EN671 Solar Energy Conversion Technology

Grid Connected PV System

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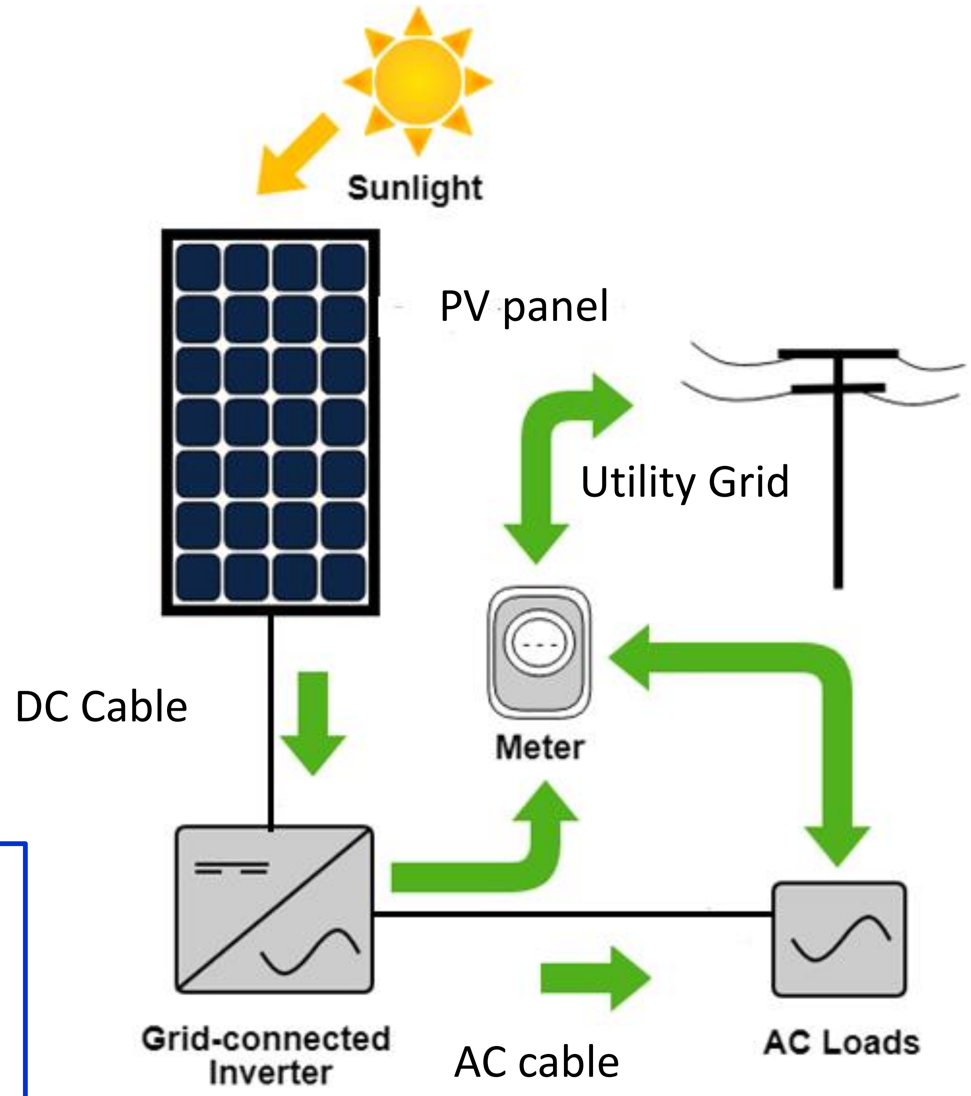
Performance analysis of a grid connected PV system

- Performance assessment of PV systems is the best way to determine the potential for PV power production in an area
- Usually performance of photovoltaic modules refers to Standard Test Condition (STC) which is not always representative for the real module operation
- PV module technology, incident radiation, temperatures, inclination, inverter and control systems, sun-tracker system, and wiring are factors which influence the performance of a PV system

Performance analysis

- ✓ Annual energy yield
- ✓ Reference yield
- ✓ Array yield
- ✓ System losses
- ✓ Cell temperature losses
- ✓ Performance ratio
- ✓ Capacity utilization factor
- ✓ Average pant efficiency



The analysis provides the useful information to policy makers and interested individual and organization about actual performance of grid connected PV system in a region or country.

