanese system by proper sizing and operating a PV system and using this data and the metrological data for hourly buying power in the electricity market. There are substantial financial savings.

Optimizing Power Purchases from the Grid. The PV output energy is determined as that extra energy consumed during peak periods over an average daily energy. This is upgraded by allowing for efficiencies of MPPT, PCS, and so on. There is a difference between the PV output during the shortest and the longest days of the year. This difference is added to the PV rating. There is also a difference between peak load levels throughout the year. This difference is added. All this helps us to arrive at the total rating of the PV panel.

Statistical data (daily) on insolation levels and on cloud and other disturbing effects (rain, snow, etc.) is collected. With this data and forecast data on weather, next-day hourly forecasts of PV panel output are worked out. The load requirements are obtained from the Web. This helps to arrive at the quantum of electricity we need to bid for in the day-ahead electricity market. Note that day-ahead meteorological data is also available in Japan. The residence buys its electricity needs either at a flat rate or a nonflat rate, that is, at the ruling market rate in open competition. With all these preparations, it is shown that there are financial gains to the tune of 38.36% in buying hourly electricity on a nonflat-rate basis (Figure 10-11).

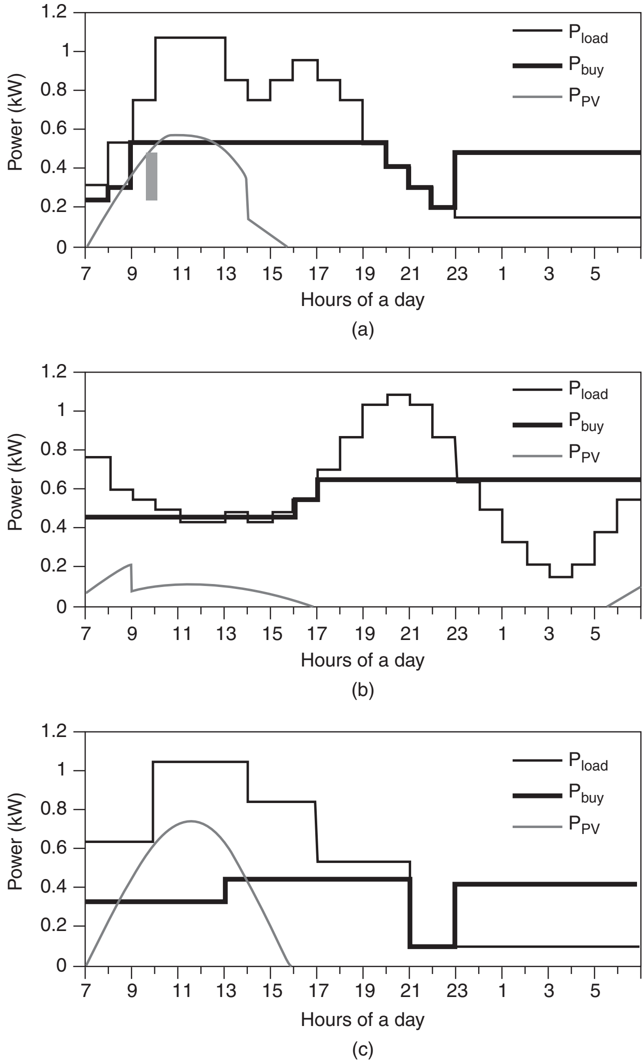

Figure 10-11. Simulated daily power patterns: (a) using Load-1, (b) using Load-2, and (c) using Load-3. (From [10], © IEEE 1992.)

With proper storage size and capacity, the residence can keep buying electricity during nonpeak hours, when it is cheap, and save on electricity purchases when different types of storage are available.

Note that the basic purpose of the PV application here is leveling of load around the year, taking into account weather and meteorological changes. This aims at attacking the costly portion of electricity buying while adhering to a common low price around the year. The purpose is not to compete with and replace grid energy totally, now or in future. This will have to wait until there are breakthroughs in solar cell technologies and as well threatening rises in fossil fuel (oil and gas). The Japanese example above shows a path that is leading to future healthy growth in utilizing solar energy.

Multistoried Buildings with a Large Number of Computers—Effect on Grid Power Factor and Harmonics. Multiple single-phase inverters are connected to the distribution system. These could be inverter interfaces for solar panels. There would be inverters as standbys along with storage batteries for computers within a building. The features of these inverters that may possibly affect power quality are power factor characteristics, harmonic distortion, DC injection, and islanding. In a building with many such inverters across a common step-down transformer from the grid supply, these characteristics will add up and pose a big problem for power quality. Let us study these effects individually.

Generally, the inverters are designed to operate at unity power factor (PF) at their rated output capacity. If the PF falls, the corresponding reactive currents add and can cause a voltage drop at the interface. Some inverters (PWMs) are programmed to provide their own reactive power and maintain a unity PF at even lower outputs. The best way to tackle this is to install suitable shunt capacitors at appropriate locations.

