EN 671 : Solar Energy Conversion Technology

Solar module, array and PV systems

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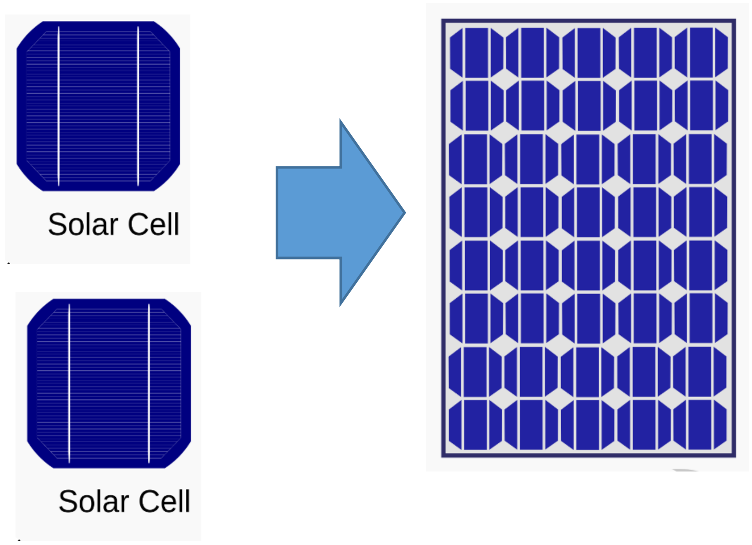
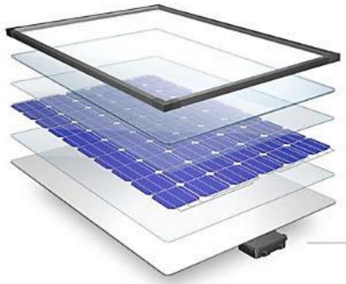
Solar module, array and PV systems

- Classification
- Specification of a module
- Cell matching of a module
- Effect of shadowing
- Maximization of solar PV output and load matching
- Maximum power point tracker (MPPT)

What is PV module?

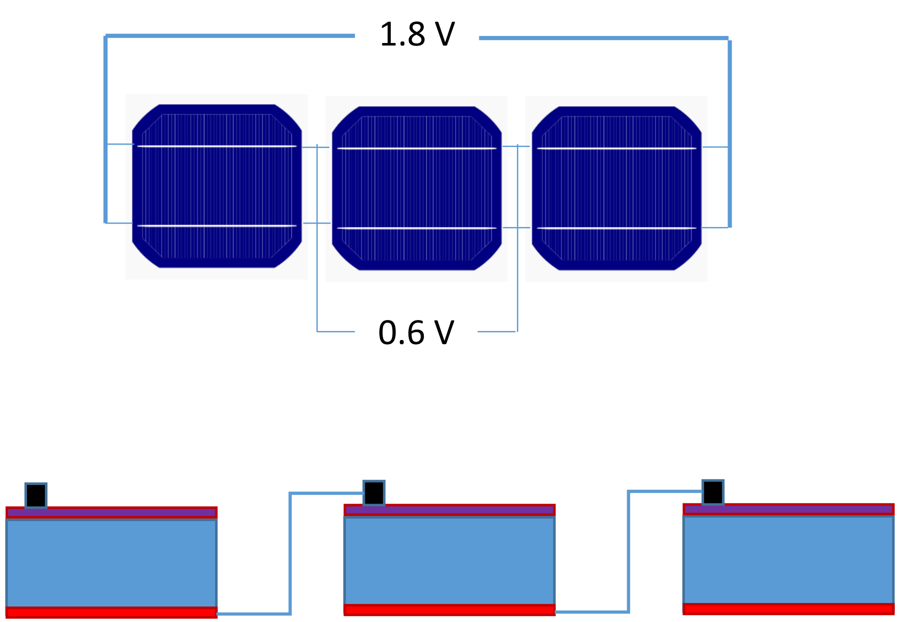


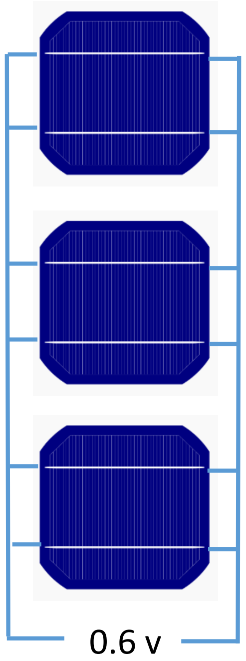
- ✓ An assembly of photovoltaic cells mounted in a framework for installation.
- ✓ A bare single cell cannot be used for outdoor energy generation – (1) output of the cell is very small and (2) it requires protection against dust, moisture, mechanical shocks and outdoor harsh conditions.
- ✓ Workable voltage and reasonable power is obtained by interconnecting appropriate number of cells.