AC Energy Output of PV array

The AC energy output of a solar array is the electrical AC energy delivered to the grid at the point of connection of the grid connect inverter to the grid.

The output of the solar array is affected by:

- ❑ Average solar radiation data for selected tilt angle and orientation
- ❑ Manufacturing tolerance of modules
- ❑ Temperature effects on the modules
- ❑ Effects of dirt on the modules
- ❑ System losses (eg. power loss in cable)
- ❑ Inverter efficiency
- ❑ Module Efficiency

Performance analysis

The instantaneous power output on the AC side is given by:

$$P_{AC}(t) = A_M G_M(t)\,\eta_M(t)\,\eta_{inverter}(t)\,\eta_{MPPT}(t)\,\eta_{other} \text{.....(a)}$$

The system efficiency is given as:

$$\eta_{system}(t) = \frac{P_{AC}(t)}{A_{tot} G_M(t)} \ldots 100\% \text{ ....(b)}$$

Instantaneous AC-side yield (also known as performance ratio)

$$Y_{ac}(t) = \frac{P_{AC}(t)}{P_{STC}(t)} \ldots 100\% \text{ ....(c)}$$

Then, the yearly energy yield at the AC side can be calculated with

$$E_{AC}^{y} = \int_{year} P_{AC}(t)\, dt \ \ \text{(Wh/year).............(d)}$$

The annual efficiency of the system

$$\eta_{system}^{y} = \frac{E_{AC}^{y}}{E_{i,system}^{y}} .\ 100\% \text{ ....(e)}$$

where, $E_{i,system}^{y}$ is the solar energy incident on the PV system throughout the year.

Performance analysis

Solar energy incident on the PV system throughout the year,

$$E^{y}_{i,system} = A_{tot} \int_{year} G_M(t)\, dt \; ....(f)$$

The yearly electricity yield,

$$Y_E = \frac{E^{y}_{AC}}{N_T \cdot PSTC} \; ....(g)$$

which is given by Wh/(year kW_p).

If the yearly energy yield exceeds the annual load, the system is well designed. Otherwise, another iteration has to be done in order to scale up the system.

Capacity Utilization Factor

CUF is defined as the ratio of actual annual energy generated by the PV system to the amount of energy the PV system would generate if it is operated at full rated power for 24 h per day for a year.

$$\boxed{CUF = \frac{E_{AC}^{Y}}{P_{PV_{rated}} \times 24 \times 365} \times 100}$$

E_{AC}^{Y} = annual ac energy output, kWh

$P_{PV\text{-}rated}$ = rated PV power, kWh

Capacity Utilization Factor

- The capacity utilization factor for a grid connected PV system is also represented by

CUF=(Peak sun hours/day)/24h/day.

✓ If a system delivers full rated power continuously, its CUF would be unity i.e. 100%. CUF is dependent on the location of the PV System.

- The higher the capacity factor, the better the PV system.
- The capacity utilisation factor of all roof top solar PV system in India is 16%–17%.

Energy loss

- The different losses in a PV system include array capture loss, system loss, soiling and degradation losses.

A. Array Capture losses (L_A): Represents the losses due to array operation that highlight the inability of the array to fully utilize the available irradiance.

- – Thermal Capture loss.
- – Miscellaneous capture loss

$$L_A = Y_R - Y_A = \frac{H_T}{H_R}\left(\mathrm{kWh/kW_p}\right) - \frac{\mathrm{E_{DC}}}{\mathrm{P_{PV,rated}}}\left(\mathrm{kWh/kW_p}\right)$$

B. System losses(L_s)

System loss is due to conversion of DC power output from PV to AC by the inverter

$$L_S = Y_A - Y_F = \frac{\mathrm{E_{DC}}}{\mathrm{P_{PV,rated}}}\left(\mathrm{kWh/kW_p}\right) - \frac{\mathrm{E_{AC}}}{\mathrm{P_{PV,rated}}}\left(\mathrm{kWh/kW_p}\right)$$

