Lecture 5: Microgrid Solar Energy and storage

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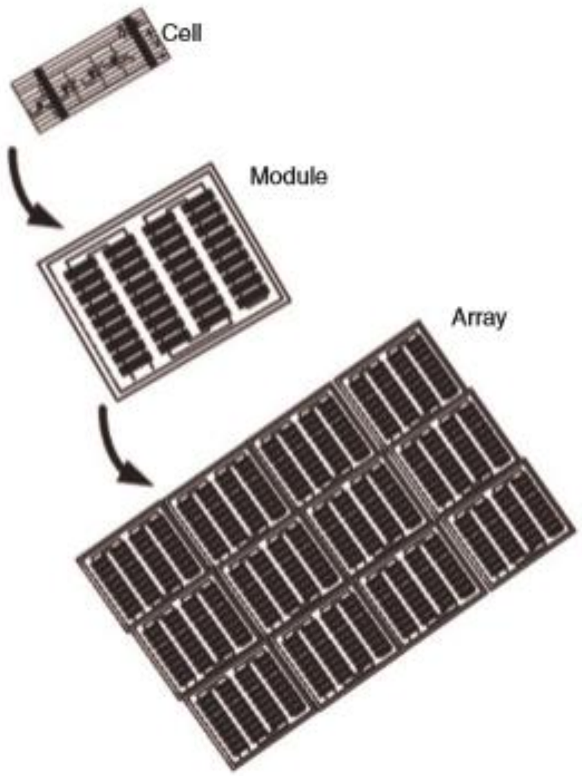
5.1 Photovoltaic power conversion

- Solar cells convert the radiation energy directly to electric energy.
- Solar cells, also called photovoltaic (PV) cells, were developed by Carlson and Wronski in 1976.
- A PV module consists of a number of PV cells. When sunlight strikes the PV cell, electrons are freed from their atoms. The freed electrons are directed toward the front surface of the solar cell.
- This process creates a current flow that occurs between the negative and positive sides. The PV photon cell charge offers a voltage of 1.1 up to 1.75 electron volt (eV) with a high optical absorption.

5.1 Photovoltaic power conversion

- Figure below depicts a solar cell structure. A photovoltaic (PV) module connects a number of PV cells in series. You may think of a PV cell as a number of capacitors that are charged by photon energy of light.



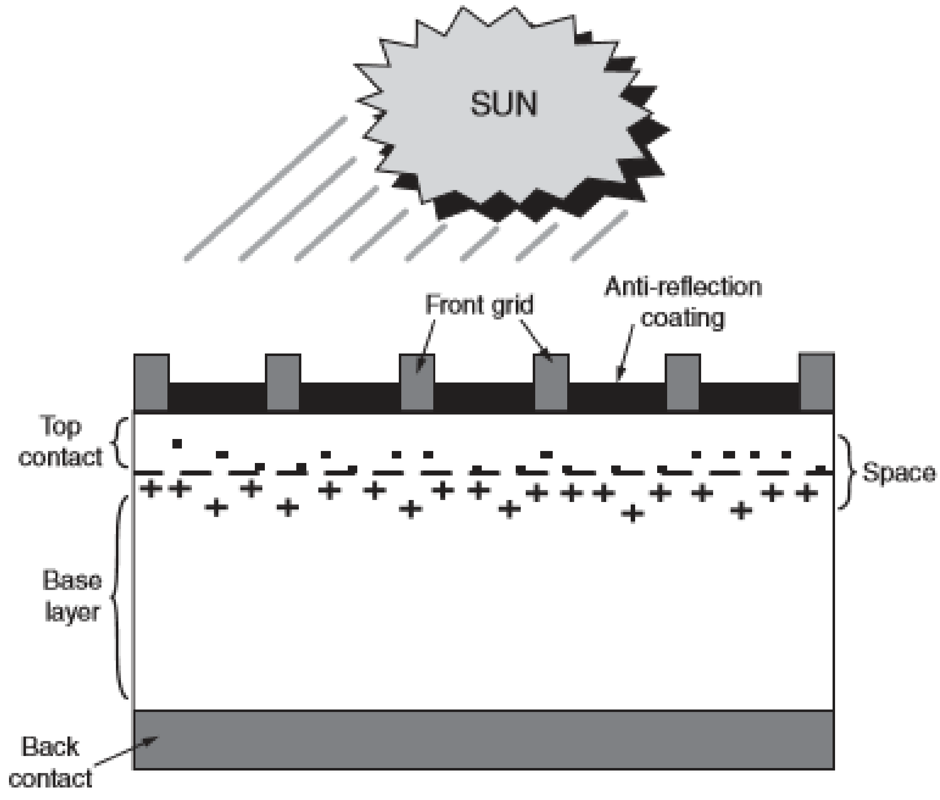


Figure 5.7 The Structure of a Photovoltaic Cell.[2]

5.2 Photovoltaic materials

- The manufacturing of PV cells is based on two different types of material:

(1) a semiconductor material that absorbs light and converts it into electron – hole pairs, and

(2) a semiconductor material with junctions that separate photo generated carriers into electrons and electron holes.

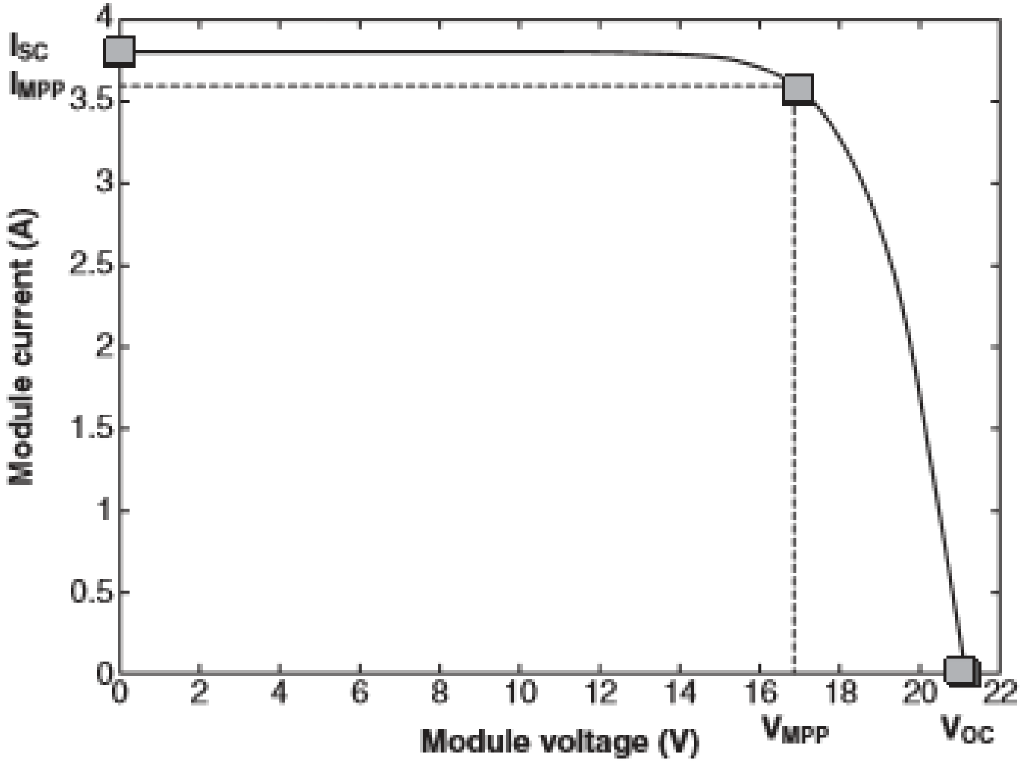
- The contacts on the front and back of the cells allow the current to the external circuit. Crystalline silicon cells (c- Si) are used for absorbing light energy in most semiconductors used in solar cells. Crystalline silicon cells are poor absorbers of light energy; they have an efficiency in the range of 11 to 18% of that of solar cells. The most - efficient monocrystalline c- Si cell uses laser-grooved, buried grid contacts, which allow for maximum light absorption and current collection.
- Each of the c- Si cells produces approximately 0.5 V.

5.2 Photovoltaic materials

- When 36 cells are connected in series, it creates an 18 volt module.
- In the thin- film solar cell, the crystalline silicon wafer has a very high cost. Other common materials are amorphous silicon (a-Si), and cadmium telluride and gallium, which are another class of polycrystalline materials.
- The thin - film solar cell technology uses a-Si and a p-i-n single - sequence layer, where "p" is for positive and "n" for negative, and "i" for the interface of a corresponding p - and n - type semiconductor.
- Due to the basic properties of c - Si devices, they may stay as the dominant PV technology for years to come. However, thin - film technologies are making rapid progress and a new material or process may replace the use of c - Si cells.

5.2 Photovoltaic characteristics

- As sun irradiance energy is captured by a PV module, the open- circuit voltage of the module increases. This point is shown in the Figure by Voc with zero - input current. If the module is short - circuited, the maximum short - circuit current can be measured. This point is shown by Isc with zero - output voltage. The point on the I versus V characteristic where maximum power point (P_{MPP}) can be extracted lies at a current I_{MPP} and the corresponding voltage point, V_{MPP}. This information is used to design PV strings and PV - generating power sources.



5.2 Photovoltaic characteristics

Module	Type 1	Type 2	Type 3	Type 4
Power (Max), W	190	200	170	87
Voltage at maximum 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

Voltage and Current Characteristics of Typical Photovoltaic Modules

Typical Cell Temperature Coefficient		
Power	$T_k(P_p)$	–0.47%/°C
Open-circuit voltage	$T_k(V_{oc})$	–0.38%/°C
Short-circuit current	$T_k(I_{sc})$	0.1%/°C

Cell Temperature Characteristics of a Typical Photovoltaic Module

5.2 Photovoltaic characteristics

- PV module selection criteria are based on a number of factors:

(1) the performance warranty,

(2) module replacement ease, and

(3) compliance with natural electrical and building codes.

- A typical silicon module has a power of 300 W with 2.43 m^2 surface area; a typical thin film has a power of 69.3 W with an area of 0.72 m^2 . Hence, the land required by a silicon module is almost 35% less. Typical electrical data apply to standard test considerations (STC).
- For example, under STC, the irradiance is defined for a module with a typical value such as 1000 W/m^2, spectrum air mass (AM) 1.5, and a cell temperature of 25 ° C.

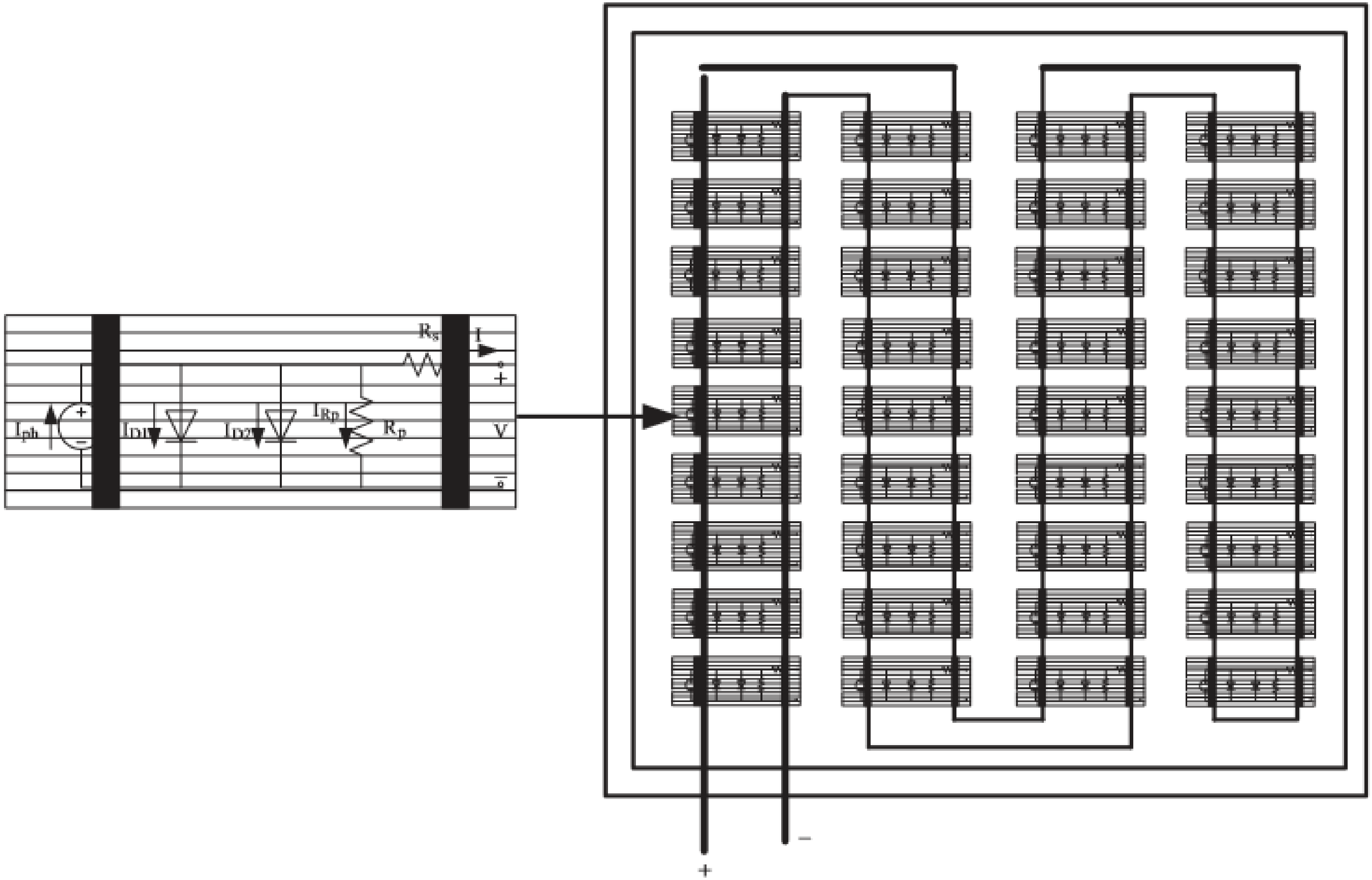
5.2 Photovoltaic characteristics

- The PV fill factor (*FF*) , as shown in Fig. below, is defined as a measure of how much solar energy is captured. This term is defined by PV module open circuit voltage (V_{oc}) , and PV module short- circuit current (I_{sc}).