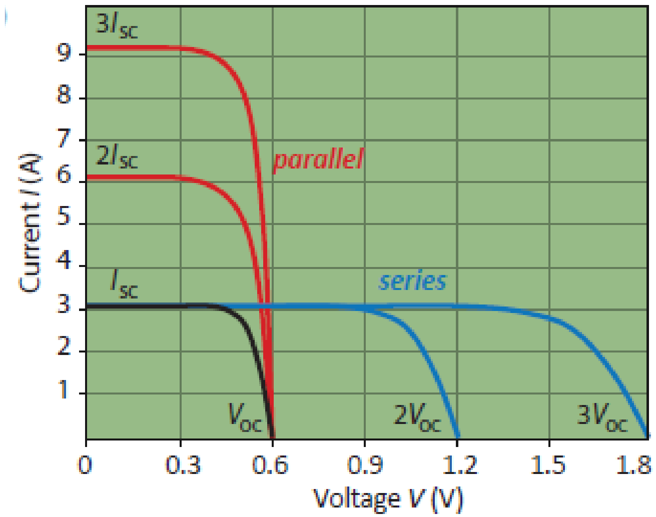


- ✓ The most common modules have series connection of 36 silicon cells to make it capable of charging a 12 V storage battery.

Series and parallel connection in PV module







Classification of modules

- Classified based on the material of the back cover used.
  - ✓If the back cover of the module is made of opaque Tedlar, it is known as a glass-to-Tedlar [Polyvinyl fluoride-$(C_2H_3F)_n$] or opaque PV module.
  - ✓If the back cover of the module is made of glass, it is known as a glass-to-glass or semi-transparent PV module.

The amount of light transmitted from a semi-transparent PV module depends on its packing factor.

Module Specification

Module size	119.1 cm x 53.3 cm
Module weight	7.5 kg
Cell size	12.5 cm x 12.5 cm
Number of cells	36
Nominal output	80 W
Nominal voltage	12 V
Maximum voltage	17 V
Voc	21.2 V
Isc	4.9 A
Conversion efficiency	12.5 %

STC: I = 1000 W/m^2, AM 1.5 spectrum, Cell Temp: 25 °C

Difficulties associated with PV Modules

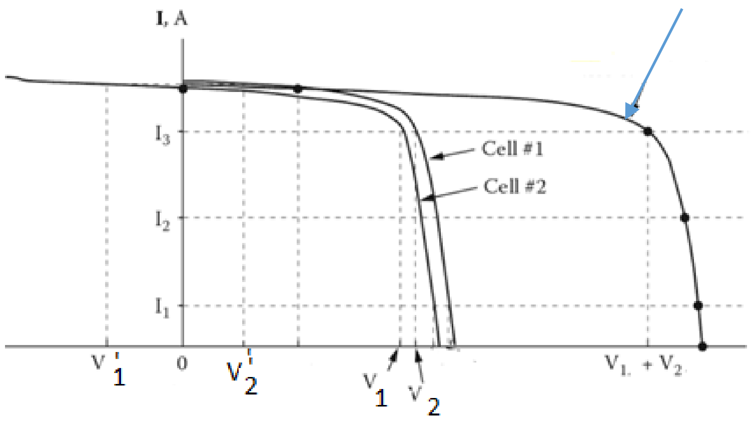
- Cell Mismatch in a module
- Effect of shadowing
  - Partial shadowing of a cell – Series connection
  - Partial shadowing of a cell – Parallel connection

Cell mismatch in a module

$$P_{\text{combined}} = P_{\text{sum of individual cells}} \left(\text{Ideal}\right)$$
$$P_{\text{combined}} < P_{\text{sum of individual cells}} \left(\text{Acual}\right)$$

- V_{oc}, I_{sc}, V_m, I_m for all cells must be exactly same.
- Any mismatch in the characteristics of these cells leads to additional mismatched loss.
- P(combined peak) always less than the sum of P(individual cell peak)
- Case I: When two cells with mismatch characteristics are connected in series and a load is applied, both the cells are bound to carry same current. - Reduces fill factor of combined IV
- Case II: When two cells with mismatch characteristics are connected in parallel – voltage of the cells are bound to be equal.