System analysis

Energy Yield

For a specified peak power rating (kW_p) for a solar array a designer can determine the systems energy output over the whole year. The system energy output over a whole year is known as the systems "Energy Yield"
The average yearly energy yield can be determined as follows:

$$E_{sys} = P_{array\_STC} \times f_{temp} \times f_m \times f_{dirt} \times H_{tilt} \times \eta_{p-inv} \times \eta_{inv} \times \eta_{inv-sb}$$

where
E_{sys} = average yearly energy output of the PV array, in watthours
$P_{array\text{-}stc}$ = rated output power of the array under standard test conditions, in watts

System analysis

Array losses

Energy Yield,

$$E_{sys} = P_{array\_STC} \times f_{temp} \times f_m \times f_{dirt} \times H_{tilt} \times \eta_{p-inv} \times \eta_{inv} \times \eta_{inv-sb}$$

The losses are:

$\rightarrow f_{temp}$ = temperature de-rating factor

$\rightarrow f_{man}$ = de-rating factor for manufacturing tolerance

$\rightarrow f_{dirt}$ = de-rating factor for dirt

$\rightarrow H_{tilt}$ = yearly irradiation value (kWh/m^2) for the selected site

$\rightarrow \eta_{inv}$ = efficiency of the inverter

$\rightarrow \eta_{pv-inv}$ = efficiency of the subsystem (cables) between the PV array and the inverter

$\rightarrow \eta_{inv-sb}$ = efficiency of the subsystem (cables) between the inverter and the switchboard

System analysis

Derating of modules output

Manufacturer Tolerance

Dirt and dust

Temperature

System analysis

Derating of modules output.

Manufacturer Tolerance

Dirt and dust

Temperature

→ The output of a PV module is specified in watts and with a manufacturing tolerance based on a cell temperature of 25 °C.

→ *As an example*, assuming the tolerance is ±5%. The adjusted output of a 160W PV module is therefore around **152W (0.95 x 160W)**, or 5% loss from the rated 160W.

System analysis

Derating of modules output.

Manufacturer Tolerance

Dirt and dust

Temperature

→ Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing PV output.
→ Sand and dust can cause erosion of the PV surface which affects the system's running performance.
→ ***Worked example continues:*** Assuming power loss due to dirt is 5% then the already derated 152 W module would now be derated further to **144.4W (0.95 x 152W)**.

System analysis

Derating of modules output.

Manufacturer Tolerance

Dirt and dust

Temperature

$$T_{op} = \overbrace{T_{amb}}^{28\,^{o}C} + \left(\overbrace{NOCT}^{47\,^{o}C} - 20\right)$$

$$T_{op} - T_{STC} = 55 - 25 = 30^{o}\,C$$

→Output power of a PV system reduces as the module temperature increases.

→The losses due to temperature is based on the temperature coefficient.

→Assume 160Wp rated polycrystalline module module is used with a derating of -0.5%/°C.

→The output power losses due to the operating temperature of 30 °C would be:

→**30 °C x 0.5 %/ °C = 15% loss**

→***Worked example continues:*** Assuming power loss due to temperature of 15% then the already derated 144.4 W module would now be derated further to **122.7W (0.85 x 144.4W)**.

System analysis

Derating module summary

Manufacturer Tolerance

Dirt and dust

Temperature

A solar module has an derated output power = Module power @ STC x Derating due to manufacturers tolerances x derating due to dirt x derating due to temperature.

For the worked example:
Derated output power = 160 x 0.95 x 0.95 x 0.85 = 122.7W

System analysis

DC Energy Output from Array

- The actual DC energy from the solar array = **the derated output power of the module x number of modules x irradiation for the tilt and azimuth angle of the array.**

- ***For the worked example*** assume that the average daily PSH is 5 and that there are 16 modules in the array. Therefore the DC energy output of the array = **122.7 x 16 x 5 = 9816Wh**

Note: Solar irradiation is typically provided as kWh/m^2 . However it can be stated as daily Peak Sun Hrs (PSH). This is the equivalent number of hours of solar irradiance of $1kW/m^2$.

System analysis

DC system losses

- The DC energy output of the solar array will be further reduced by the power loss in the DC cable connecting the solar array to the grid connect inverter.