$$FF = \frac{V_{MPP} I_{MPP}}{V_{OC} I_{SC}}$$

and $$P_{\max} = FF \cdot V_{OC} I_{SC} = V_{MPP} I_{MPP}$$

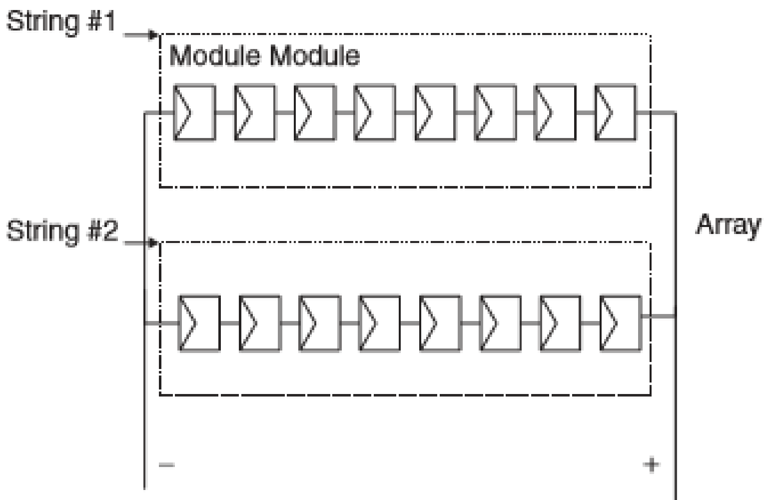
- Some PV modules have a high fill factor. In the design of PV system a PV module with a high FF would be used. For high-quality PV modules, FFs can be over 0.85. For typical commercial PV modules, the value lies around 0.60.



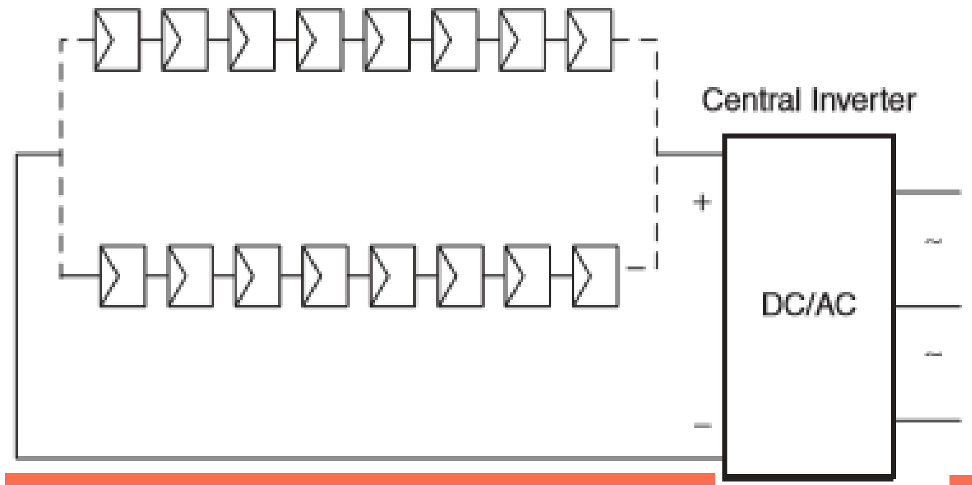
A Photovoltaic Module Consisting of 36 Photovoltaic Cells. If each cell is rated at 1.5 V, the module rated voltage is 54 V.

5.3 Photovoltaic efficiency

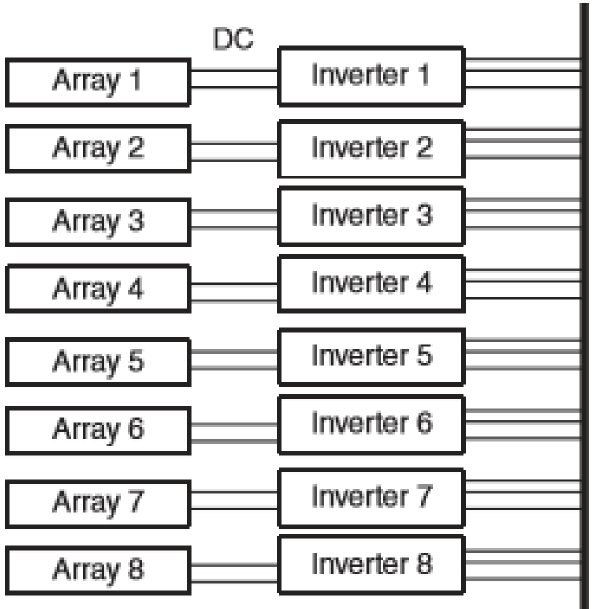
- A string is designed by connecting a number of PV modules in series. A number of strings connected in parallel make an array. Two general designs of PV systems can be envisioned.



Basic Configuration Showing Modules, Strings, and an Array



Central Inverter for a Large-Scale Photovoltaic Power Confi-guration.



General Structure of Photovoltaic Arrays with Inverters.

5.3 Photovoltaic efficiency

- Basically, to provide a higher DC operating voltage, modules are connected in series. To provide a higher operating current, the modules are connected in parallel.

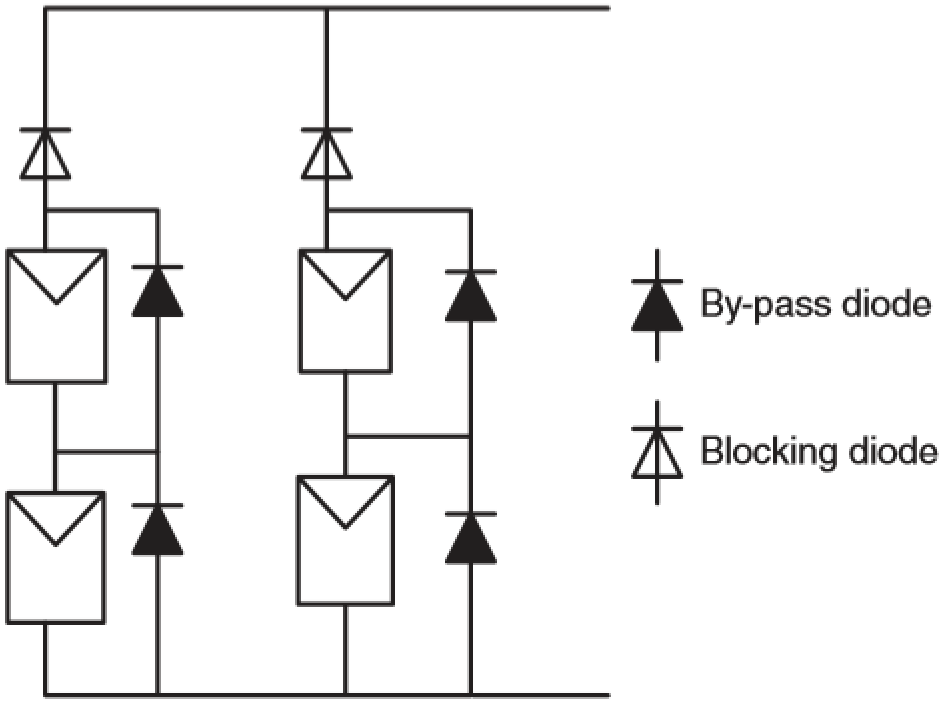
$$\text{V (series connected)} = \sum_{j=1}^{n} V_j;\ n\text{: number of series connected panels}$$

- For parallel connected panels

$$\text{I (parallel connected)} = \sum_{j=1}^{m} I_j;\ m\text{: number of parallel connected panels}$$

- In a PV system consisting of a number of arrays, all arrays must have equal exposure to sunlight: the design should place the modules of a PV system such that some of them will not be shaded. Otherwise, unequal voltages will result in some strings with unequal circulating current and internal heating producing power loss and lower efficiency. Bypass diodes are usually used between modules to avoid damage.

5.3 Photovoltaic efficiency



Bypass and Blocking Diodes in a Photovoltaic Array

5.4 The design of Photovoltaic systems

- In concrete terms, if we are designing a PV-generating system, we are using manufactured PV modules that have certain characteristics.
- However, in defining the overall objective of the PV systems we are putting into place, then some PV modules may satisfy those objectives and some may not. Therefore, we need to test available PV modules against our design specifications.
- For a PV - generating system, the first specification is the power requirement in kW or MW that we intend to produce. If the PV system is to operate as an independent power generating station, the rated load voltage is specified.
- For example, for a residential PV system, we may install from a few kilowatts of power to serve the residential loads at a nominal voltage of 120 V and 207.8 V. If the residential PV is connected to the local utility, then the interconnection voltage must be specified for the design of such a system.

5.4 The design of Photovoltaic systems

- We already know that a PV module generates a DC voltage source and DC power. How high a DC voltage is safe in a residential system is determined by the electric codes of a particular locality. In principle, we may want to design the residential PV system at a lower DC voltage and higher PV DC voltage for more - involved power systems at commercial and industrial sites.
- Another design consideration for residential users may be the weight and surface area needed for a PV system. Finally, it is understood that the PV designer always seeks to design a PV system to satisfy site constraints at the lowest installed and operating costs.

5.4 The design of Photovoltaic systems

- One PV module has a limited power rating; therefore, to design a higher power rating, we construct a string by connecting a number of PV modules in series.

$$SV = NM \times V_{OC}$$

- where SV defines, the string voltage and Voc is the open circuit voltage of a module. As an example, if the number of modules is five and the open-circuit voltage of the module is 50 V, we have

$$SV = 5 \times 50 = 250\ V\ \mathrm{DC}$$

- This may be a high voltage in a residential PV system. We can think of a PV cell, a module, or an array as a charged capacitor. The amount of charge of a PV system is a function of sun irradiance. At full sun, the highest amount of charge is stored that will generate the highest open- circuit voltage for a PV system. In general, the open - circuit voltage of a PV panel for a residential system might be set at a voltage lower than 250 V DC.

5.4 The design of Photovoltaic systems

- The string power, SP, is the power that can be produced by one string.

$$SP = NM \times PM$$

where *NM* is the number of modules and *PM* is the power produced by a module. or example, if a design uses four PV modules, each rated 50 W, then the total power produced by the string is given as

$$SP = 4 \times 50 = 200 \text{ W}$$

As we discussed, for producing higher rated power from a PV - generating station, we can increase the string voltage. In addition, we can connect a number of strings in parallel and create an array. Therefore, the array power, AP is equal the number of string times the string power.

$$AP = NS \times SP$$

5.4 The design of Photovoltaic systems

- If the number of strings is 10 and each string is producing 200 W, we have:

$$AP = 10 \times 200 = 2000 \text{ W}$$

- To obtain the maximum power out of an array, the maximum power point (MPP) tracking method is used. The MPP tracking method locates the point on the trajectory of power produced by an array where the array voltage and array current are at its maximum point and the maximum power output for the array. The array MPP is defined as

$$P_{MPP} = V_{AMPP} \times I_{AMPP}$$

where V_{AMPP} is the array voltage at MPP tracking and I_{AMPP} is the array current at its maximum power point tracking (MPPT). An array is connected to either an inverter or a boost converter and the control system operates the array at its MPP tracking.

5.4 The design of Photovoltaic systems

- The final design of a PV system is based on the MPP operation of a PV array generating station. Keeping in mind, however, the converter control system is designed to locate the maximum operating point based on generated array voltage and array current, thus accommodating the changing irradiance energy received by an array as the sun' s position changes during the day.
- The inverter output voltage is controlled by the inverter amplitude modulation index. To process the maximum power by an inverter, the amplitude modulation index, M_a should be set at maximum value without producing the unwanted harmonic distortion. The value of M_a is set less than one and in the range of 0.95 to produce the highest AC output voltage.

Example 1: Design a PV system to process 10 kW of power at 230 V, 60 Hz single phase AC. Determine the following:

i) Number of modules in a string and number of strings in an array

ii) Inverter specification and one - line diagram

Solution

The load voltage is specified as 230 V single - phase AC. To acquire maximum power from the PV array, we select a modulation index of Ma =0.9. The inverter input voltage is given by

$$V_{idc} = \frac{\sqrt{2}V_{ac}}{M_a}$$

So that:

$$V_{idc} = \frac{\sqrt{2} \times 230}{0.9} = 361.4\ V$$

5.4 The design of Photovoltaic systems

- The inverter is designed to operate at the MPPT of PV array. Therefore, the number of modules to be connected in series in a string is given by

$$NM = \frac{V_{idc}}{V_{MPP}}$$

where VMPP is the voltage at the MPP of PV of the module: $NM = \frac{361.4}{50.6} \approx 7$

- The string voltage is given as $SV = NM \times V_{MPP}$

- Using this module (Table below, Vmpp=50.6V) we get $SV = 7 \times 50.6 = 354.2\ V$

5.4 The design of Photovoltaic systems

- The power generated by one string is given by:

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

where Pmpp is the nominal power generated at the MPP tracking.