Series combination



To reduce mismatch losses,

✓ Modules are fabricated from cells belonging to same batch,

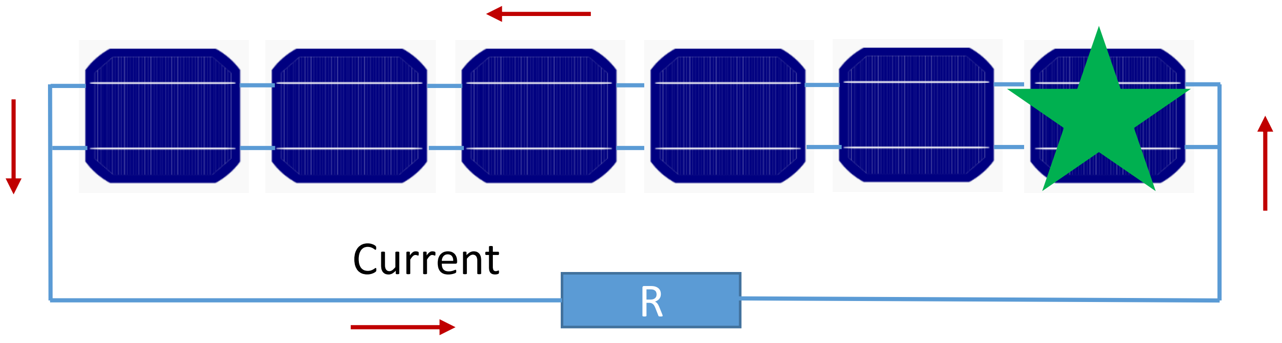
✓ Cell sorting is carried out to categorized cells having matches parameters with specified tolerance.

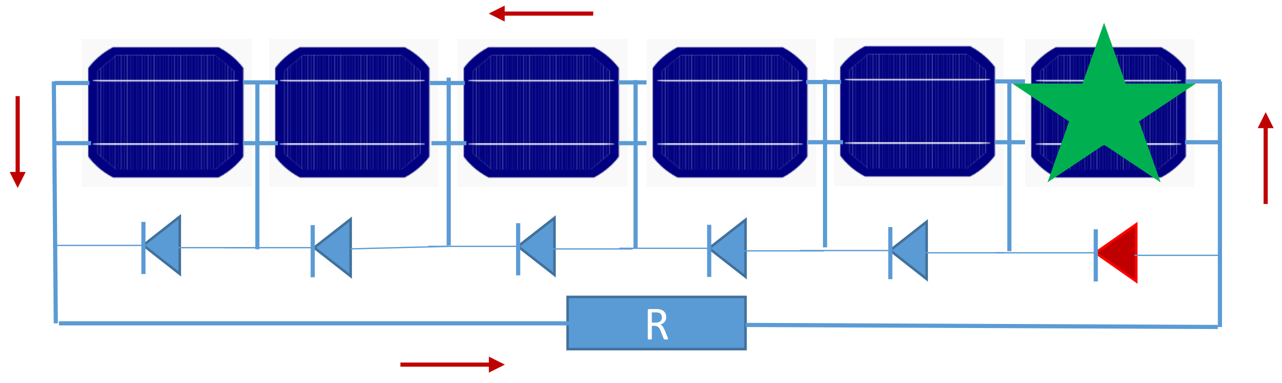
Larger the number of cells in a module. More would be the possibility of quantum of mismatch loss.

Effect of shadowing

- ✓ Partial shading can have significant consequences for the output of solar module.
- ✓ Current generated by shaded cell is significantly reduced.

- ✓ **In a series connection** the current is limited by the cell that generates the lowest current – this cell dictates the maximum current flowing through the module.
- ✓ Shaded solar cell does not generate energy but starts to dissipate energy and heats up – lead to decrease of PV output (encapsulation material cracks /wear out of other material)
- ✓ The problems occurring from partial shading can be prevented by installing bypass diodes in the module.





