5.11 A BATTERY STORAGE SYSTEM

The capacity of a battery is rated in ampere-hours (Ah). The Ah measures the capacity of a battery to hold energy: 1 Ah means that a battery can deliver one amp for 1 hour. Based on the same concept, a 110 Ah battery has a capacity to deliver 10 amps for 11 hours. However, after a battery is discharged for an hour, the battery will need to be charged longer than one hour. It is estimated it will take 1.25 Ah to restore the battery to the same state of charge. Battery performance also varies with temperature, battery type, and age. Lead-acid battery technology is well established and is a widely adopted energy source for various power industries.

Recent advances in the design of the deep-cycle lead-acid battery have promoted the use of battery storage systems when rapid discharge and charging are required. For example, if the load requires a 900 Ah bank, a number of battery storage systems can be designed. As a first design, three parallel strings of deep-cycle batteries rated 300 Ah can be implemented. The second design can be based on two strings of deep-cycle 450 Ah batteries. Finally, the design can be based on a single large industrial battery. Lead-acid batteries are designed to have approximately 2.14 V per cell. For an off-the-shelf 12 V battery the voltage rating is about 12.6 to 12.8 V.

The fundamental problem is that if a single cell in a string fails, the entire storage bank will rapidly discharge beyond the required discharge level; this will permanently destroy the bank.

It is industry practice not to install more than three parallel battery strings. Each string is monitored to ensure equal charging and discharging rates. If a storage bank loses its equalization, it will result in accelerated failure of any weak cells and the entire storage bank. The battery characteristics change with age and charging and discharging rates. It is industry practice not to enlarge an old battery bank by adding new battery strings. As the battery ages, the aging is not uniform for all cells. Some cells will establish current flow to the surrounding cells and this current will be difficult to detect. If one cell fails, changing the resistance in one battery string, the life of the entire string can be reduced substantially. Therefore, the storage system will fail. By paralleling several strings, the chances of unequal voltages across the strings increases; therefore, for optimized battery storage systems, the system should be designed using a single series of cells that are sized for their loads.

The battery capacity can be estimated for a given time duration by multiplying the rated load power consumption in watts by the number of hours that the load is scheduled to operate. This results in energy consumption in watt hours (or kilowatt hours [kWh]), stated as

$$\mathrm{kWh} = \mathrm{kV} \cdot \mathrm{Ah} \tag{5.25}$$

For example, a 60-W light bulb operating for one hour uses 60 watt-hours. However, if the same light bulb is supplied by a 12-V battery, the light it will

TABLE 5.23 Typical Battery Storage Systems.

Class 1	34–40 Ah	12 V
Class 2	70–85 Ah	12 V
Class 3	85–105 Ah	12 V
Class 4	95–125 Ah	12 V
Class 5	180–215 Ah	12 V
Class 6	225–255 Ah	12 V
Class 7	180–225 Ah	6 V
Class 8	340–415 Ah	6 V

consume 5 amp-hours. Therefore, to compute Ah storage required for a given load, the average daily usage in W should be divided by the battery voltage. As another example, if a load consumes 5 kWh per day from a 48-V battery storage system, we can determine the required Ah by dividing the watt-hours by the battery voltage. For this example, we will need 105 Ah. However, because we do not want to discharge the battery more than 50%, the battery storage needed should be 210 Ah. If this load has to operate for 4 days, the required capacity is 840 Ah. If the battery cabling is not properly insulated from earth, the capacitive coupling from the DC system with earth can cause stray current flow from the DC system to underground metallic facilities, which will corrode the underground metallic structure.

Battery energy storage is still expensive for large-scale stationary power applications under the current electric energy rate. However, the battery storage system is an important technology for the efficient utilization of an intermittent renewable energy system such as wind or PV in the integration of the renewable energy in electric power systems. Utility companies are interested in the large-scale integration of a battery storage system in their substations as community storage to capture the high penetration of solar energy and wind in their distribution system. The community storage system with the ramping capability of at least an hour can be utilized in power system control. This is an important consideration for utility companies because the installed energy storage system can be used as spinning reserve.

The storage system must be effectively and efficiently scheduled for the charging, discharging, and rest time of each string. Therefore, the battery storage system requires extensive monitoring and control. These issues are currently being studied.[13,14]

5.12 A STORAGE SYSTEM BASED ON A SINGLE-CELL BATTERY

The rapid electrification of the automotive industry has a large impact on storage technology and its use in stationary power. At present, nickel metal hydride (NiMH) batteries are used in most electric and hybrid electric vehicles available to the public. Lithium-ion batteries have the best performance of the available batteries. The cost of energy storage for grid-level renewable energy storage at present is approximately around \$300–\$500 per kWh. The price is rapidly decreasing as more companies are developing new technologies.

The large battery storage system is constructed from single-cell batteries[13–15] and is considered a multicell storage system. The performance of multicell storage is a function of output voltage, internal resistance, cell connections, the discharge current rate, and cell aging.[13–15]

Single-cell battery technology is rapidly making new advances, e.g., a new lithium-ion battery is being developed. The price of a single-cell battery has also been dropping dramatically. In comparison to the regular lead-acid battery where 12 cells are internally connected in a 12-V battery, the single-cell batteries can be individually connected and reconfigured. Also, because the individual single-cell's rate of charging and discharging can be monitored, the health and performance of all cells in a string can be evaluated. Figure 5.33 depicts three single cells in a string.

Figure 5.34 depicts a battery storage system consisting of two strings of three single cells that are connected in parallel making an array.

Table 5.24 presents the energy densities and power density of two single-cell batteries.

Table 5.25 presents the energy density and the cost of a storage system of lead-acid batteries as compared with single-cell batteries. In all batteries, the

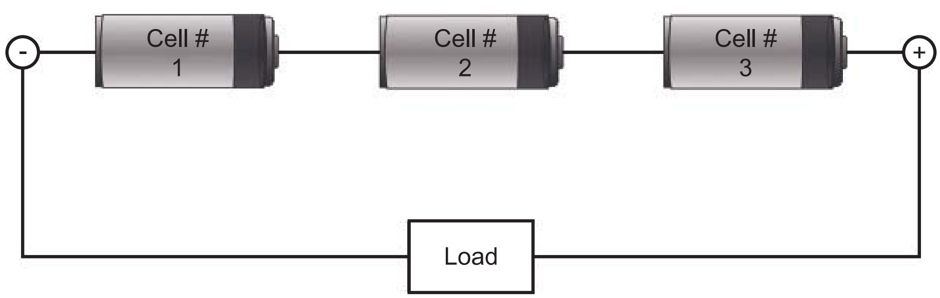

Figure 5.33 Three Single Cells in a String.

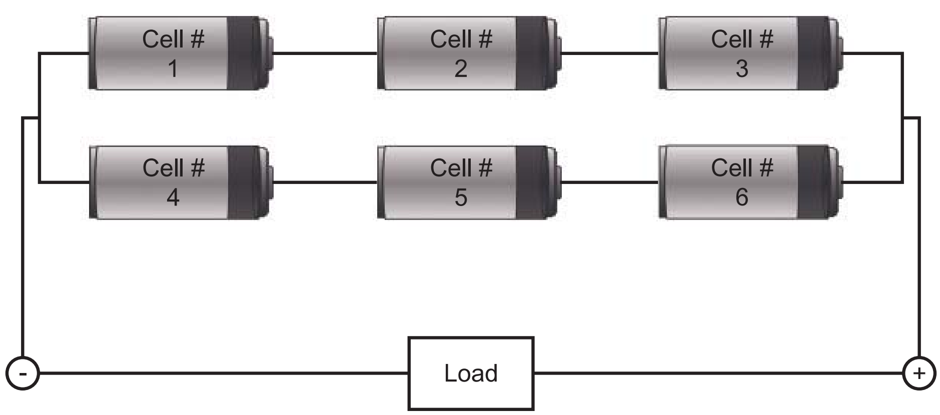

Figure 5.34 Two Strings of Three Single Cells Connected in Parallel.

TABLE 5.24 Comparison of Battery Energy Density and Power Density.[15]

Application/ Battery Type	Energy Density (Wh/kg)	Energy Stored (kWh)	Fraction of Usable Energy (%)
NiMH hydride	65	40–50	80
Lithium-ion	130	40–50	80

TABLE 5.25 The Energy Density and the Cost of a Storage System.

Type	Wh/kg	Wh	Weight Kg (1)	$/kg	$/kWh	$/kW
Standard	25	1875	75	2.5	100	9.35
Thin-film	20	1000	50	4.0	200	10.0
NiMH hydride	45	1800	40	22.5	500	45.0
Lithium-ion	65	1170	18	45	700	41.0

performance will change with repeated charging at the discharge current rates. As expected, the higher the discharge current rate is the lower will be the remaining capacity and output voltage and the higher the internal resistance. However, the reduced capacity as the result of a higher discharge current rate will be recovered after the battery system is allowed to rest before the next discharge cycle.

Therefore, the design and optimization of a multicell storage system require an understanding of the storage system's discharge performance under various operation conditions. Furthermore, if the battery storage system is to be used as a community storage system in a power grid distribution system, dynamic models of the battery systems are needed. The dynamic model of a storage system will facilitate dispatching power from intermittent green energy sources.

Example 5.5 Design a microgrid with the load of 1000 kW rated at 460 V AC and connected to the local power grid at 13.2 kV using a transformer rated 2 MVA, 460 V/13.2 kV and 10% reactance. To support the emergency loads, the microgrid needs a 200 kWh storage system to be used for 8 hours a day. Data for a three-phase inverter is given in Table 5.26. The data for the PV system is given in Example 5.4.

Determine the following:

i) The ratings of PV arrays, converters, inverters, storage systems and a single-line diagram of this design based on the minimum surface area. Also, compute the cost, weight, and square feet area of each PV type and give the results in a table.

ii) Per unit model for the design

TABLE 5.26 Three-Phase Inverter Data.