Power (max)	300 W
Maximum voltage, P_{MPP}	
Voltage at maximum power point (MPP), V_{MPP}	50.6 V
Current at MPP, I_{MPP}	5.9 A
V_{oc} (open-circuit voltage)	63.2 V
I_{sc} (short-circuit current)	6.5 A

The Voltage and Current Characteristics of a Typical Photovoltaic Module

Photovoltaic specifications for 10 kW Generation

Modules per String	Strings per Array	Number of Arrays	String Voltage (V)
7	5	1	354.2

5.4 The design of Photovoltaic systems

- The power generated by a string for this design is given as

$$\text{kW per string} = 7 \times 300 = 2100\ W$$

- To calculate the number of strings for a 10 kW PV system, we divide the PV power rating by power per string

$$NS = \frac{AP}{SP}$$

where NS is the number of strings and AP is the array power and SP is the string power.

- For this design we have:

$$NS = \frac{10 \times 10^3}{2100} = 5$$

5.4 The design of Photovoltaic systems

- Therefore, we have five strings and one array to generate 10 kW of power.
- In the final design, the inverter should be rated such that it is able to process generation of 10 kW and supply the load at 230 V AC from its array at its MPPT. Based on the PV module described before, the string voltage is specified as

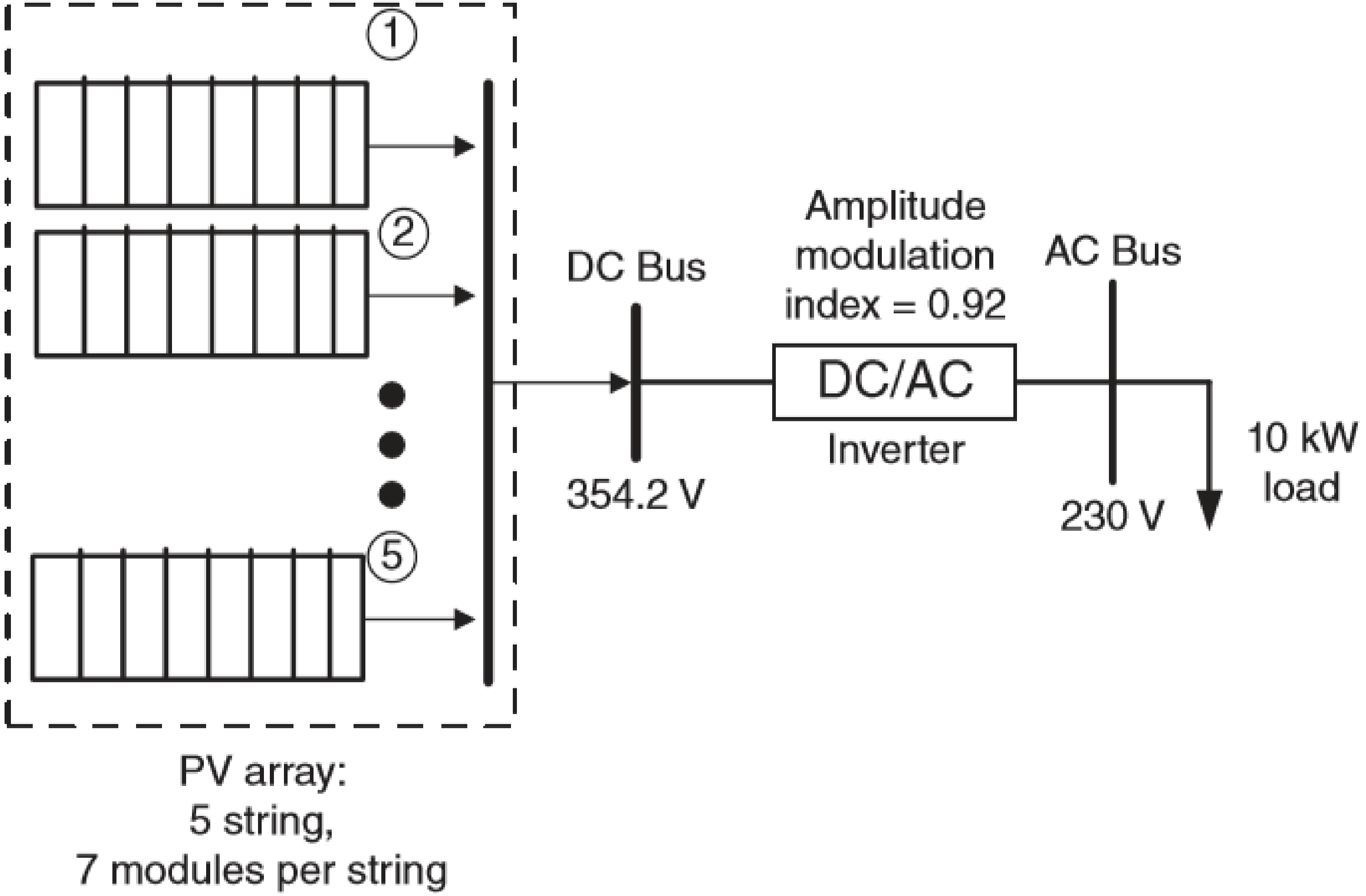
$$V_{idc} = 354.2\ V$$

and the modulation index is given as follows:

$$\mathrm{M_a} = \frac{\sqrt{2} \times 230}{354.2} = 0.92$$

- Let us select a switching frequency of 6 kHz. Therefore, the frequency modulation index is given by:

$$M_f = \frac{f_S}{f_e} = \frac{6000}{60} = 100$$



One-line diagram

Example 2: Design a PV system to process 500 kW of power at 460 V, 60 Hz, three - phase AC, and using PV data of Example 5.1. Determine the following:

i) Number of modules in a string and number of strings in an array
ii) Inverter and boost specification
iii) The output voltage as a function and total harmonic distortion
iv) The one - line diagram of this system

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, we have the following input DC voltage for a three- phase inverter:

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

- We will limit the maximum string voltage to 600 V DC. Therefore, we can use a boost converter to boost the string voltage to 835 V.
- If we select an approximate string voltage of 550 V, we have:
- The number of modules in a string is given by

$$\frac{V_{string}}{V_{MPP}} = \frac{550}{50.6} \approx 11$$

where V_{MPP} is the voltage of a module at MPPT.

- The string power, SP can be computed as $SP = NM \times P_{MPP}$
- Using a module rated at 300 W, we have: $SP = 11 \times 300 = 3300\ W$
- The string voltage is given as: $SV = NM \times V_{MPP}$
- Therefore, the string voltage, SV, for this design is $SV = 11 \times 50.6 = 556.6\ V$

Modules per String	Strings per Array	Number of Arrays	String Voltage (V)
11	6	25	556.6

Photovoltaic specifications

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

$$NS = \frac{power\ of\ one\ array}{power\ of\ one\ string} = \frac{20}{3.3} = 6$$

- The number of array, *NA*, for total power generation is $NA = \frac{PV\ generation}{power\ of\ one\ array}$

- Therefore, $NA = \frac{500 \cdot kW}{20 \cdot kW} = 25$

5.4 The design of Photovoltaic systems

- The inverters should be rated to withstand the output voltage of a boost converter and should be able to supply the required power. The inverter is rated at 100 kW with input voltage of 835 V DC and the amplitude modulation index of 0.9. The output voltage of inverter is 460 V AC.

- The number of inverters, *NI*, needed to process a generation of 500 kW is given by

$$NI = \frac{PV\ generation}{power\ of\ one\ inverter}$$

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

5.4 The design of Photovoltaic systems

- Hence, we need to connect five inverters in parallel to supply the load of 500 kW, if a switching frequency is set at 5.04 kHz.

- Therefore, the frequency modulation index, M_f, is given by

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

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	84

Inverter specifications

5.4 The design of Photovoltaic systems

Number of Boost Converters	Input Voltage, V_i (V)	Power Rating (kW)	Output Voltage, V_o (V)	Duty Ratio, D
25	556.6	20	835	0.33

Boost converter specifications

3^{rd} Harmonic	5^{th} Harmonic	7^{th} Harmonic	9^{th} Harmonic
0.01%	0.02%	0	0.03%

Harmonic content of line to neutral voltage relative to fundamental

5.4 The design of Photovoltaic systems

- The number of boost converters needed is the same as the number of arrays, which is 25, and the power rating of each boost converter is 20 kW.
- The boost converter input voltage is equal to the string voltage: $V_i = 556.6\ V$
- The output voltage of the boost converter is equal to the inverter input voltage:

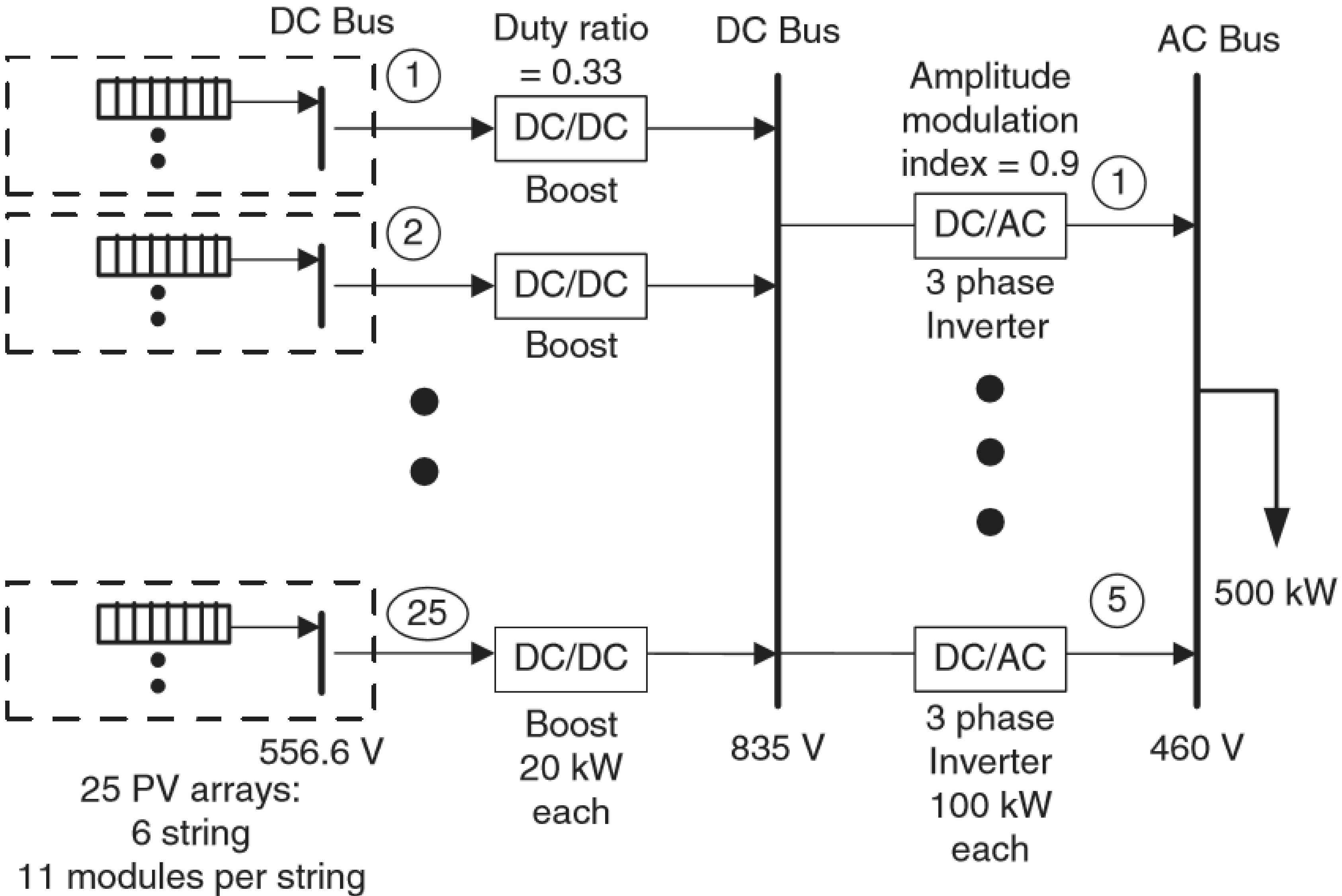
$$V_{idc} = V_o = 835\ V$$

- The duty ratio of the boost converter is given by:

$$D = 1 - \frac{V_i}{V_o} = 1 - \frac{556.6}{835} = 0.33$$

5.4 The design of Photovoltaic systems

The One - Line Diagram



The output line-to-neutral voltage as a function of time is (as a Fourier series):

$$
\begin{aligned}
V_{ac} = {} & \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi 60 \cdot t) + \frac{0.01}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 3 \times 60 \cdot t) \\
& + \frac{0.02}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 5 \times 60 \cdot t) + \frac{0}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 7 \times 60 \cdot t) \\
& + \frac{0.03}{100} \times \frac{460\sqrt{2}}{\sqrt{3}} \cdot \sin(2\pi \times 9 \times 60 \cdot t) \\
= {} & 376 \sin(2\pi 60 \cdot t) + 0.037 \sin(6\pi 60 \cdot t) + 0.075 \sin(10\pi 60 \cdot t) \\
& + 0.113 \sin(18\pi 60 \cdot t)
\end{aligned}
$$