Current

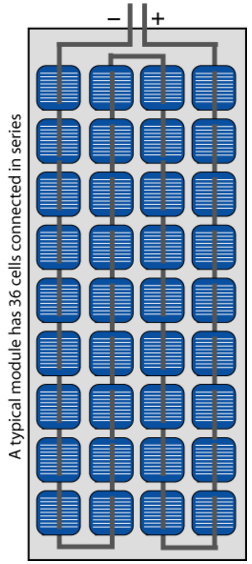
- ✓ Diode blocks the current when it is under –ve voltage
- ✓ Conducts when it is under +ve Voltage

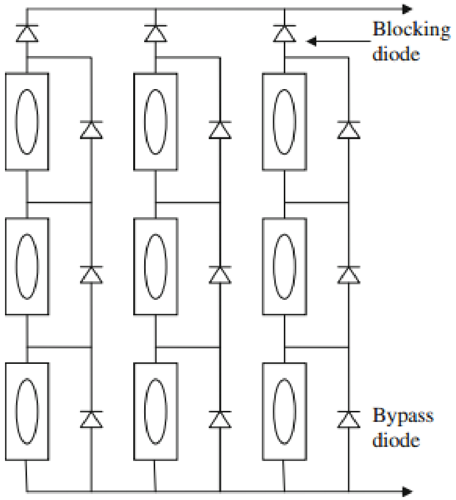
- **When cells are connected in parallel**
    - ✓ Partial shading is less of a problem because the current generated in the other cells do not need to travel through the shaded cell.
- For a module consists of 36 cells in parallel will generate vary high current (above 100 A) combined with a very low voltage (0.6 V). This combination would lead to very high resistive losses in cables.
- Combining the cells in series and using by pass diodes is much better option to do.

- One bypass diode for every 18 crystalline silicon solar cell is provided. Thus the modules having 36 cells would contain two bypass diodes placed inside its terminal box.

Series-parallel connection of modules with blocking and bypass diode

- ✓ In parallel connection, blocking diodes are connected in series, so that if any string fails, the power output of the remaining series strings will not be absorbed by the failed string.
- ✓ Bypass diodes are installed across each module, so that if one module fails, the output of the remaining modules in a string will bypass the failed module.
- ✓ Some modern PV module come with internally embedded bypass diodes.





Packing Factor of the PV Module

The packing factor is defined as the ratio of total solar cell area to the total module area and can be expressed as:

$$\beta_c = \frac{\text{area of solar cell}}{\text{area of PV module}}$$

It is clear that packing factor is less than unity (pseudo solar cell), and it has maximum value of one when all area is covered by the solar cell (e.g., rectangular solar cell).

Efficiency of the PV Module

The electrical efficiency of a PV module, $\eta_{em} = \tau_g \times \beta_c \times \eta_{ee}$