Inverter	Type 1	Type 2	Type 3	Type 3
Power	100 kW	250 kW	500 kW	1 MW
Input voltage DC	900 V	900 V max	900 V	900 V
Output voltage AC	660 VAC/ 60 Hz	660 VAC/ 60 Hz	480 VAC/ 60 Hz	480 VAC/ 60 Hz
Efficiency	Peak efficiency 96.7%	Peak efficiency 97.0%	Peak efficiency 97.6%	Peak efficiency 96.0%
Depth	30.84″	38.2″	43.1″	71.3″
Width	57″	115.1″	138.8″	138.6″
Height	80″	89.2″	92.6″	92.5″
Weight	2350 lbs	2350 lbs	5900 lbs	12000 lbs

TABLE 5.27 Inverter Specifications.

Number of Inverters	Input Voltage V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
4	835	250	460	0.90	84

Solution

i) The load is 1000 kW rated at 460 V AC. Based on the voltage of the load and an amplitude modulation index of 0.9, we have the following input DC voltage for the inverter:

$$V_{idc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}\cdot M_a} = \frac{2\sqrt{2}\times 460}{\sqrt{3}\times 0.9} = 835\ V$$

Selecting an inverter rated 250 kW, the total number of inverters, *NI*, for the processing of 1000 kW is given as

$$NI = \frac{PV\ generation}{rating\ of\ inverters}$$

$$NI = \frac{1000}{250} = 4$$

For this design, four inverters should be connected in parallel. If we select a switching frequency of 5.04 kHz, the frequency modulation index is

$$M_f = \frac{f_S}{f_e} = \frac{5040}{60} = 84$$

TABLE 5.28 A Photovoltaic System Design Based on Photovoltaic Type.

PV Type	Surface Area of One Module (ft^2)	Power Rating (W)	Area per Unit Power (ft^2/W)
1	12.47	190	0.066
2	15.68	200	0.078
3	16.97	170	0.100
4	7.07	87	0.081

Students should recognize that other designs are also possible. The input DC voltage of PV specifies the output AC voltage of inverters. Table 5.28 gives the data for each PV type.

As noted in Table 5.28, the PV module of type 1 requires minimum surface area. Selecting PV type 1 and string open circuit voltage of 550 V DC, the number of modules, NM is

$$NM = \frac{string\ voltage}{V_{MPP}}$$

where V_{MPP} is the voltage at MPP of the PV module from the PV data.

$$NM = \frac{550}{54.8} \approx 10 \quad \text{for type 1 PV}$$

The string voltage, SV, under load is given as:

$$SV = \text{NM} \times V_{MPP}$$
$$SV = 10 \times 54.8 = 548\ V$$

The string power, SP, is given as

$$SP = NM \times P_{MPP}$$

where P_{MPP} is the power generated by the PV module at MPP.

$$SP = 10 \times 190 = 1.9\ kW \quad \text{for type 1}$$

If we design each array to generate a power of 20 kW, then the number of strings, NS, is given by:

$$NS = \frac{power\ of\ one\ array}{power\ of\ one\ string}$$

$$NS = \frac{20}{1.9} = 11$$

The number of arrays, NA, is given by

$$NA = \frac{PV\ generation}{power\ of\ one\ array}$$

$$NA = \frac{1000}{20} = 50$$

The total number of PV modules, TNM, in an array is given by

$$TNM = NM \times NS \times NA$$

where NM is number of modules in a string, NS is the number of strings, and NA is the number of arrays in a PV station.

$$NA = 10 \times 11 \times 50 = 5500 \quad \text{for PV module of type 1}$$

The total surface area needed, TS for type 1 PV module is as

$$TS = \frac{5500 \times 34.6 \times 51.9}{144} = 68{,}586\ ft^2 = 1.57\ acre$$

The total weight, TW, needed for a type 1 PV module is the product of the number of modules and the weight of each module.

$$TW = 5500 \times 33.07 = 181{,}885\ lb$$

The total cost for a PV module is the product of the number of modules and the cost of each module.

$$\text{Total cost} = 5500 \times 870 = \$4.78\ million \quad \text{for PV module type 1}$$

TABLE 5.29 The Photovoltaic Specifications.

PV Type	Number of Modules per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Total Area of the PV (ft^2)	Total Weight of the PV (lb)	Total Cost of the PV (Million $)
1	10	11	50	548	68,586	181,885	4.78

TABLE 5.30 Boost Converter Specifications.

Number of Boost Converters	Input Voltage V_i (V)	Power Rating (kW)	Output Voltage, V_o (V)	Duty Ratio, D
50	548	20	835	0.34

The output voltage of the boost converter, V_o, is the same as the input voltage, of the inverter, V_{idc}.

$$V_o = V_{idc} = 835\,V$$

The boost input voltage, V_i, is same as the string voltage, $SV = V_i = 548$ V

The duty ratio of the boost converter is given by

$$D = 1 - \frac{V_i}{V_o}$$

For this design, it is,

$$D = 1 - \frac{548}{835} = 0.34$$

We need one boost converter for each array. Therefore, the number of boost converters is 50 and each is rated 20 kW.

Table 5.23 presents a number of batteries for storing 200 kWh of energy. In storage design, we need to limit the number of batteries in a string and limit the number of arrays to three. These limitations are imposed on lead-acid-type batteries to extend the life of the storage system. We select the Class 6 batteries that are rated at 255 Ah at 12 V. In this design, three batteries per string and three strings in each array are used. The string voltage, SV, of the storage system is

$$SV = 3 \times 12 = 36\,V$$

The string energy stored, SES, in each battery is given by the product of the Ah and the battery voltage.

$$SES = 255 \times 12 = 3.06\,kWh$$

Each array has nine batteries. Therefore, the array energy stored, AES, is given as:

$$AES = 9 \times 3.06 = 27.54\,kWh$$

TABLE 5.31 Battery Array Specifications.

Battery Class	Number of Batteries per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Energy Stored per Array (kWh)
6	3	3	8	36	27.54

The number of arrays, NA, needed to store 200 kWh is given by

$$NA = \frac{total\ energy}{energy\ in\ each\ array}$$

$$NA = \frac{200}{27.54} \approx 8$$

Because we have eight storage arrays, we use one buck–boost converter for each array storage system. We need a total of eight buck-boost converters. The buck–boost converters are used to charge-discharge the battery storage system.

In this design, the buck–boost converter input is 835 V of the DC bus and its output must be 36 V DC to charge the battery storage system. If the storage systems are to be used for 8 hours, they can be discharged to 50% of their capacity. Therefore, they can be used to supply 100 kWh. The power, P, supplied by the storage system is given by

$$P = \frac{kWh}{hour}$$

$$P = \frac{100}{8} = 12.5\ kW$$

The array power, AP, rating is given by

$$AP = \frac{power}{number\ of\ arrays}$$

$$AP = \frac{12.5}{8} = 1.56\ kW$$

Let us select a buck–boost converter rated at 1.56 kW. The duty ratio is given by

$$D = \frac{V_o}{V_i + V_o}$$

TABLE 5.32 Buck–Boost Converter Specifications.

Number of Buck-Boost Converters	Input Voltage V_i (V)	Power Rating (kW)	Output Voltage, V_o (V)	Duty Ratio, D
8	835	1.56	36	0.04

$$D = \frac{36}{835 + 36} = 0.04$$

Figure 5.35 depicts the one-line diagram of the PV system.

ii) To compute the per unit system, we let the base volt-ampere be $S_b = 1\,MVA$. The base values for the system of Fig. 5.35 are:
The base value of watt-hours is therefore, $E_b = 1\,MWh$
The base voltage on the utility side is 13.2 kV.
The base voltage on the low-voltage side of the transformer is 460 V.
The new p.u reactance of the transformer on the new 1-MVA base is given by:

$$X_{p.u\,trans(new)} = X_{p.u\,trans(old)} \times \frac{S_{b(new)}}{S_{b(old)}} \times \left(\frac{V_{b(old)}}{V_{b(new)}}\right)^2$$

$$X_{p.u\,trans(new)} = 0.1 \times \frac{1}{2} \times \left(\frac{13.2}{13.2}\right)^2 = 0.05 \text{ p.u}$$

The per unit power, $P_{p.u}$, rating of the inverters is given by

$$P_{p.u} = \frac{power\ rating}{S_b}$$

$$P_{p.u\text{-}inverter} = \frac{250 \times 10^3}{1 \times 10^6} = 0.25\ p.u$$

And, the per unit power rating of the boost converters

$$P_{p.u\,boost} = \frac{20 \times 10^3}{1 \times 10^6} = 0.020\ p.u$$

The base voltage of the DC side of the inverter is 835 V. Therefore, the p.u voltage of the DC side, V p.u, of the inverter is