- The total harmonic distortion is given by

$$THD = \sqrt{\sum (\%harmonic)^2} = \sqrt{0.01^2 + 0.02^2 + 0^2 + 0.03^2} = 0.04\%$$

5.4 The design of Photovoltaic systems

Example 3

- Design a PV system to process 1000 kW of power at 460 V, 60 Hz three - phase AC using the PV data given in Table below. Determine the following:

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

ii) DC/AC Inverter and boost converter specifications and the one - line diagram of the system

Photovoltaic Data

Module	Type 1
Power (Max), W	190
Voltage at MPP, V	54.8
Current at MPP, A	3.47
V_{OC} (open-circuit voltage), V	67.5
I_{SC} (short-circuit current), A	3.75
Efficiency	16.40%
Cost	$870.00
Width	34.6″
Length	51.9″
Thickness	1.8″
Weight	33.07 lbs

- The load is 1000 kW rated at 460 V AC. Based on the voltage of the load and an amplitude modulation index of 0.85, the input DC voltage for a three - phase inverter is:

$$V_{idc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}M_a} = \frac{2\sqrt{2} \times 460}{\sqrt{3} \times 0.85} = 884\ V$$

- For this example, we will limit the maximum voltage that a string is allowed to have to 600 V. Therefore, we use a boost converter to boost the string voltage to 884 V.
- If we select string approximate voltage of 550 V, the number of modules in a string, *NM*, is given as

$$NM = \frac{V_{string}}{V_{MPP}} = \frac{550}{54.8} \approx 10$$

5.4 The design of Photovoltaic systems

- The string power is: $SP = NM \times P_{MPP} = 10 \times 190 = 1900\ W$

- And the string voltage, SV , is: $SV = 10 \times 54.8 = 548\ V$
- If each array is to have a rating of 20 kW, the number of strings, *NS*, in an array is:

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

- The number of arrays, *NA*, for this design is

$$NA = \frac{PV\ generation}{power\ of\ one\ array} = \frac{1000}{20} = 50$$

- The total number of PV modules, *TNM*, is given by the product of the number of modules per string, the number of strings per array, and the number of arrays:

$$TNM = NM \times NS \times NS \; = 10 \times 11 \times 50 = 5{,}500$$

- The surface area of one module, *SM*, is given by the product of its length and width.

$$SM = \frac{34.6 \times 51.9}{144} = 12.5 \; ft^2$$

- The total surface area, *TS* , is therefore given by the total number of modules and the surface area of each module:

$$TS = 5500 \times 12.5 = 68{,}750 \; ft^2 = \frac{68{,}750}{43{,}560} = 1.57 \; acre$$

5.4 The design of Photovoltaic systems

- The total cost of PV modules is given by the product of the number of PV modules and the cost of one module.

$$\text{The total cost} = 5500 \times 870 = \$4.78\ \mathit{million}$$

- The total weight of PV modules is given by the product of the number of PV modules and the weight of one module.

$$\text{The total weight} = 5500 \times 33.07 = 181{,}885\ lb$$

- The inverters should be rated to withstand the output voltage of the boost converter and should be able to supply the required power. Selecting an inverter rated at 250 kW, we have the number of inverters, *NI*, needed to process the generation of 1000 kW as given by:

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

5.4 The design of Photovoltaic systems

- Hence, we need to connect four inverters in parallel to supply the load of 1000 kW.
- Selecting a switching frequency of 5.40 kHz, the frequency modulation index is given by:

$$M_f = \frac{f_S}{f_e} = \frac{5400}{60} = 90$$

Modules per String	Strings per Array	Number of Arrays	String Voltage (V)	Total Area (ft^2)	Total Weight (lbs)	Total Cost (million \$)
10	11	50	548	68,750	181,885	4.78

Photovoltaic Specifi cations for 1000 kW Generation

5.4 The design of Photovoltaic systems

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	884	250	460	0.85	90

Inverter specifications

- The number of boost converters needed is the same as the number of arrays, which is 50. Selecting a boost converter rating of 20 kW and the boost converter input voltage to be equal to the string voltage: $V_i = 548\ V$
- The output voltage of the boost converter is equal to the inverter input voltage:

$$V_{idc} = V_o = 884\ V$$

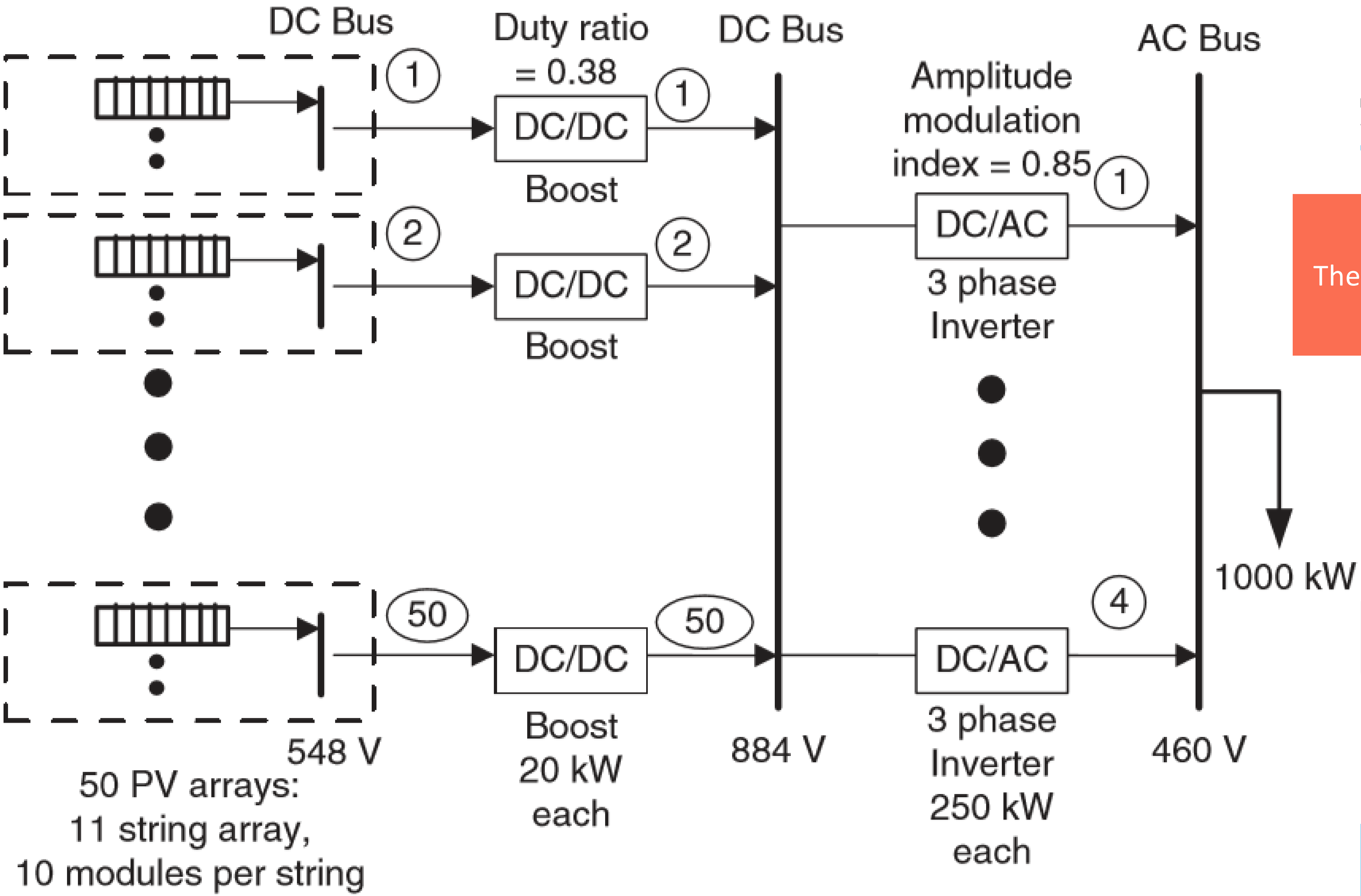
- The output voltage of the boost converter is equal to the inverter input voltage:

$$V_{idc} = V_o = 884\ V$$

- The duty ratio of the boost converter is given by

$$D = 1 - \frac{V_i}{V_o} = 1 - \frac{548}{884} = 0.38$$

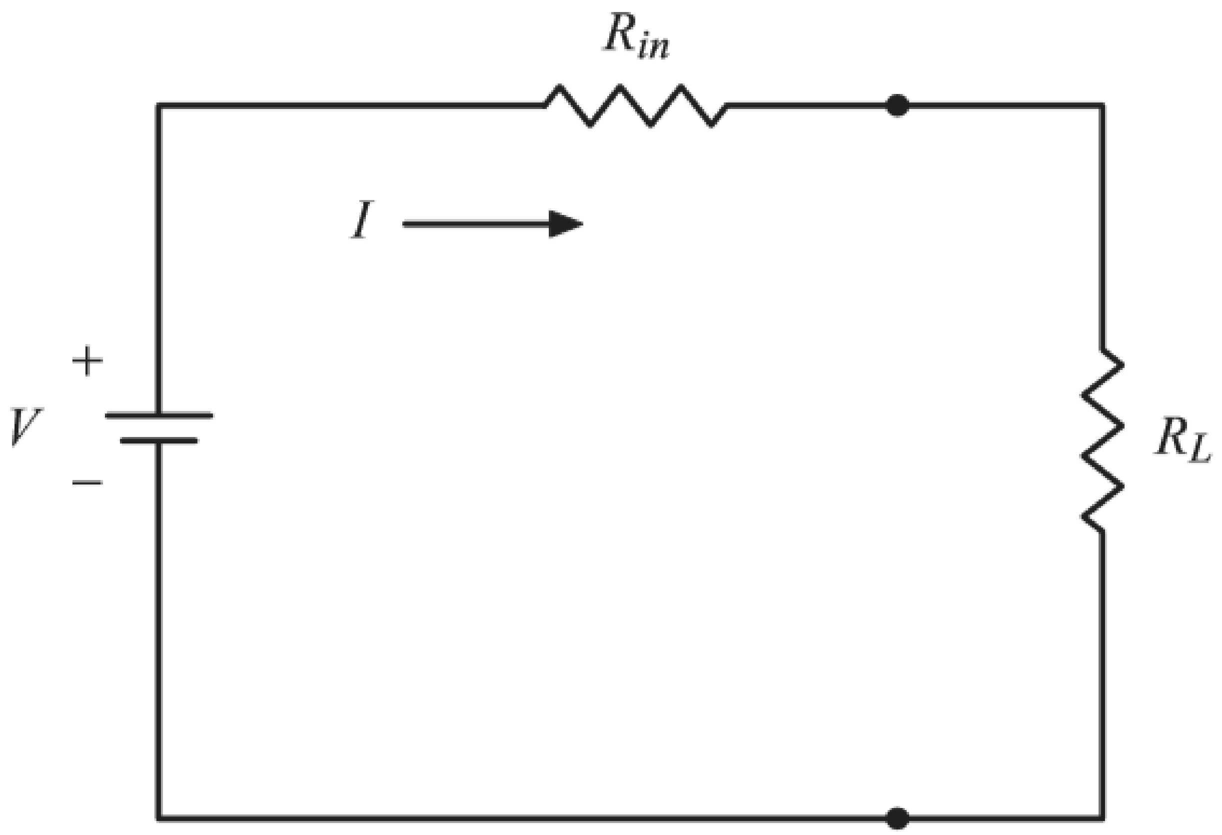
ystems



The one-line diagram

5.5. The maximum power point of a photovoltaic array

- First, let us review the maximum power transfer in a resistive circuit. Consider the circuit of Fig. below. Assume a voltage source with an input resistance, R_{in} . This source is connected to a load resistance, R_L .



A DC Source with a Resistive Load

5.5. The maximum power point of a photovoltaic array

- The current supplied to the load is: $I = \dfrac{V}{R_{in} + R_L}$

- The power delivered to the load R_L is

$$P = I^2 R_L = V^2 \frac{R_L}{(R_{in} + R_L)^2}$$

- Differentiating with respect to RL : $\dfrac{dP}{dR_L} = V^2 \dfrac{R_{in} - R_L}{(R_{in} + R_L)^3}$

- Setting the above to zero, we can calculate the operating point for the maximum power. The MPP can be delivered to the load when $R_L = R_{in}$.