Harmonic distortion is a much more serious problem. Current harmonic distortion is important. IEEE 549 limits total current harmonic distortions to 5%. Figure 10-12 gives the spread of harmonics across an inverter interface. Table 10-4 tabulates these results. Two features may be noted: the second harmonic is sizeable and lower harmonics are predominant.

Within an inverter, a reference sine wave is either picked up from the grid supply or created within itself. The source of second harmonic is traced to the presence of the same in the reference sine wave that is, in the supply itself. Second harmonics along with other even harmonics may add to unwanted negative sequence currents, adversely affecting three-phase loads. There are stiff limitations on second harmonic current distortion. It should be less than 1%.

Note that the inductive reactance to the propagation of harmonics is low at lower frequencies and rises at higher frequencies. As a result, high-frequency harmonics attenuate rapidly and do not build up.

At the lower frequencies, except for the second harmonic, there is a possible phase shaft between successive/different waves, leading to an almost mass cancellation of the harmonic effects from different sources. However, Infield [11] reports that the phase shift between different inverter outputs of low harmonics is minor and tend to add. They also will not propagate due to cancellation by an aggregation effect, tet they can cause a nuisance between inverters.

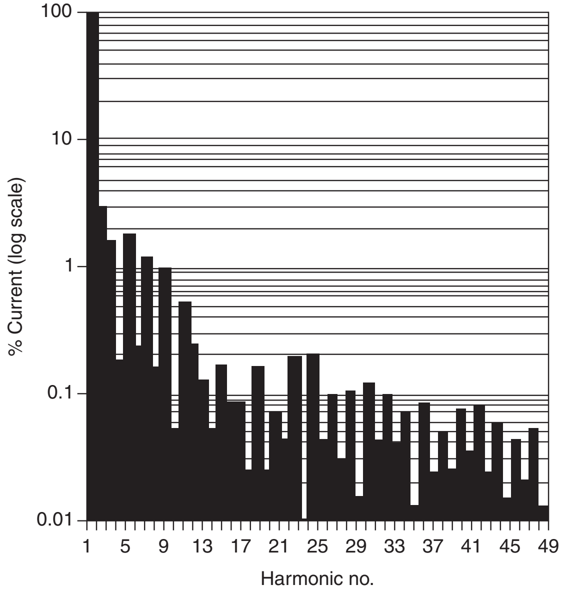

Figure 10-12. Harmonics from a single inverter at rated output. (From [12], © 1988.)

DC injection, if it accumulates and flows into the supply transformer, can distort its working. Its presence there is strictly prohibited. IEEE Std 1547/1710 on PV restricts DC injection to less than 0.5%. Many inverters use an isolating transformer for an interface with the grid. However, Infield has noted that under an aggregation effect, the aggregate DC components also tend to zero.

A PV Package for Power Factor Improvement. At the far end of a utility system, the voltages are low and line losses are high, because the loads are drawing high reactive power. A PV system with a PWM-type power conditioner is installed at this end. The power conditioner produces sufficient reactive power locally. Not only that, it makes up for the shortage of power as well, which a power factor improving shunt capacitor cannot do. Technically, this is a good proposal but financially it is not. As will be detailed below, capital costs of a PV system will be around US$10.65/W as against US$0.04/VA for a PF capacitor. The efficiency of a capacitor is also very high—99.5%.

Table 10-4. Harmonics up to the fifteenth order

Harmonic order	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Percentage	3.01	1.62	0.18	1.80	0.21	1.13	0.17	0.96	0.05	0.51	0.22	0.12	0.04	0.16

Source: [12].

Typical installed costs of a PV system (Austin, Texas, capacity 300 kW) are:

PV module costs	\$5.61/W
Power conditioning system	\$0.78/W
Site preparation	\$0.30/W
Installation	\$0.99/W
Structural	\$0.90/W
Data acquisition system	\$0.36/W
Electrical	\$0.36/W
Administrative	\$0.40/W
Total	\$10.65/W

The above breakdown gives pre-1990 costs. These have come down substantially. The costs involved in other supporting items will also have come down.

A PV Panel on Top of an Automobile. In all the systems described above, the insolation does not change rapidly and frequently. This happens when we fit a PV panel on the top of an automobile in order to take advantage of the solar energy. The PV versus tme curve has a gradient. To deal with this, a widely adopted system called perturb and observe (P and O) is used. It senses consecutive signals and determines whether they are rising or falling. The control point moves accordingly. If the sensing time interval is too large, the system will oscillate and lose power. If the sensing interval is too small, there will be no oscillations, but the system will take a long time to reach the maximum power point. Logarithms have been developed to automatically adjust this sensing interval [13].

On solar panels on rooftops, the operation has long periods of steady operation, except under cloudy conditions when blocking of insolation will be very frequent and MPPTs must operate in the self-adjusting mode for the P and O mode.

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