$$V_{p.u} = \frac{835}{835} = 1\ p.u$$

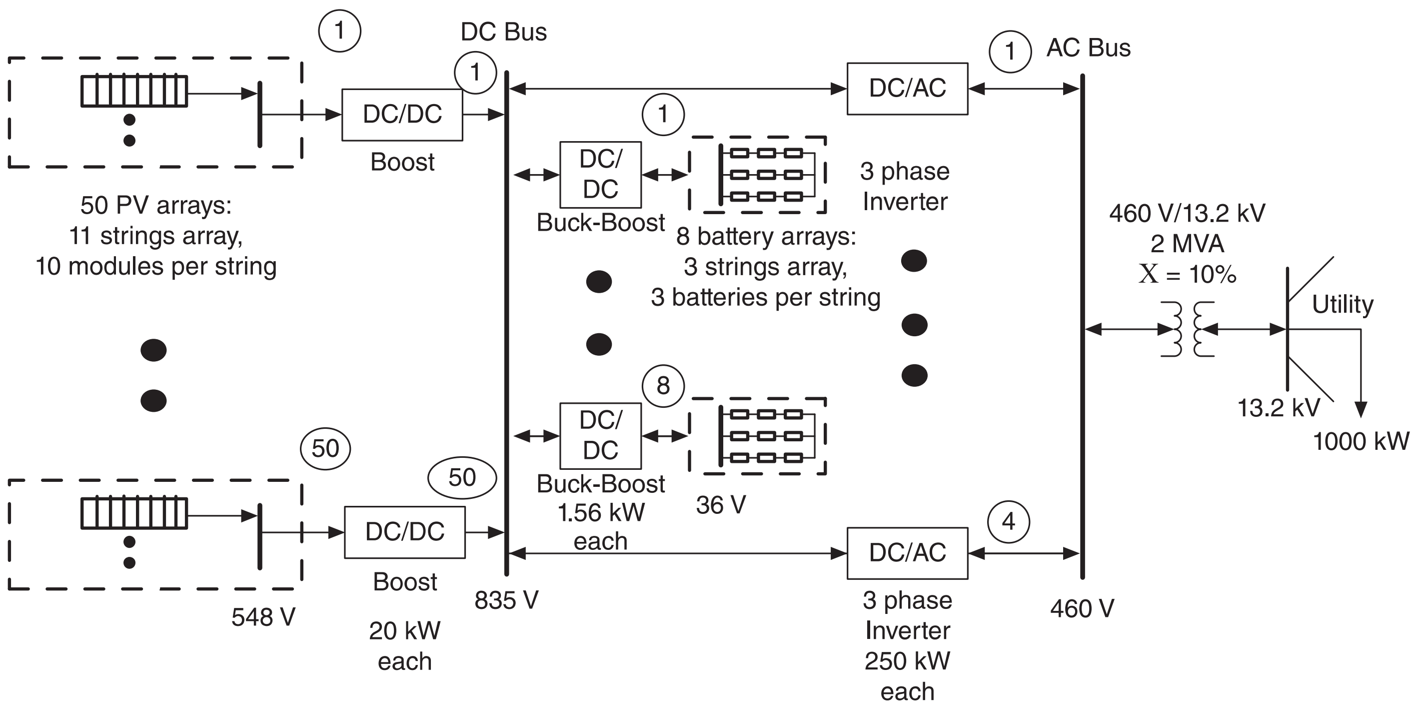

Figure 5.35 The One-Line Diagram of Example 5.5.

Because the base voltage of the low-voltage side of the boost converter is the same as the rated voltage, the per unit value is 1 p.u. The same is true for the storage system.

Similarly, the per unit power for the buck–boost and the energy storage system can be computed.

$$P_{p.u\,buck-boost} = \frac{1.56\times 10^3}{1\times 10^6} = 0.001\ p.u$$

$$\text{Energy stored} = \frac{27.54\times 10^3}{1\times 10^6} = 0.027\ p.u$$

The p.u model of the system is shown in Fig. 5.36.

Example 5.6 Design a microgrid of PV system using the data in Table 5.17, assume the total load is 500 kW at 460 V, 60 Hz three-phase AC.

For each type of PV system, determine the following:

i) The number of modules in a string, number of strings in an array, number of arrays, weight, and surface area

ii) The boost converter and inverter specifications, and the one-line diagram.

Solution

The load is 500 kW rated at 460 V AC. Based on the voltage of the load and an amplitude modulation index of 0.9, the input DC voltage for the three-phase inverter from Equation 5.16 is:

$$\frac{2\sqrt{2}\times 460}{\sqrt{3}\times 0.9} = 835\ V$$

i) Limiting the maximum voltage for a string to 600 V DC, a boost converter has to be used to boost the string voltage.

If we select string voltage, SV, to 550 V, the number of modules, NM from Equation 5.13 is

$$\begin{aligned} \text{NM} &= \frac{550}{54.8} \approx 10 \quad \text{for type 1} \\ &= \frac{550}{26.3} \approx 21 \quad \text{for type 2} \\ &= \frac{550}{28.7} \approx 20 \quad \text{for type 3} \\ &= \frac{550}{17.4} \approx 32 \quad \text{for type 4} \end{aligned}$$

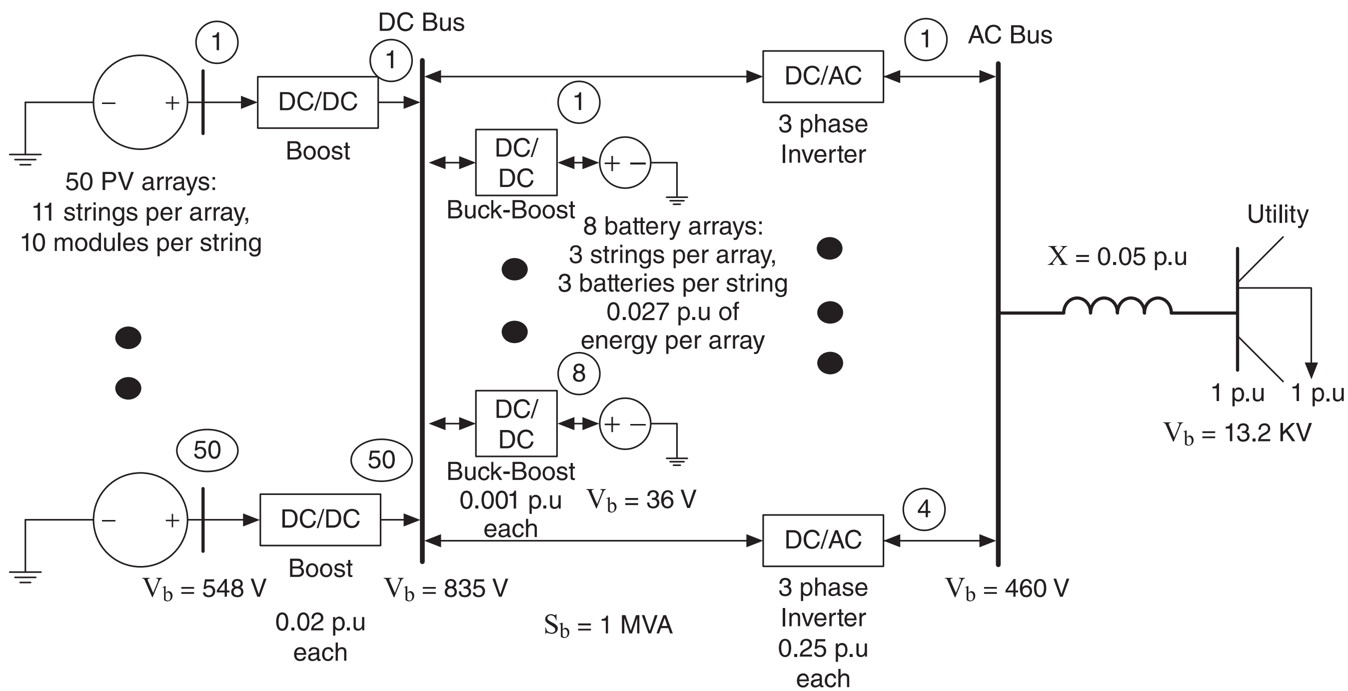

Figure 5.36 The Per Unit Model of the System Outlined in Example 5.5.

The string voltage, SV, from Equation 5.14 is

$$
\begin{aligned}
SV &= 10 \times 54.8 = 548\ V \quad \text{for type 1} \\
&= 21 \times 26.3 = 552\ V \quad \text{for type 2} \\
&= 20 \times 28.7 = 574\ V \quad \text{for type 3} \\
&= 32 \times 17.4 = 557\ V \quad \text{for type 4}
\end{aligned}
$$

String power from Equation 5.9:

$$
\begin{aligned}
\mathrm{SP} &= 10 \times 190 = 1.9\ kW \quad \text{for type 1} \\
&= 21 \times 200 = 4.2\ kW \quad \text{for type 2} \\
&= 20 \times 170 = 3.4\ kW \quad \text{for type 3} \\
&= 32 \times 87 = 2.784\ kW \quad \text{for type 4}
\end{aligned}
$$

If we design each array to generate power of 20 kW, then the number of strings, *NS*, from Equation 5.15 is

$$
\begin{aligned}
NS &= \frac{20}{1.9} = 11 \quad \text{for type 1} \\
&= \frac{20}{4.2} = 5 \quad \text{for type 2} \\
&= \frac{20}{3.4} = 6 \quad \text{for type 3} \\
&= \frac{20}{2.784} = 8 \quad \text{for type 4}
\end{aligned}
$$

The number of arrays, *NA*, is given by Equation 5.17:

$$NA = \frac{500}{20} = 25$$

The total number of PV modules, *TNM* as given by Equation 5.19:

$$
\begin{aligned}
TNM &= 10 \times 11 \times 25 = 2750 \quad \text{for type 1} \\
&= 21 \times 5 \times 25 = 2625 \quad \text{for type 2} \\
&= 20 \times 6 \times 25 = 3000 \quad \text{for type 3} \\
&= 32 \times 8 \times 25 = 6400 \quad \text{for type 4}
\end{aligned}
$$

The total surface area, *TS*, needed by each PV type can be computed from the number of modules and each module's area in square feet.

$$TS = \frac{2750 \times 34.6 \times 51.9}{144} = 34{,}294\ ft^2 = 0.787\ acre \quad \text{for type 1}$$
$$= \frac{2625 \times 38.6 \times 58.5}{144} = 41{,}164\ ft^2 = 0.944\ acre \quad \text{for type 2}$$
$$= \frac{3000 \times 38.3 \times 63.8}{144} = 50{,}907\ ft^2 = 1.169\ acre \quad \text{for type 3}$$
$$= \frac{6400 \times 25.7 \times 39.6}{144} = 45{,}232\ ft^2 = 1.038\ acre \quad \text{for type 4}$$

The total weight is

$$\text{Total weight} = 2750 \times 33.07 = 90{,}943\ lb \quad \text{for type 1}$$
$$= 2625 \times 39.00 = 102{,}375\ lb \quad \text{for type 2}$$
$$= 3000 \times 40.70 = 122{,}100\ lb \quad \text{for type 3}$$
$$= 6400 \times 18.40 = 117{,}760\ lb \quad \text{for type 4}$$

The total cost for each design is

$$\text{Total cost} = 2750 \times 870 = \$2.39\ million \quad \text{for type 1}$$
$$= 2625 \times 695 = \$1.82\ million \quad \text{for type 2}$$
$$= 3000 \times 550 = \$2.09\ million \quad \text{for type 3}$$
$$= 6400 \times 397 = \$2.54\ million \quad \text{for type 4}$$

ii) We need to use one boost converter for each array. The total number of converters is 25—each can be selected with 20 kW rating. The nominal output voltage of the boost converter is the same as the input of the inverter.

$$V_{idc} = V_o = 835\ V$$

TABLE 5.33 The Photovoltaic Specifications for Each Photovoltaic Type.