5.5. The maximum power point of a photovoltaic array

The PV system should be operated to extract the maximum power from its PV array as the environmental conditions change in relation to the position of the sun, cloud cover, and daily temperature variations. The equivalent circuit model of a PV array depicted in Fig. below can be presented during its power transfer mode to a load RL as shown in Fig. 5.2

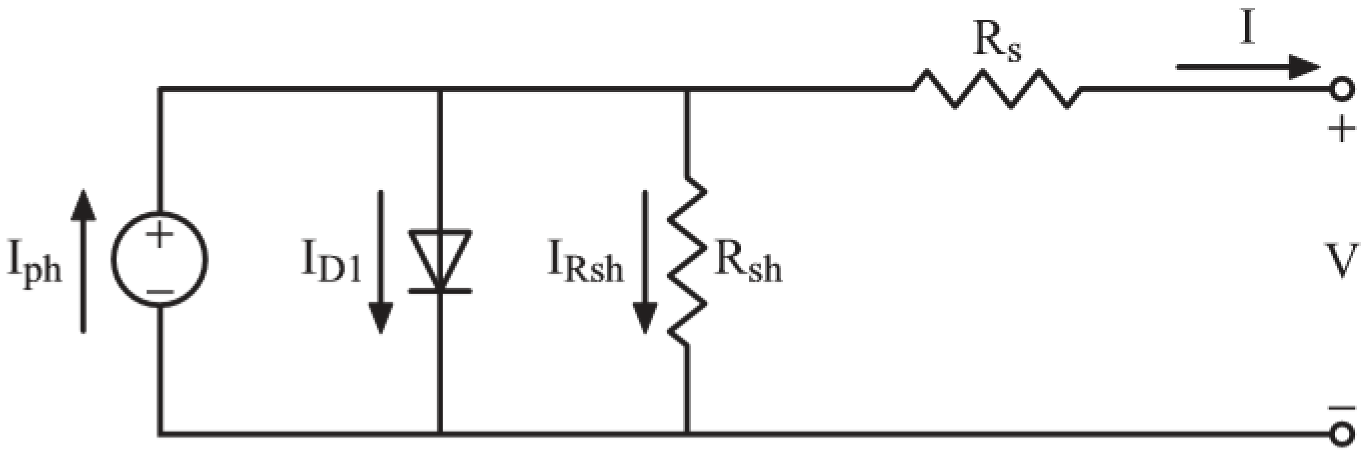
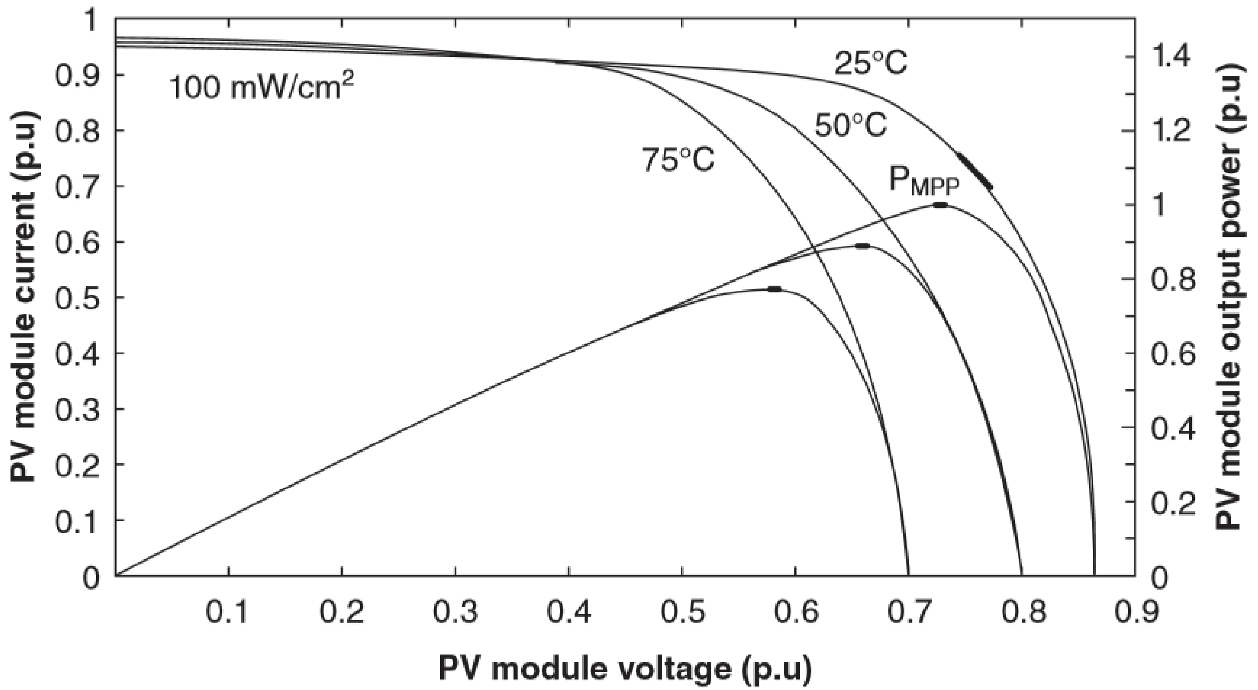


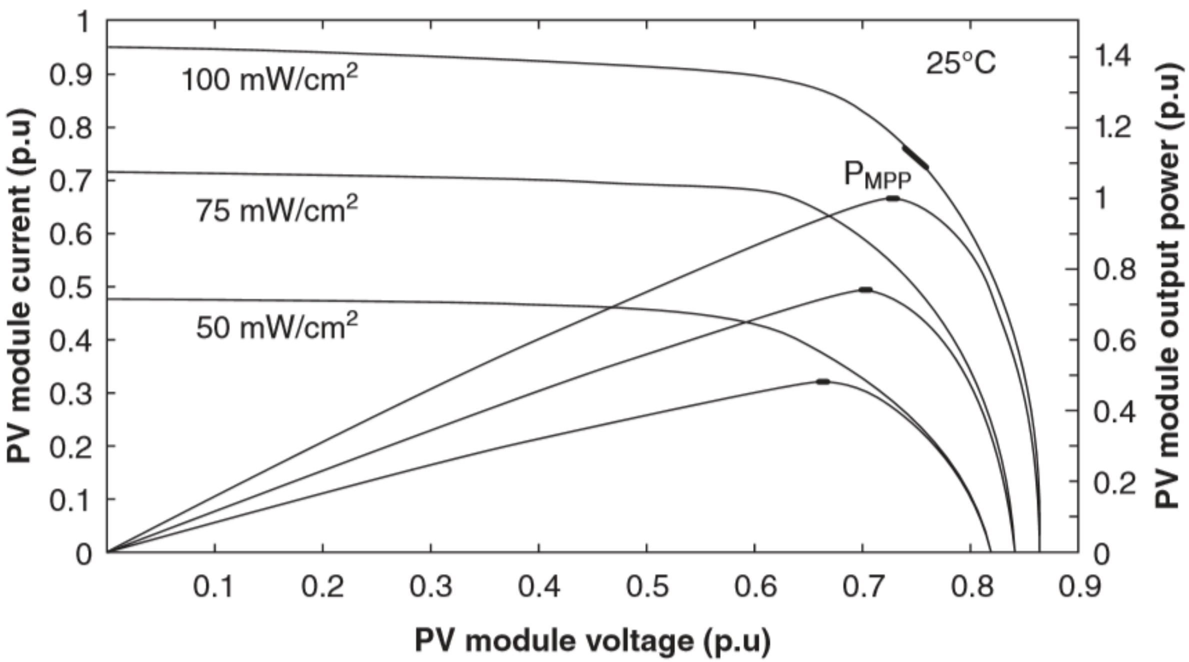
Fig. 5.1: The Single Exponential Model of a Photovoltaic Module

5.5. The maximum power point of a photovoltaic array



The Output power in W/m 2 at Various Irradiances as a Function of Module Current and Output Voltage.

Figure 5.2 The PV Output Current versus Output Voltage and Output Power as a Function of Temperature Variation.



5.5. The maximum power point of a photovoltaic array

- Figure 5 .3 presents the circuit model for a PV source by a current source that has a shunt resistance, R_{sh} and series resistance, R_s. The shunt resistance has a large value and series resistance is very small. The load resistance is represented by R_L .
- In Fig. 5.3, R_L is the reflected load because in practice the load is connected to the converter side if the PV operates as a standalone. When the PV is connected to the power grid, the load is based on the injected power to the power grid. The equivalent voltage source circuit model of current source model is depicted by Fig. 5.4.

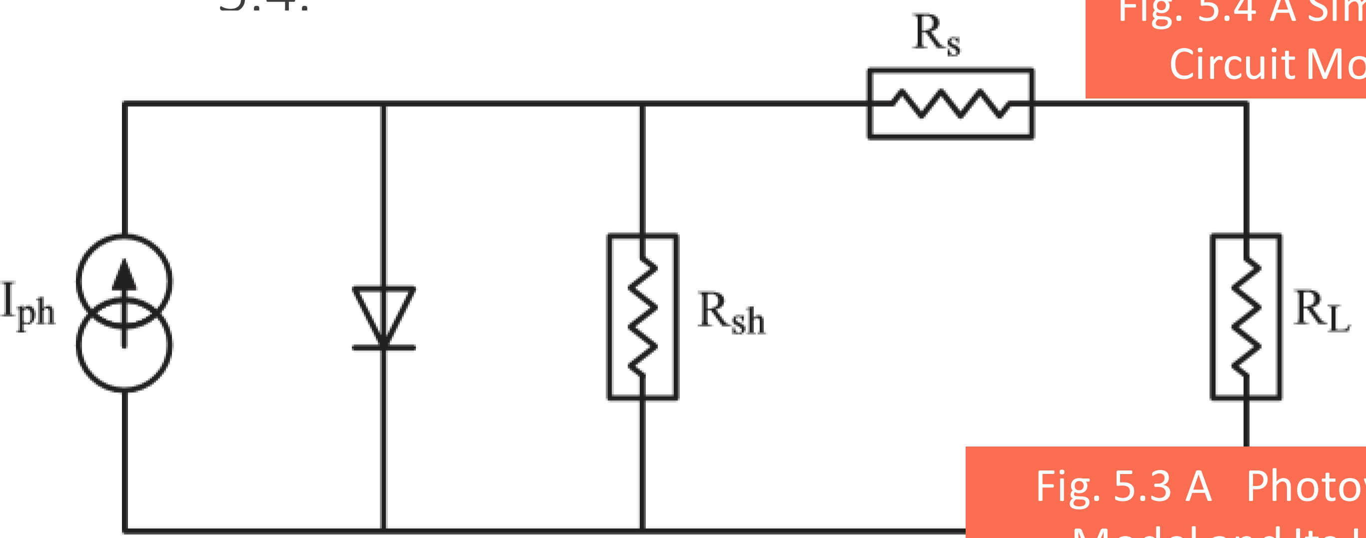


Fig. 5.3 A Photovoltaic Model and Its Load.

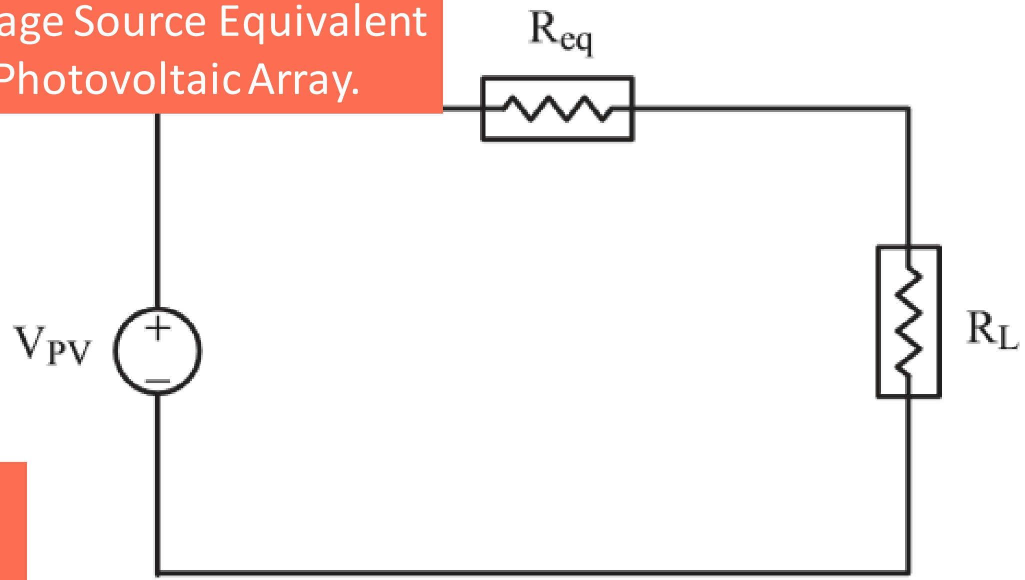


Fig. 5.4 A Simple Voltage Source Equivalent Circuit Model of a Photovoltaic Array.

5.5. The maximum power point of a photovoltaic array

- As can be seen in Fig. 5.2, the characteristics of a PV module are highly nonlinear. The input impedance of a PV array is affected by irradiance variation and temperature. The corresponding output power is also shown in Fig. 5.2.
- Figure 5.5 depicts the PV energy processing system using a boost converter to step up the voltage and an inverter to convert the DC power to AC. To achieve maximum power transfer from the PV array, the input impedance of the PV generator must match the load.
- The MPPT control algorithm seeks to operate the boost converter at a point on the PV array current and voltage characteristics where the maximum output power can be obtained. For a PV power generating station, the control algorithm computes the $dP/dV>0$ and $dP/dV<0$ to identify if the pick power has been obtained.