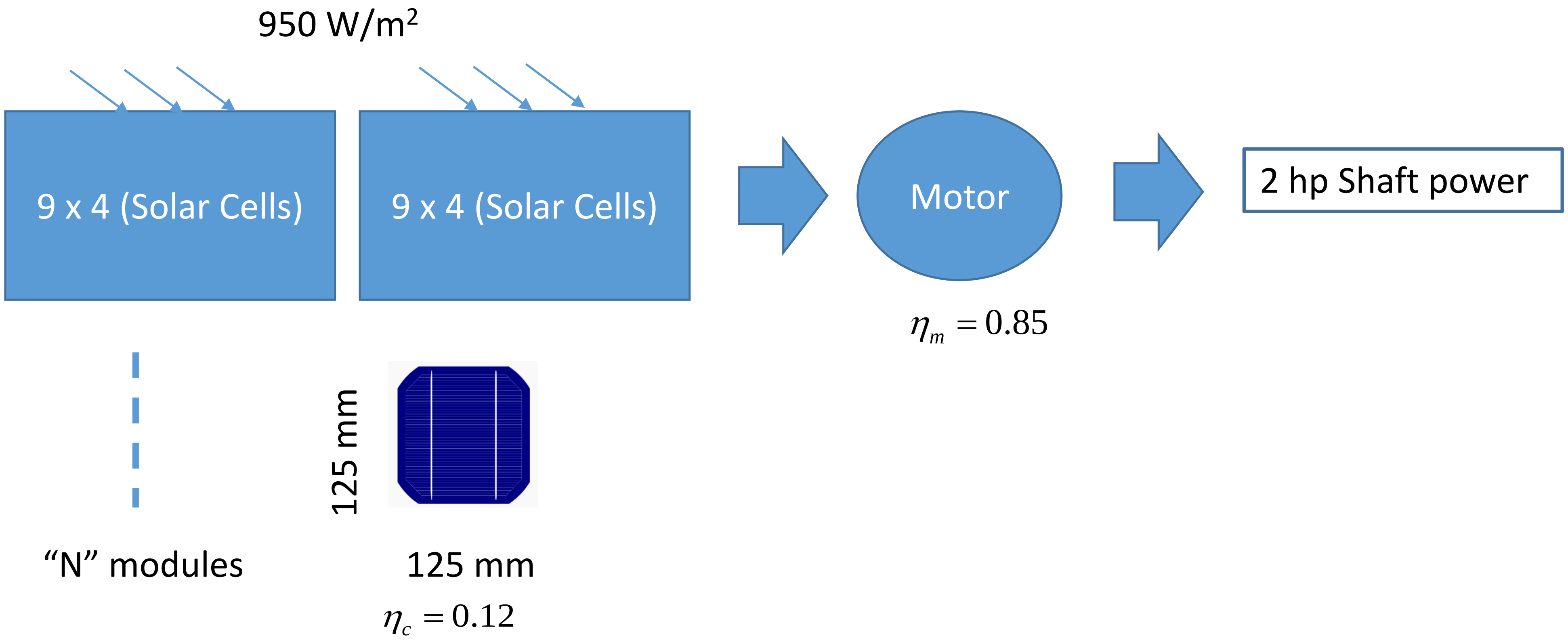
For $\beta_c = 1$ $\quad \eta_{em} = \tau_g \times \eta_{ee}$ $\quad$ or $\quad \eta_{em} = \tau_g \times \left(\dfrac{\mathrm{FF} \times I_{sc} \times \mathrm{V}_{oc}}{\mathrm{A}_m \times I_p} \right) \times 100$

This shows that the electrical efficiency of a PV module is less than the electrical efficiency of solar cell due to presence of glass over the solar cell.

The temperature-dependent electrical efficiency of the PV module: $\eta_{em} = \eta_{mo} \times \left[1 - \beta_0 \left(T_c - 298\right)\right]$

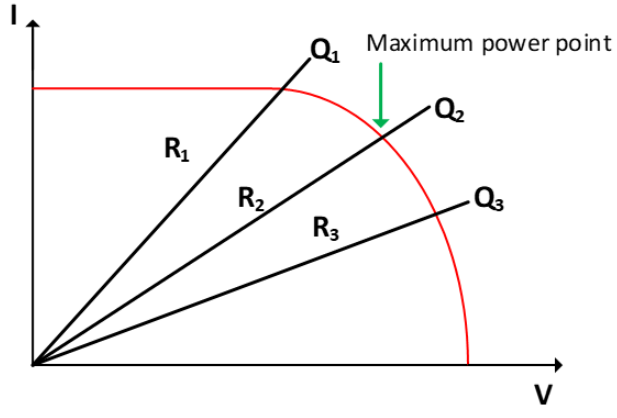
Where, η_{mo} is the electrical efficiency of the PV module under standard test conditions (STC).

Q1: A PV system is utilized to power a DC motor to produce 2 hp shaft power. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in a 9 x 4 matrix. The cell size is 125 mm x 125 mm and the cell efficiency is 12%. Calculate the number of modules required in the in the PV array. Assume global radiation incident normally to the panel as 950 kW/m^2.



Solar PV output maximization

- ✓Mechanically tracking the Sun
- ✓Electrically tracking (by manipulating the load to maximize the power output under changing condition of insolation and temperature)
  - ➢Maximum power point tracker (MPPT)