- ***For the worked example*** assume that the cable losses for the DC cables is 3%. This is a DC subsystem efficiency of 97%. Therefore the DC energy from the array that will be delivered to the input of the inverter will be **= 9816 x 0.97 = 9521 Wh**

System analysis

Inverter efficiency

- The DC energy delivered to the input of the inverter will be further reduced by the power/energy loss in the inverter.

- *For the worked example* assume that the inverter efficiency is 96%. Therefore the AC energy delivered from the output of the inverter will be **= 9521 x 0.96 = 9140 Wh**

System analysis

AC system losses

- The AC energy output of the inverter will be further reduced by the power loss in the AC cable connecting the inverter to the grid, say switchboard where it is connected.
- **For the worked example** assume that the cable losses for the AC cables are 1% (AC subsystem efficiency of 99%). Therefore the AC energy from the inverter (and originally from the array) that will be delivered to the grid will be **= 9140 x 0.99 = 9048 Wh**

System analysis

Specific Energy yield

The specific energy yield is expressed in kWh per kWp and it calculated as follows:

$$SY = \frac{E_{sys}}{P_{array\_STC}}$$

- *The worked example:* *A*n array of 16 modules each with a STC rating of 160Wp. Therefore P_{array_STC} **= 2560 Wp**.
- The average daily AC energy that was delivered by the array to the grid was 9048Wh or 9.05kWh.
- Therefore over a typical year of 365 days then Energy Yield of the solar array is = **365 days x 9.05 kWh/day = 3303 kWh/year**
- Therefore the specific energy yield is **3303/2.560= 1290 kWh per kWp**

System analysis

Ideal Energy

The PV arrays ideal energy yield E_{ideal} can determined as follows:

$$E_{ideal} = P_{array\_STC} \text{ X } H_{tilt}$$

H_{tilt} = yearly average daily irradiation, in kWh/m^2 for the specified tilt angle

P_{array_STC} = rated output power of the array under standard test conditions, in watts

For the worked example: The average daily PSH was 5. Therefore the yearly irradiation (or PSH) would be **5 x 365= 1825 kWh/m^2** (that is 1825 PSH).

$$\boldsymbol{P_{array\_STC}} = \mathbf{2560\ Wp}\ (@1\ \text{kWh/m}^2)$$

Therefore the ideal energy from the array per year would be:

2.56kW x 1825h = 4672kWh

System analysis

Performance ratio

The performance ratio (PR) is used to access the installation quality. The PR provides a normalized basis so comparison of different types and sizes of PV systems can be undertaken. The performance ratio is a reflection of the system losses and is calculated as follows:

$$\mathbf{PR} = \frac{E_{sys}}{E_{ideal}}$$

where

E_{sys} = Actual yearly energy yield from the system

= 3303 kWh/year (continuing example)

$E_{\ ideal}$ = the ideal energy output of the array

= 4672 kWh/year (continuing example)

Therefore, Performance ratio, $\text{PR} = \frac{E_{sys}}{E_{ideal}} = 3303/4672 = 0.71$

- Hence the system losses is 29% (that is 1-0.71=0.29)

Average System Efficiency and CUF

Average System Efficiency

$$\eta_{System}(t) = \frac{E_{AC}^{Y}}{A_{tot} G_M(t)} \times 100\%$$

Average System Efficiency = 3303/365*5*1*16*72*0.125*0.125 = 10.05%

- Capacity Utilization Factor

$$CUF = \frac{E_{AC}^{Y}}{P_{PV_{rated}} \times 24 \times 365} \times 100$$

- CUF = (3303 kWh/0.160x16x24x365)*100% kWh= **14.72%**

Summary

- Systematically studied the performance analysis of a Grid connected PV system having PR =0.71 (system losses 29%)
- An example analyzed to determine the energy yield, specific yield, performance ratio, capacity utilization factor and average system efficiency of a grid connected PV system
- Understand how the real performance of the plant is deviating from the theoretical performance

✓ Rate power output of the module = 160 Wp
✓ Derated power output of the module = 160 x 0.95 x 0.95 x 0.85 = 122.7W

Thank you