5.5. The maximum power point of a photovoltaic array

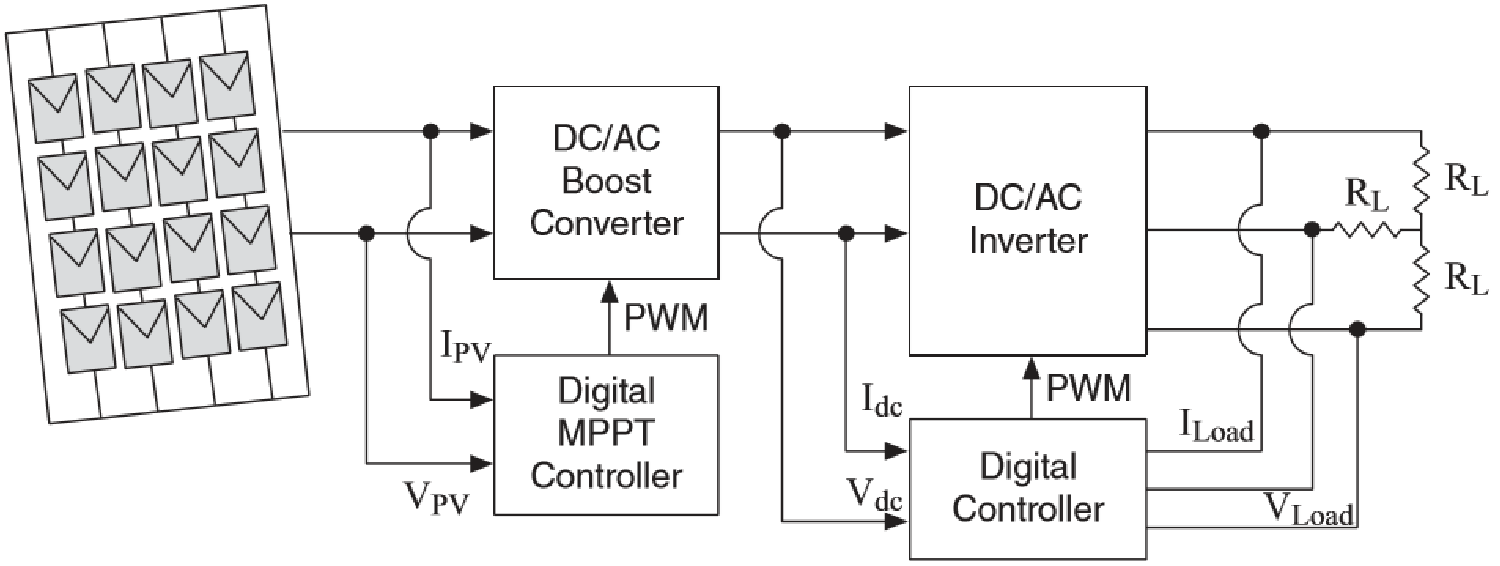


Fig. 5.5 Photovoltaic Energy Processing Using a Boost Converter to Step Up the Voltage and an Inverter

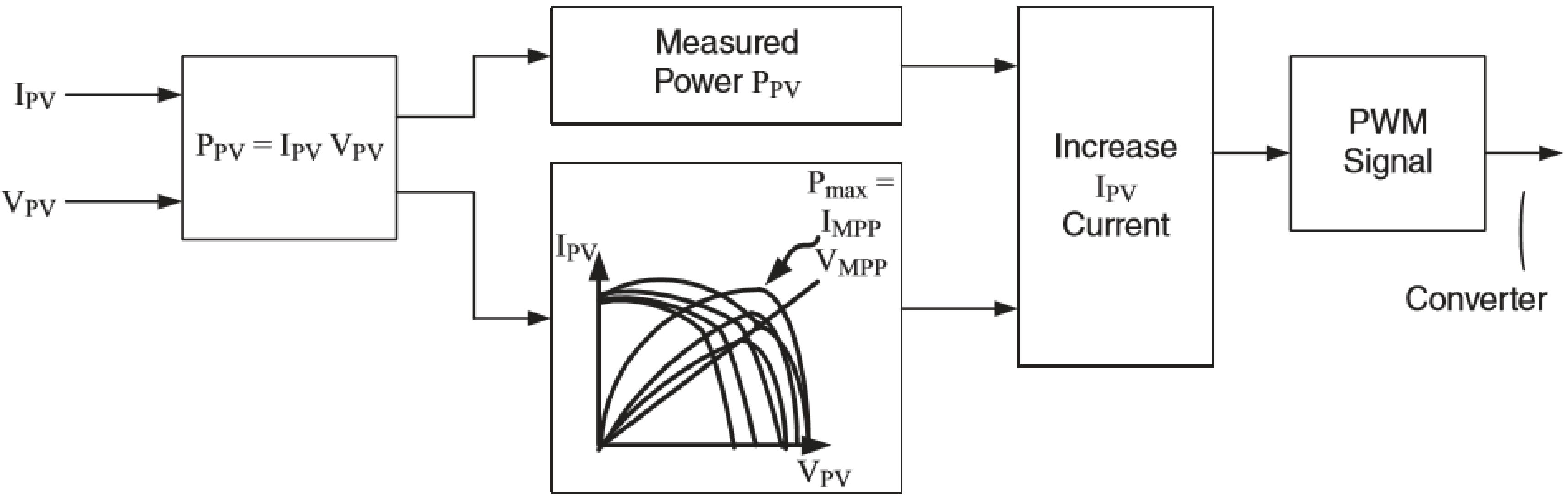


Fig. 5.6 Maximum Power Point Tracking Control Algorithm

5.5. The maximum power point of a photovoltaic array

- Depending on application, a number of designs of a PV system can be proposed. When the PV system is to charge a battery storage system, the PV system can be designed as depicted by Fig. 5.7 using a boost converter or as in Fig. 5.8 (next slide) using a buck converter.

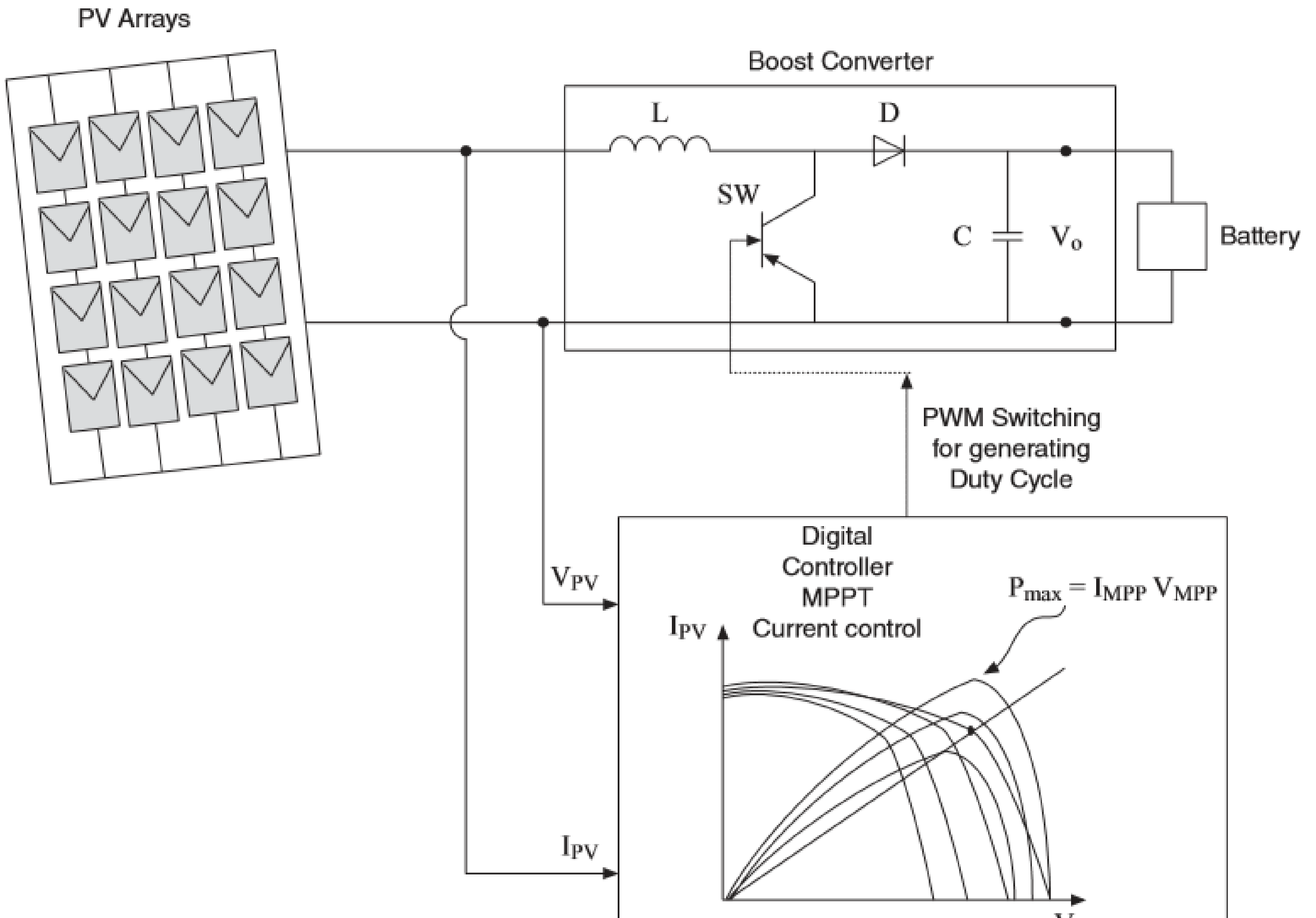


Fig. 5.7 Maximum Power Point Tracking Using Only a Boost Converter

5.5. The maximum power point of a photovoltaic array

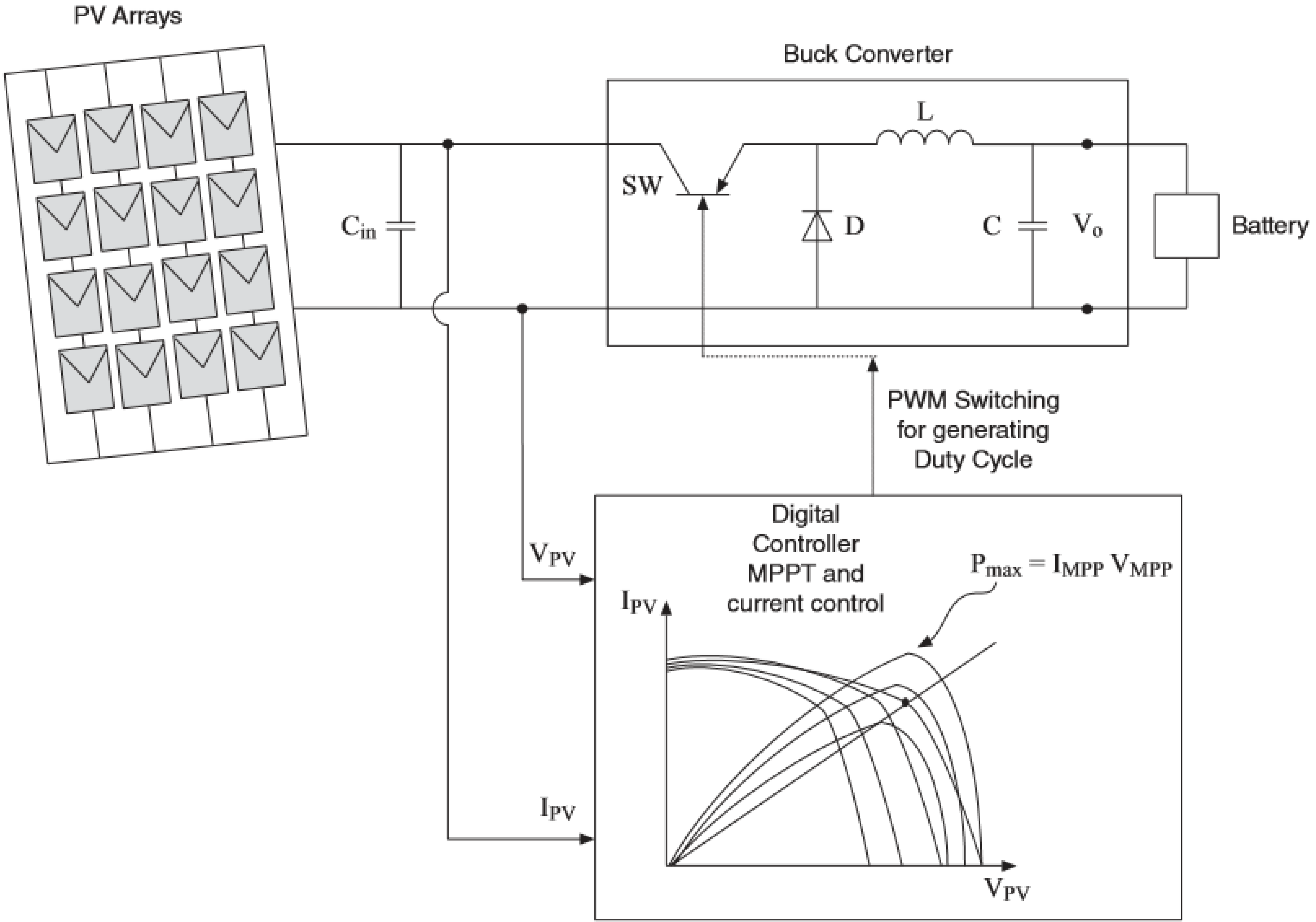


Fig. 5.8 Maximum Power Point Tracking Using a Buck Converter

5.5. The maximum power point of a photovoltaic array

- Figure 5.9 depicts the design of a PV- generating system and MPPT using an inverter when the PV - generating station is connected to a local utility. Again, the digital controller tracks the PV station output voltage and current and computes the MPPT point. The control algorithm issues the PWM switching policy to control inverter current such that the PV station operates at its MPP. However, the resulting control algorithm may not result in minimum total harmonic distortion.
- The design presented by Fig. 5.6 has two control loops. The first control loop is designed to control DC/DC converter and the second control loop can control the total harmonic distortion and output voltage.