PV Type	Number of Modules per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Total Area of the PV (ft^2)	Total Weight of the PV (lb)	Total Cost of the PV (Million $)
1	10	11	25	548	34,294	90,943	2.39
2	21	5	25	552	41,164	102,375	1.82
3	20	6	25	574	50,907	122,100	2.09
4	32	8	25	557	45,232	117,760	2.54

The input voltage, V_i, of the boost converter is equal to the string voltage.

$$V_i = 548\,V \quad \text{for type 1}$$
$$V_i = 552\,V \quad \text{for type 2}$$
$$V_i = 574\,V \quad \text{for type 3}$$
$$V_i = 557\,V \quad \text{for type 4}$$

The duty ratio of the boost converter is given by

$$D = 1 - \frac{V_i}{V_o}$$

$$\begin{aligned} D &= 1 - \frac{548}{835} = 0.34 \quad \text{for type 1 PV} \\ &= 1 - \frac{552}{835} = 0.34 \quad \text{for type 2 PV} \\ &= 1 - \frac{574}{835} = 0.31 \quad \text{for type 3 PV} \\ &= 1 - \frac{557}{835} = 0.33 \quad \text{for type 2 PV} \end{aligned}$$

The inverters should be rated to withstand the output voltage of the boost converter and should be able to supply the required power. We can select each inverter having a rating of 100 kW, the input voltage of the inverter to be $V_{idc} = 835\,V$ with amplitude modulation index of 0.9 and output voltage of the inverter at 460 V AC.

The number of inverters, NI, from Equation 5.18, needed to process a generation of 500 kW is given by

$$NI = \frac{500}{100} = 5$$

TABLE 5.34 Boost Converter Specifications.

PV Type	Number of Boost Converters	Input Voltage, V_i (V)	Power Rating (kW)	Output Voltage, V_o (V)	Duty Ratio, D
1	25	548	20	835	0.34
2	25	552	20	835	0.34
3	25	574	20	835	0.31
4	25	557	20	835	0.33

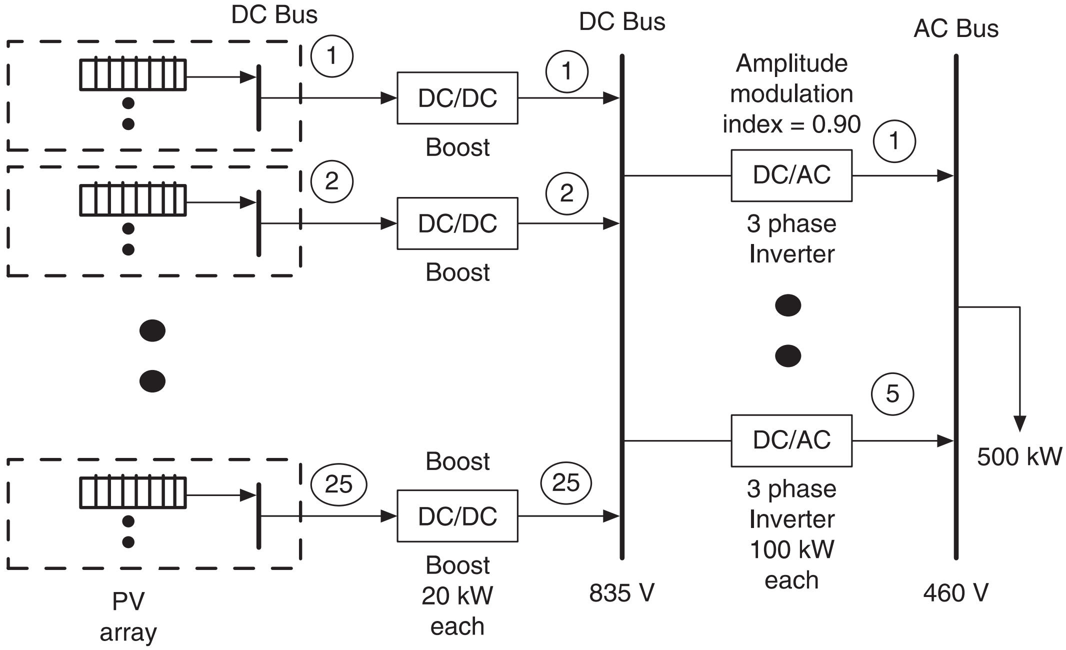

Figure 5.37 The One-Line Diagram of Example 5.6.

TABLE 5.35 Inverter Specifications.

Number of Inverters	Input Voltage, V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
5	835	100	460	0.90	166.67

Hence, we need to connect five inverters in parallel to supply the load of 500 kW

Selecting a switching frequency of 10 kHz to limit the total harmonic distortion, the frequency modulation index is given by

$$M_f = \frac{f_S}{f_e} = \frac{10000}{60} = 166.67$$

The one-line diagram of the system is shown in Fig. 5.37.

Example 5.7 Assume a residential house total load is 7.5 kW from 11 P.M.–8 A.M. and 15 kW for the remaining 24 hours. Determine the following:

i) Plot load cycle for 24 hours

ii) Total kWh energy consumption for 24 hours

iii) If the sun irradiance is 0.5 sun for 8 hours daily, what is the roof space needed to generate adequate kWh for 24 hours operation?

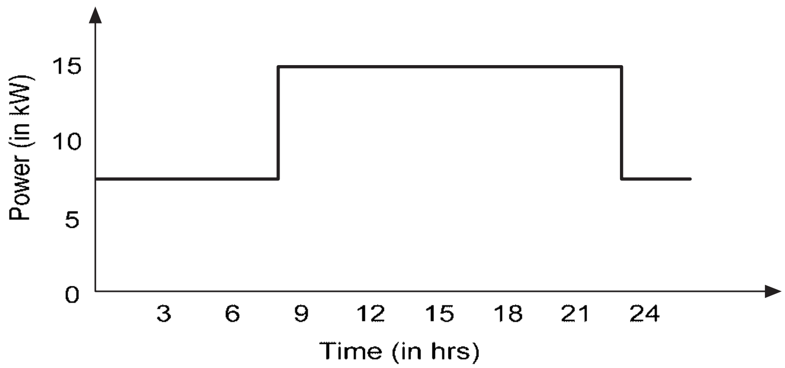

Figure 5.38 Plot of the Daily Load Cycle for Example 5.7.

iv) Assume the maximum kWh to be used during the night is 40% of the total daily load. Search the Internet to select a battery storage system and give your design data.

Solution

i) The load is 7.5 kW for 9 hours (11:00 P.M. to 8:00 A.M.) and 15 kW for 15 hours (8:00 A.M.–11:00 P.M.). The load cycle is as given in Fig. 5.38.

ii) The total kWh energy consumption for 24 hours is the area under the curve of the daily load cycle and is given by kWh = kW × hours.
Therefore, the energy consumption $= 7.5 \times 9 + 15 \times 15 = 292.5\ kWh$

iii) The type 1 PV is selected because it needs the minimum area per unit power produced.

The amount of power produced by type 1 PV (See Table 5.17) is equal to 190 W per module for 1 Sun. Therefore, the energy produced for 0.5 sun for 8 hours is given by: $0.5 \times 190 \times 8 = 0.76\ kWh$

The number of modules, *NM*, needed is given by

$$NM = \frac{total\ energy\ demand}{energy\ of\ one\ panel}$$

$$NM = \frac{292.5}{0.76} \approx 385$$

The surface area, *SM*, of one module is given by $width \times length$

$$SM = 34.6 \times 51.9 / 144 = 12.47\ ft^2$$

The total area, *TS*, for 292.5 kWh is given by the product of the number of modules and the area of one module:

$$TS = 385 \times 12.47 = 4801.11\ ft^2$$

iv) The energy used during the night is 40% of the total energy. Therefore, the energy demand for one night $= 0.4 \times 292.5 = 117\ kWh$.

From Table 5.23, a Class 6 battery storage system is chosen to store the kWh needed for the night. For battery storage conservation, the batteries should not be discharged more than 50% of their capacity.

The energy stored per battery is given by amp-hours × voltage (Ah × V). Therefore, the energy stored in one battery $= 255 \times 12 = 3.06\ kWh$. The number of batteries, *NB*, needed is given by

$$NB = \frac{2 \times energy\ demand}{energy\ stored\ per\ battery}$$

$$NB = \frac{2 \times 117}{3.06} = 77.$$

We can use three batteries in a string; the maximum number of strings in an array is three. Therefore, the maximum number of batteries in the array is $3 \times 3 = 9$.

The number of arrays of battery is given by

$$NA = \frac{total\ number\ of\ batteries}{number\ of\ batteries\ per\ array}$$

$$NA = \frac{77}{9} = 8$$

Example 5.8 Consider a microgrid with 2 MW. The system operates as part of a microgrid connected to the local utility at 13.2 KV.

The local utility uses the following design data:

a) The transformer specifications are 13.2 kV/460 V, 2 MVA, and 10% reactance; 460 V/220 V, 20 kVA, and 5% reactance.
b) The data for the PV system are given in Table 5.17.