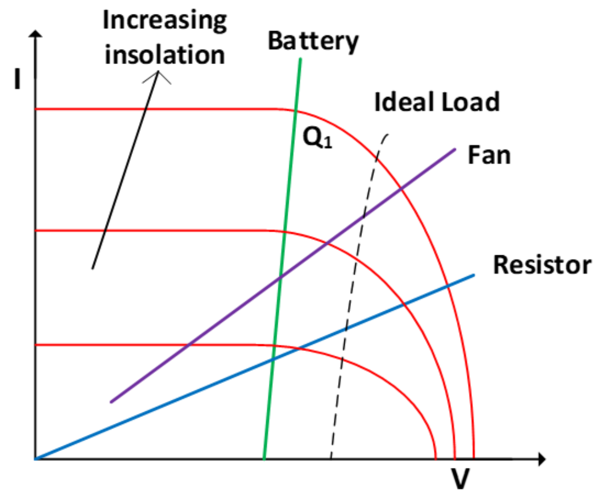
Load matching with reactive load

Load Matching

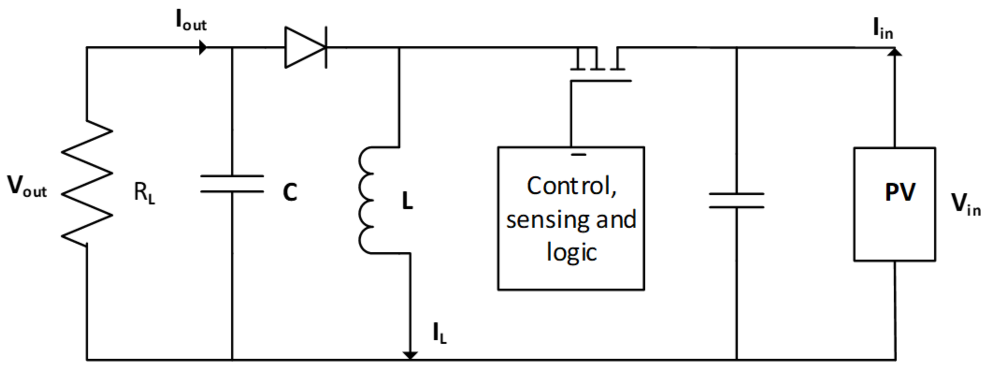
- ✓ The operating point of an electrical system is determined by the intersection of source characteristics and load characteristics.

Maximum power point tracker (MPPT)

- The I-V characteristics keeps on changing with insolation and temperature.
- To receive maximum power, the load must adjust itself accordingly to track the maximum power point.
- An ideal load is one that tracks the maximum power point.
- If the operating point deviates significantly from the maximum power point, it may be desirable to interpose an electronic maximum power point tracker between PV system and load.



- ✓ MPPT is an adaption of dc-dc switching voltage regulator.
- ✓ Coupling to the load for maximum power transfer may require either providing a higher voltage at a lower current or lower voltage for higher current
- ✓ A buck-boost scheme is commonly used with voltage and current sensors tied into a feedback loop using a controller to vary the switching time.



MPPT using buck-boost converter

The power output of PV system is $\boxed{P = V \times I}$

$$P + \Delta P = (V + \Delta V) \times (I + \Delta I)$$
$$\Rightarrow P + \Delta P = V \times I + V \times \Delta I + \Delta V \times I + \Delta V \times \Delta I$$

After ignoring small terms simplifies to

$$\boxed{\Delta P = \Delta V \times I + \Delta V \times \Delta I}$$

$\because \Delta P$ must be zero at peak point.

At peak point the above expression reduces to,

$$\boxed{\frac{dV}{dI} = -\frac{V}{I}}$$

Dynamic Impedance

Static Impedance

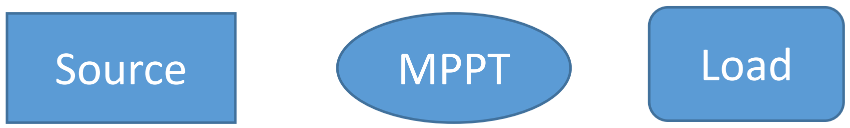
Possible strategies for operation of a MPPT

- By monitoring static and dynamic Impedances
  - ✓A small signal current is periodically injected into the array bus and the dynamic as well as static bus impedance are measured.
  - ✓The operating voltage is then adjusted until the condition Z_d=-Z_s is achieved.
- By monitoring power output
  - ✓Voltage is adjusted and power output is sensed.
  - ✓Operating voltage is increase as long as dp/dV is +ve (increased output).
  - ✓If dp/dV is sensed –ve, the operating voltage is deceased.
  - ✓The voltage is held unaltered if dp/dv is near zero.
- By fixing output voltage as a fraction of Voc (Frictional open circuit voltage method - indirect)