5.5. The maximum power point of a photovoltaic array

- When the MPPT control is performed as part of the inverter as shown in Fig. 5.9, the tracking of MPPT may not be optimum. In this type of MPPT the current to the inverter flows though all modules in the string. However, the I - V curves may not be the same and some strings will not operate at their MPPT. Therefore, the resulting energy capture may not be as high and some energy will be lost in such systems.

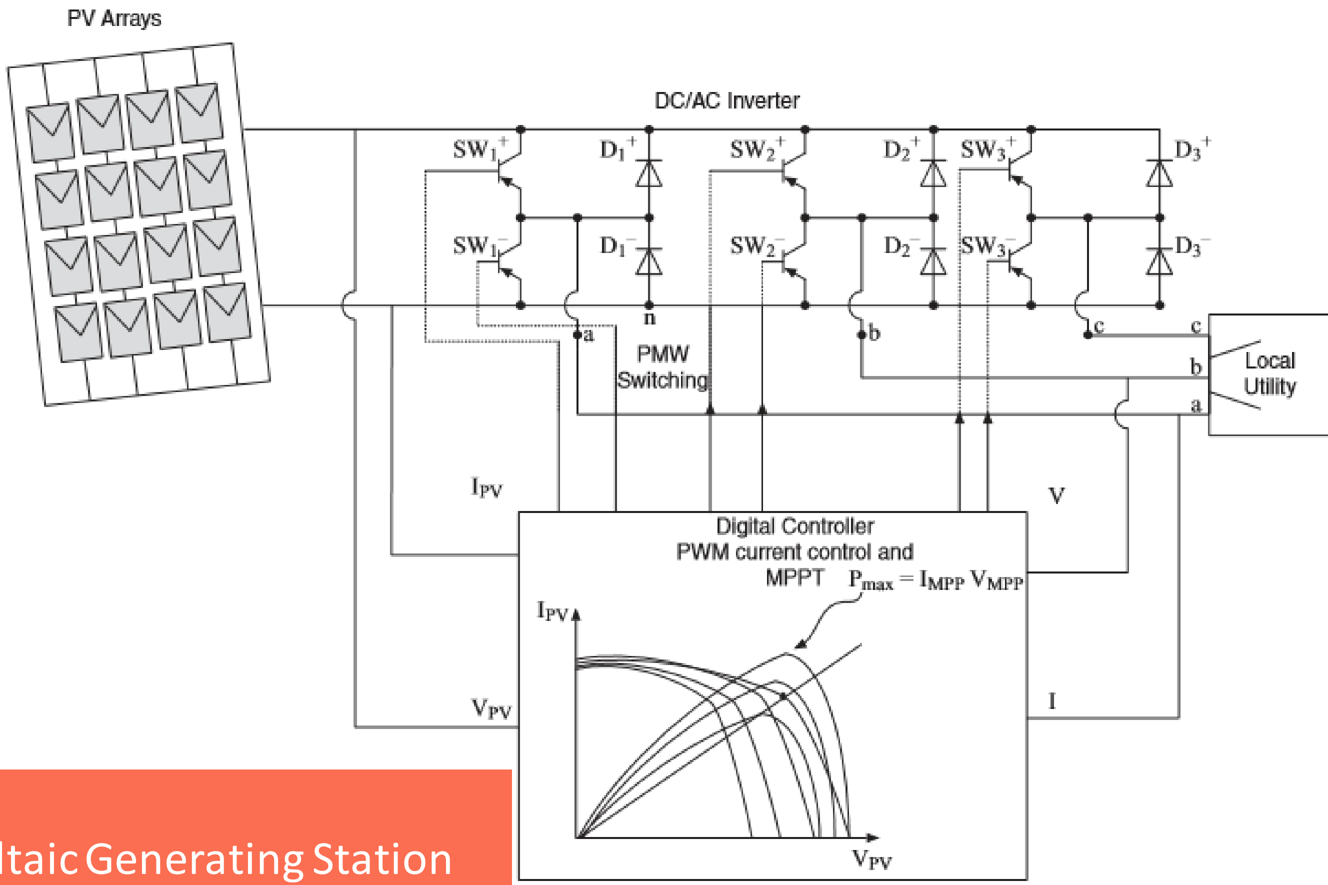


Fig. 5.9 A Photovoltaic Generating Station Operating at Maximum Power Point Tracking when the Photovoltaic System Is Connected to a Local Power Grid.

5.5. The maximum power point of a photovoltaic array

- Figure 5.10 (next slide) depicts a PV-generating station with a battery storage system when the PV system is connected to the local utility. The DC/DC converter and its MPPT are referred to a charger controller.
- The charger controllers have a number of functions. Some charger controllers are used to detect the variations in the current - voltage characteristics of a PV array. MPPT controllers are necessary for a PV system to operate at voltage close to MPP to draw maximum available power as shown in Fig. 5.6. The charger controllers also perform battery power management. For normal operation, the controllers control the battery voltage, which varies between the acceptable maximum and minimum values. When the battery voltage reaches a critical value, the charge controller function is to charge the battery and protect the battery from an overcharge. This control is accomplished by two different voltage thresholds, namely, battery voltage and PV module voltage.

5.5. The maximum power point of a photovoltaic array

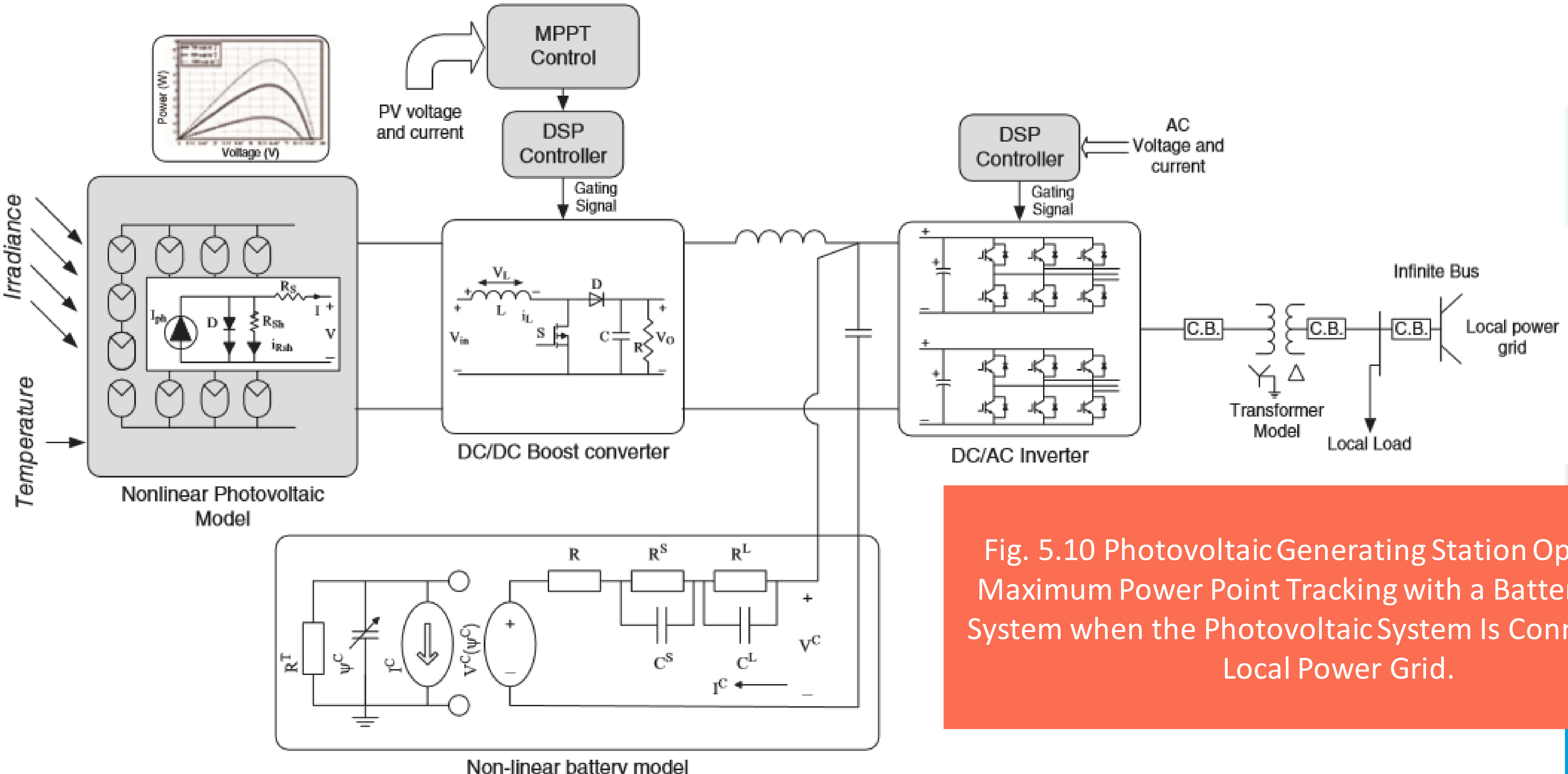


Fig. 5.10 Photovoltaic Generating Station Operating at Maximum Power Point Tracking with a Battery Storage System when the Photovoltaic System Is Connected to a Local Power Grid.

5.6. 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.
- 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 $\mathrm{kWh} = \mathrm{kV} \cdot \mathrm{Ah}$

5.6. A battery storage system

- 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 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.

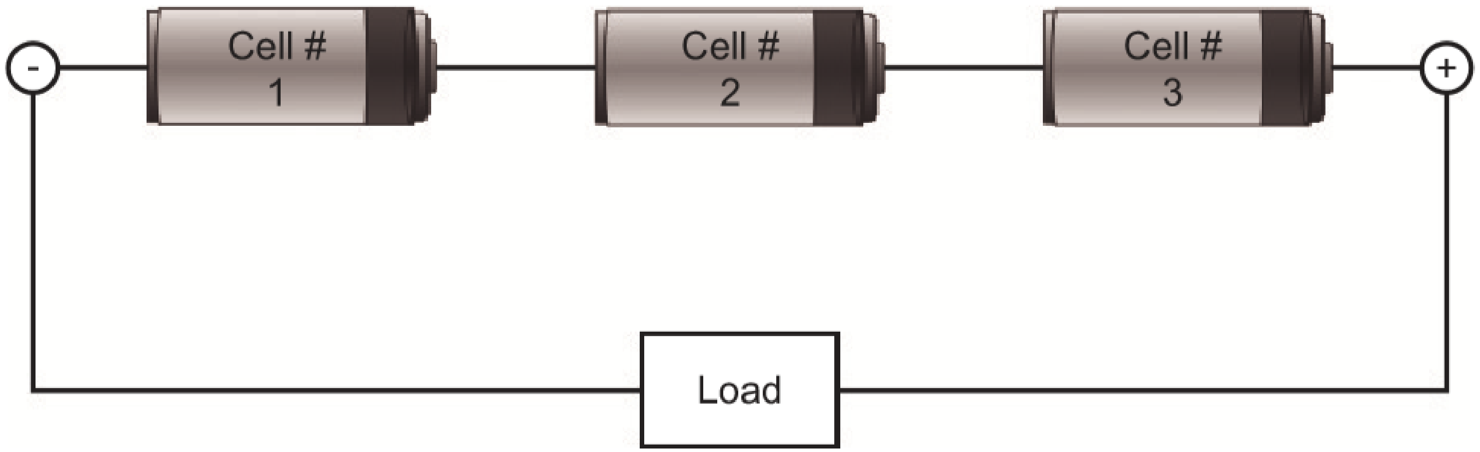
5.6. A battery storage system

- 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 and integration of an intermittent renewable energy system such as wind or PV 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 a spinning reserve.