Determine the following:

i) The number of modules in a string, number of strings, number of arrays, surface area, weight, and cost
ii) The inverter specification and the one-line diagram

Solution

A three-phase inverter rated at AC voltage 220 V can process approximately 20 kW. Based on 20 kW three-phase inverter and 220 volts AC output and the modulation index of 0.9, the input DC voltage is as given by Equation 5.16.

TABLE 5.36 Weight Per Unit Power.

PV Type	Surface Area of One Module (ft^2)	Power Rating (W)	Weight per Unit Power (lb per W)
1	33.07	190	0.174
2	39.00	200	0.195
3	40.70	170	0.239
4	18.30	87	0.210

$$V_{idc} = \frac{2\sqrt{2}\times 220}{\sqrt{3}\times 0.9} = 399\ V$$

i) Table 5.36, tabulates the data for each of the four types of PV modules.

Table 5.36 shows the PV module type 1 has the minimum weight per unit power; hence, our choice. The string voltage, SV of the PV system should be close to the rated inverter input voltage, V_{idc}.

Using string voltage, SV of 400, from Equation 5.13, we have

$$NM = \frac{399}{54.8} \approx 7$$

Using seven modules, string voltage, *SV*, as given by Equation 5.14 is

$$SV = 7\times 54.8 = 384\ V$$

The string power, *SP*, from Equation 5.9 is

$$SP = 7\times 190 = 1.33\ kW$$

Designing an array to generate 20 kW, the number of strings, *NS*, in an array is as given by Equation 5.15:

$$NS = \frac{20}{1.33} = 15$$

The number of arrays, *NA*, needed for this design is given by Equation 5.17:

$$NA = \frac{2000}{20} = 100$$

And, the total number of PV modules from Equation 5.19, $TNM = 7\times 15 \times 100 = 10,500$

TABLE 5.37 The Photovoltaic Specifications for 2000 kW.

PV Type	Number of Modules per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Power per String (kW)	Total Area of the PV (ft^2)	Total Weight of the PV (lb)	Total Cost of the PV (million $)
1	7	15	100	384	1.33	130,940	347,235	9.14

The total surface area, TS, needed by the type 1 PV module is computed from the area of one module and the total the number of modules.

$$TS = \frac{10,500 \times 34.6 \times 51.9}{144} = 130,940\ ft^2 = 3\ acre$$

The total weight, TW, for the type 1 PV module can be computed in a similar manner as

$$TW = 10,500 \times 33.07 = 347,235\ lb$$

The total cost for the type 1 PV module is the product of the number of modules and the cost of each module as given below.

$$\text{Total cost of PV modules} = 10,500 \times 870 = \$9.14\ million$$

ii) We will use one inverter for each array. Hence, the rating of each inverter will also be 20 kW.

The number of inverters, NI, needed for a generation of 2000 kW as from Equation 5.18

$$NI = \frac{2000}{20} = 100$$

For 2000 kW PV-generating station, we need 100 inverters to operate in parallel. Other designs using higher rating inverters are also possible. For this design, the final input DC voltage of the inverter is specified by the string voltage as

$$V_{idc} = V_{string} = 384\ V$$

With nominal DC input, the voltage of the inverter is selected, the amplitude modulation index, M_a is given as

$$M_a = \frac{2\sqrt{2} \times 220}{\sqrt{3} \times 384} = 0.93\ V$$

If the switching frequency is selected at 10 kHz, the frequency modulation index, M_f is given as

$$M_f = \frac{f_S}{f_e} = \frac{10000}{60} = 166.67$$

The one-line diagram of the system is given in Fig. 5.39. We will use 100 transformers of 20 kVA and 5% reactance, which are connected to the inverters to step the voltage up from 220 V to 460 V. Finally, one transformer of 460 /13.2 kV and 10% reactance of 2 MVA is used to connect the system to the local power grid.

Again, students should recognize that many designs are possible. Each design specification has its own limitation that must be taken into account. The above analysis can be altered as needed to satisfy any design requirements.

TABLE 5.38 Inverter Specifications.

Number of Inverters	Input Voltage V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
100	384	20	220	0.93	166.67

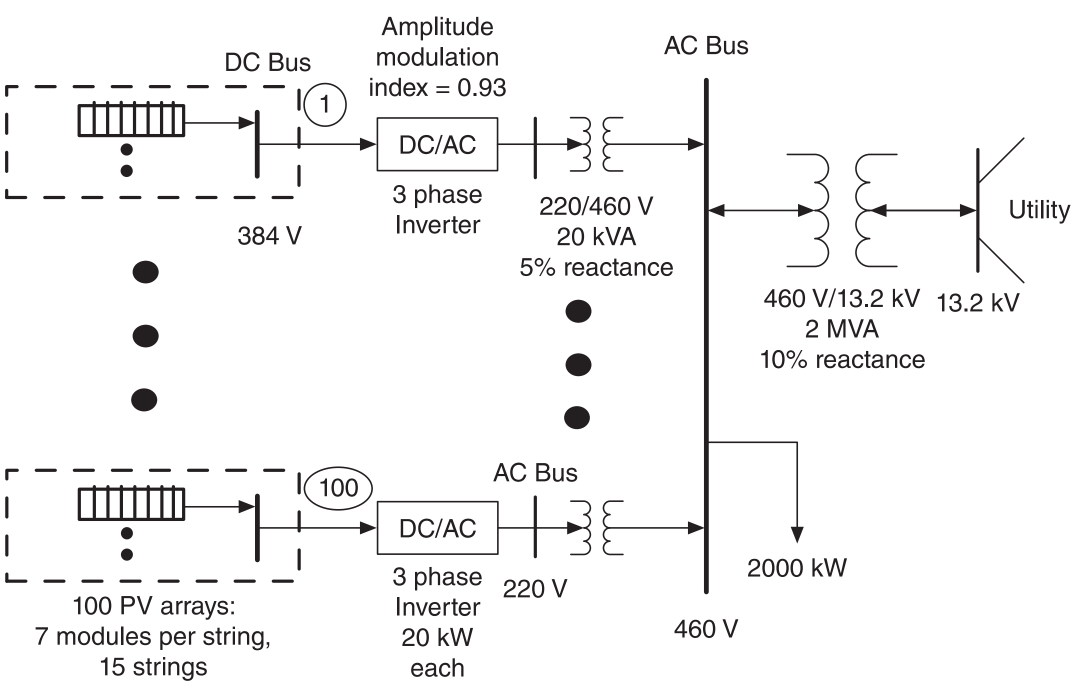

Figure 5.39 The One-Line Diagram of the System of Example 5.8.

Example 5.9 Design a microgrid of a PV system of 1000 kW that is connected to the local utility bus at 13.2 kV by a 220V/13.2kV, 500 kVA, 5% reactance transformer. A local load of 500 kW is supplied at 220 V. A battery storage system of 100 kWh is fed from an AC bus of a PV system using a bidirectional rectifier that is used 8 hours a day.

Solution

Figure 5.40 depicts the microgrid of Example 5.9. We can select a type 1 PV module that has the most minimum weight among the four PV types as shown in Table 5.36. The number of modules can be specified, based on the selection of string voltage, *SV*, as given by Equation 5.13.

$$NM = \frac{400}{54.8} \approx 7$$

If the *NM* is equal to 7, then, the SV, from Equation 5.14 is

$$SV = 7 \times 54.8 = 384\ V$$

The string power, *SP*, from Equation 5.9 is

$$SP = 7 \times 190 = 1.33\ kW$$

If we design based on 20 kW in an array, then the number of strings, *NS*, in an array from Equation 5.15 is

$$NS = \frac{20}{1.33} = 15$$

We can compute the number of arrays, *NA*, from Equation 5.17 as

$$NA = \frac{1000}{20} = 50$$

The total number of PV modules, the *TNM* from Equation 5.19 is

$$TNM = 7 \times 15 \times 50 = 5{,}250$$

The surface area, *TS* for type 1 PV modules is

$$TS = \frac{5{,}250 \times 34.6 \times 51.9}{144} = 65{,}470\ sq\ ft = 1.50\ acre$$

In a similar manner, we can compute the total weight and total cost.