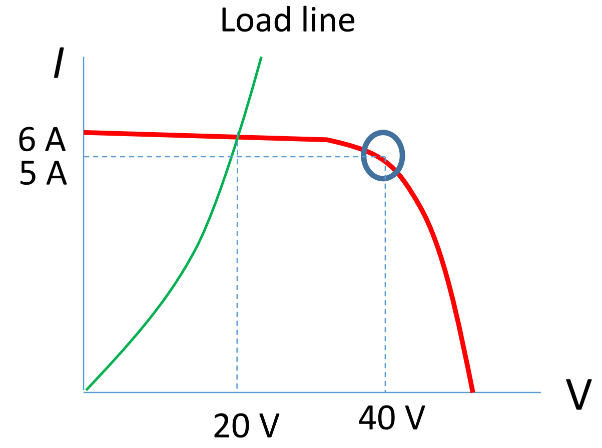
$$\frac{V_m}{V_{oc}} = k \Rightarrow V_m = k \times V_{oc}$$

  - ✓For high quality crystalline silicon cell, *k= 0.72*
  - ✓An additional identical unloaded cell is installed on the array to face same environment as the module in use and its open circuit voltage is continuously measured.
  - ✓The operating voltage of the array is then set at k times Voc

Ex.2: A PV source is supplying power to a load whose line intersect the I-V characteristics at 20 V, 6 A. The voltage and current at maximum power point are 40 V and 5A respectively. Determine the additional power gained if an MPPT is interposed between the source and the load. Consider the efficiency and cost of the MPPT are 93% and Rs.3500 respectively. For how long does the system need to operate in order to recover the cost of MPPT? Assume per unit cost of electricity as Rs.6.5/-.



$$\eta_{\text{MPPT}} = 93\%$$



Load characteristics of PV system

- Power produced (without MPPT) = 20 x 6 = 120 W
- Maximum power production capability of the PV system = 40 x 5 = 200 W
- Actual power produced with MPPT: 200 x 0.93 = 186 W
- Surplus power produced when MPPT is installed = 186 – 120 = 66 W
- Surplus energy produce in t hours = 66x t/1000 = 0.066 x t kWh
- Cost of surplus energy (Rs.) = 6.5 x 0.066 x t = 0.429 x t
- Time required to recover the cost of MPPT, t = 3500/0.429 = 8158.50 hrs

PV Array

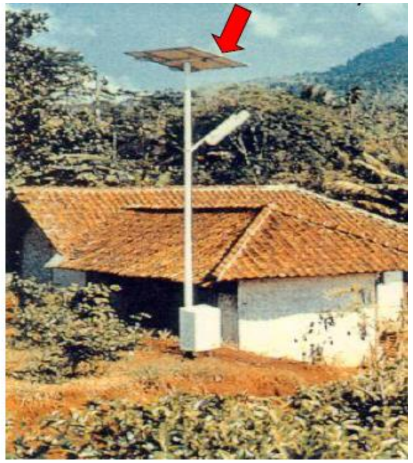
A photovoltaic (PV) array is a collection series or parallel, or both series and parallel, connected photovoltaic (PV) modules.

Solar PV systems

- Central power station system

- Distributed system
  - ***Stand alone system***: It is located at the load Centre and dedicated to meet all the electrical loads of a village / community or a specific set of loads
  - ***Grid interactive system***: This system is connected to the utility grid with two-way metering system. It may be a small roof top system or a relatively bigger system meant for whole village.
  - ***Small system for consumer applications***: These systems are meant for low energy consumer devices requiring power in the range of micro watts to 10W

Module



Solar PV applications

- Grid-interactive PV power Generation
- Water pumping
- Lighting
- Medical refrigeration
- Village power
- Telecommunication and signaling
- Space applications

Specifications of a typical street

- Lighting system
- Module: 1
- Height of pole: 4 m
- Number of lamps: 1
- Type of lamp: CFL (11 W)
- No of Batteries: 1 (12 V, 90 Ah)
- Hours of operation: Dusk to dawn
- Cost : Rs.25000/- appx

Summary

- Classification of PV modules
- Effect of shadowing
- Packing factor and module efficiency
- Ways of maximization of PV module performance
- MPPT and possible strategies for operation of MPPT
- PV Arrays
- PV systems

Thank you