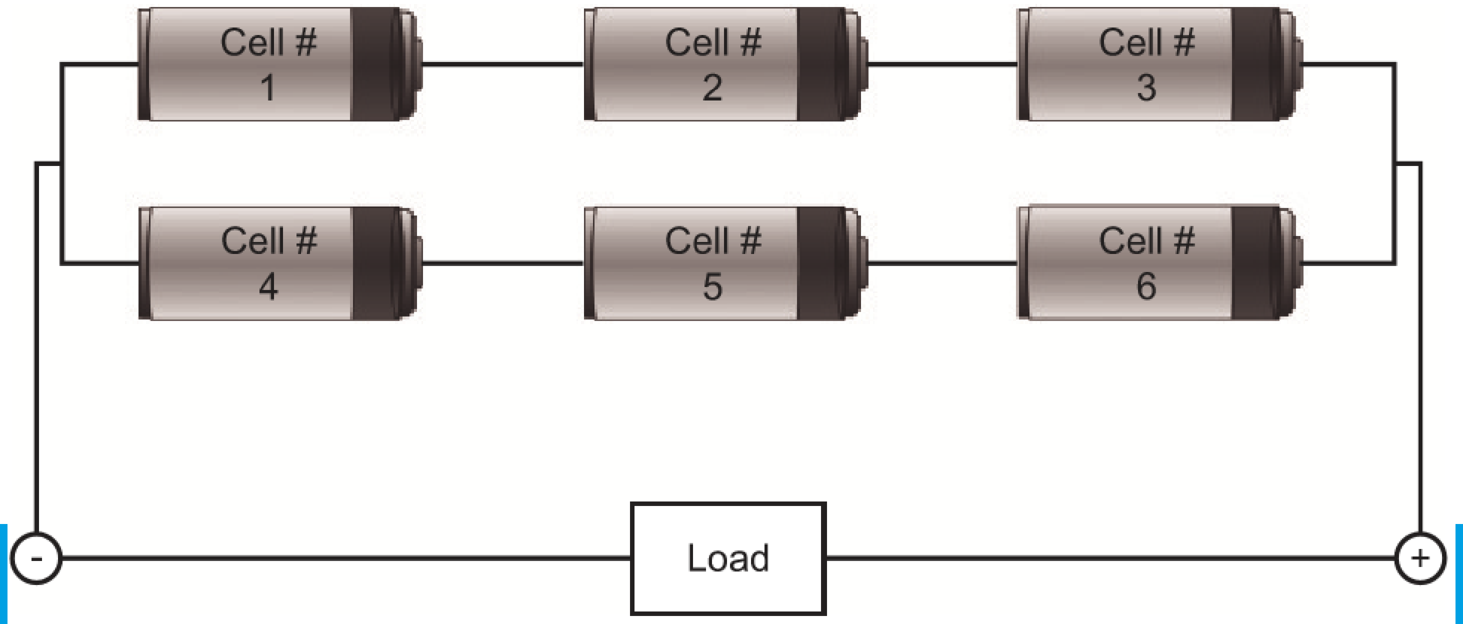
5.7. A storage system based on a single cell battery

- 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 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. 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.

5.7. A storage system based on a single cell battery



Three Single Cells in a String



Two Strings of Three Single Cells Connected in Parallel

5.7. A storage system based on a single cell battery

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

Comparison of Battery Energy Density and Power Density

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

The Energy Density and the Cost of a Storage System

5.7. A storage system based on a single cell battery

- As expected, the higher the discharge current rate is, the lower the remaining capacity and output voltage and the higher the internal resistance. However, the reduced capacity 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 requires an understanding of the storage system 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 modeling of the battery systems are needed. The dynamic model of a storage system will facilitate dispatching power from intermittent green energy sources.

Example 4

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 and the PV system are given in the following slides.

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

5.7. A storage system based on a single cell battery

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

Three - Phase Inverter Data

JAUNTY Erasmus+

5.7. A storage system based on a single cell battery

Module	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

Typical PV modules data

5.7. A storage system based on a single cell battery

- 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

$$NI = \frac{PV\ generation}{rating\ of\ inverters} = \frac{1000}{250} = 4$$

5.7. A storage system based on a single cell battery

- 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

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

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

5.7. A storage system based on a single cell battery

- Students should recognize that other designs are also possible. The input DC voltage of PV specifies the output AC voltage of inverters.
- Table given in previous slide gives the data for each PV type. As, 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:

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

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

$$SV = 10 \times 54.8 = 548\ V$$

5.7. A storage system based on a single cell battery

- The string power, SP, is given as:

$$SP = 10 \times 190 = 1.9\ kW$$

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

$$NS = \frac{power\ of\ one\ array}{power\ of\ one\ string} = \frac{20}{1.9} = 11$$

- The number of arrays, NA, is given by $NA = \dfrac{1000}{20} = 50$

5.7. A storage system based on a single cell battery

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

$$TNM = NM \times NS \times NA \quad = 10 \times 11 \times 50 = 5500$$

- 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.

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

5.7. A storage system based on a single cell battery

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

$$\text{Total cost} = 5500 \times 870 = \$4.78\ \textit{million}$$

- 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, $SV = V_i = 548\ \text{V}$
- The duty ratio of the boost converter is given by

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

5.7. A storage system based on a single cell battery

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

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

5.7. A storage system based on a single cell battery

- 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:

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

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

$$NA = \frac{total\ energy}{energy\ in\ each\ array} = \frac{200}{27.54} \approx 8$$

5.7. A storage system based on a single cell battery

- 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

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

5.7. A storage system based on a single cell battery

- The array power, AP, rating is given by

$$AP = \frac{power}{number\ of\ arrays} = \frac{12.5}{8} = 1.56\ kW$$

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

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

5.7. A storage system based on a single cell battery

- To compute the per unit system, we let the base volt - ampere be $S_b = 1\,MVA$
- The base values for the system 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:

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

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

5.7. A storage system based on a single cell battery

- The per unit power, Pp.u, rating of the inverters is given by:

$$P_{p.u} = \frac{power\ rating}{S_b} = \frac{250 \times 10^3}{1 \times 10^6} = 0.25\ p.u$$

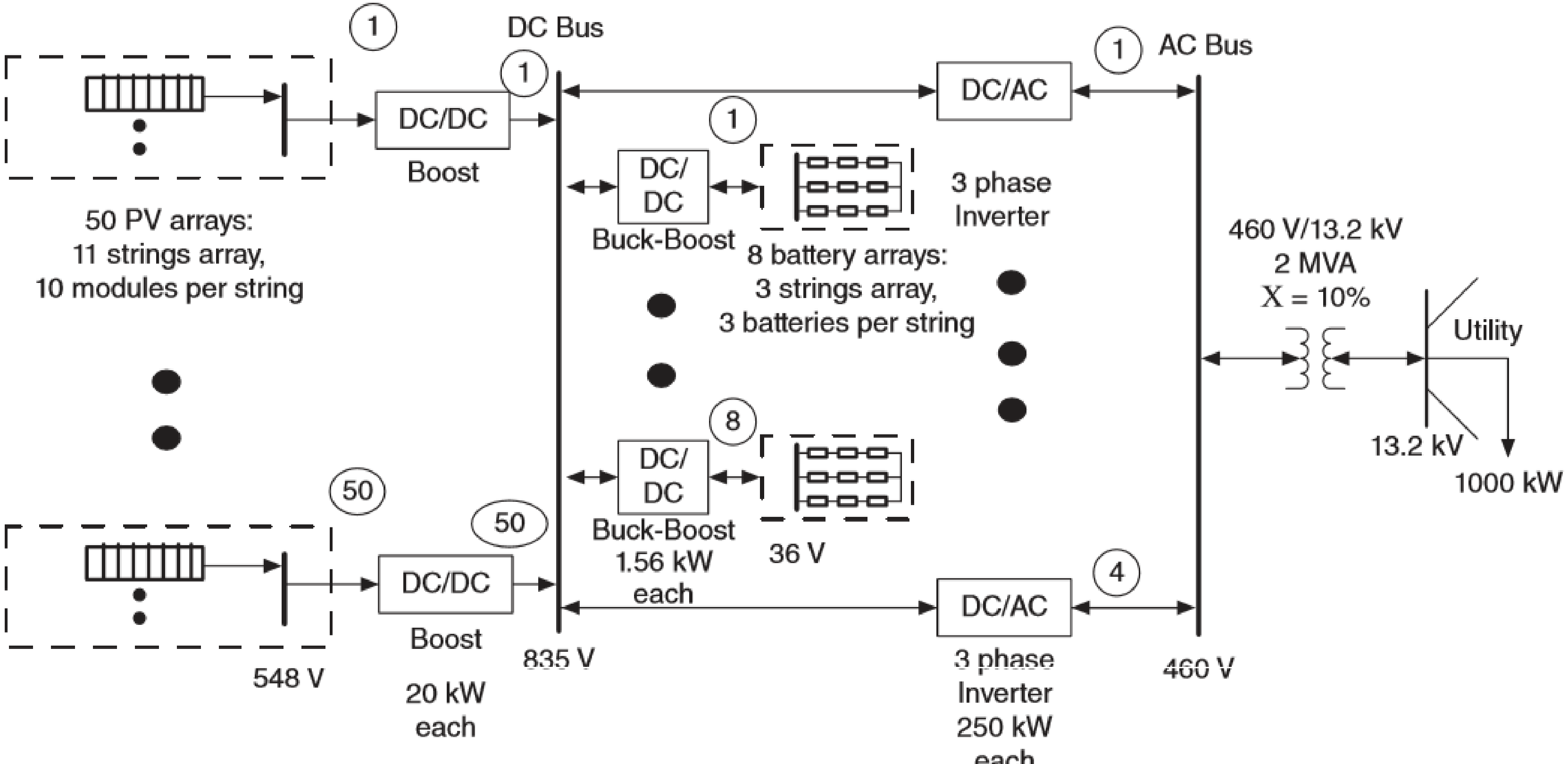
- And, the per unit power rating of the boost converters:

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

5.7. A storage system based on a single cell battery

- 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

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



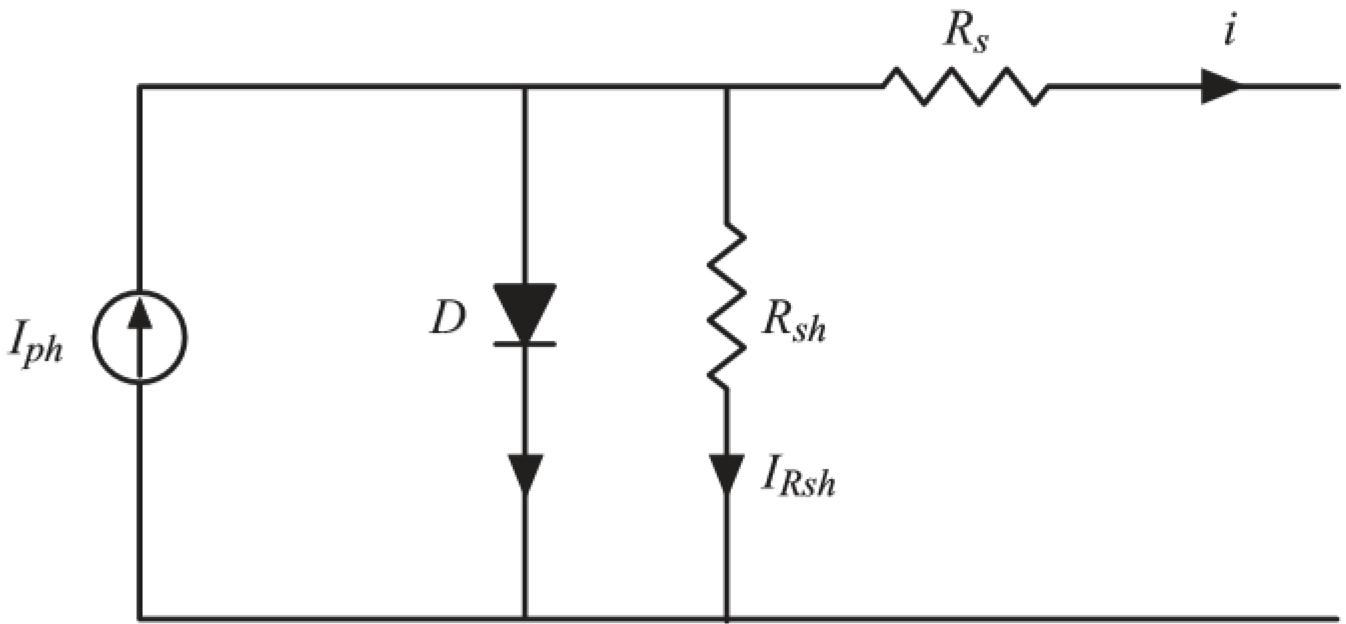
The one-line diagram of example 4

5.8. The estimation of Photovoltaic module model parameters

- The single diode model below presents the current-voltage characteristics for a single cell of a PV module. The model of a module consisting of a number of cells, n_c can be presented as:

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{n_c V_t}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (5.1)$$

- In this equation, V_t, the junction thermal voltage, is given as: $V_t = \frac{AkT_{stc}}{q}$ (5.2)



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

5.8. The estimation of Photovoltaic module model parameters

- 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 previous equation, we have:

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

- The term STC denotes standard test conditions for measuring 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 5.1, 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.

5.8. The estimation of Photovoltaic module model parameters

- 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 below summarizes the measured data at STC used for model development.

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

The Measured Data Used in Model Estimation

- The model of Equation 5.2 is evaluated at the measured data points as defined in Table above.

$$I_{sc} = I_{ph} - I_o e^{\frac{I_{sc}R_s}{n_c V_t}} - \frac{I_{sc}R_s}{R_{sh}} \quad (5.3)$$

5.8. The estimation of Photovoltaic module model parameters

$$I_{mpp} = I_{ph} = I_o e^{\frac{V_{MPP}+I_{MPP}R_s}{n_c V_t}} - \frac{V_{MPP} + I_{MPP} R_s}{R_{sh}} \quad (5.4)$$

$$I_{oc} = 0 = I_{ph} - I_o e^{\frac{V_{oc}}{n_c V_t}} - \frac{V_{oc}}{R_{sh}} \quad (5.5)$$

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

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

5.8. The estimation of Photovoltaic module model parameters

- 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}:

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

- Hence, five equations with five variables have been established.

Exercises for understanding:

1. Design a microgrid of 600 kW of power rated at 230 V AC. 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

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

Photovoltaic Module Data

References and further reading

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