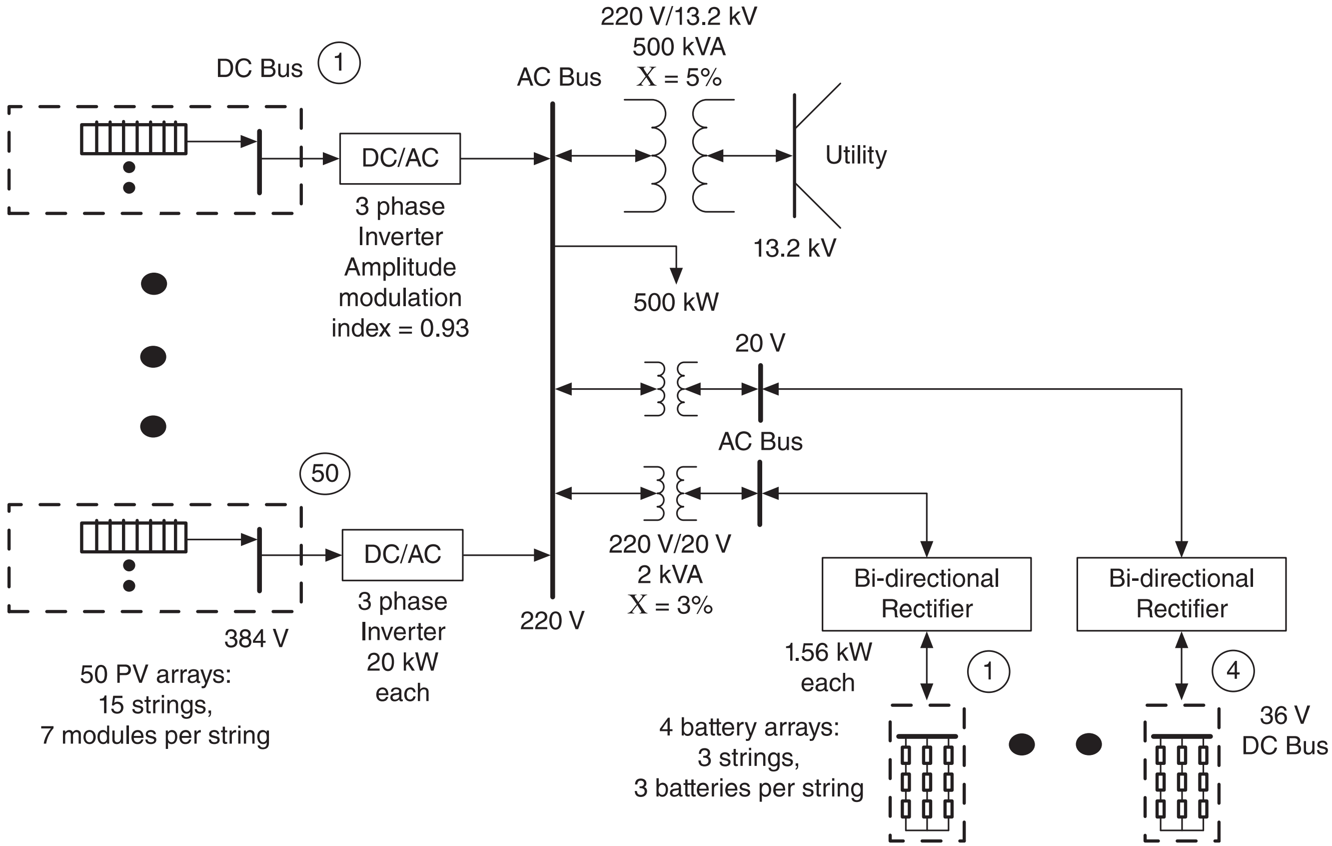

Figure 5.40 The One-Line Diagram of the PV System for Example 5.9.

TABLE 5.39 The Photovoltaic Specifications for 1000 kW.

PV Type	Number of Modules per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Total Area of the PV (ft^2)	Total Weight of the PV (lb)	Total Cost of the PV (Million $)
1	7	15	50	384	65,470	173,618	4.56

TABLE 5.40 Inverter Specifications.

Number of Inverters	Input Voltage, V_{idc} (V)	Power Rating (kW)	Output Voltage, V_{AC} (V)	Amplitude Modulation Index, M_a	Frequency Modulation Index, M_f
50	384	20	220	0.93	84

$$\text{Total weight} = 5,250 \times 33.07 = 173,618\ lb$$

$$\text{Total cost} = 5,250 \times 870 = \$4.56\ million$$

The rating of each inverter should be the same as the power generated by each array—20 kW. Because the input DC of the inverter is 384 V DC and output AC voltage of the inverter is 220 V AC, the amplitude modulation index, M_a of the inverter is given by

$$M_a = \frac{2\sqrt{2} \times 220}{\sqrt{3} \times 384} = 0.93$$

The number of inverters, NI, for a 1000 kW PV system from Equation 5.18 is

$$NI = \frac{1000}{20} = 50$$

Therefore, we need to connect 50 inverters, one for each array for generation of 1000 kW.

Let us select a switching frequency of 5.04 kHz. Therefore, the frequency modulation index is given by

$$M_f = \frac{f_S}{f_e} = \frac{5040}{60} = 84$$

One design choice for storing 100 kWh of energy is to use Class 6 batteries from Table 5.23.

TABLE 5.41 The Battery Storage Array Specification for 100 kWh.

Battery Class	Number of Batteries per String	Number of Strings per Array	Number of Arrays	String Voltage (V)	Energy Stored per Array (kWh)
6	3	3	4	36	27.54

These batteries are rated at 255 Ah at 12 V. Using three batteries per string and three strings in each array, we will have a battery storage system consisting of nine batteries in an array.

The string voltage, *SV*, for the battery storage system is given below.

$$SV = 3 \times 12 = 36\ V$$

The energy stored, *ES*, is

$$ES = Amp\text{-}hours \times Voltage$$

$$ES = 255 \times 12 = 3.06\ kWh$$

The energy stored in an array, *ESA*, is given by

$$ESA = number\ of\ batteries \times kWh\ of\ one\ battery$$

$$ESA = 9 \times 3.06 = 27.54\ kWh$$

The number of arrays, *NA*, needed to store 100 kWh is given by

$$NA = \frac{total\ energy}{energy\ in\ each\ array}$$

$$NA = \frac{100}{27.54} \approx 4$$

If the battery storage system is to supply PV loads for 8 hours, the battery storage system should be designed to discharge to 50% of capacity. Therefore, the power supplied by the battery storage system is 50% of the storage system capacity. For this design, using 50 kWh:

$$Storage\ kW = \frac{50}{8} = 6.25\ kW$$

And each array needs to supply one fourth of the total kW or 1.56 kW.

TABLE 5.42 Bidirectional Rectifier Specifications for Charging the Storage System.

Number of Bidirectional Rectifiers	Input Voltage (V) AC	Power Rating (kW)	Output Voltage (V) DC	Amplitude Modulation Index
4	20	1.56	36	0.9

A bidirectional rectifier can be used to charge and discharge the stored energy system from the AC bus of a PV-generating station (see Example 5.9). One bidirectional rectifier is used for each array of the battery storage system.

A bidirectional rectifier with an amplitude modulation index of 0.9 with the output DC voltage equal to that of the battery array is selected. The AC input of the rectifier for an output of 36 V, with a modulation index of 0.9 is given by

$$\begin{aligned} V_{L-L} &= \frac{\sqrt{3}\times M_a \times V_{odc}}{2\sqrt{2}} \\ &= \frac{\sqrt{3}\times 0.9\times 36}{2\sqrt{2}} = 20\,V\ AC \end{aligned}$$

One rectifier is connected to each of the battery arrays and each rectifier is designed to be rated at the same power rating of the battery array.

The total power rating of all the rectifiers together is $= 4\times 1.56 = 6.24\,kW$.

The bus voltage at the inverter output terminals is 220 V. One transformer of 220/20 V, 3% reactance, 2 kVA is used to step down the voltage from 220 V to 20 V for each of the bidirectional rectifiers.

A 500 kVA, 220 V/13.2 kV, 5% reactance transformer is used to connect the system with the local power grid.

5.13 THE ENERGY YIELD OF A PHOTOVOLTAIC MODULE AND THE ANGLE OF INCIDENCE

To estimate the energy yield of a photovoltaic module, the angle of inclination for a module with respect to the position of the sun must be determined. The angle of inclination is defined as the position that a magnetic needle makes with the horizontal plane at any specific location. The magnetic inclination is 0° at the magnetic equator and 90° at each of the magnetic poles. The irradiance is defined as the density of radiation incident on a given surface expressed in W/m^2 or W/ft^2. When the sun rotates, the angle at which the rays of sun reach a PV module change. The PV energy yield at a location as a function the PV module inclination angle is given in Appendix C.

5.14 THE STATE OF PHOTOVOLTAIC GENERATION TECHNOLOGY

In recent years, the shift towards the development and installation of PV sources of energy has resulted in an explosion of growth in the research, development, and manufacture of PV systems. Specifically, as of 2008, 13.4 GW of PV capacity has been installed in Western countries, which is an annual growth rate of 71%, with Germany leading in terms of installed capacity, followed by Spain. Importantly, in recent years, this growth has been fueled by an increase in grid-connected systems. Today, 35% of the share of grid-connected cumulative installed capacity is comprised of grid-PV-connected centralized applications. This further highlights the growing relevance of PV systems in fulfilling the ever-increasing energy demands of the 21st century.

The current PV modules have about 12–16% efficiency. However, there are modules in production with 36% efficiency that would change the panels from 300 W to 900 W in the same footprint. Research into the development of more efficient PV modules is ongoing worldwide. The theoretical limit for a PV module constructed from multilayered cells is 60%. In the future, we can expect PV panes rated 1,500 W; concentrated solar PV has the potential to go up to 200 suns today.

The technology of high power inverters is reaching into the 2 MW class. Solar panels are being designed at 600 V bus voltage. In Italy, the Rende installation uses one MW inverter and produces 1.4 GWh per year.[16] This design uses 180 W panels. Five or 10 years from now, we can envision a scalable design of a rooftop solar PV system that can produce 2 MW. It won't take much to get there from the PV side. Students are urged to search the Internet for up-to-date developments in PV systems.[1–6]

5.15 THE ESTIMATION OF PHOTOVOLTAIC MODULE MODEL PARAMETERS

Recall the equivalent circuit of a single-diode model of a PV cell.

The model of Figure 5.41 presents the current-voltage characteristics for a single cell of a PV module.[17–20] The model of a module consisting of a number of cells, n_c can be presented as:

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{n_c V_t}} - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{5.26}$$

In Equation 5.26, V_t, the junction thermal voltage, is given as:

$$V_t = \frac{AkT_{stc}}{q} \tag{5.27}$$

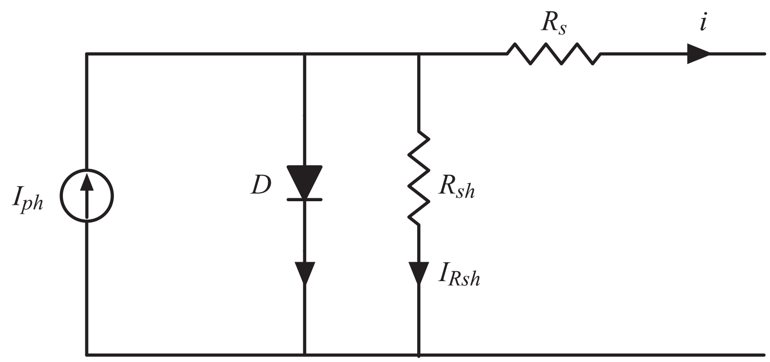

Figure 5.41 The Single Exponential Model of a PV Module.[17]

TABLE 5.43 The Photovoltaic Module Parameters of a Single Diode Model.

I_{ph}	Photo-generated current at STC
I_o	Dark saturation current at STC
R_s	Panel series resistance
R_{sh}	Panel parallel (shunt) resistance
n_c	Number of cells in the panel connected in series
V_t	Junction thermal voltage
A	Diode quality (ideality) factor
k	Boltzmann's constant
T_{stc}	Temperature at STC in Kelvin
q	Charge of the electron

It is helpful to express the equations in terms of V_t rather than A. The value of A can be determined easily if V_t is found, by simply rearranging the terms of Equation 5.27, we have:

$$A = \frac{qV_t}{kT_{stc}} \tag{5.28}$$

Table 5.43 features a description of the variables used in modeling a module presented by Equation 5.26.

The term STC denotes the standard conditions used to measure the nominal output power of photovoltaic cells. The cell junction temperature at STC is 25°C, the irradiance level is 1000 W/m^2, and the reference air mass is 1.5 solar spectral irradiance distributions. In Equation 5.26, the term "-1" is much smaller than the exponential term and it is generally ignored.

The problem of estimating the model parameters is to determine the five parameters, I_{ph}, I_o, R_s, R_{sh}, and A from the data sheet provided by the manufacturer of the PV module measured under STC. Because A can be expressed

TABLE 5.44 The Measured Data Used in Model Estimation.

I_{SC}	Short-circuit current at STC
V_{OC}	Open-circuit voltage at STC
V_{mmp}	Voltage at the maximum power point (MPP) at STC
I_{mpp}	Current at the MPP at STC

easily in terms of V_t, q, k, and T_{stc}, of which only the former is unknown, the approach will be to first obtain V_t, and then solve Equation 5.27 for A.

The V-I characteristic will be employed to estimate the model parameters. These characteristics are the short-circuit current, the open-circuited voltage, and the MPP. Table 5.44 summarizes the measured data at STC used for model development.

The model of Equation 5.26 is evaluated at the measured data points as defined in Table 5.44.

$$I_{sc} = I_{ph} - I_o e^{\frac{I_{sc}R_s}{n_c V_t}} - \frac{I_{sc}R_s}{R_{sh}} \tag{5.29}$$

$$I_{mpp} = I_{ph} = I_o e^{\frac{V_{MPP}+I_{MPP}R_s}{n_c V_t}} - \frac{V_{MPP}+I_{MPP}R_s}{R_{sh}} \tag{5.30}$$

$$I_{oc} = 0 = I_{ph} - I_o e^{\frac{V_{oc}}{n_c V_t}} - \frac{V_{oc}}{R_{sh}} \tag{5.31}$$

Because the MPP corresponds to the point where the power is maximum on the V-I characteristic, we have:

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{MPP}\\ I=I_{MPP}}} = 0 \tag{5.32}$$

We are estimating five parameters; therefore, a fifth equation is still needed. The derivative of the current with the voltage at short-circuit is given as the negative of the reciprocal of R_{sho},

$$\left.\frac{dI}{dV}\right|_{I=I_{sc}} = -\frac{1}{R_{sho}} \tag{5.33}$$

Hence, five equations with five variables have been established. The detailed derivation of five parameters from five equations are given in references 17–19.

In this chapter, we studied solar energy systems, specifically the development and design of a PV system with PV microgrid modeling. We also learned how to estimate the energy yield of a photovoltaic module based on the angle of inclination for a PV string with respect to the position of the sun. The irradiance was defined as the density of radiation incident on a given surface expressed in W/m^2 or W/ft^2. Finally, we developed an estimation method to construct a model for a PV module.

PROBLEMS

5.1 Search the Internet and specify four PV modules. Give a table as shown below (Table 5.45) and compare the rated voltage, cost, width, length, and weight.

5.2 Search the Internet to find the voltage-current characteristic of four PV modules. Make a table of input impedances as current varies for each operating temperature. Develop a plot of input impedance as a function of PV load current for each operating temperature.

5.3 Design a microgrid of PV rated at 100 kW of power at 230 V AC using a PV module with the following voltage and current characteristics. Determine the following:
- *i*) Number of modules in a string for each PV type
- *ii*) Number of strings in an array for each PV type
- *iii*) Number of arrays
- *iv*) Inverter specifications
- *v*) One-line diagram of this system

5.4 Design a microgrid of a PV system rated at 600 kW of power at 460 V AC using a PV module with the data given in Table 5.46.

TABLE 5.45 Voltage and Current Characteristics of a Typical PV Module.

Power (max)
Voltage at maximum power point (MPP)
Current at MPP
V_{oc} (open-circuit voltage)
I_{sc} (short-circuit current)
Efficiency
Cost
List five operating temperatures for V_{oc} vs. I_{sc}
Width
Length
Height
Weight

TABLE 5.46 Photovoltaic Module Data for Problem 5.3.

Power (max)	400 W
Voltage at Maximum Power Point (MPP)	52.6 V
Current at MPP	6.1 A
V_{oc} (open-circuit voltage)	63.2 V
I_{sc} (short-circuit current)	7.0 A

Determine the following:

i) Number of modules in a string for each PV type
ii) Number of strings in an array for each PV type
iii) Number of arrays
iv) Inverter specifications
v) One-line diagram of this system

5.5 Search the Internet for four single-phase inverters and summarize the operating conditions in a table and discuss the results.

5.6 Search the Internet for DC/DC boost converters and DC/AC inverters and create a table summarizing the operating conditions of four DC/DC boost converters and DC/AC inverters and discuss the results and operations.

5.7 Design a microgrid of 50 kW, rated at 230 V AC. Use the PV module of Problem 5.3 and the converters of Problem 5.5. The design should use the least number of converters and inverters. Determine the following:

i) Number of modules in a string for each PV type
ii) Number of strings in an array for each PV type
iii) Number of arrays
iv) Converter and inverter specifications
v) One-line diagram of this system

5.8 Design a microgrid of 600 kW of power rated at 230 V AC. Use the PV module of Problem 5.3. The design should use the least number of converters and inverters. Determine the following:

i) Number of modules in a string for each PV type
ii) Number of strings in an array for each PV type
iii) Number of arrays
iv) Converter and inverter specifications
v) One-line diagram of this system

5.9 Design a microgrid of a PV system rated at 2 MW and connected through a smart net metering to the local utility at 13.2 kV. The local loads consists of 100 kW of lighting loads rated at 120 V and 500 kW

TABLE 5.47 Photovoltaic Module Data.

Panel	Type 1	Type 2	Type 3	Type 4
Power (Max), W	190	200	170	87
Voltage at max. power point (MPP), V	54.8	26.3	28.7	17.4
Current at MPP, A	3.47	7.6	5.93	5.02
V_{OC} (open-circuit voltage), V	67.5	32.9	35.8	21.7
I_{SC} (short-circuit current, A	3.75	8.1	6.62	5.34
Efficiency	16.40%	13.10%	16.80%	>16%
Cost	$870.00	$695.00	$550.00	$397.00
Width	34.6″	38.6″	38.3″	25.7″
Length	51.9″	58.5″	63.8″	39.6″
Thickness	1.8″	1.4″	1.56″	2.3″
Weight	33.07 lbs	39 lbs	40.7 lbs	18.3 lbs

of AC load rated at 220 V. The system has a 700 kWh storage system. Local transformer specifications are 13.2 kV/460 V, 2 MVA, and 10% reactance; 460 V/230 V, 250 kVA, and 7% reactance; and 230V/120 V, 150 kVA, and 5% reactance. The data for this problem are given in Table 5.47.

i) Search the Internet for four DC/DC boost converters, rectifier, and inverters and create a table. Summarize the operating conditions in a table and discuss the results and operations as they relate to this design problem. Develop a MATLAB testbed to perform the following:

ii) Select a boost converter, bidirectional rectifier, and inverters for the design of a microgrid from commercially available converters. If commercial converters are not available, specify the data for a new design of a boost converter, bidirectional rectifier, and inverters.

iii) Give the one-line diagram of your design. Make tables and give the number of modules in a string for each PV type, number of strings in an array for each PV type, number of arrays, converters, weight and surface area required for each PV module type.

iv) Design a 1700 kWh storage system. Search online and select a deep-cycle battery storage system. Give the step in your design and including the dimension and weight of the storage system.

v) Develop a per unit model of the PV microgrid system

5.10 Design a PV microgrid system operating at voltage of 400 V DC serving a load of 50 kW and at 220 V AC. Use the data sets given in Tables 5.48 and 5.50. Perform the following:

i) Select a deep-cycle battery to store 100 kWh

ii) Select a boost converter, bidirectional rectifier, and inverters for the design of a microgrid from commercially available converters

TABLE 5.48 Typical Deep-Cycle Battery Data.

		Overall Dimensions				Capacity Ampere-Hours							
Part Number	Volts	Length (mm)	Weight (mm)	Height (mm)	Unit Wtlbs (kg)	1-H Rate	2-H Rate	4-H Rate	8-H Rate	24-H Rate	48-H Rate	72-H Rate	120-H Rate
PVX-340T	12	7.71 (196)	5.18 (132)	6.89 (175)	25 (11.4)	21	27	28	30	34	36	37	38
PVX-420T	12	7.71 (196)	5.18 (132)	8.05 (204)	30 (13.6)	26	33	34	36	42	43	43	45
PVX-490T	12	8.99 (228)	5.45 (138)	8.82 (224)	36 (16.4)	31	39	40	43	49	52	53	55
PVX-560T	12	8.99 (228)	5.45 (138)	8.82 (224)	40 (18.2)	36	45	46	49	56	60	62	63
PVX-690T	12	10.22 (260)	6.60 (168)	8.93 (277)	51 (23.2)	42	53	55	60	69	73	76	79
PVX-840T	12	10.22 (260)	6.60 (168)	8.93 (277)	57 (25.9)	52	66	68	74	84	90	94	97
PVX-1080T	12	12.90 (328)	6.75 (172)	8.96 (228)	70 (31.8)	68	86	88	97	108	118	122	126
PVX-1040T	12	12.03 (306)	6.77 (172)	8.93 (227)	66 (30.0)	65	82	85	93	104	112	116	120
PVX-890T	12	12.90 (328)	6.75 (172)	8.96 (228)	62 (28.2)	55	70	72	79	89	95	98	102

TABLE 5.49 Boost Converters.

Input Voltage (V)	Output Voltage (V)	Power (kW)
24–46	26–48	9.2
24–61	26–63	12.2
24–78	26–80	11.23
24–78	26–80	11.23
24–78	26–80	13.1
24–98	26–100	12.5
80–158	82–160	15.2
80–198	82–200	14.2
80–298	82–300	9.5

TABLE 5.50 Single-Phase Inverter Data.

Inverter	Type 1	Type 2	Type 3	Type 3
Power	500 W	5 kW	15 kW	4.7 kW
Input Voltage DC	500 V	500 V max	500 V	500 V
Output Voltage AC	230 VAC/60 Hz @ 2.17 A	230 VAC/ 60 Hz @ 27 A	220 VAC/ 60 Hz @ 68 A	230 VAC/ 60 Hz @ 17.4 A
Efficiency	Min. 78% @ full load	97.60%	> 94%	96%
Length	15.5″	315 mm	625 mm	550 mm
Width	5″	540 mm	340 mm	300 mm
Height	5.3″	191 mm	720 mm	130 mm
Weight	9 lbs	23 lbs	170 kg	20 lbs

(see data in Tables 5.48–5.50). If commercial converters are not available, specify the data for the new design of a boost converter, bidirectional rectifier, and inverters.

iii) Give the one-line diagram of your design. Make tables and give the number of modules in a string for each PV type; number of strings in an array for each PV type; number of arrays, converters, weight, and surface area required for each PV module type.

5.11 Write a MATLAB testbed for the design of a PV system with minimum weight and minimum number of inverters using the data of Tables 5.47–5.51.

Perform the following:

i) PV system for 5000 kW at 3.2 kV AC: Specify the inverter operating condition

TABLE 5.51 Three-Phase Inverter Data.

Inverter	Type 1	Type 2	Type 3	Type 3
Power	100 kW	250 kW	500 kW	1 MW
Input voltage DC	900 V	900 V max	900 V	900 V
Output voltage AC	660 VAC/60 Hz	660 VAC/ 60 Hz	480 VAC/ 60 Hz	480 VAC/ 60 Hz
Efficiency	Peak efficiency 96.7%	Peak efficiency 97.0%	Peak efficiency 97.6%	Peak efficiency 96.0%
Depth	30.84″	38.2″	43.1″	71.3″
Width	57″	115.1″	138.8″	138.6″
Height	80″	89.2″	92.6″	92.5″
Weight	2350 lbs	2350 lbs	5900 lbs	12000 lbs

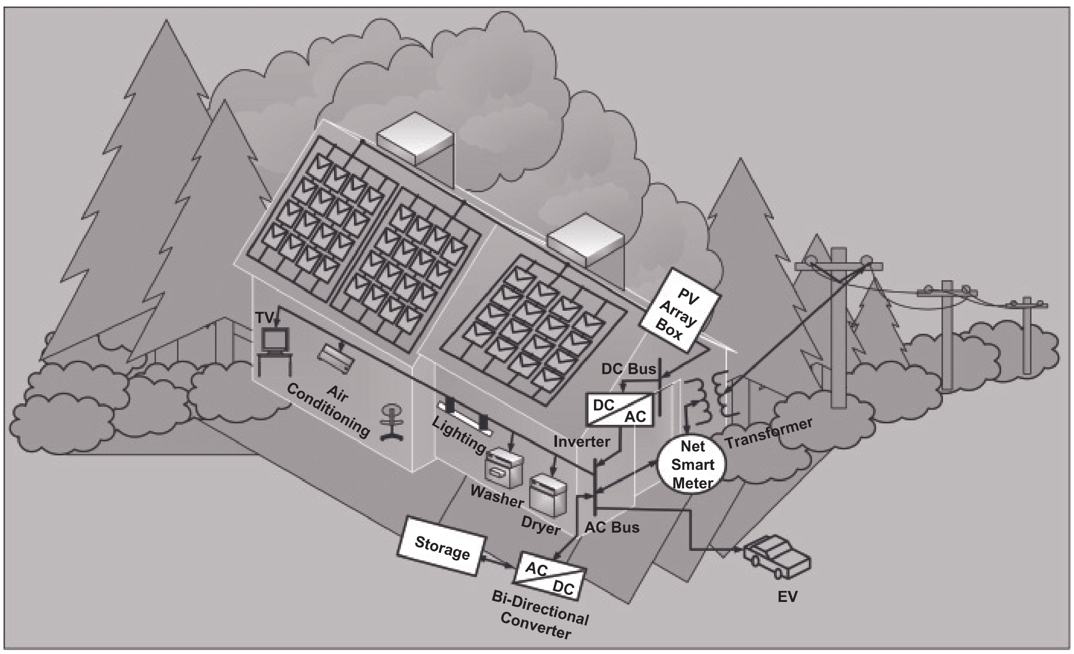

Figure 5.42 Figure for Problem 5.12.

ii) PV system for 500 kW at 460 V AC: Specify the inverter operating condition

iii) PV system for 50 kW at 120 V AC: Specify the inverter operating condition

5.12 Consider the residential home of Fig. 5.42. Perform the following:

i) Estimate the load consumption of the house.

ii) Plot the daily load cycle operation of the house's loads over 24 hours and calculate the total energy consumption.

iii) Search the Internet and select a PV module and design the PV array for the house. Compute cost, weight of PV array, and roof areas needed for the PV system. Search the Internet and select an inverter, battery storage, and bidirectional converter.

5.13 For Problem 5.11, if only 25% of the load is operated during the night, use the data of Problem 5.10 and specify a battery storage system to store the required energy for operating 25% of the load during the night.

5.14 If the price of kWh from a utility company is $0.3 for buying or selling energy, estimate the net operating cost or revenue for the house of Problem 5.12.

5.15 Design a PV system rated 50 kW using a boost converter and a DC/AC inverter. The system operates as a standalone and supports a water pumping system with a rated load voltage of 120 V AC. Use the data given in Problem 5.10.

5.16 Design a residential PV system. The load cycle is 10 kW from 11 P.M. to 8 A.M. and 14 kW for the remaining 24 hours. Determine the following:

i) Total kWh energy consumption for 24 hours

ii) What is the roof space needed to generate adequate kWh for 24 hours operation?

iii) Assume the maximum kWh to be used during the night is 40% of the total daily load. Search the Internet to select a battery storage system and compute the required energy for nightly operation. Give your design data.

5.17 Design a microgrid for a PV system rated one MW of power at 220 V, 60 Hz with all the PV strings connected to the same DC bus. The transformer data are 220/460, V 250 kVA, and 5% reactance; and 460 V / 13.2 kV of 1 MVA, and 10% reactance. Use the data given in Tables 5.47 through 5.51.

Determine the following:

i) Number of modules in a string for each PV type, number of strings in an array for each PV type, number of arrays and surface area, weight and cost for each PV type.

ii) Boost converter and inverter specifications and the one-line diagram of this system

5.18 Assume a sample value for the global daily irradiation, G = [1900, 2690, 4070, 5050, 6240, 7040, 6840, 6040, 5270, 3730, 2410, 1800] for 12 months of the year. Assume a reflectivity of 0.25. Perform the following:

i) Write a MATLAB M-file program to (a) compute the irradiation on different inclination angles, (b) tabulate the irradiance for each month at different inclination angles, (c) tabulate the overall irradiance per year for different inclination angles, and (d) find the optimum inclination angle for each month and a year.

ii) If the sun irradiance is 0.4 sun for 8 hours daily for this location what is the roof space needed to capture 20 kW at an optimal angle?

iii) If the sun irradiance is 0.3 sun on the average over a year for 5 hours daily for this location what total kW can be captured over 1500 square feet at the optimum inclination angle?

5.19 Assume the global daily irradiation (G) for the city of Columbus solar irradiation data, G, on the horizontal surface is as follows:

G = [1800, 2500, 3500, 4600, 5500, 6000, 5900, 5300, 4300, 3100, 1900, 1500] for 12 months of the year. The latitudinal location of Columbus is 40 degrees. Assume a reflectivity of 0.25. Perform the following:

i) Write a MATLAB M-file to (a) compute the irradiation on different inclination angles, (b) tabulate the irradiance for each month at different inclination angles, (c) tabulate the overall irradiance per year for different inclination angles, and (d) find the optimum inclination angle for each month and a year.

ii) If the sun irradiance is 0.4 sun for 8 hours daily for this location what is the roof space needed to capture 50 kW at an optimum inclination angle?

iii) If the sun irradiance is 0.3 sun on the average over a year for 5 hours daily for this location what total kW that can be captured over 1500 square feet at the optimum inclination angle?

5.20 For your city, search the Internet for solar irradiation data, G, on the horizontal surface and its latitudinal location. Perform the following:

i) Write a MATLAB M-file to (a) compute the irradiation on different inclination angles, (b) tabulate the irradiance for each month at different inclination angles, (c) tabulate the overall irradiance per year for different inclination angles, and (d) find the optimum inclination angle for each month and a year.

ii) If the sun irradiance is 0.3 sun on the average over a year for 5 hours daily for this location what is total kW that can be captured over 1500 square feet at the optimum inclination angle?

TABLE 5.52 Data for Problem 5.21.

a_1 (Isc)	3.87 A
a_2 (Voc)	42.1 V
a_3 (VMPP)	33.7 V
a_4 (IMPP)	3.56 A
a_5 (nc)	72

5.21 For a PV module given below (Table 5.52), write a MATLAB simulation testbed using Gauss–Seidel iterative approximation and estimate the module parameters (use Internet resources and learn about Gauss–Seidel iterative approximation).

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